Organic User Interfaces for Interactive Interior Design

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Dedication

I would like to dedicate this thesis to my loving family…

My mum, the Chief Architect Officer, the designer, tailor, crafter and maker.

My dad, the Professor of Architecture, the researcher, educator, author and inventor.

My dear husband, to whom I owe so much, the love, compassion and understanding.

My adorable daughters, Janna & Mariam, for whom I am deeply thankful.

You were all part of this.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and acknowledgements. This dissertation contains fewer than 80,000 words excluding appendices and bibliography.

Sara Nabil
March 2020

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بسم الله الرحمن الرحيم . الحمد لله رب العالمين

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Abstract

Organic User Interfaces (OUIs) are flexible, actuated, digital interfaces characterized by being aesthetically pleasing, physically manipulated and ubiquitously embedded within real-world environments. I postulate that OUIs have specific qualities that offer great potential to realize the vision of smart spaces and ubiquitous computing environments. This thesis makes the case for embedding OUI interaction into architectural spaces, interior elements and decorative artefacts using smart materials – a concept I term 'OUI Interiors'. Through this thesis, I investigate: 1) What interactive materials and making techniques can be used to design and build OUIs? 2) What OUI decorative artefacts and interior elements can we create? and 3) What can we learn *for design* by situating OUI interiors? These key research questions form the basis of this PhD and guide all stages of inquiry, analysis, and reporting.

Grounded by the state-of-the-art of Interactive Interiors in both research and practice, I developed new techniques of seamlessly embedding smart materials into interior finishing materials via research through design exploration (in the form of a Swatchbook). I also prototyped a number of interactive decorative objects that change shape and colour as a form of organic-actuation, in response to seamless soft-sensing (presented in a Product Catalogue). These inspirational artefacts include table-runners, wall-art, pattern-changing wall-tiles, furry-throw, vase, cushion and matching painting, rug, objets d'art and tasselled curtain. Moreover, my situated studies of how people interact idiosyncratically with interactive decorative objects provide insights and reflections on the overall material experience. Through multi-disciplinary collaboration, I have also put these materials in the hands of designers to realize the potentials and limitations of such a paradigm and design three interactive spaces. The results of my research are materialized in a tangible outcome (a Manifesto) exploring design opportunities of OUI Interior Design, and critically considering new aesthetic possibilities.

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Chapter 1. Introduction

1.1 Overview

Interior design is not just about style, but rather takes a holistic view of the way that people use and enjoy the spaces that they inhabit (Dodsworth, 2009). Interior design does not only imply space renovation and refurbishment, but also incorporates the design and realization of the decorative scheme of the space. The meaning of a 'decorative scheme' goes beyond the superficial and shallow term of 'decoration', to include the careful choice of all the interior elements, binding them together, and introducing *variety* that complete the sensory experience of the space (Dodsworth, 2009). In his book on "The Fundamentals of Interior Design", Simon Dodsworth introduced interior decoration as the "human interface", where its elements define the space and are the prime communicators of the designed environment.

Despite this, the fields of Human-Computer Interaction (HCI) and User Interface (UI) design have not introduced much to interior design beyond Graphical User Interfaces for Computer-Aided Design (CAD) tools which support the design process itself. However, interaction design has more to offer to interior design practice in terms of the physical space elements themselves. From Weiser's Ubiquity (Weiser, 1991) to Ishii's Radical Atoms (Ishii et al., 2012), HCI research has been trying to bridge the gap between our digital interfaces and our own physical environments. The recent notions of Human-Building Interaction (Alavi et al., 2016) and Interactive Architecture (Dalton et al., 2016) suggest new directions to address this field, such as adaptive architecture, transformable materials and tangible or organic interfaces. Following the first (i.e. man-machine coupling) and second (i.e. information communication) interface paradigms (Harrison et al., 2007), Organic User Interfaces (OUI) lie in the third generation of interface paradigms (i.e. situated interaction in our environment) and have recently seen increased interest amongst the Human-Computer Interaction (HCI) research community (Coelho et al., 2009; Girouard et al., 2011, 2013).

OUIs are defined as tactile and flexible interfaces that may include both sensing and actuation capabilities allowing for more natural interaction in everyday environments (Holman and Vertegaal, 2008; Vertegaal and Poupyrev, 2008). Within the paradigm of OUIs, entire buildings could be reshaped as computers (Oosterhuis and Biloria, 2008) made out of networks of actuated and interactive OUIs in a framework where the environment *is* the interface (Vertegaal and Poupyrev, 2008). In this sense, everyday objects, surfaces and spaces can be capable of both displaying information and being used as interactive interfaces, which can have flexible shapes and, beyond that, dynamically change their appearance, colour, or physical form. Instead of being rigid and static, everyday objects of tomorrow will have interactive and morphological capabilities that accommodate the context of use (Girouard et al., 2013). Apart from typical rigid sensors, emissive displays and motor actuators, OUIs can be designed using soft circuits of connected e-textiles, capacitive sensing fabrics, and flexible sensors to detect input interactions, alongside shape-changing threads and wires, with colour-changing pigments, employed as output modalities. Equipped with such sensing and actuating capabilities, OUIs enable a range of interactive responses to user input that aim to leverage the nuanced and complex ways in which humans already interact with and manipulate regular everyday objects.

In this sense, HCI and interaction design have wide potentials to offer to interior design. Such computational technology and ubiquitous interactions lie in HCI within notions of "Physical Computing" in general; "Ambient Technology" especially heat and light-based interactions; "Calm Technology" (Weiser and Brown, 1996) representing the abundance of emissive displays and other demanding technology; "Embedded", "Embodied" and "Wearable Computing" specifically for bodily-attached garments and wristband gadgets; "Tangible User Interfaces" (TUI) (Ishii, 2008b,a) for physical objects; "Shape-Changing Interfaces" (SCI) (Rasmussen et al., 2012) for mostly motor-based actuations; and "Organic User Interfaces" (OUI) (Vertegaal and Poupyrev, 2008) to emphasize the potential morphological and malleable capabilities of interfaces as everyday things. Terms like "soft interfaces", "smart fabrics" and "e-textiles", among others, imply different priorities, and connotations, but their interchangeable use is common, and are included in the OUI notion. The conflated use of terms is also a reflection of the multi-disciplinary legacy of the field as well as being relatively new.

Through exploring and delineating these concepts as the paradigms of post-WIMP interfaces and ubiquitous computing, I refer to my interfaces as OUIs, being the most physically flexible, deformable and tactile by definition (Vertegaal and Poupyrev, 2008). In this thesis, I present the idea of interactive interior design and explore how we can make decorative artefacts that are user interfaces. Accordingly, a specific subset of OUI applications is explored to 1) highlight the opportunities and potentials of designing interactive interior spaces; and 2) demonstrate the use of different interactive materials within decorative interfaces. The latter includes interactive interior artwork, actuating decorative elements, interactive tableware and responsive interior objects. Figure 1.1 illustrates examples of OUI interior decorative objects in Interaction Design and HCI literature.

Early explorations of OUI followed two directions for designing and prototyping interactive surfaces and artefacts: i) using relatively expensive emissive and flexible display technologies (e.g. OLED (Organic Light Emitting Diodes) (Coelho et al., 2009)), that are significantly limited with regard to the scalability and affordability of the end product thus narrowing the design space to emissive displays; and ii) supporting and facilitating rapid prototyping using screen projection on non-interactive materials (e.g. normal paper (Holman and Vertegaal, 2008), cardboard (Akaoka et al., 2010) and fabric (Lepinski and Vertegaal, 2011)), to simulate the interaction with their designs. Transitioning between (i) emissive displays and (ii) screen projection, a lot of tactility and natural interaction is lost, rendering everyday materials hardly interactive.

Figure 1.1 Examples of interactive decoratives: a) Anabiosis (Tsuji and Wakita, 2011), b) History Tablecloth (Gaver et al., 2006), c) LivingWall (Buechley et al., 2010), d) Soft-User-Interfaces (Sugiura et al., 2011)

With the availability of a large range of new interactive materials that are relatively inexpensive and easy to use, researchers and practitioners are now – technologically – in a position to design and build a new generation of interactive spaces, surfaces and artefacts that are affordable, scalable and interactively more deformable than ever before. Examples of such interactive materials are low fidelity capacitive materials, soft and flexible sensors and morphological materials such as hydromorphic, photomorphic and thermomorphic materials that change their appearance (shape or colour) by reacting to change in humidity, light or heat (respectively). Therefore, such smart materials can be both electronically and/or physically controlled and programmed to be interactively responsive to inhabitants of a space, the environment within it or with one another. Yet, despite their great promise their widespread uptake has been slow, such that organic (that is soft, flexible and morphic) user interfaces are currently unlikely to be found within real-world interior spaces or as part of everyday products (Nabil et al., 2017b).

This thesis makes the case for the opportunity of embedding interaction into architectural spaces, interior elements and decorative artefacts, not as stand-alone digital devices, but seamlessly using smart materials – a concept I term 'OUI Interiors'. I have developed this concept through exploring the potentialities and affordances of particular sensing and actuating materials via a series of design experiments as a process of 'research through design' (Stappers and Giaccardi, 2017). I argue that everyday interior elements that are physically interactive, aesthetically pleasing, and morphologically mutable, can potentially be key to productively, embedding ubiquitous interaction within our interior spaces. With this vision, a new generation of 'smart spaces' might be possible in the near future. To explore this novel concept, I propose the use of a set of 'smart materials' as a means of sensing and actuation that are paintable, printable, sewable, weavable and programmable onto everyday finishing materials, such that interactivity might be (sometimes literally) woven into the building fabric. In order to support designers who wish to work with these materials, and who wish to realize the interactive potential of OUI Interiors, this research has developed a detailed guide about how such smart materials support and facilitate designing smart spaces of tomorrow in the form of interactive interior spaces, surfaces and soft furnishings.

It is worth mentioning that this research is not suggesting that we should only adhere to 'decoration' in designing interactive objects and surfaces, but rather suggesting that the time is right for interior interaction design to evolve beyond conventional switches, LEDs, motor actuators and emissive displays. It is indeed a missed opportunity that recent work is still depending on such interface elements which -despite establishing a breakthrough in their time- do not achieve seamlessness or work towards Weiser's vision of how "technology will disappear in the background" (Weiser, 1991). Although physical computing paradigms such as TUI and SCI are promising to bring us closer to 'ubiquity with everyday objects' and make 'our surrounding environment become the interface', it is not realistic to claim that LEDs, motors and digital displays can form natural interaction or create normal everyday objects. Consequently, the aim of this research project is to investigate the potential of smart materials to seamlessly embed interactive capabilities into everyday objects without losing their common affordances and aesthetic expectations. This research utilizes decorative objects and interior elements as a vehicle for experimenting with and validating this vision.

1.2 Motivation

My personal motivation behind the work undertaken in this PhD stems from both my background knowledge and personal passion. My childhood dream was always to pursue a career in 'interior design', but I eventually studied computing, due to family ties. Progressing in my profession led me to senior-level expertise in software development. Alongside, training and steering another parallel career in the interior design practice contributed to my faculty for designing and managing residential refurbishment projects as a business. These two concurrent paths reshaped my vision and purpose into a new interdisciplinary practice of merging interaction design with interior design. My hypothesis was that blending technology into our built environment in seamless and aesthetic ways can introduce new dimensions of living quality and that building interactive spaces can help us explore the experiential impacts of this paradigm.

My main driver for developing 'OUI Interiors' was to turn everyday objects in interior spaces (such as table runners, cushions, throws, wallpaper, paintings and objets d'art) into interactive artefacts that can change their appearance dynamically, either passively or actively, responding to interactions with (or between) space occupants. By redesigning these objects to include seamless sensing and actuation capabilities (woven into the material of the objects themselves) they will be able to sense and respond to presence, movements, or physical manipulations. Such interactive capabilities can trigger alterations of their appearance, pattern and/or shape, with the goal of exploring how this might engage, motivate and inspire the space occupants and support new kinds of relationship to both the designed objects and the built environments housing them.

This motivation also came from the opportunity to create non-static multi-faceted artefacts (Davis et al., 2013) that embody dynamics and playfulness, reflecting more subtle and poetic (Berzowska, 2005) aspects of the identity of both people and places, as well as supporting their well-being and enhancing their quality of living. The motive behind this research is to 1) explore the potentials, affordances, and limitations of interactive spaces and decorative artefacts, 2) investigate how people interact with, interpret and experience seamless sensing and actuation, and how it might change their experience of space and activity, and 3) explore, from a practice-based perspective, possibilities and areas of future development for interactive spaces and materials.

The inspiration behind considering aesthetics here comes from the fact that not only the design of an object or a product determines the tendency of people to adopt it and want to live with, but also because the design of the space and objects within it -being functional as furniture or decorative as wall art- contributes essentially to quality of living experience of people inhabiting or using the space. In essence, interior adornment serves a purpose in people's lives that goes beyond that of functionality, even within contexts of austerity, decorating spaces is a valuable and vital aspect of living, coping and supporting people's sense of identity and pride (Nabil et al., 2018b). Accordingly, technology can help create new opportunities for how people share their spaces and resources in ways that suit their identity and needs, potentially empowering them to craft their own dynamic spaces and artful designs.

The general benefits of interactive interior interventions have been discussed in related prototype installations (Gaver et al., 2006; Meese et al., 2013; Mennicken et al., 2014b), which only scratch the surface of possibilities for promising smart and dynamic spaces yet to come, providing people with potential benefits at both the emotional and physical level. Beyond academic demonstrations, this research project brings the field of interior design to HCI, offering a challenging context for this kind of design-making-deploying type of 'Research-through-Design' that paves the way for investigating challenges of resilience, issues of contextually relevant behavioural repertoires, cultural and contextual affordances, and challenges of designing technologies to live with, rather than to evaluate at the lab. Moreover, by embracing an interior design perspective, we can seize the opportunities of how the emotional and psychological effect of interactive interiors, e.g., colours, lights, shapes and textures, can have a significant impact on space occupants, potentially leading to improved quality of life through novel, possibly serendipitous experiences and sensory stimulations (Nabil et al., 2017b).

1.3 Research Questions

This PhD research aims to define and explore the design space of interactive interiors and encourage both researchers and practitioners to adopt and develop OUIs as a means of creating the next generation of smart spaces. To achieve this goal, I have designed and developed several actuating artefacts that can change their physical form, shape or appearance as a means of interaction with users i.e. space occupants. I have studied OUIs as decorative artefacts in different environments, collaborated with designers, recruited participants, installed and evaluated these interfaces in situated studies, to evaluate how people perceive, interact with and experience such OUIs. The interfaces are everyday decorative objects and are not meant to be alien-looking devices or stand out from their settings. Finally, designing and building these interactive artefacts and spaces helped to understand this novel design space and answer the research questions of this project.

The overall theme and main aim of this research is to **explore the design space, opportunities and challenges of creating interactive spaces with OUIs**.

With this aim in mind, the research addresses the following research questions:

1. **What interactive materials and making techniques can be used to design and build OUIs?**

   OUI interior artefacts should be designed using seamless sensing and actuation embedded ubiquitously within everyday materials. What are the materials that have physical sensing or morphological properties and can be painted, stitched or weaved inside soft furnishing and decorative elements? What are the crafting and making techniques that can help us embed such smartness into interior designs? And how can we program and control these 'smart materials'? Design knowledge gained from designing of (and with) materials can bring insights towards new materialities, interactions, animations and morphological capabilities of everyday materials, objects and spaces.

2. **What OUI decorative artefacts and interior elements can we create?**

   If there are interactive materials that can be embedded seamlessly within everyday physical objects, what can we make with them? What could we use these materials for in an interior setting? How can we use such making and crafting techniques to build interactive decorative objects and design interior spaces? Different objects have different affordances that should not be compromized. Soft furnishing, in particular, should stay soft and malleable, with no rigid parts or perceptible electronic circuits that could -in many cases- jeopardize the aesthetics and associated norms of this everyday object. Can we make a fully-functioning interactive painting, that looks like a normal piece of wall-art, with no hole in the wall? Is a soft interactive cushion with no rigid inner-body and no external power cable feasible? These practical concerns place great challenges to creating interactive artefacts and spaces on top of the technical, aesthetic and experiential limitations associated.

3. **What can we learn *for design* by situating OUI interiors?** Situating OUI decorative prototypes in real-world settings and studying the aesthetic experiences, materialities and interactivities outside a lab setting can help produce insights and contribution to the knowledge of interactive spaces and artefacts. What interesting aspects can be possibly drawn from getting people to use such designs in situated deployments? Could OUI Interiors enhance user spatial experience enable positive interpersonal/social interactions? How would people experience them and how would they perceive their interactive spaces and artefacts? And would that change the way people perceive and interact with their daily physical objects and with each other?

   Situating OUI design resources in designers' practices and developing OUI prototypes with them can also help produce insights for design and explore a wide range of opportunities and limitations. How will designers (re)create their designs to be interactive and think through their interactive and experiential qualities? OUIs should be designed with a different set of values and functionalities in mind when set to be deployed in different contexts. This can be addressed through critically reflecting on the materials themselves in addition to encounters with people in different settings.

In order to answer these research questions and reach an understanding of the overall design space of OUIs, this research project involves the design of OUI decorative artefacts and the study of OUI interior spaces and artefacts that I have designed and/or enabled designers to develop. Throughout the project, I have designed and crafted ten different OUI decoratives to exemplify interactive interior elements. Two of which were deployed in-the-wild (restaurants, café and home) as case studies that validate and evaluate the overall concept of OUI interiors. Moreover, my situated studies include two multi-disciplinary collaborations with design practices of architecture and interior design generating transferable deeper insights on designing interactive interior design.

1.4 Thesis Structure

As shown in figure 1.2, the road map of this thesis consists of seven chapters. Chapter 1, the present chapter, serves as an **introduction** to the general topic and summarizes the objectives and motivations for the dissertation. Furthermore, the chapter presents the three research questions of this PhD research project, the structure outline and the key contributions of this thesis.

After this introduction, Chapter 2 re-envisions smart spaces and contextualizes this research with regards to the **literature review** on Organic User Interfaces (OUI) and relevant previous work on three levels: i) interior spaces, ii) decorative objects, and iii) OUI materials. These levels are not independent but can often be overlapping and are highly intertwined. Through examining the state-of-the-art in such OUI relevant work, I lay out the design space of OUI Interiors and the play-of-possibilities that they can offer. The review draws on HCI and interaction design literature as well as work in practice in the fields of architecture and interior design. The chapter identifies gaps in existing literature and design practices that this research endeavours to address and offers a context, position and grounding for this research.

Chapter 3 explains the **methodological approach** on which this research project was based. Through a research-through-design approach, this project took the vision into practice, by extensive experimentation and exploration of materialities, methods and tools. This exploratory process relied mainly on three methodological strands i) Critical Making, ii) Critical Speculation, and iii) Critical Engagement. In this chapter, I explain each of these methodological strands and how it is employed in my research. My critical making has been systematically documented by photographs, shots of video recording footage and observations, all of which were noted in a lab book as a form of 'annotated portfolio' (Bowers, 2012) (see Appendix A). The critical speculations developed included both diegetic and mimetic elements, represented in the form of a design catalogue (see Appendix B) and design fiction stories (see Appendix C). Finally, the situated deployments of the critical engagement strand place this paradigm in the hands of both end-users and designers. Such accounts are then analysed using qualitative analysis of individual interviews, group discussions and design crits. All these forms of research-through-design outputs helped shape the exploratory nature of the project in a self-reflecting and developing experimental design process.

The next three chapters delve into the three entangled threads of work in this research: i) experimenting materials, ii) prototyping decorative OUIs and iii) studying OUI artefacts in real-world settings and design practice. These three activities overlapped, interrelated, and progressed in parallel rather than sequentially, but -for the clarity of their accounts- are discussed in three chapters (4, 5 and 6) within the thesis.

Chapter 4 explores **OUI materials** that are embeddable in interior finishing, have interactive capabilities appropriate for building interactive decorative artefacts. Commencing my research-through-design with sketching and digital illustrations of my designs and ideas, I start my exploratory journey of crafting and making with soft-sensing, colour-changing and shape-changing materials. The latter being the most sophisticated, required me to undergo a series of systematic experiments on 100+ samples of soft actuation to reach a level of understanding

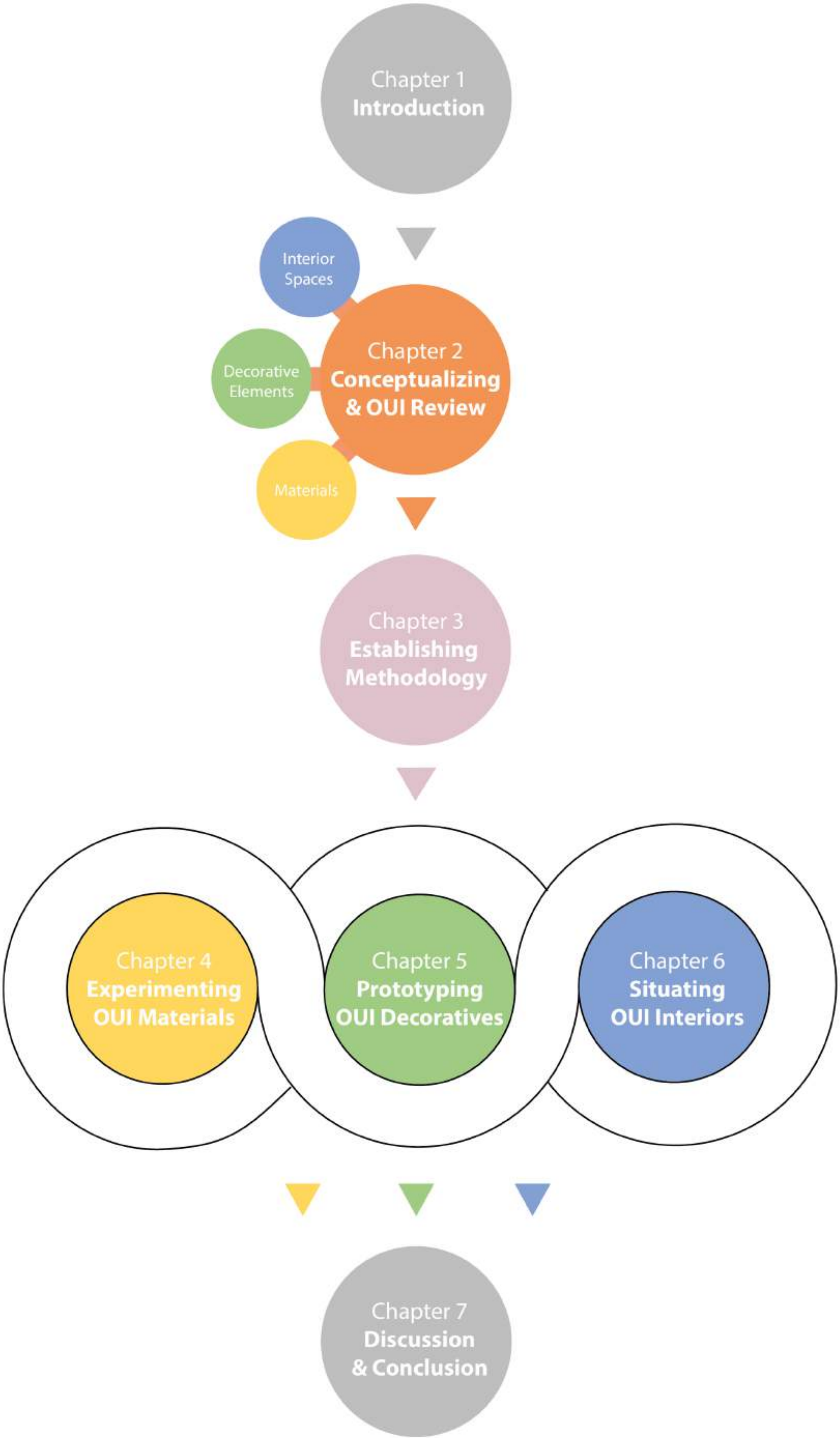

Figure 1.2 The thesis roadmap

of the material behaviour and its interactive, multi-faceted and aesthetic qualities. The chapter presents this flow of learning through making and introduces a number of the novel techniques I have developed for achieving my OUI concept of aesthetically-seamless technology. From hand painting and tie-dyeing to machine-sewing and embroidery, different crafting techniques utilized to embed everyday materials with interactive capabilities are of great benefit and are crucial to designing OUI artefacts and spaces.

Chapter 5 presents the design and prototyping of **OUI decoratives**. By exploring the aesthetic and sensory experiences of materials in the form of interactive objects, I draw insights and design knowledge from both the *making* and *use* of OUI artefacts. Through ideation of the design concepts, to the crafting, making and implementation phases, each developed prototype produced valuable and practical insights. Such designs and implementations, together, serve as inspirational artefacts that embody learnings from (and to) Chapter 4 and feeds back knowledge towards future iterations of the same artefact and/or further design work of other artefacts.

Chapter 6 discusses studying **OUI interiors** in a number of situated studies, some of which are real-world deployments, while others are situated in design practices. The former studies were carried out in the wild to capture how people would perceive, interact and respond to such design interventions. The qualitative data from these studies were analysed using a 'Thematic Analysis' process to understand people's behaviour, engagement and expectations of OUI designs. Two more case studies were inter-disciplinary work with collaborators from the fields of architecture and interior design practice. These practitioners were all wishing to engage in and realize innovative designs of interactive interior spaces and artefacts.

Chapter 7 outlines key findings in a **discussion** that unpacks all the case studies and draws them together with reflections on the materiality experience and sense-making, the aesthetic qualities and value of my designs, and their complex behavioural repertoire. In doing so, I discuss notions of discoverability, revelation and multi-faceted aesthetics, or multi-aesthetics, as well as spatio-temporality, spatio-autonomy and interdisciplinarity as key considerations for designing interactive interior spaces and artefacts. Then, the set of opportunities and benefits for the role of OUIs in interior design are highlighted, as a tangible outcome, in the form of a Manifesto of interactive interior design. The challenges for researchers and practitioners are articulated afterwards identifying the most important aspects that future research needs to address as the 'way forward'. Finally, the chapter and the thesis both come to an end with a final **conclusion** clarifying how the vision of OUI interactive interiors has never been closer to realization.

1.5 Contributions

My PhD research has culminated in a body of work, both physical and conceptual that has relevance for both design practice and theory. The key contributions to knowledge are claimed in 3 main areas:

1. **Practical resources for making** and makers of OUI interactive interior spaces and decorative artefacts blending ubiquitously into our environments, rather than standing out as digital devices. Such use of smart materials generated a contribution in threefold:
   (a) Identifying the range of materials with sensing or morphological capabilities that can be seamlessly embedded into everyday finishing materials (e.g. fabric, leather, acrylic, wood, paper, ceramic) and categorizing them in a **taxonomy** that lays out a *palette of smart materials* which can be used to realize OUI Interiors.
   (b) Introducing **novel techniques** for embedding both sensing and morphological actuation into fabrics (e.g. machine-sewing shape-changing materials, digital embroidery of touch-sensing) in addition to identifying the *design factors/ parameters* that directly affect the deformation intensity of malleable and soft materials when embedded with shape-changing materials.
   (c) Generating a **swatch book** physical portfolio of such techniques and materials with technical, practical and aesthetic potentials of each.
2. **Inspirational artefacts** and interactive spaces that embody my learning of designing and making OUIs. A **design catalogue** that presents these artefacts in a format that can better inform professional design practice, utilizing the common plot devices (Blythe, 2017) of a well-understood format for presenting designs, in the form of a product catalogue.
3. **Critical reflections** on the design space, opportunities and challenges of OUI Interactive Interiors from situated studies in both design practices and real-world deployments. This contribution does not only expand on previous knowledge of OUI blending its interaction with interior design and interior decoration, but also yields a **manifesto** for OUI Interiors and identifies both the *opportunities* and the ‘way forward’ in terms of the key *challenges* that need to be addressed.

1.6 Publications

Some of the work presented in this thesis was published throughout the course of this research in the form of conference and journal papers (see Appendices E - H). While the writing of these publications was often undertaken in collaboration with supervisors and colleagues which have undoubtedly shaped the development of this research, I will predominantly focus in this thesis on my individual contribution and my creative practice which these publications present.

Conference Papers

1. **Sara Nabil**, Jan Kučcera, Nikoletta Karastathi, David Kirk, Peter Wright (2019). Seamless Seams: Crafting Techniques for Embedding Fabrics with Interactive Actuation.

   In Proceedings of the 2019 Conference on Designing Interactive Systems (DIS'19), 987-999, San Diego, CA, USA. *(Chapter 4)*

   DOI: https://doi.org/10.1145/3322276.3322369

2. **Sara Nabil**, Aluna Everitt, Miriam Sturdee, Jason Alexander, Simon Bowen, Peter Wright, David Kirk (2018). ActuEating: Designing, Studying and Exploring Actuating Decorative Artefacts.

   In Proceedings of the 2018 Conference on Designing Interactive Systems (DIS'18), p 327-339, Hong Kong. *(Chapter 5)*

   DOI: https://doi.org/10.1145/3196709.3196761

3. **Sara Nabil**, David Kirk, Thomas Plötz, Julie Trueman, David Chatting, Dmitry Dereshev, Patrick Olivier (2017). Interioractive: Smart Materials in the Hands of Designers and Architects for Designing Interactive Interiors.

   In Proceedings of the 2017 Conference on Designing Interactive Systems (DIS'17), p 379-390, Edinburgh, UK. *(Chapter 6)*

   DOI: https://doi.org/10.1145/3064663.3064745

4. **Sara Nabil**, Thomas Plötz, David Kirk (2017). Interactive Architecture: Exploring and Unwrapping the Potentials of Organic User Interfaces.

   In Proceedings of the International Conference of Tangible and Embedded Interaction (TEI'17), p 89-100, Yokohama, Japan. *(Chapter 2 and 7)*

   DOI: https://doi.org/10.1145/3024969.3024981

Journal Articles

5. **Sara Nabil**, David Kirk, Thomas Plötz, Peter Wright (2017). Designing Future Ubiquitous Homes with OUI Interiors: Possibilities and Challenges.

   Interaction Design and Architecture(s) Journal, Volume 32, p 28-37. *(Chapter 1)*

Book Chapters

6. **Sara Nabil** and David Kirk (2019). Interactive Interior Design and Personal Data.

   In People, Personal Data and the Built Environment (1st Edition), Chapter 5, Holger Schnädelbach and David Kirk (Eds.) Springer Book Series in Adaptive Environments. Springer International Publishing.

   ISBN: 978-3-319-70874-4 2019.

Workshops

7. Holger Schnädelbach, Nils Jäger, **Sara Nabil**, Nick Dalton, David Kirk, Elizabeth Churchill (2017). People, Personal Data and the Built Environment.

   In Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems (DIS'17), p 360-363, Edinburgh, UK.

   DOI: https://doi.org/10.1145/3064857.3064864

Workshop Position Papers

8. **Sara Nabil**, Simon Bowen, Peter Wright (2018). Developing Architaction from Interioraction and Decoraction Design.

   Workshop positioning paper for the ACM DIS 2018 Workshop: From Artifacts to Architecture.

9. **Sara Nabil**, David Kirk, Thomas Plötz (2016). Future of Ubiquitous Home Interaction with OUI Interiors.

   Workshop positioning paper for the ACM CHI 2016 Workshop: Future of Human-Building Interaction (HBI).

Exhibitions

10. AMR Pharmacy Interactive Installation (2018), Combating Anti-Microbial Resistance.

    London Design Festival, UK. 15 - 23 Sep 2018.

11. BacterioChromic (2018) at the Living with Adaptive Architecture Exhibition.

    Lakeside Arts Gallery, Nottingham, UK. 12 May - 17 Jun 2018.

12. Immersive Hive (2018) at the "Bees!" Exhibition.

    The Great North Museum (Hancock), Newcastle, UK. 17 Mar 2018.

13. Enchanted Architecture Gallery (2016) at the "2016 CHARRETTE WEEK" Exhibition.

    School of Architecture, Newcastle University, UK. 7 Oct 2016.

Chapter 2. Conceptualizing OUI Interiors

Before delving into OUI Interiors as a research focus, it is necessary to have a full understanding of the concept of OUI (Organic User Interface) and how it is different from previous interface notions. Therefore, this chapter begins by explaining the OUI paradigm in terms of its definition, history, interactivity and materiality with respect to relevant paradigms of post-WIMP interfaces and ubiquitous computing. Then, I review the state-of-the-art in OUIs with respect to applications on three levels: interior design, interior decoration and materials. The review draws on HCI and interaction design literature as well as work in practice in relevant design disciplines. The literature survey presents each previous work in terms of technical, aesthetic and experiential aspects in addition to the overall 'design concept' or rationale behind it, that gives it its meaning and value. Through investigating what has been done so far in this literature review using this approach, I lay out the play-of-possibilities that OUI can offer to this research area.

2.1 Unwrapping OUI

> *"Organic User Interfaces are non-planar interfaces that can have any 3D shape, and can potentially change this shape, morphing either actively or passively, to support direct physical interaction."* (Vertegaal and Poupyrev, 2008).

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Organic User Interfaces (OUIs) (Vertegaal and Poupyrev, 2008; Girouard et al., 2011, 2013) arguably represent the flexible, adaptive and malleable version of both Tangible User Interfaces (TUIs) and Shape-changing Interfaces (SCIs). Initially introduced as 'organic tangible interface' or 'organic TUI' (Ishii, 2008a), OUI evolved offering radical new materialities and form factors that underpin both input and output interactions, coinciding with Ishii's vision for the future of user interfaces as 'Radical Atoms' (Ishii et al., 2012). Therefore, over recent years OUIs have seen increased interest amongst the Human-Computer Interaction (HCI) community following the publication of the special issue of Communications of the ACM on OUIs (Vertegaal and Poupyrev, 2008) that presented the concept and framed the essence of this field, then the first workshop on OUIs and transitive materials at CHI'09 (Coelho et al., 2009), the second workshop on OUIs at TEI'11 (Girouard et al., 2011), and finally the special issue on OUI in the Interactions Journal (Girouard et al., 2013) that sought to debate and develop further the concepts behind the OUI vision and stimulate research in related areas, such as tangible, embedded and embodied interfaces.

By definition, OUIs can have any physical shape that everyday products can have (Girouard et al., 2013) to enable both tactile sensing input (like TUIs) and change of appearance as output (like SCIs), in flexible forms that support intuitive interaction. Therefore, OUI conceptually depends on the 'shape' of the interface being the 'key' for interaction; that is: the physical 'form' conveys its function and invites users to familiar interactions such as deformable and non-deformable hand manipulations as a means of tactile user input; and multi-sensory feedback such as actuating its physical form as a means of output interaction.

In this sense, the OUI paradigm is based upon a set of principles following the natural-physics laws (Holman et al., 2006) of intuitiveness, fluidity, calmness, seamlessness and robustness. *Intuitiveness* here refers to the natural understanding of the underlying functionality of OUIs and makes use of their clear affordances in terms of physical interaction and hand manipulations. For example, the interactivity with an OUI blanket should rely on its natural affordance of wrapping, folding and crumpling i.e. tactile sensing. *Fluidity* refers to the potential malleability, deformability and softness of both the interactivity and materiality of OUIs. *Calmness* is where the OUI flows smoothly between the background and foreground of our focus, and the output is represented in a non-intrusive way, which is immediately available if needed but otherwise not distracting. In this sense, OUIs should avoid LEDs and motor actuators in favour of other potentially calm colour and shape-changing actuations. *Seamlessness* is also a key feature of OUIs where the object is not perceived as a digital device, but is rather part of the environment. For example, an OUI chair should not have power cables coming out of it to the electric socket, and an OUI rug should not have buttons/switches to detect that you're standing on it. Once we forget that we are operating a machine (through intuitive physical sensing and calm organic actuation), we can experience interfaces as part of our environment. *Robustness* does not only refer to the sturdiness of construction, but also the ability to manoeuvre errors through the organic (non-mechanic) behaviour of the interface. This can be measured outside the lab, to evaluate whether an OUI can withstand situated studies and to evaluate people's sense-making of it in-use.

Three guidelines for OUI design were developed (Vertegaal and Poupyrev, 2008) based on these principles: 1) Input equals Output (i.e. the input device is the output device), 2) Function equals Form (i.e. interfaces can take any physical shape), and 3) Form follows Flow (i.e. interfaces can change their shape). Early examples of OUIs range from surface computing, volumetric (e.g. spherical (Benko et al., 2008), polygonal (Nabil and Ghalwash, 2015), cylindrical (Beyer et al., 2011)) and bendable computers to flexible displays or paper computers (Akaoka et al., 2010). Similarly, OUI can utilize sensing, deformable, skin-changing and shape-changing materials in order to cover, embed and surround real-world objects and environments.

The concept of OUI was initially built on organic electronics or 'Transitive Materials' (Coelho et al., 2009; Ishii et al., 2012) allowing displays/ devices to be malleable and actuated in an aesthetically pleasing way. Examples of such flexible and controllable displays include flexible Organic Light Emitting Diodes (OLED), Electrophoretic displays (EPDs), and Electroluminescent Lighting (EL). In addition to flexible displays, OUI can be designed using all ranges of flexible sensing and/or actuating materials; from paper or fabric to wood and glass that has embedded thin and flexible electronic sensors, microcontrollers and actuators, such as muscle wires, metal powder, conductive materials (thread, fabric and paint), optical fibres, colour-changing pigments and e-textiles. Such materials and technologies pave the way for rethinking user interfaces that can be embedded into everyday objects. Accordingly, OUI has great potential for radically new applications, e.g., dynamic artwork, pattern-changing fabrics, reactive architectural facades or even entire interactive spaces.

Examples of OUIs that have specifically explored new materialities or developed complicated fabrication methods include FuSA (Nakajima et al., 2011) the furry display, ClothDisplays (Lepinski and Vertegaal, 2011), Hairlytop (Ooide et al., 2013), the hydromorphic bioLogic (Yao et al., 2015), the thin-film paper actuator Foldio (Olberding et al., 2015) and uniMorph (Heibeck et al., 2015) a curved actuated interface that enables designers to print custom responsive OUIs in flexible forms. In addition, one of the key potentials of OUI is their malleability (Follmer et al., 2012) enabling actuated manipulations and deformations as both input and output interactions. Several other possibilities of deformable display materials have been motivating researchers for the past few years leading to new ideas and flexible design materials (Alexander et al., 2012).

Therefore, OUI supports the paradigms of *ubiquitous computing* (Weiser, 1991), *calm technology* (Weiser and Brown, 1996), *slow interaction* (Odom et al., 2012) and *seamless and seamful* interaction (Chalmers and MacColl, 2003), where technology disappears in the background of our environment and our attention towards it effortlessly shifts between the centre and the periphery, empowering and informing us without overwhelming. In their book, Bolter and Gramola (Bolter and Gromala, 2003) argued that "user interface design need not deliver information and then erase itself from our consciousness but can engage us in an interactive experience of form and content" using windows and mirrors as metaphors for seamless (transparent/ invisible) and seamful (reflective/ visible) design, discussing the balance between them.

These kinds of interactive technologies have enormous potential to not only change the nature of our interactions with technology but also to change the very environments we inhabit. Weiser (1991) argued that "computational processes and interactivity will become increasingly embedded within our real-world environments", which will also increasingly react to our presence through embedded sensing, now with the additional potential to change form and function on demand. Accordingly, technologies such as 'Reactive Architecture' (Schnadelbach et al., 2012) and 'Kinetic Architecture' (Khoo and Salim, 2013) offer substantial scope for redefining current architecture. However, such architectural interventions are quite rare, and commonly only possible as new builds (thereby ignoring existing building stock) and largely neglect interior design, focusing more on dynamic structural features or interactive service layers within the building fabric.

Contextualizing OUI with regards to the state-of-the-art -in both practice and research- supports formulating the research agenda for OUI as a means of interactive interior design. The next sections explore a specific subset of OUI application areas to demonstrate the general concept of Organic User Interfaces and to highlight the advantages and benefits of designing interactive interior spaces. In the following contextual review, I divide relevant OUI applications into three levels: 1) Interior Design; 2) Interior Decoration; and 3) Materials. Although these three levels are not mutually exclusive or complementary (see figure 2.1), they are interrelated in many aspects and I tackle each level as to present OUI potentials from a holistic large-scale experience to the smallest ornamental detail.

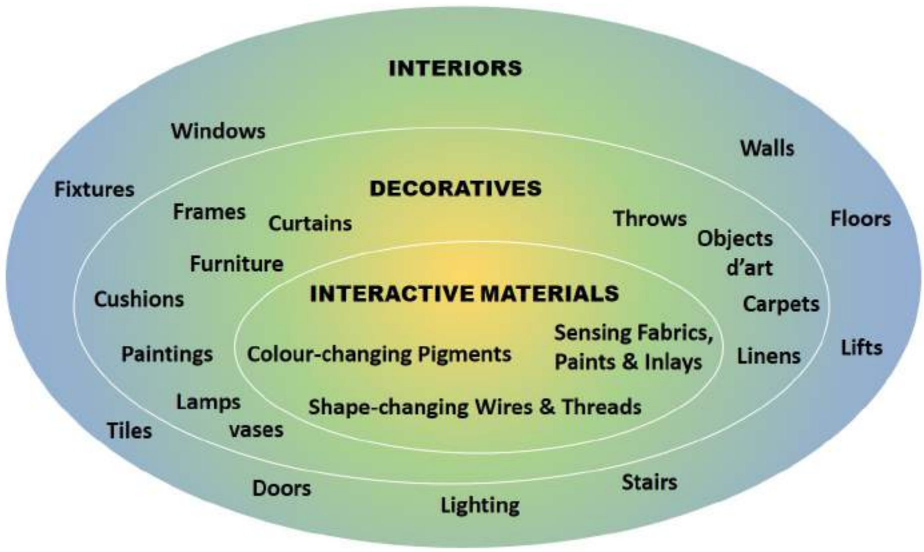


Figure 2.1 Defining subset layers of OUI throughout Interior Design, Interior Decoration and OUI Materials.

The first level focuses on interior spaces that could be reactive to our presence, movements or physical manipulation, including context-aware spaces, reactive surfaces and interactive wallpaper. The second level goes into the interior elements such as interactive furniture and soft furnishings, dynamic decorative elements and interactive interior artwork. Finally, the third level reaches the materiality level of the building blocks of above-mentioned layers exploring interactive and smart materials that can be seamlessly embedded into interior finishing materials to empower them with OUI interactivity.

My literature survey brings light to the implemented design work that has been realized so far with the latest technological advances, some of which were designed as interactive design interventions or for material exploration in its own right, while others were designed with the aim of studying users' experience of such responsive environments, objects or materialities and the possibilities and potentials of such adaptive technologies.

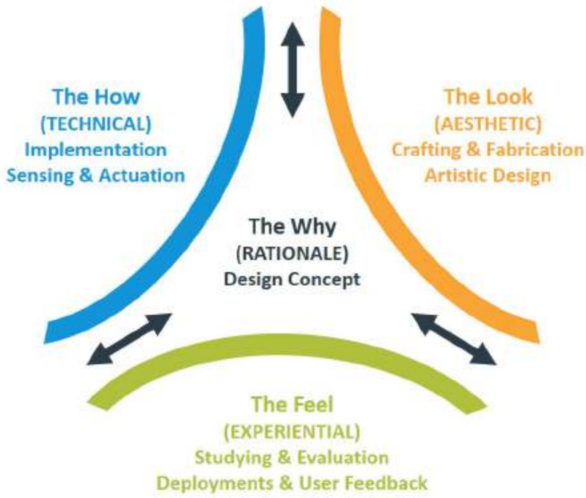


Figure 2.2 Four Design Aspects of this survey: the rationale is in the core of the technical, aesthetic and experiential aspects.

This contextual review critiques relevant work with respect to four key design aspects (see figure 2.2):

1. **The Why (Rationale):** the design concept, purpose and value the interactivity of the artefact holds -whether emotional, experiential or functional- and what impact does it aim for? and why? This is the core design aspect that implies the *intended* meaning and purpose of the interactive intervention. This implies the designer's intention for the design, which may differ than the value of the artefact in use, as they are not necessarily the same.

2. **The How (Technical):** the interactive materials and electronic components, including the *implemented* sensing and actuating capabilities will be embedded? and how? This requires electronics expertize and may not be fully realized in early prototypes (e.g. demos, mock-ups, or wizard-of-oz-ed). However, to fully realize the 'rationale' behind the designed interactivity, the technical aspect should be 'hidden', 'seamless' and 'calm' as much as possible to avoid any interruption with the 'aesthetic' and 'experiential' aspects.

3. **The Look (Aesthetic):** the visceral values and artistic design of the product (or space) that is *fabricated or crafted*, including the quality of finish and decorative style in addition to the making techniques, material affordance, pattern and texture.

4. **The Feel (Experiential):** the *actual* experience that people encountered and felt during interaction, including potential social engagement, playfulness, sense of identity and ongoingness. This aspect can only be realized through real-world applications and situated deployments that give insights and reflections on people's actual interpretation and sense-making of the interactive design, which may differ -often significantly- than the intended design concept.

2.2 OUI Interior Design

Although interior spaces are typical of static nature requiring an interior designer or architect to facilitate changes to their appearance and function, the idea of dynamic interiors has recently gained popularity. Interior elements such as surfaces (walls, floors, ceilings) and openings (doors, windows) can be augmented with digital technology to enhance both their aesthetic impact and potential dynamic functionalities. Examples of interactive interior walls are Smart Wall (Farrow et al., 2014), LivingWall (Buechley et al., 2010) and LivingSurface (Yu et al., 2016), while GravitySpace (Branzel et al., 2013) is an interactive floor. However, ceilings seem to be neglected from similar interaction design in spite of all opportunities that could potentially be addressed especially in bedrooms where users lie down facing their normally plain ceilings.

In general, other research on building interactive surfaces and walls has taken two approaches: either wall-sized emissive displays (Farrow et al., 2014; Branzel et al., 2013) or subtle ambient designs (Buechley et al., 2010; Yu et al., 2016). Wall-sized displays are either light-emissive (i.e. LED displays) or projection-based, while subtle tactile designs focus on embedding interactivity in conventional coating, lighting or different finishing materials, such as wood panels, ceramic tiles and wallpaper. An example of the former approach is Smart Wall (Farrow et al., 2014) where the wall display is divided into large pixel-like, reconfigurable cells that users can select and/ or drag each cell representing a certain function, utilizing room dividers and interior walls in user interaction design. The Smart Wall uses physical interaction, to perform different functions, often spanning multiple cells as canonical input mechanisms, turning them into menus and widgets. The wall is designed as a stack of adjacent hexagonal blocks, each hexagon represents a single cell that detects touch and proximity using capacitive sensing and responds by lighting in vibrant different colours, each colour representing a certain function. The design of Smart Wall was not deployed to scale but rather introduces a reconfigurable module and envisions a future library of blocks that provide a variety of functions such as controlling ventilation and sunlight.

Similarly, GravitySpace (Branzel et al., 2013) is an interactive space designed for smart rooms using real-time tracking, a floor display and a set of passive touch-sensitive furniture. This interactive floor prototype can display both virtual objects and reflections of physical objects as well as respond to occupants' interactions with it and with each other. Using a high-resolution back-projected $8m^2$ floor display, the GravitySpace was designed to explore how much a smart room can infer about its inhabitants solely based on the pressure imprints that people and objects leave on the floor. For detecting multiple users, their positions/ orientations, and furniture, pressure-based sensing was used (instead of usual camera-based techniques) offering benefits such as more privacy for space occupants, consistent coverage of rooms wall-to-wall, avoiding occlusion between users and simpler recognition algorithms. Technical evaluation of GravitySpace was carried out on three system components (pressure cluster classification, user identification and pose recognition) using data from user testing (i.e. lab members and visitors). For example, algorithms and neural network training and classification were used to identify four poses of occupants: standing/walking, sitting, sitting on furniture, and kneeling. However, no experiential evaluation was carried out as to explore what participants felt when standing and moving around the room, or how it can be used to alter the appearance of the floor and therefore the psychological and physiological effects of this. For instance, changing the smart floor to display a fringed warm-coloured oriental wool rug on antique oak wood flooring in a rustic style may infuse a warm cosy feeling to some, or trigger childhood holiday memories to others.

Figure 2.3 The LivingSurface: the bio-sensing interactive wall patterns (Yu et al., 2016). Photo courtesy of Bin Yu

Alternatively, Living Wall (Buechley et al., 2010) is an example of a non-emissive subtle design. Living Wall is an interactive wallpaper that uses conductive paint connected to detachable sensors and actuators for interactivity. It detects touch and proximity to create a playful experience as an interactive interior wall and a large ambient dynamic wallpaper. Authors *propose* that their Living Wall can be used in "functional and fanciful" applications including lighting, appliance control, environmental sensing and ambient information display. This wallpaper consists of three layers: 1) a magnetic layer (to hold electronic components in place), 2) a circuitry layer (as a routing circuit board using conductive paint), and 3) a decoration layer (masking some of the magnetic and circuitry layers). Therefore, there are no wires or hidden electronics, but rather magnetically mounted electric components, thus enabling users to move them around on the wallpaper. Electric components were chosen in a tear-drop design, matching the aesthetics of the print including the microcontroller, light and motion sensor modules and output modules (including LEDs, motors, and SMA flowers that open and close). The wallpaper is programmed to continuously store all sensed data, in an online database, thus generating an interaction history. No studies or in-situ deployments were held to investigate how people might perceive interacting and/or living with it.

Likewise, LivingSurface (Yu et al., 2016) is a shape-changing surface that interacts with users through its non-emissive material that rather changes its physical shape in response to sensed user physiological data, reflecting their internal body processes such as heart rate and blood volume pulse. The shape-changing interaction of LivingSurface is designed using laser-cut incisions in the wallpaper that is actuated to form different interesting 3D shapes, see figure 2.3. Actuation is deployed in a back layer embedded with hidden servo-motors, vibration motors and small fans controlled using Arduino microcontrollers to vibrate, swing, bulge, or rotate in order to display physiological information in dynamic physical forms. The same effect could have been implemented without motors using non-mechanical linear actuators such as muscle wire or Shape-Memory Alloys (SMA) that are light-weight thin wires with strong and silent actuation capabilities. LivingSurface was installed at the Dutch Invertuals Exhibition at Milan Design Week in three samples placed in 40x40x10 cm wooden frame boxes, hung on the wall. Authors report field observation of visitors' interactions and sense-making during the exhibition. After wearing the pulse sensor (wired to each) in their index finger, visitors would directly look to the surface in anticipation of an immediate response, of which the slow actuation and lack of instant interaction to their input caused confusion as to what it was responding to. As with Exobuilding, the LivingSurface is an architectural design intervention that aims to create a 'living environment' that connects people with their own physiology by bringing awareness to how their conscious control could affect their internal physiological process.

Figure 2.4 The Engaging Retail Space by Dalziel & Pow, at the RDE 2015, London, UK. Photo courtesy of Dalziel & Pow.

On the other hand, interior design studios and offices are starting to explore how the use of technology and user-interaction can innovate designs aiming to create more meaningful and exciting experiences. For example, the Dalziel & Pow's retail 'EngagingSpace' (Dalziel & Pow, 2015) that has been exhibited at the Retail Design Expo (RDE) in London 2015 responds to touch using capacitive paint seamlessly integrated into drawings on the wooden wall panels and reacts through playful audible sounds and storytelling projected graphical animations, see figure 2.4. The Engaging Space was described by its designers as innovative, playful and exploratory as well as "pushing the boundaries of storytelling within a space", and "putting the idea before the hardware" (Dalziel & Pow, 2015). The team who designed the Engaging Space was described as multi-disciplinary bringing technologists with interior designers together on the same table to create this interactive experience.

Another example is the Aegis Hyposurface (Goulthorpe, 2000), a massive kinetic wall that actuates its shape-changing mechanism either autonomously (pre-programmed), interacting with people's gestures, movements and hand manipulations, or responding to ambient sounds and noise. Its large scale spans over 3 m tall and 20 m wide create waves and stream animated text and logos moving in 3D as if through the surface, creates an entirely different experience than a 2D flat display. It is realized through a hig speed information bus that controls a matrix of thousands of pliable and robust pneumatic pistons that deform a complex 3D rubber/ metal surface that delicately appears to breath as a perforated skin as the pistons press behind it. The Aegis Hyposurface is not just a single exhibition installation, but rather a product that has been awarded numerous international awards and has been constantly upgraded, enhanced and deployed since 2000 at different venues and events, to encourage public engagement with this transforming and 'living' surface that generates "long lasting impressions" [ibid].

Similarly, Antenna Design has presented their interactive installation 'The Emperor's New Clothes' at the Artists Space in New York, USA. The interactive fitting space featured interactive hangers and a fitting room with a 'magic mirror'. Five illuminated hooks carry five coat-hangers that carry nothing but 'invisible clothes' which people are encouraged to pick up and take it to the adjoining fitting room. When a hanger is placed on a hook inside the fitting room, the 'magic mirror' shows floating animated images superimposed onto the viewer's reflection in the mirror, where each hanger triggers different alterations. The images react to the person's body and movement, thereby enforcing a notion of altered/augmented self where no clothes are projected, but the effects of transformations that the invisible clothes produce. This use of spatial arrangements of interior elements is what Calderon (2009) described in his book as an illustration of good practice to the morphological dimension of interactive spaces.

Figure 2.5 The Bonding Buffet by KLM in Amsterdam's Schiphol Airport, 2016. Photo courtesy of KLM©.

In Amsterdam's Schiphol Airport, KLM installed the interactive 'Bonding Buffet' to engage people in a playful experience during the holiday season of 2016, see figure 2.5. The latter being a multi-user dining table that has pre-served dinner elevated from reach, but keep approaching the seats downwards as people join the table and activate the pressure-sensitive seats. Eventually, the interactive dining table of free food is only accessible if the twenty seats are occupied. The Bonding Buffet therefore invites twenty strangers in the airport hall, of possibly twenty different nationalities, cultures, interests and lives to interact, share and engage together through the interactive interior space.

Lighting is also a primary aspect in interior design practice and finding creative ways of manipulating lighting creates other forms of kinetic actuations to realise user interaction. Examples of interior interventions that involve LED interactivity are: Light-Form, designed by Francesca Rogers and Daniele Gualeni Design Studio (2010) (see figure 2.6) and the Luminous Patterns (Philips Lighting, 2016), both creating interesting playful experiences. More immersive experiences can be also found in some novelists' work such as Nicolas Schoffer's Spatiodynamic Luminodynamic & Chromodynamic Space (Schöffer, 2005) that plays with light and colour in harmony to create dynamic spatial experiences. All these examples were designed and built to extend the user experience in the space by pushing the boundaries and adding a dynamic nature to the interior design instead of being just static as traditional designs.

Figure 2.6 Light-Form interactive wall, designed by Francesca Rogers, 2010. Photo courtesy of Daniele Gualeni Design Studio©.

The above examples show the gap between the interior design practice and interaction design research in terms of style, aesthetics and design concept. In spite of forming a rich inspiration for artists, designers and architects, they only scratch the surface of possibilities for promising OUI interiors yet to come. Besides being expensive uptakes and mostly hard to retrofit, most of these examples lack two essential aspects. First, they all rely on technology in the form of light emission (LEDs or screen projection) or motor actuators. These designs could be pushed further into being *calm*, blending in the background of the interior space in non-intrusive ways, only available if needed but otherwise not distracting. By avoiding LEDs and motor actuators in favour of other potentially calm colour and shape-changing actuations, we should be able to realize more potentials of interior designs using OUIs. Second, there are no accounts of how most of these examples were built or accounts of being subjected to situated studies where research can understand and explore the opportunities and challenges of their deployment in real-world settings or in context. In terms of either reflecting on user testing or design critique, such situated studies, if held, could have contributed findings that can be analysed and used to drive further investigation, supporting both researchers and designers wishing to develop interactive spaces.

2.3 OUI Interior Decoration

In interiors, we find decoration in many places, from wall paintings, sculptures and lampshades to furniture, rugs and curtains, all of which can be augmented to be both interactive and artistic (Nabil et al., 2017b). Although aesthetic decorative patterns are perceived to be a prosaic feature providing rich potential for interactivity (Meese et al., 2013), interfaces built upon this are very limited. Most examples are still bound to activating some form of emissive display (or lights) such as tabletops (e.g. History-Tablecloth (Gaver et al., 2006)), interactive curtains (Funk et al., 2015; Takashina et al., 2015) and interactive furniture (EmotoCouch (Mennicken et al., 2014a), Long-Living-Chair (Pschetz and Banks, 2013)). Fewer examples employ more organic and intuitive interactions such as colour-change (Digital Lace (Taylor and Robertson, 2014)) and shape-change (e.g. shape-changing-bench (Gronvall et al., 2014), lampshades (Heibeck et al., 2015; Jung et al., 2010)) and other interior 'Soft User Interfaces' (Sugiura et al., 2011).

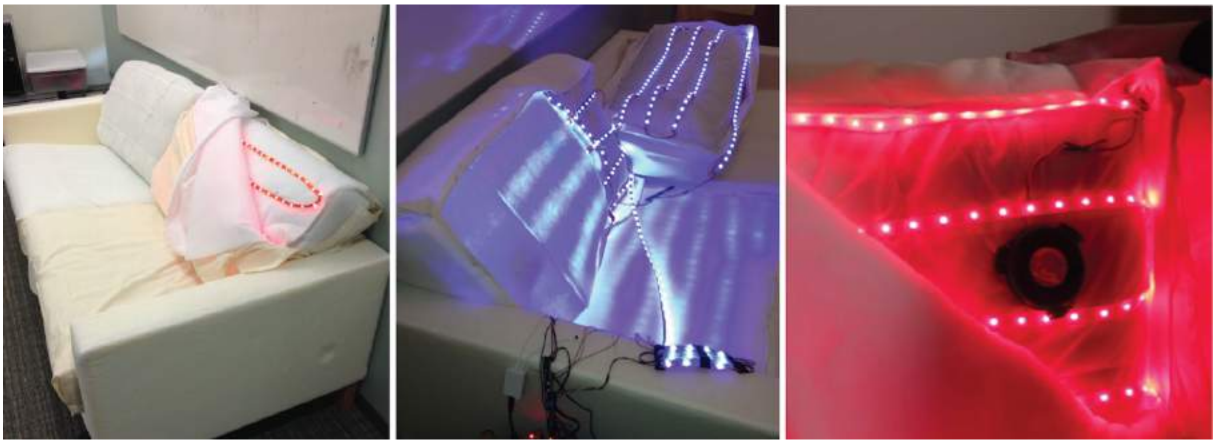


Figure 2.7 EmotoCouch: the colour-changing couch that has its own emotions (Mennicken et al., 2014a,b). Photo courtesy of Sarah Mennicken

EmotoCouch (Mennicken et al., 2014a,b) was an actuating couch, which was implemented using a plain-white IKEA KARLSTAD couch. Four of the couch's cushions were embedded with individually controlled total of 640 RGB LEDs, plus a voice coil as a bass speaker for playing subsonic sounds as a means of haptic feedback. LEDs were used to change the couch's colour (i.e. embedded light) representing six different emotional states (see figure 2.7). Its intended rationale was to study how furniture might dynamically express emotions and explore how this might affect home occupants by delighting, comforting, exciting them and encouraging socialized family activity. However, the actual experience was evaluated based on online surveys and user interviews after a lab study to gather user feedback, with no deployment in-the-wild, as there was no actual interaction implemented, but the light-change was pre-set before asking participants to associate it with an emotion.

CoMotion (Gronvall et al., 2014), on the other hand, was deployed in three different public spaces: a concert hall foyer, an airport departure hall and a shopping mall centre. CoMotion is a custom-made flat-modern horizontal bench seat that changes its height and angle using 8 embedded linear motor actuators, hidden beneath its grey and black upholstery. The designers explored users' experiences and sense-making around its affordances and transitions and also their interpretations of such a physically dynamic object testing it (average of 2 minutes per user) in three in-the-wild studies to investigate people's responses in different interior settings. However, coMotion was also remotely controlled, as no sensing was actually embedded. The actual experience was analysed through field observations and brief interviews (average of 5 minutes) with people post-engagement, to evaluate their sense-making in terms of anticipating, connecting, interpreting, reflecting, appropriating and recounting.

In a contrary approach, the Textile Mirror (Davis et al., 2013) was not followed by a user study, but was in itself a result of two prior online surveys designed to enable people to map emotions to textiles, of which the results then informed and inspired the design of its prototype. The overarching aim of this was the sensational and emotional effects of multi-aesthetic and deformable interfaces. The Textile Mirror (Davis et al., 2013) was designed by Felecia Davis as a shape-changing wall curtain that simulates how soft interfaces can actively mirror and transform our feelings through traditional materials in our environments i.e. texture-changing fabrics can modify one's emotional state from stressed or angry to happy and calm. The Textile Mirror was made using laser-cut felt fabric interlaced with Shape-Memory-Alloy (SMA) wire that is actuated by a person's mood (self-rated through a mobile phone app). Two years later, Davis (2015) also explored a variety of different emotional expressions that can be communicated to users through texture-changing artefacts, persuading designers to explore shape-change and textural expressions. However, she did so by carrying out a study with participants entering a room, examining and evaluating fabric swatches that were hung on a wall, mounted on foam board boxes that hid servo-motors.

The Long Living Chair (Pschetz and Banks, 2013), is a rocking chair that detects and stores, in an internal memory, the frequency and pace of its usage over extended periods of time (months and years). The chair is augmented with a motion sensor to detect its usage and reflect this information in a subtle black and white display that only shows a graph representing long-term interactions, where each pixel represents a time span of 6 days, with a total of 96 columns of pixels i.e. 96 years of interaction. Focusing on this single function, and promoting 'slow interaction' (Odom et al., 2012), Long Living Chair acts as any normal chair in terms of its affordances, aesthetics and interactions. It encourages users to forget it has a digital component and is 'tracking' usage. For this sake, its aesthetic design was inspired by the iconic RAR rocking chair designed by Charles and Ray Eames, recognized as a stylish high quality and desirable decorative object. Moreover, the motion sensor and small display were strategically placed, carved and embedded in one of the chair wooden rails, keeping them out of the sight of the person sitting on the chair. This allows it to blend into the background of everyday life, keeping patterns of engagement intuitive and implicit, whilst opening up opportunities to critically examine the utility and role of long-term data about object interactions in the home. Although this design concept sounds intriguing and interesting to study, no actual deployments, studies or surveys were held to put this rationale into test and evaluate the actual experiential outcomes of such a carefully-designed interactive intervention.

On the other hand, TRANSFORM (Ishii et al., 2015) is a shape-changing table that does not resemble a traditional table but is designed with a rationale of presenting novel deformations that change the ergonomics, functionality and aesthetic dimensions of furniture. TRANSFORM is made up of three sets of the shape-changing display inFORM (Follmer et al., 2013) that moves its physical 'pixels' upwards and downwards using 1,152 motors to conform to other physical objects, tangibilize digital information and animate physical activities in three modes (Wave, Machine, Escher). For this sake, TRANSFORM is implemented using a sophisticated mechanism, beyond crafting, employing custom-designed PCBs, motor drivers, custom Arduino boards and motorized slide potentiometers, among others. User input and movements are detected using a Microsoft Kinect mounted 4m above TRANSFORM, with no direct physical sensing. The enclosure design of TRANSFORM was outsourced to the furniture designer Amit Zoran to enable housing hundreds of motors inside an aesthetic sleek design that reflects its concept of "collision and fusion of design and technology". In this sense, TRANSFORM was presented as a design for interactive furniture that enhances people's experience, remembers their preferences and adapts to their needs. However, it transformed a piece of static furniture into a huge "motorized machine" (Ishii et al., 2015). TRANSFORM was finally exhibited at the Milano Design Week 2014, where visitors were observed interacting with its different animated modes, but no research account was published to discuss or reflect on such user engagement.

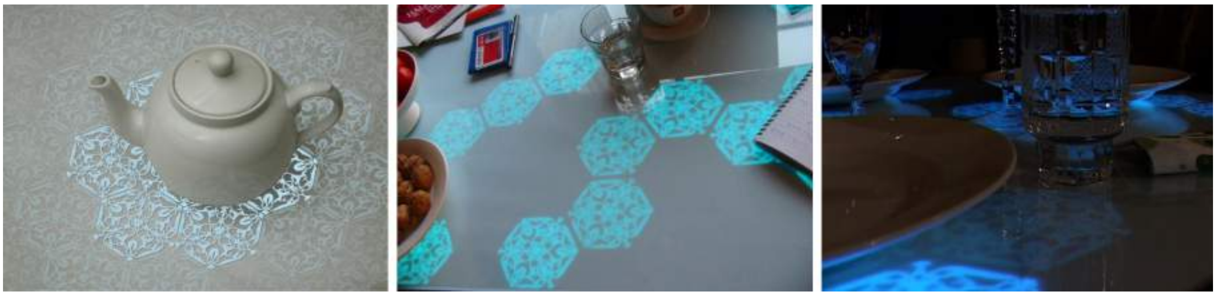


Figure 2.8 Example of a domestic interactive prototype: The History Tablecloth (Gaver et al., 2006). Photos courtesy of Interaction Research Studio©

Bill Gaver's well-known History Tablecloth (Gaver et al., 2006), an electronic tabletop, was designed to display glowing printed patterns when objects are left on the table, with a halo that grows over time as the object remains in place, see figure 2.8. Technically, the actuation was realized with a thin electroluminescent film, and load sensors were placed under the table's legs to track the position of multiple objects on the tabletop, then a microprocessor interfaced this input to a dedicated PC which ran a location-tracking algorithm to track the history of objects and control the lighting of the History Tablecloth. The illuminating pattern was designed by textile designer Rachel Wingfield, while a specialized company was responsible for the electroluminescent screen-printing. The final design included screen-printing 5 layers of conductive ink, insulating materials, and the electroluminescent material onto a flexible plastic substrate, while a wide ribbon cable for electrical connections ran from one of the ends of the Tablecloth. Then a sheet of semi-opaque paper was used on top to mask the "offensive pattern" borders. Moreover, a piece of glass was mounted on top to prevent small folds, cracks, short-circuiting and cell burn-outs in the thin electroluminescent film. Although, interaction in this case was implicit (i.e. placing objects on top of the table), the "system" was equipped with a large red "panic button" and a "power switch" mounted on the front and back of the "housing" for reset and reboot respectively, to fix “erroneous readings”. The design concept of the History Tablecloth was to open up opportunities in the home to reflect on patterns of use of objects, and the routines we have in our homes around these objects and the materials of everyday living. This was intended to foster social engagement around these reflections. The History Tablecloth is a prominent example of a long-term study of situated interactive furniture. The 4-months study in a single 2-person household, provided a deeper insight into what it means to design artefacts in a real-world environment and how could people find “interactional and interpretative aspects to the aesthetics” of an everyday object such as a kitchen table. Today still, as Gaver stated a decade ago, less purposeful, more exploratory and playful engagements that encourage people to explore, speculate and wonder, are poorly served by current technologies and therefore still needs further research.

Other examples include embedded interactivity through non-emitting colour-change. For instance, Digital-Lace (Taylor and Robertson, 2014) is a table runner that dynamically changes its black Holland Linen fabric colour using white-scattering liquid-crystal thermochromic dye and polymer optical fibres controlled digitally by microcontrollers. Textile designers and researchers Sarah Taylor and Sara Robertson “crafted” it using traditional hand-printing combined with weave preparation and fibre etching techniques as a re-interpretation of rare 17^{th} century heritage lace in a digitally controlled responsive textile. Digital-Lace was designed to explore multifaceted aesthetics exploiting responsive materials within the fabrics of an everyday object such as a table runner. Using novel materials and playing with tonal effects, Digital-Lace used colour-change and light/shadow interplay to create novel subtle multifaceted/layered visual effects that reveal, disappear then reveal again. However, it was not interactive in the sense that no input was required for its actuation. This award-winning design was exhibited at ISWC’14, yet was not studied, deployed or evaluated by any participants, probably as it did not ‘sense’ or ‘respond’ to any external stimuli.

Interactive Decoration for Tableware (Meese et al., 2013) explored designing tableware patterns and motifs that are both visually appealing and digitally meaningful, but without any physical sensing or actuation. Hypothesizing that decorative patterns are ubiquitous features of everyday objects, their idea was to use such patterns in everyday objects developed using visual codes to make the objects themselves “machine-readable” without resorting to otherwise aesthetically limited barcodes and QRcodes. Two ceramic designers and a textile designer were commissioned to produce visually appealing designs on tableware as valid codes for a recognition software to run on a scanning mobile phone app. Then the designed plates, placemats and menus acted as “trackable tableware” and together with the associated mobile app were deployed in a restaurant as a real-world setting. In-situ deployment challenges included cast shadows, glazed surfaces and food on plates, all of which obscured areas of the patterns from being scanned. Interactive Decoration was aimed to investigate how designers might design complex interactive patterns yet stick to the rules at which the digital scanning applications can be able to interpret. This functionality was realized through exploiting the differences of how humans and systems construct patterns from images.

Alternatively, the Photobox (Odom et al., 2014) designed by Mark Selby, is an antique oak chest digitally equipped with a Bluetooth-enabled printer allowing it to print photos from the owner's Flickr album at random unexpected intervals and was studied in a long-term deployment. Although such technology might not be categorized as 'sensing and actuating' in terms of seamless sensing, shape-change or colour-change, it still introduces a new form of interaction that enables meaningful experiences. Photobox supported and expanded the notion of slow technology (Odom et al., 2012) and provoked self-reflection, anticipation and revisitation of memories and past events in a creative and autonomous yet subtle behaviour, in a domestically situated study. This challenged traditional ideas of technology being always on and accessible (Odom et al., 2014), and envisions domestic technology that is calm, subtle, slow and creates no burden. The printed paper photos also inspired a "sense of perceived durability" contrasting that of digital files displayed on screen displays. Moreover, the patina of the wooden chest chosen for the study (caused by age and wear) challenged the contemporary ideas of technology being bespoke, modern and sleek devices and gadgets. This further shows how existing objects, designed aesthetically to fit domestic spaces (such as a writing box) can be augmented with new kinds of digital functionality to create new user experiences in domestic spaces.

As a holistic experience, Marianne Graves Peterson was looking into designing an interactive interior space that is engaging and playful, through installing interactive interventions in a domestic setting to allow co-located family members to collectively and actively engage in playful activities as part of their everyday life. Her playful home interior Squeeze (Petersen, 2007) consisted of a house camera and oversized interactive sack chair where inhabitants explore the history of the home through captured pictures (taken with the camera for situations and objects around the house) and projected on the adjacent wall. The sack chair is designed in a dynamic form, with embedded sensors and when not occupied, the most recent picture is displayed. Its soft and flexible design allows accommodating multiple people based on the occupants' presence and adapting to the shifting circumstances of the home. In this prototype, two 'active zones' indicated in the sack's fabric are embedded with a pressure sensor (that enables moving backwards and forward in the history) and a flex-sensor (for stretching and bumping pictures), deliberately placed in each end, to encourage collaboration and negotiation around the control of the display. Also, a piezo cable is wrapped around the sack to sense activity rate, then the more activity on different places on the furniture, the more pictures are displayed on the wall. The flexible design of this furniture piece and the way pictures are displayed creates room for interleaving focus on the pictures with open conversations and chats, thus gradually shifting the interface between the foreground and background as a 'calm technology'. This design concept focused on the aesthetics of interaction, ludic engagement and playfulness, rather than functionality, efficiency and precision. More than a decade ago, she argued that "this is for the most part an unexplored design space, which is awaiting the interest of the CHI community". Squeeze (Petersen, 2007) has been only published as a work-in-progress extended abstract suggesting that the next step is an in-situ evaluation with different families, but a full study paper was not released since.

Other examples envision future everyday objects with ‘living-like’ capabilities including homeware objects that reveal a ‘personality’ or a ‘will of their own’. For instance, the Power-Aware Cord (Gustafsson and Gyllenswärd, 2005) uses dynamic electroluminescent glowing patterns to increase awareness of energy consumption; the Impatient Toaster (Burneleit and Hemmert, 2009) bursts in nervous movements signalling hunger to motivate regular healthy eating; the Escaping Chair (Oozu et al., 2017) on wheels has range sensors to run away from bystanders; the Earthquake Shelf (Selby and Kirk, 2015) shakes with earthquakes and may break objects -depending on their magnitude- leaving behind material evidence of a remote event; the Thrifty Faucet (Togler et al., 2009) changes its shape in reward and denial gestures responding to water consumption, through organic body postures; and the ADA Lamp (Angelini et al., 2015) also shows how everyday objects can be augmented with ‘smartness’ that interacts implicitly and expresses their own excitement, autonomy and affection.

Table 2.1 shows the input and output capabilities implemented in built previous work alongside their research environment. Although these examples have been designed and deployed with the aim of studying users’ experience with interactive objects, there was limited focus on physical manipulations. Generally, direct physical manipulation and seamless sensing in interior objects has received limited study, despite the potential of deformable and non-deformable interactions (Ishii et al., 2012; Rekimoto, 2008) seen in OUI prototypes (Lepinski and Vertegaal, 2011; Sugiura et al., 2011; Nakajima et al., 2011). The limited work on interactive decorative artefacts has been mostly published as extended abstracts (not full papers) with no mention of user studies, deployment or evaluation, such as actuating plants (Cheng et al., 2014; Poupyrev et al., 2012), the TextileMirror (Davis et al., 2013) and the interactive pictorial art Anabiosis (Tsuji and Wakita, 2011). Additionally, relevant work on soft interfaces and fabric interactivity has been more around ‘fashion and wearables’ (Berzowska and Coelho, 2005; Kettley et al., 2017; Devendorf et al., 2016; von Radziewsky et al., 2015) and less around ‘interior design’.

The design of home ‘devices’ is now tending towards more aesthetic appeal and decorative stylish designs. The latest products that are now available in the market are designed to blend in our interior spaces, and often disappear in the background of our environments, rather than stand out as ‘digital devices’. For example, Bang & Olufsen’s powerful wireless sound speakers, such as their classically-designed Beoplay A9, the Beoplay M5 that is inspired by modern Scandinavian interior and furniture design, and the BeoSound Shape designed in modular hexagonal tiles that are entirely user-customizable and scalable into any forms, patterns and colours to match users’ aesthetic and acoustic preferences (bang-olufsen.com).

Similarly, Samsung released the innovative TV set ‘the Frame’ describing it as “The most beautiful TV you’ve never seen”. The Frame transforms into a piece of art when the 4K UHD TV is not being viewed, seamlessly blending into any the design of the interior space. Moreover, with the ‘invisible’ connection kit, customizable surrounding frame (black, walnut, beige wood, or white) and no-gap wall-mount, this TV is unusual, see figure 2.9. The artwork displayed on the Frame (while it is not used as a TV) is arguably highly realistic via brightness sensors and motion sensors that detect the lights and shadows in the room to render the artwork to appear as a physical wall-art painting and not a displayed image. In this sense, its existence as a

Related Work	Intuitiveness Sensing Method	Calmness Output Mode	Situated Study Research Environment
Digital Lace (Taylor and Robertson, 2014)	—	Peripheral	None
EmotoCouch (Mennicken et al., 2014b)	WoO	Focus-demanding	Laboratory
*CoMotion (Gronvall et al., 2014)	WoO	Focus-demanding	Real World
TextileMirror (Davis et al., 2013)	WoO	Peripheral	None
TRANSFORM (Ishii et al., 2015)	Camera Tracking	Focus-demanding	None
*PhotoBox (Odom et al., 2014)	[External] Flikr	Peripheral	Real World
Earthquake Shelf (Selby and Kirk, 2015)	[External] Network	Focus-demanding	None
*ID Tableware (Meese et al., 2013)	Camera Scanning	—	Real World
*Living Surface (Yu et al., 2016)	Physical Sensing	Focus-demanding	Exhibition
Escaping Chair (Oozu et al., 2017)	Ultra Sound	Focus-demanding	None
*Gravity Space (Branzel et al., 2013)	Physical Sensing	Focus-demanding	Laboratory
Anabiosis Wall-art (Tsuji and Wakita, 2011)	Physical Sensing	Peripheral	None
Living Wall (Buechley et al., 2010)	Physical Sensing	Focus-demanding	None
LongLivingChair (Pschetz and Banks, 2013)	Physical Sensing	Peripheral	None
*History Table Cloth (Gaver et al., 2006)	Physical Sensing	Focus-demanding	Real World
Squeeze (Petersen, 2007)	Physical Sensing	Focus-demanding	None
Mood Fern (Cheng et al., 2014)	Physical Sensing	Peripheral	None

Table 2.1 Overview of related work compared within the discussion section. Publications with * refer to full-length papers.

Figure 2.9 The Frame: Samsung's TV turned off (i.e. in Art Mode) in different artwork and frame colours (black, beige wood, white, walnut brown). Photos courtesy of Samsung©

digital device disappears and its presence as conventional wall-art reveals in the press of a button, blending itself into the interior space. With a large array of paintings, prints, photos, and frames to suit owners, the Frame TV goes beyond entertainment and allows space occupants to express themselves in new ways. As Weiser envisioned decades ago, technology will recess into the background of our lives and will become far less obtrusive.

Yet, everyday decorative objects, that are not inherently digital devices, are still mostly static in their design, affordance and appearance. It is a design challenge, to find creative, accessible and organic ways of embedding everyday objects with manipulative sensing and actuation. Rather than designing machine-like interfaces we should design interactive decorative patterns and interior elements, which can also act in unison as networks of decorative artefacts, capable of dynamically interacting together. In addition, there is a clear gap in research focusing on situated deployment, studying and evaluating how would people perceive, interact and live with such ubiquitous and seamless interventions designed as interactive spaces, surfaces and interior elements.

2.4 OUI Materials

Interactive interior and decorative elements can be made possible through a range of *smart materials*; that is, tactile sensing and metamorphic (colour-changing and shape-changing) materials currently available, which can make normal finishing materials such as wood, fabric, paper, ceramic, glass and paints interactive. This section presents and critiques some interactive materials that offer great potential to interior decorations to help designers think about interactive spaces in new ways. Interactive or 'smart' materials are those that have conductive or changeable properties. Conductive materials allow seamless sensing and come in both solid and textile forms, the latter specifically useful for soft sensing and smart textiles (Kettley, 2016). Changeable materials respond to physical or chemical influences in reversible and repeatable behaviours (Ritter, 2015).

2.4.1 Sensing Materials

Tactile sensing (Rekimoto, 2008) can be achieved using a range of conductive materials providing physical artefacts with a range of soft sensing without the need for electronic sensors. Conductive materials can be used for both tactile input and electric circuit connectivity within soft objects instead of wires to avoid losing aesthetic or visceral associations. For example, users are unlikely to feel comfortable handling a non-soft cushion or standing on a rug with wires beneath. Therefore, the range of soft-sensing materials, available today, offers substantial potential for not only embedding touch, but stroke, squeeze and other tactile sensing, into soft furnishing. Moreover, research has shown the ability to recognize different gestures and levels of the same physical manipulation (Sato et al., 2012). In this sense, a finger touch can be identified from a hand touch, a weak grip and a firm grip for instance. Figure 2.10 shows an array of conductive materials that I elaborate on in the following sub-sections.

Conductive Paints: Capacitive paints or inks are formed using conductive powder (e.g. carbon or silver) prepared as acrylic pigments and used as a 'paintable and printable' material (Buechley et al., 2010) and used for prototyping, hand-drawing and fixing electronic circuits. Some have used conductive paint to envision bio-sensitivity on human skin, as proven to be non-toxic and washable. As such, capacitive inks can be either ink-jet printed (Kawahara et al., 2014), manually brush painted or screen-painted on a variety of different materials from paper and fabrics to wood, glass, ceramic or plastic giving touch-sensitive capabilities to different non-conductive materials. Conductive paint/ink is easy to apply to any non-conductive material (e.g. wood, paper, plastic, fabric, glass and ceramic) to convert it into touch or proximity sensitive. For example, Dalziel & Pow used conductive paint in their interactive installation, the EngagingSpace, in the Retail Design Expo 2015 (RDE15), to make the interface as 'painted murals on wooden wall panels' rather than a typical touch screen, see figure 2.11. Bare Conductive (2018) have been recently producing and promoting their conductive paints for DIY projects including decorative wall-painted light switches and DIY proximity dimming lamps. Conductive paints are safe, non-toxic, but spreads when applying if not masked and needs coating/insulation to prevent its

Figure 2.10 Examples of sensing materials that can be embedded within decorative objects. 1) Conductive Fabrics, 2) Stretch-sensing Fabric, 3) Conductive Fabric Tape, 4) Conductive Ribbon, 5) Conductive Fibre, 6) Conductive Thread, 7) Conductive Paint, 8) Metal Powders, 9) Copper and Aluminium Sheets, and 10) Velostat Paper.

Figure 2.11 Conductive (black) paint used for touch-sensing in the EngagingSpace by Dalziel & Pow in the Retail Expo 2015 (Image courtesy: dalzeil&Pow)

wear out over time. This insulation can be simply obtained by adding a layer of acrylic paint on top (whether clear or coloured) that should not affect its sensitivity. Although conductive inks are quite flexible being 'printable' and 'paintable', a major limitation -to some designs- is their base-colour (e.g. black/ silver). However, another printed or painted layer can be added on top to alter its appearance.

Conductive Fabrics: Conductive fabrics are also now commercially available -although in small samples not in large quantities- and available from different suppliers in disparate forms: e-textiles/fabric, thread yarns and fibres made of thin stainless steel threads. All of which provide tactile and tangible interaction to soft and flexible user interfaces that are safe to use and can engage users in emotional communication (Flagg et al., 2012). Conductive thread is used to replace electric wires in wearables (Berzowska and Coelho, 2005) and malleable OUIs (Follmer et al., 2012) in soft furnishing, creating seamless embedded soft circuits. Conductive fabrics come in various forms and materials, from thick opaque woven, non-woven and lycra to light dentelle and chiffon. Although most conductive fabrics come in metallic colours (silver, gold and brass), as they are made of thin metal threads, which are odd for fabrics, some colourful yarns are supplied by karl-grimm, lessEMF and habutextiles, and some have dyed conductive threads with thermochromic pigments (Kuusk, 2015; Devendorf et al., 2016). Coloured conductive thread yarns are made from typically 30% stainless steel and 70% colourful linen, wool or silk thread wrapped around the stainless steel, which makes them seamlessly conductive to the naked eye. Figure 2.11 shows, among other conductive materials, two spools of silk stainless steel thread in elegant beige and turquoise colours. Conductive fibre is quite playful because of its tactile manipulability, but is often poorly insulated and comes in silver colour only. A good way to solder fibre is using silver crimp beads, as it is unsolderable in itself. Similarly, conductive thread is safe and suitable for replacing wires inside wearables, fabrics and soft interfaces. Also, conductive thread is easy to use, whether by hand-stitching or machine sewing, when avoiding cross-overs that may cause short circuiting if used as electric connections. Otherwise, they can be used safely as soft-sensing stitches, seams or embroidery (Gilliland et al., 2010; Hamdan et al., 2018) or fabric layers (such as an embellishing metallic silk organza (Berzowska, 2005)). Project Jacquard (Poupyrev et al., 2016) has been ongoing looking into producing large-scale conductive fabrics that can enable invisible ubiquitous interactivity in everyday textiles.

Conductive Paper: Conductive paper such as carbon Velostat and copper sheets or tapes can be used to add sensitivity inside soft objects that are made of normal non-conductive fabrics or other flexible materials. Velostat foil sheets are flexible enough to be used as both pressure or bend sensor that can detect the bend angle through its resistance change (Heibeck et al., 2015). However, their durability over continuous long-term use is uncertain. Conductive paper foil or tape made of copper is another inexpensive material that is capacitive and often comes in adhesive forms, therefore, replacing the need for electric wire -and soldering- for simple DIY prototyping of OUI objects. Anabiosis (Tsuji and Wakita, 2011) wall art used copper foil as its capacitive touch material while JammingUI (Follmer et al., 2012) used copper tape as a transmitting conductive electrode layer. Although adhesive copper tape is very easy to use as a 'stick and play', it is not reliable on large-scale objects nor in the long-term and its relative stiffness could affect the ergonomics of flexible objects. Still, adhesive copper tape is still recommended for prototyping and paper circuitry (Qi and Buechley, 2014) due to its simplicity, wide availability and significantly low price. Combining both, a Velostat layer between two strips of copper tape was used as a layered conductive material in the jamSheets OUI (Ou et al., 2014), to sense squeeze, pressing and bend interactions as the conductive layers contact. Generally, conductive paper (Velostat and copper tape) is efficient for rapid and small-scale DIY prototyping, but should be replaced with other soldered connections for reliable long-term functioning.

Conductive Powder: Although not widely known or used as an electronic component or a prototyping material in interaction design, conductive metal powder is a unique material for designing decoractives. Metal powders come in basic metallic colours (gold, silver, brass/copper)

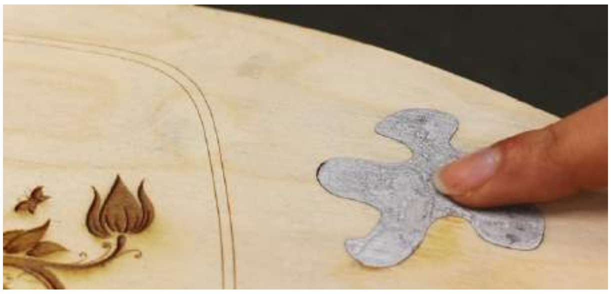


Figure 2.12 Silver metal powder inlay in plywood engraving is touch-sensitive to finger and hand proximity

and can be filled and glued to almost any designed engraving in different materials such as wood or acrylic. Therefore, they are potentially capable of augmenting interior elements with fine ornamental engravings that are touch-sensitive (see figure 2.12). However, there has been no use of metal powders as a touch-sensitive engraving material in relevant research, as far as I found, but only online tutorials of DIY Arduino projects (Treece, 2015). It is relatively difficult to carefully place the metal powder inlay in the engraving and drop the epoxy resin or CA (cyanoacrylate) glue to evenly saturate the powder that quickly soaks it up, then after it completely dries, a card scraper or sandpaper should be used to remove the excess powder from the surface. As it takes some effort and expertize to glue and time to dry, it is not considered as a rapid-prototyping material. However, for final versions of interactive wooden furniture and artwork, metal powder can be an exquisite choice for interactive inlay engravings and touch-sensitive ornamental details. In conclusion, metal powders come in classic metallic colours and can, therefore, add creative aesthetic input controls for interiors, e.g. a sofa arm wooden table with engraved buttons replacing the remote control. Yet, they are relatively difficult to apply and require some time and expertize to learn to work with.

2.4.2 Actuating Materials

Actuation can involve a number of types of deformations, responding to the sensed inputs (discussed in the previous section). The two most organic and dramatic actuations (i.e. colour-change and shape-change) are discussed in more detail below.

Colour-Change: Colour-changing or ‘chromogenic materials’ are materials that react to external stimuli by changing colour or intensity. This is caused by microstructural changes in such materials causing their optical characteristics (transparency or light diffraction) to change in response to physical or chemical stimuli in the surrounding environment (Ferrara and Bengisu, 2013). Known stimulating conditions are heat, light, electric current, magnetism and chemical/acidity, and are called thermochromic, photochromic, electrochromic, magnetochromic and chemochromic respectively (Ritter, 2015). Other chromogenic materials are also being investigated such as mechanochromic/piezochromic, biochromic and radioactive (Ferrara and Bengisu, 2013). Different chromogenic materials react to the change of their stimulating conditions at certain thresholds by disappearing and are usually reversible by reappearing with the stimuli being reversed or vanishing for a certain time (Ritter, 2015). The reaction time and threshold are not only determined by the properties of each material, but also by the combination of chemicals the chromogenic molecules are blended in or the medium painted on (Dumitrescu et al., 2018). Herein, I focus on thermochromics as a programmable colour-change capability that can be electronically controlled and at the same time is widely-available off-the-shelf in an array of vibrant colours. Other colour-changing pigments are either not easily electronically controlled, or are only available off-the-shelf in limited colours.

Thermochromic pigments in particular are widely available nowadays in the form of off-the-shelf dyes and pigments, in a variety of colours, making it easy to apply to different kinds of materials covering both solid and flexible surfaces including fabrics (Persson, 2013), providing a variety of rich colour-changing materials for interior design and decoration. The palette that can be obtained using thermochromic inks has therefore been explored by several researchers in the field of textile interaction design such as Maggie Orth, Linda Worbin, Marjan Kooroshnia and Anna Persson (Dumitrescu et al., 2018). Moreover, thermochromic colour-change can be electronically programmed using heating agents underneath.

Figure 2.13 Thermochromic Colour-Changing Tiles by MovingColor (Photos courtesy of MovingColor.net)

Thermochromics are applied as normal colour pigments, but are chemically prepared in a way that makes one of its colour components disappear at a certain temperature threshold or transform into another colour. Although common thermochromics have one activation threshold, bi-stable thermochromics allow reversible actuation between two thresholds (e.g. activate above 70°C and deactivate below 0°C). In addition to transparency, careful combinations between different foreground and background colours can lead to the revealing or disappearing of specific patterns, graphics or textual notifications. I call both of these techniques positive and negative colour change respectively. Positive colour-change can be achieved by applying the hidden pattern or notification using normal paint then covering it with a thermochromic darker foreground that would disappear to reveal what is beneath. The other way around is used to achieve the negative colour-change, where a pattern or notification would disappear or dim (i.e. turn off) when it's painted with thermochromic foreground on normal background paint, regardless darker or lighter.

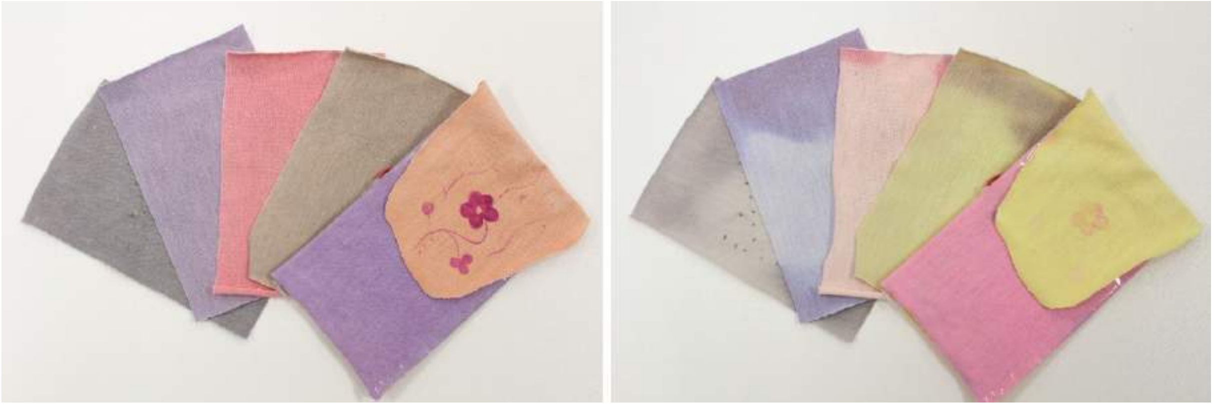


Figure 2.14 Swatches of thermochromic fabric supplied from bodyfaders.com; a) Colours in room temperature; b) actuated colours when fabrics are heated above 35°C.

Today, there are different applications for thermochromics and mature products in the market focusing on autonomous heat indicators including decorative thermometers, colour-changing wearable accessories, garments and electric devices such as kettles. MovingColor designs and supplies colour-changing ceramic tiles that are made with different shades of thermochromic colours, with body heat thresholds, for use in various purposes, such as floor tiles, bed headboards, and walk-in shower rooms (see figure 2.13). Thermochromic inks also became widely available to consumers in forms of powder pigments, acrylic dyes, screen printing paints and fabrics (see figure 2.14). Bi-stable thermochromics have also provided means for reversible printing allowing updatable appearance of everyday objects without re-fabrication (Saakes et al., 2012). Stacey Kuznetsov is known for engaging participants of her workshops with thermochromic pigments as a low-cost smart material for embedding interactivity onto a range of materials (e.g. paper, fabric, plastic, wood, or vinyl) through DIY crafting techniques such as screen printing (Kuznetsov et al., 2018).

Thermochromic OUI can be either autonomous with ambient heat (when in contact with a hot object or when room temperature changes) if the threshold is at a relatively low degree (e.g. 15°C to 20°C) or electronically controlled if the threshold is at a high temperature (e.g. above 40°C). The latter can be controlled using micro-controlled heating-agents (e.g. flexible heating pads, thermoelectric peltiers (Peiris et al., 2013)) or heat generating materials (e.g. nichrome wire, copper enamelled wire, conductive thread, silver ink or carbon paste (Tsuji and Wakita, 2011)). Such controlled colour-change is of specific interest to interaction design and research as it can be controlled via different connected sensing techniques creating context-aware decorative OUIs that are pattern-changing such as AmbiKraf Byobu (Peiris et al., 2013), animated colour-changing such as Anabiosis (Tsuji and Wakita, 2011) and potentially style-changing which should be consequently feasible. This should support interaction and interior designers to collaborate creating not only innovative appearance-changing decorative OUIs, but OUI interior elements that have camouflage, chameleon and other display capabilities (Morin et al., 2012).

Thermochromic paints are the most useful and widely available colour-changing pigments that react to temperature change and can be simply controlled using heat triggered by electricity. Thermochromics can be potentially further used to change patterns, styles or texture effects.

As thermochromics can take a few seconds to actuate (depending on the efficiency of heating agent and circuit resistance), they do support slow interaction -which better suits interior spaces designed for rest and relaxation- through non-instantaneous colour transitions. Thermochromics are suitable for designing ambient displays, but should not be considered for either prompt feedback or multi-user input, as it takes time to cool down and be ready for new actuation. Thermochromics come in various colours and can be mixed with normal acrylic paints so there are no aesthetic boundaries for artistic creativity. Moreover, they can be used to dye fabrics and yarns. High threshold thermochromics are better for user input interaction but require high power to control the heating agent (heating pads/ thermoelectric peltier /nichrome wire), while low threshold thermochromics are better for 'enviro-smart' interaction (non-controlled) and thus are entirely sustainable.

Although research has shown some benefits of colour-changing interactions (Kaihou and Wakita, 2013), much of the potential of colour-changing interfaces has not been explored. There is an opportunity to develop interiors and decorative elements that can change their colour and/or pattern possibly creating new decorative themes among a 'soft network' of pillows, curtains, rugs and upholstery, actuating in harmony to alter the interior atmosphere. This is not just for aesthetic purposes, but could be used to influence emotion and mood of vulnerable people, support the treatment and psychological well-being of patients in a clinical context, stimulate focus of students in a classroom, energize gym users or control appetite for those fasting, all of which are reported benefits of ambient colour manipulation.

Shape-Change: Shape-change not only refers to kinetics but also the material property of changeable physical form for either a part or the whole of an object's structure. This includes subtle movements/deformations of the object's skin/envelope, often referred to as skin-changing or texture-changing interfaces. Changeability can be designed using different techniques, from kinetic mechanical motions of servomotors and vibration motors to soft pneumatic actuation (Yao et al., 2013; Harrison and Hudson, 2009) and shape-changing organic materials (Coelho and Zigelbaum, 2011). We can, therefore, find numerous ways to embed shape-change, skin-change or texture-change in everyday objects either passively (responding to configured input) or actively (smartly autonomous).

Although miniature servomotors are used to design kinetic interactions in some adaptive spaces, yet they produce noisy sounds and artificial robotic motion, in addition to their bulky structure, rigid shape and behaviour. Alternatively, pneumatic actuators can be soft and more organic in their shape-change, but depend mostly on the expandable fabricated materials such as silicon rubber (Yao et al., 2013) or latex sheets (Harrison and Hudson, 2009). Pneumatic actuators are also somewhat "messy" requiring tubes, pumps, valves and chambers that may become prone to leaking and degrade in performance over time (Harrison and Hudson, 2009). This might limit the design space where it can be challenging to embed them within normal decorative objects without losing their aesthetics and/or affordance such as curtains, throws, cushions, runners and rugs. However, other shape-changing materials can be 'woven' into textiles (Persson, 2013) and traditional soft-furnishing with silent and subtle deformations such as hair-thin metal alloys that have reversible and repeatable shape-memory properties, known as Shape-Memory Alloys (SMA). An example of SMA is the NiTi (Nickel-Titanium alloy also referred to as Nitinol or Flexinol) that can be physically programmed to transform into a certain shape at a specified temperature threshold. Thin flexible wires (and springs) made of Nitinol alloy are often physically-programmed to shrink/retract with heat/electricity and are thus commonly known as muscle wires.

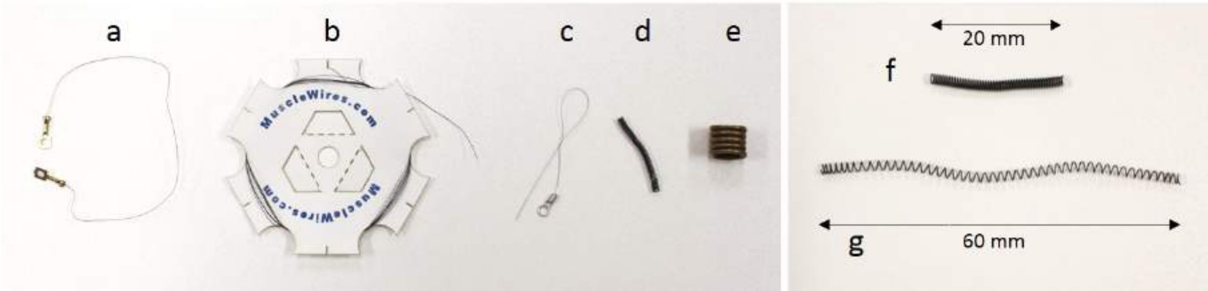


Figure 2.15 Examples of off-the-shelf SMA Nitinol muscle wire. a) Muscle wire 0.015mm (lightstitches.co.uk), b) Flexinol 0.015mm 70°C (musclewire.com), c) TOKI BMX75 0.075mm (biometal.biz), d) Nitinol Springs 0.25mm 45°C (kelloggsresearchlabs.com), e) 2-way muscle spring (mindsetonline.co.uk), f) Austenite retracted memory shape, g) Martensite room-temperature malleable shape

Such SMA 'smart wires' are available off-the-shelf, and can be sewn to most fabrics, and are mainly useful for bend, curl, crumble and deformation actuations. Metal springs made of Nitinol -called muscle springs- are programmed to return to their original retracted (austenite) spring shape with heat or electric current regardless of the physical deformation forced upon them in their malleable (martensite) state in room temperature. Likewise, muscle wire can be re-trained to remember a new shape (called the austenite form/state) in a process called 'annealing' (Sun et al., 2012) by heating it up to 400-500°C while fixed in that shape (e.g. using a mould or a metal frame). The muscle wire is malleable and easily deformable in room temperature (called the martensite form/state) and only transforms into the memory (austenite) shape when activated by 40-90°C, through heating with hot water, air or electric current. In this sense, muscle wires and springs can then be connected to microcontrollers and electronically controlled, see figure 2.15.

Related case studies that used controlled SMA include wearables such as Kukkia and Vilkas (Berzowska and Coelho, 2005), Lumina architectural-skin (Khoo and Salim, 2013), Shutters (Coelho et al., 2009) and MoodFern (Cheng et al., 2014) (see figure 2.16). Alternatively, the shape-changing wall panels of LivingSurface (Yu et al., 2016) used servomotors, vibration motors and fans to actuate shape-change. Possible decorative applications could utilize Nitinol to create various dynamic objects such as a light lamp that can change the shape of its shade, a decorative sculpture that can take on new shapes silently and slowly or a shaggy rug that waves its fabric and moves across a room. By connecting muscle wires to microcontrollers and embedded sensing, shape-changing interfaces can be programmed to react to any sensory data and thus be context-aware of the surrounding environment, user(s) and other objects. Therefore, muscle wires and springs create a great opportunity for embedding controlled shape-change in everyday soft and flexible interfaces.

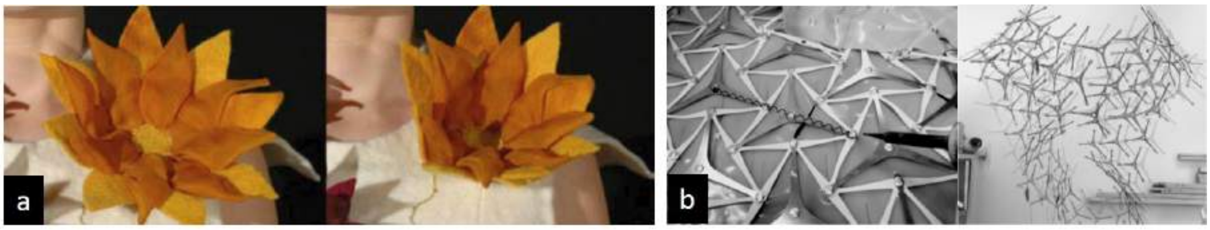


Figure 2.16 Examples of shape-changing decorative elements using SMA Nitinol wires and springs. a) Kukkia and Vilkas (Berzowska and Coelho, 2005), b) Lumina architectural-skin (Khoo and Salim, 2013)

SMA or muscle wire can be used to add either motion feedback or shape-changing interaction. Muscle wire is suitable with thin light soft materials and is entirely silent unlike servomotors, but similarly requires high power to actuate. Special consideration and alteration to the amount of voltage and electric current given to an SMA circuit will result in a different effect ranging from instantaneous sudden movement or alteration of the physical form to subtle and slower organic-like breeze motion. As it can get hot, designers should avoid use with flammable materials. Muscle wire often requires a long iterative prototyping process to achieve the required actuation or movement effect. When using SMA, two aspects need to be taken into account: first, the aesthetic design of both the static state and the dynamic motion, and second, the materiality on which the SMA is fixed, its stiffness, weight, affordance and its ability to deform and recover back to its default state. Both thermochromics and muscle wire can be used in conjunction to make use of the heat generated from SMA to actuate colour-change as well, providing much richer feedback and dramatic decorative interaction.

2.5 Summary

In this chapter, I have distinguished between the overlapping, yet different, concept of tangible, shape-changing and organic interfaces (i.e. TUI, SCI, and OUI) to give grounds for using the term of OUI to describe my interactive materials, objects and spaces hereafter. By reviewing the state-of-the-art in OUIs on the levels of OUI interior design, interior decoration and materials, I was able to point out the potentials and the gaps to this area of research. It is now clear how relevant work on both sides (research and practice) in relevant disciplines (HCI and interior architecture) is held separately from one another, yet with the same vision.

Technology is converging to bring together a new generation of devices and interactions built around OUI materials. The vision of smart spaces and ubiquitous environments has never been closer to realization. Previous visions of interactive architecture have been just visions, largely unrealizable at a scale that would actually impact people in an everyday context (being largely restricted to specific experimental builds). The advances in interactive materials mean that it is now possible to make architectural interventions at the interior scale, in seamless, dynamic and aesthetic ways.

Older building stock can be retrofitted with such materiality to dynamically alter spaces and make environments responsive in ways not possible before. No longer do we need to make the case for building entirely new spaces when existing everyday objects can be adapted with technology to make them interactive. The imminent proliferation of *smart spaces* is making the general populace more switched on to the idea of technologically enhanced and reactive environments. Now is, therefore, the time to invest in thoroughly exploring a new future of interactive, dynamic and reactive interior design. This requires a fundamental attack from multidisciplinary and interdisciplinary researchers to begin to address the challenges and opportunities of OUIs, which offer us the strongest means through which to deliver a future of interactive interior design.

In the following chapters, I start taking on different roles, in an attempt to bridge these gaps, challenging some methodologies (e.g. lab studies vs. situated deployments) and blending in others (e.g. critical making with design-fictions), in addition to playing the role of a maker, crafter and interior designer to experiment with materials and build interactive spaces. This chapter explored the state-of-the-art of OUI interactive interior spaces, decorative elements and materials, and set the arguments of why we should design and build OUI Interiors. After establishing my research methodologies, I will address, in the following chapters of this thesis, my research questions and explain how can we design and build OUI Interiors through the different methods that can help us achieve this.

Chapter 3. Methodological Approach

By adopting design-led and practice-based research approaches, we can bring interaction design and interior design together, or rather melt them into one new field of 'interactive interior design'. Although Computer Science and Ubiquitous Computing are traditionally problem-solving fields, the nature of design is usually driven by imaginative thinking and (re)framing of ideas which triggers questions (that emerge out of the process of design) rather than searching for solutions of an initial problem (Koskinen et al., 2011; Stappers and Giaccardi, 2017). Therefore, the traditional problem-led (or problem-solving) approaches are not appropriate (as there is no solution-focused agenda to deal with), but I found a number of research methodologies that are more suitable for my exploration-led research providing insights towards my three fundamental research questions.

Through an evolving process of **Research-through-Design** (Durrant et al., 2017), I utilize methodologies of: 1) Critical Making, 2) Critical Engagement, and 3) Critical Speculation. Figure 3.1 shows how these methodologies employ relevant research methods and are integrated together throughout my research with Research-through-Design as the overarching approach tying them all together. In this chapter, I unwrap each of these research methods clarifying how they support my research investigation and how they work together seeking to answer my research questions in the parallel research activities happening concurrently (as explained in Section 1.4).

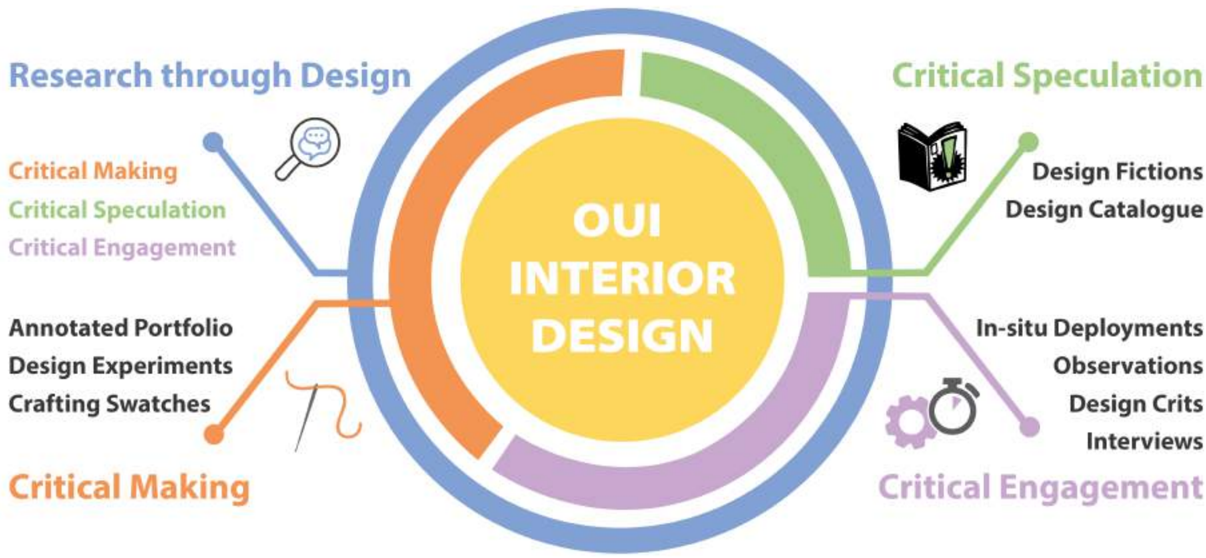


Figure 3.1 Research through design research methodologies including: Critical Making, Critical Engagement and Critical Speculation.

3.1 Research Through Design

Research through Design (RtD) is a "research approach that employs methods and processes from design practices as a legitimate method of inquiry" (Zimmerman et al., 2010) that is increasingly adopted by researchers in the borderlands between HCI research and design (Dalsgaard, 2016). Peter Dalsgaard has introduced Rheinberger's concept of 'Experimental Systems' (Rheinberger, 2010) to RtD in ways that resonate with how the epistemology of experimentation and how we generate new valuable knowledge and learn from experiments can be a design-led inquiry where practice turns into scientific research (Dalsgaard, 2016). Moreover, Rheinberger stated that as long as artworks and their concepts remain vague, they generate a productive tension in reaching out to the unknown, transforming into tools of research, and inviting us to think (Rheinberger, 2010). Such artistic research is, therefore, the "articulation of this unfinished thinking" (Schwab, 2013), giving the process of **critical making** and reflection on the 'making' and 'crafting' of artful objects the ability to generate new knowledge and understanding.

Nevertheless, a balanced blend between the roles of a thinker/finder and a tinkerer/maker requires tangiblizing some of the ideas and designs in situated studies through **critical engagement**, where material experience can be evaluated *through use* by different people reflecting on how they perceive, interact and enjoy (or not) engaging with such technology. This involves both deployments in-the-wild and situated studies in design practices. Therefore, such research methods also supports the critical reflection of designers through interviews, group discussions, collaborations and 'design crits'.

In this case, *qualitative analysis* research methods that are common to the HCI discipline helps study and evaluate the different aspects of how my designs and ideas are perceived and interacted with. Transcribing audio and video recorded data and analysing it simultaneously with field notes and observations of situated studies creates rich qualitative research data. Such input is then subjected to a common form of analysis in HCI qualitative research, namely 'thematic analysis'. The output of this process codifies individual quotes and data elements to find re-occurring patterns and themes across the dataset.

Finally, to ease the tension between practicality versus imagination, I found refuge in alternative creative RtD methods that complement the other adopted approaches. On one hand, mimetic design of digital illustrations in the shape of a themed product catalogue is one way -I've used- of tangibilizing future design ideas (that are proven to be valid and feasible) without the need to undergo all the making and deployment steps required for a situated study. On the other hand, diegetic fictional stories or vignettes are equally useful for exploring the play-of-possibilities in various (even hypothetical) scenarios avoiding causing any possible harm to users of situated studies. These methods of **critical speculation** that are framed in *design fictions* challenge both the utopian and dystopian futures -respectively- of my ideas and designs of OUI Interiors.

3.2 Critical Making

This research is mostly based on the ‘Critical Making’ approach, aligning with what Tim Ingold advocated in his prominent book ‘Making’ (Ingold, 2013) around the ‘art of inquiry’ and how knowledge can grow from our practical and observational engagement with the materials we work with. Through a Research-through-Design (Durrant et al., 2017) approach, I explore my research inquiry by co-designing with my materials using three methods: a) crafting swatches, b) design experiments, and c) design portfolio. Departing from relevant literature (Gaver, 2012) on how design portfolios and workbooks have been used as a way of documenting research through making, this research has significantly relied on such materialistic documentation of pieces of design research, in the form of an ‘annotated portfolio’ (Bowers, 2012). All these forms of research-through-design outputs helped shape the exploratory nature of my PhD in a self-reflecting and developing experimental design process.

Critical making (Ratto, 2011) is an RtD approach that focuses on using experimenting with materials and ‘making things’ as part of a concept elaboration, commonly within design and art practices. Ratto (2011) describes this approach as the bridging between the conceptual (critical thinking) and the physical (making) that could together be two sides of the same coin. I utilize this approach through extensive experimentation and exploration of materialities, techniques and tools.

With a background in interior design practice, my materials of interest are contemporary finishing materials such as wood, paper, acrylic, ceramic and textiles (e.g. fabrics, leather and carpets). Therefore, my design-led inquiry is looking at practical crafting and making techniques as a tool to embed interactivity into interior elements. My practice-based work is borrowing techniques (such as painting, sewing and tiling) to embed sensing and actuation within everyday artefacts translating interactivity into crafted forms of meaningful artefacts. In order to achieve this, I produced a vast array of *crafted swatches* where interaction is embedded seamlessly within interior materials.

Rather than adopting the common prototyping techniques of attaching electronic components to digitally fabricated devices, I explore an alternative approach of *design experiments* for creating interactive objects, to develop ways of incorporating OUI materials directly into the crafting and making stages of the material. OUI materials that have morphological capabilities such as thermochromic inks and shape-memory wires can -theoretically- be stitched, knitted, weaved and felted into different textiles. Similarly, colour-changing pigments can be used to paint or screen-print wallpaper, ceramic tiles or patterned fabrics. This design experimentation aims to explore how can we do this, what can we use them for, and what different emergent materialities (Pink et al., 2016) can we learn from embedding finishing materials with such OUI materials, all through a critical making approach.

Furthermore, this research draws on the insights of Gaver (Gaver, 2012), who frames the production of ‘annotated portfolios’ as a rigorous theory and a developing form of research-through-design, to underpin my presentation of a series of design experiments. My exploratory process of making has been systematically documented by sketches, notes, photographs, shots of video recording footage and observations. Such documentation is physicalized in my swatchbook (see Appendix A) as a form of an *annotated portfolio*.

This portfolio of design explorations, from my own creative practice, offers insight into the interactive potentials of the techniques this research has exploited. Unlike scientific methods where scientists are abstracted from their experiments, design researchers impose a lot of their personal perspectives and skills to their research projects and practices (Schön, 1983). Accordingly, a researcher of an exploratory study will have their own repertoire and their own palette of materials that informs how they encounter them and what they can achieve.

3.3 Critical Engagement

Within my ‘Research-through-Design’ approach, going out in-the-wild was also a key strategy for critical engagement with both end-users and designers. Koskinen argued if we can really study design in a laboratory and if this -in many cases- costs us a “decontextualization” price as opposed to design research in real-world settings (field) and in showrooms (design exhibitions) (Koskinen et al., 2011). Rather than only evaluating the design object itself, I argue in favour of a focus on the dynamic and tactile experiences (Redström, 2005) of users while engaging with the object. To explore how people would perceive and interact with OUIs as decorative artefacts, they should be embedded as interior elements and contextualized within in-situ deployments, away from the lab.

Extending typical duration of user interaction to over an hour (instead of an average of 2 minutes in relevant previous work (Gronvall et al., 2014)) allows people the time to observe, practise, learn and develop a variety of interaction scenarios. While most researchers of previous work (Mennicken et al., 2014a; Nakajima et al., 2011; Everitt and Alexander, 2017; Vink et al., 2015; Follmer et al., 2013) have experimented their prototypes in a lab setting, a few have also adopted in-situ deployments (Gronvall et al., 2014; Gaver et al., 2006). The latter pattern-changing History Tablecloth (Gaver et al., 2006) is a prominent example of a long-term study of situated interactive furniture. The 4-months study in an actual household provided a deeper insight into what it means to design artefacts in a real-world environment. However, today’s real-world applications that fit into our interior spaces are still quite limited.

Accordingly, this research involves a series of design explorations, critically examining the OUI Interiors by providing inspirational artefacts and case-studies supporting others who might wish to design and develop actuating decorative artefacts for different contexts. For example, my situated deployments included a home, a café, a restaurant, a gallery and a museum. In each case study, a complex experience with a long set of details was planned and carefully prepared and organized, to explore a natural experience, evaluate interactions and cover a variety of cases as possible.

These studies offered an open-ended set of observations in terms of user behaviour, interpretation, reactions and expectations. The intention was not studying the gallery visiting or the dining experience in itself, but to explore the design of interactive artefacts and how people may perceive, interact with and experience such technologies in relevant settings and to gain deeper knowledge and insight into designing interactive everyday objects as decorative artefacts.

With tens of participants in a variety of places, such in-situ studies show how different people interact idiosyncratically with a number of conventional decorative objects (e.g. wall-art, table-runner) that are ‘actuating’, yet concur when interpreting its interactions and discussing its impacts on their experience. Furthermore, these situated deployments helped frame realistic findings and reflections with regards to the overall experience, the social engagement in an interactive space as well as insights of people’s sense-making outside of a lab-setting and in-the-wild.

Lab experiments are usually constrained in terms of space design, user comfort and artificial reactions of participants that vary in their feeling of potential un-ease as being closely monitored in a possible unfamiliar situation. On the contrary, my objective was to observe and explore people's experience around an interactive artefact as an integral part of their interior space, not as a separate or independent one. To investigate in-the-wild how people perceive and interact with such technology embedded within an everyday decorative object that is conventionally just static, it had to blend into the background of the perceived space. This helped in realizing the potential of such interactive decoratives when developing interactive interior spaces in different contexts. In addition, such study allowed investigating what interesting interactions users might understand, develop and adopt in such contexts.

Moreover, for the same prototype, I varied the location of the study to enhance the ecological validity of my exploration. Also, participants who joined these studies were selected or recruited from a range of cultures (i.e. South-Eastern Asian, Middle-Eastern, European and African), with balanced mixed genders, family groups and individuals from different backgrounds (e.g. Health-care, Business, Bio-technology, Computing, Architecture, Education, Social Work and Engineering). This does not only reflect the diversity of my research group, but also the fact that they are neither familiar with OUI technology nor selected within a specific group of people (e.g. HCI researchers). In all these studies, participants were not briefed about the technological intervention in the space, or that there was an interactive element to give them the chance of having their experience as usual and discovering the interactivity themselves.

During each of the in-situ deployments, qualitative data was gathered for the purpose of further analysis and insights. All studies were audio recorded and some were video recorded from different angles to capture as many of the users' expressions, interactions and conversations as possible. Situated studies would last a minimum of one hour, with the longest spanning over 8 hours. In some studies, I held audio-recorded interviews with participants after unscheduled drop-ins, while in others I joined participants for a post-study 'design crit', a group discussion, lasting from 30 to 90 minutes, where participants had the opportunity to express their reflections on their experience and provide me with critical feedback on my design and further design opportunities.

The design crit group discussions were held to evaluate the critical engagement with, and design of, my OUIs in terms of: 1) Sense-making and interpretation (how did the OUI make them think? Does the OUI look, feel and sound right?); 2) Interaction and emotional engagement they had with it, and with each other in relation to it; 3) Complex scenarios and interactions beyond expected legible interactivity; 4) Proposing possible enhancements (in terms of design, interaction, purpose, meaning/value and/or context) in light of: constructive feedback about the design itself; materiality (evaluating the material quality and finish), and pros and cons (what is bad and what is good about the design).

Overall, my qualitative analysis relied on the gathered data that consisted of selective transcripts of audio recordings of the studies, the group discussions and/or design crits, plus selective interaction analysis to the video recordings, in addition to informal unstructured interviews (in case of individuals). The collected data was also supplemented by sketches, schematic architectural drawings, textual written descriptions of ideas and designs, and most importantly my observational notes made throughout the studies.

Qualitative Data from the critical engagement studies and the post-studies design crits was transcribed and then subjected to Thematic Analysis (Braun and Clarke, 2006). The orientation to use a 'situated design crit' as an evaluatory mechanism means that the emphasis of the results is less on the contextual experience and more on a critical reflection on the design of the interactivity in the space. Accordingly, the resultant 'themes' unpack the OUI Interior experience, exploring how users made sense of OUIs, and how they imagine they could be better designed, used or employed.

3.4 Critical Speculation

Design fiction is a valuable means of critical speculation, providing concrete scenarios that contextualize the use of forthcoming technology. The use of design fiction methods has recently started gaining interest amongst the HCI community (Troiano et al., 2016), blurring the boundaries between traditional design practices and narrative explorations of potential futures (Tanenbaum et al., 2012). Different methods of critical speculation can be employed, from Sci-Fi movies inspirations (Troiano et al., 2016) to fictional stories, illustrations and sketching (Sturdee et al., 2018). Such methods, in the form of either diegesis or mimesis, can be used to inform the design of technology and help envisioning how it will be used in the future.

To present the utopian near-future of OUI interactive interiors, I utilized the "Ikea Catalogue from the Future" (Near Future Laboratory, 2015) to create a Design Catalogue (see Appendix B) illustrating my vision. In briefly presenting this, I attempt to simply contextualize the materials, showing how they might be realized within actual products. This moves beyond the 'design workbook' (Gaver, 2011) or 'annotated portfolio' (Bowers, 2012) approaches to detailing design process and insight, by utilizing the common plot devices (Blythe, 2017) of a well understood 'fiction' (the product catalogue), to emphasize placement, context and relative materiality of groups of artefacts, which are potentially usefully inspirational qualities in these kinds of design-spaces.

The ideas presented in this catalogue are not specifying what should be made, but rather showing some "what ifs?" and some possibilities as exemplary decorative OUIs presented to inspire design. This catalogue should not be thought of as a presentation of a futuristic vision, but rather an achievable reality of what could be done with the technology we have at hand, and what I have actually designed and made myself. Figure 3.2 shows the cover page of my 'Decoraction Catalogue' presenting 4 different interactive decorative objects: a wall-art painting, a matching cushion, a lampshade, and a throw.

Figure 3.2 Decoraction Catalogue of interactive OUI Interiors

Alternatively, diegetic accounts are also useful in providing counter narrations. I articulated four fictional short stories (see Appendix C), of interactive technologies, contrasting their technopositive accounts, common often to research literature. In doing so, I presented design fictions of dystopian alternative interpretations, to support a deeper reflection on the potential pitfalls of increased interactivity in our habitable spaces (Nabil and Kirk, 2019). In critically reviewing each of these case studies, I draw on a tradition of critically-minded design fiction (Blythe, 2014) to tell stories about the potential frictions that such technologies might cause, to help us tease out some of the critical research agendas around interactive interiors and data futures in the built environment, that are yet to be addressed.

These dystopian fictional stories can help bring near-future dilemmas closer to our attention. I utilize these examples not to focus on 'what is' or 'what has been' developed so far, but to critically examine future realities. In doing this, I try to address a gap in our current approaches to technology design which are all too frequently idealistic, and techno-deterministic. This is mainly built on the speculative turn in studies of Human-Computer Interaction (Mancini et al., 2010; Elsden et al., 2017, 2016) which has sought to engage critically with the social implications of new and proposed technologies (Dunne and Raby, 2001).

Whilst Mancini et al. (2010) have argued for presenting both utopian and dystopian perspectives, others have argued for the importance of dystopic visions as a counter to the perhaps inevitable utopian speculation that surrounds the launch of new technologies (a bias to which the HCI academic community is not immune). My choice of using a design fiction approach is useful as it, in essence, supports risk modelling, allowing me to explore the play-of-possibilities in a tech scenario without putting participants at risk.

To highlight some of these challenges and to cut against what is inevitably a technopositive account of new technologies in academic literature (after all, how often are academic papers written to detail how dangerous, foolhardy or invasive our designs are?) are presented as dystopian short stories, a known form of design fictions (Blythe, 2014). These short vignettes presented cases of new technologies and then problematized the discourse to raise tensions around the designs of these classes of technology, to allow the reader to ponder some of the challenges that may be raised by technological intervention in these spaces.

3.5 Summary

In this chapter, I have presented the methods used to carry out parallel components of my design-based research and tackle my research questions. This thesis relies mainly on Research-through-Design as the overarching methodology of which different approaches revolve around in parallel activities. To "*explore the materials and making techniques of OUI Interiors*" (i.e. Research Question 1), I adopt a 'critical making' approach (Section 3.2) including methods of crafting swatches, design experiments and producing an annotated portfolio.

Then, using 'critical engagement' (Section 3.3) I explore "*what can we learn for design by situating OUIs?*" (Research Question 3) through utilizing research methods of in-situ deployments and qualitative analysis. Qualitative data of people's engagement with OUI Interiors were gathered throughout my in-situ deployments using methods of interviews, group discussions/ design crits, field notes and observations.

Concurrently, through 'critical speculation' (Section 3.4) add to that 'design fictions' to explore "*what OUI artefacts can we make?*" (i.e. Research Question 2) and challenge what has been done so far and extend the *what if* beyond the horizon of today's interactive designs. In this case, I used two methods: diegetic (articulating four fictional stories) and mimetic (producing a product design catalogue). Consequently, I explored the extreme dystopian and utopian speculative designs of OUI Interiors that may or may not be included in both 'critical making' and 'critical engagement'.

Through a trajectory of scale, the next three chapters delve into OUI Interiors from 'experimenting with materials' (Chapter 4) to 'prototyping OUI decoratives' (Chapter 5) and finally 'studying OUI interiors' (Chapter 6). Despite being presented in this sequence, the work discussed in these three chapters was carried out in parallel to each other. That is, I would use critical making to experiment some crafting techniques on swatches, then I can prototype an interactive decorative artefact accordingly, which might require re-visiting my making techniques, and eventually (in some cases) evaluate the critical engagement of this OUI interior element in a situated study. This iterative design process feeds into every phase of the design and enriches self-reflection on the overall design space and towards other unrealized opportunities and limitations.

Chapter 4. Experimenting with OUI Materials

Through the first part of the thesis (Chapters 1,2 and 3), I laid the foundation to the concept, literature and methodologies of designing OUI Interiors as future interactive spaces. To explore this paradigm, it is essential to first delve into the building blocks of such a vision, and materialize the components of this design space, which are not just the decorative elements, but the very materials they are made of (e.g. fabrics, wood, ceramic and acrylic). This can be achieved by carrying out learning-through-making in exploratory research to understand ways of embedding such materials with interactivity, through utilizing embeddable 'OUI materials' and extensive experimentations of different crafting techniques that could help us do so.

Responding directly to **Research Question 1**: "What interactive materials and making techniques can be used to design and build OUIs?", this chapter explores interactive and smart materials that are deemed embeddable in interior finishing and appropriate for building interactive decorative artefacts *seamlessly*. The literature Survey in Chapter 2 categorized the different kinds of these advanced materials and defined the sensing and morphological capabilities that can be utilized by researchers and practitioners wishing to engage with OUI Interiors. This categorization, or taxonomy, covers materials that are deformable or paintable, and either electronically or physically programmable thereby affording hand manipulations, context awareness and/or change of physical appearance (shape, colour, texture, and pattern). Based on this, I categorized OUI materials into three main categories: 1) Sensing Materials (manipulative and capacitive), 2) Colour-changing Materials, and 3) Shape-changing Materials. Each category and its sub-types were thoroughly explained in Chapter 2. Herein, this chapter describes how I unpack each of these materials and experiment with different ways of embedding them into decorative materials (e.g. textiles, paper and beads). Then, I start developing and reappropriating new crafting techniques to explore how they could be embedded in real-world interior objects and decorative artwork on a large scale.

As this chapter presents 'critical making' work done throughout my research and in parallel to prototyping OUIs, it offers insights from which practical resources for making resulted in the form of a taxonomy and a swatchbook of OUI materials. This generation of knowledge depends on the experience of making with these materials. In addition, I draw on the inspirations that the materials give, in the context of interior design in terms of what can these materials do, afford and be used for? and how? The potentials of these materials in interactive interior design can be realized through a practical, meaningful and aesthetics-focused design exploration. I introduce this herein by exploring making and crafting techniques (e.g. sketching, sewing, dyeing and painting) that can be used for embedding interactive materials in everyday designs and pushing previous work forward. Such techniques can then raise interesting avenues, beyond interaction design, in fields including not only interior design but product design and fashion design as well.

4.1 Design Research Methods

In a practice-based exploratory approach, I began my research through design (Stappers and Giaccardi, 2017; Zimmerman et al., 2007) with the most fundamental element of an interior space i.e. the materials themselves. I started to untangle the complex relationship between the properties and embodiments of materials and the practices that develop with and through such materials. I adopted an exploration-led approach and started introducing practice-oriented accounts of materiality and their interactivities through existing practices of crafting (e.g. sewing and painting). Design researchers argue that understanding material experience will pave the road for a new way of designing digital artefacts and enable envisioned practices to unfold (Giaccardi and Karana, 2015), in addition to empowering people to assimilate tech-making and design with their ongoing crafting and making practices. This is indeed true and I have experienced this throughout my journey of ‘critical making’ (Ratto, 2011) and exploratory experimentation and was, therefore, able to develop new ways of designing interfaces.

4.1.1 Ideation

In early stages, I relied mostly on sketching to express my ideas and designs. Thinking through sketching and getting abstract ideas down on paper is common in arts and design practices. Sketching is also a recognized technique in HCI in general (Sturdee et al., 2018) and for designing shape-changing interfaces (Sturdee, 2018) in particular. I sketched early ideas with freehand drawing (see figure 4.1) and also with digital illustrations (see figure 4.2).

4.1.2 Making

After ideation, sketching and digital illustration, comes the crafting and making phase. At this point, I started learning through making how I can embed OUI materials -seamlessly- into the finishing material of the artefact (i.e. interior element) that I want to make interactive. I experimented different types of interactive materials (soft sensing, colour-changing and shape-changing) onto an array of finishing materials (e.g. different fabrics and textiles, paper, acrylic, beads, lace and leather). During this exploratory process, I documented my learning, making and observations of material behaviour (particularly of shape-changing materials) in a lab book, or a swatchbook portfolio (see Appendix A). This portfolio of design explorations, from my own creative practice, offers insight into the interactive potentials of the materials I have exploited. I created this design-research portfolio following the ‘design workbook’ (Gaver, 2011) or ‘annotated portfolio’ (Bowers, 2012) approaches for detailing the making/ learning process. Figure 4.3 shows some pages of my portfolio that I used to document different pieces of crafted actuating or sensing materials beside annotations, observations and recording parameters of my design in addition to potential uses in OUI Interiors.

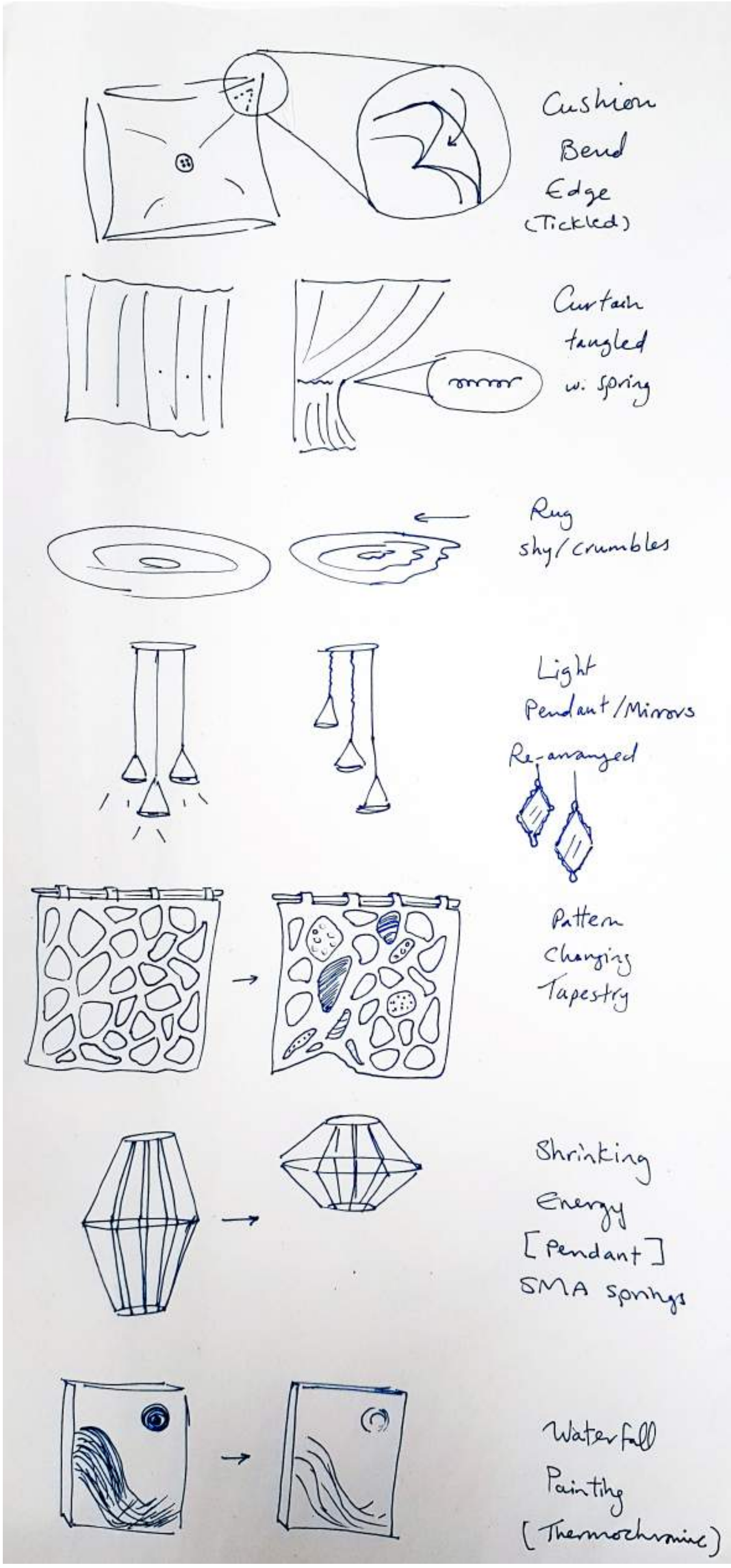


Figure 4.1 Thinking through sketching interactive decorative elements using OUI materials.

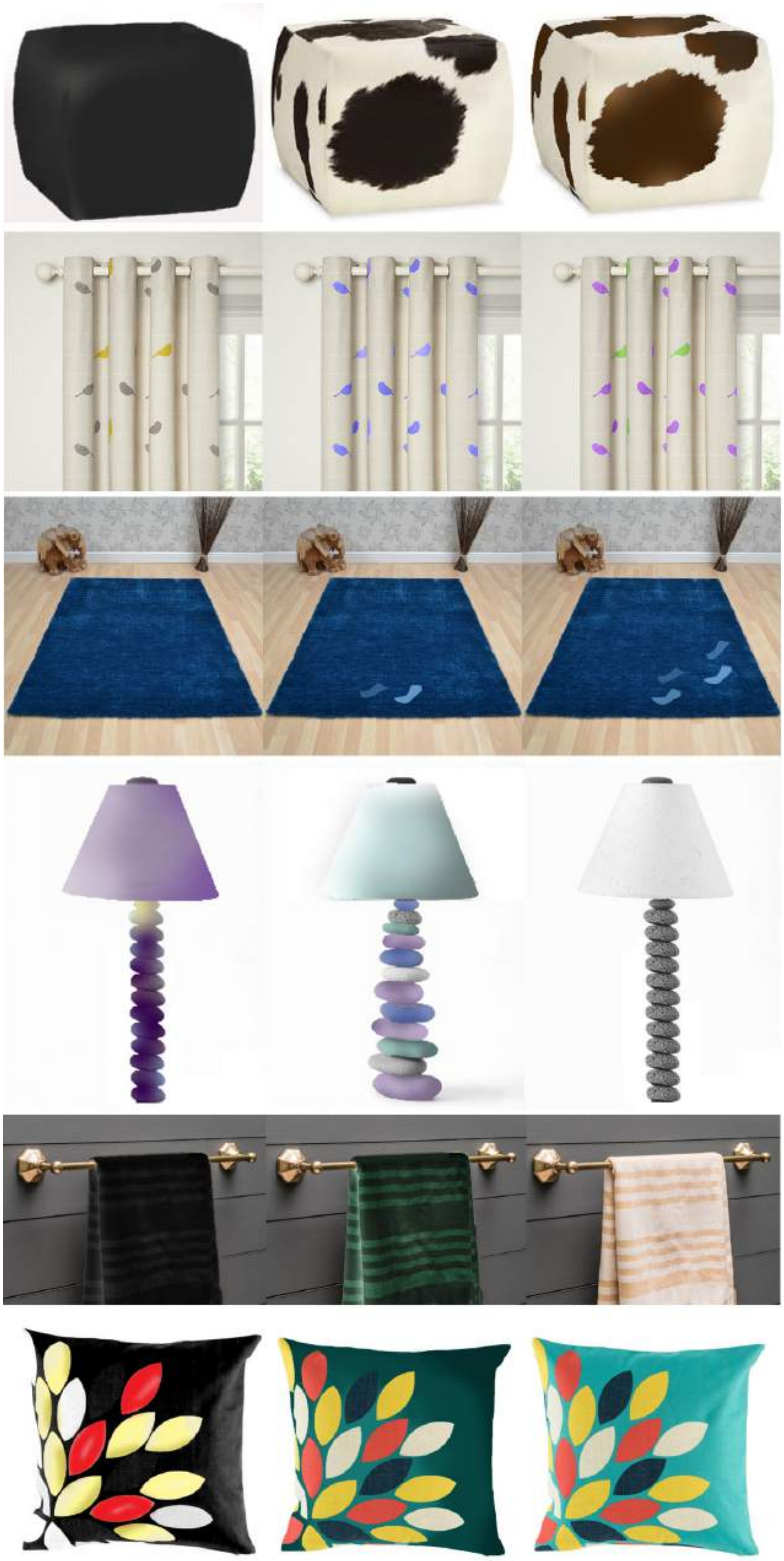


Figure 4.2 Thinking through designing digital illustrations of interactive decorative elements using OUI materials.

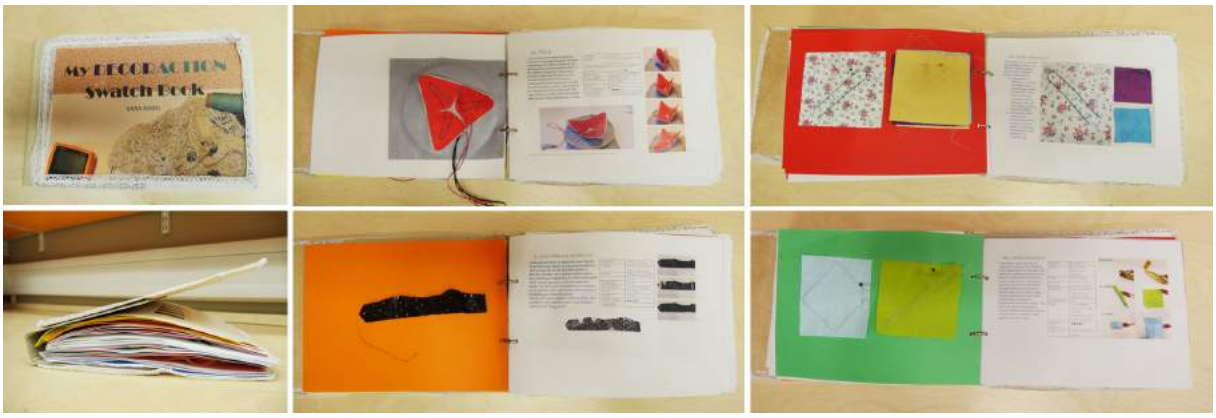


Figure 4.3 Learning through making design-research portfolio documenting my exploratory experiments of OUI materials.

4.1.3 Experimentation Setting

The term ‘experimentation’ used throughout this thesis does not imply ‘the process of executing scientific formal experiments in a laboratory with one or more pre-defined hypotheses’ as suggested in a chemistry research for instance. The use of this terminology herein rather refers to exploring a space, conducting ‘observations’ of material behaviours, and trying out new ideas, making techniques and crafting materials.

My experimentation process implied performing an exploration-led examination and testing of which materials work and how. My gauge of material choices leaned towards interactive materials that can be seamlessly embedded within interior finishing materials. The experiments thus spanned over this area of materiality and interactivity. Hence, unlike common public keep-clear maker-spaces, I needed a studio-like clutter-accumulating space to keep ideas flowing and evolving from, across and through each other. My work involved a lot of experimentation and exploration with a variety of materials that cannot be kept in boxes every night. While I understand that some might have a different -more organized- method of making, the nature of my research was entangled and intricate, involving a range of disparate techniques: from annealing SMAs, soldering wires, testing circuits and programming microcontrollers to crafting, designing artefacts, sketching, stitching, sewing, embroidering, dyeing, drying and painting. These making techniques can take weeks for each individual piece, involving the use of different swatches, samples and inspirational print-outs. This necessarily requires a design space which I have set (see figure 4.4) accommodating my crafting, tech-making and documenting processes.

4.1.4 Data Gathering

A data collection process was exercised to record and document my experiments. For documenting the making and learning process, I recorded frequent notes and observations. For actuating design work, a stationary camera on a tripod above the desk facing downwards was used for taking photographs and video recording. Video recordings were often fragmented into a series of still-images showing the actuation in a timescale, appropriate for paper-format

Figure 4.4 My OUI work desk is more like a design-studio than a maker-space, highlighting the entangled and 'messy' nature of my practice.

documents. Rigorous and repeatable experimentation was carried out to identify the design factors of actuating pieces. This was all added to my annotated portfolio as a documenting process allowing accumulative knowledge and self-reflection in later stages.

4.1.5 Drama Index

For experiments of shape-change, an indicator was needed to measure or compare the intensity of deformation in each designed sample or swatch. Therefore, I established a 'drama index', an integer numerical scale from 0 to 10, where 0 represents "no deformation happened", 5 means "moderate movement", and 10 represents "significant dramatic deformation". This index helped record how dramatic a sample deforms, supporting the observational evaluation of the resultant deformation on a measurable scale. Despite the limitation of this index, being a subjective rating, it still formed a benchmarking method to help eliminate factors causing poor actuation. The drama index also helped better understand material capabilities and the impacts of other design factors on its interactivity. Moreover, it enabled speculating and predicting the impact of design decisions on future prototypes.

4.2 Developing a Taxonomy

Embedding sensing and actuation in everyday materials has inspired recent research in areas such as tangible, organic and soft user interfaces (Ishii et al., 2012; Vertegaal and Poupyrev, 2008; Sugiura et al., 2011). Some take the approach of innovating new materials that have computational properties (Lo and Girouard, 2014; Groeger and Loo, 2016; Ou et al., 2014; Yao et al., 2013), while others fix electronic sensors, pneumatic or motor actuators into existing materials, such as paper, fabrics and wood (Yu et al., 2016; Strohmeier et al., 2012; Kao et al., 2017; Morin et al., 2012).

In Chapter 2, I surveyed a number of interactive materials that could be used without the need for either innovating new materials, or fixing electronic components to decoratives. In doing so, I clarified the difference between some interactive materials (that have sensing or morphological properties of themselves) and the alternative commonly-used electronic components. For example, conductive materials can replace switches and create seamlessly *tactile sensors* embedded within the texture of material finish, while thermochromics can replace LEDs for *colour-change* and SMA can replace motors for seamless *shape-change*. This is well aligned with the three main components of 'decorative schemes', which are: texture, colour and form (or shape), in addition to other components such as lighting and sound (acoustic) design (Dodsworth, 2009).

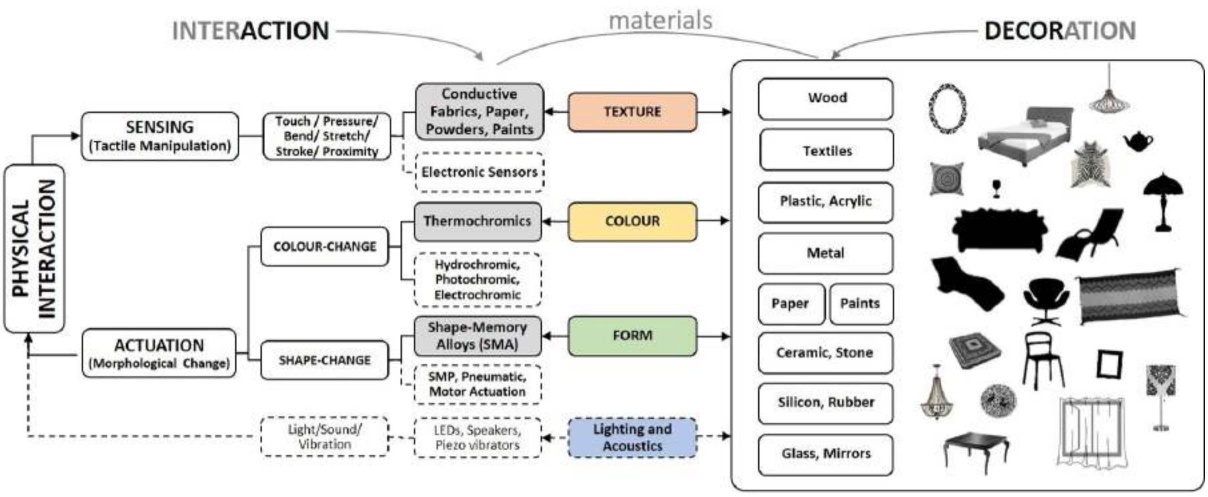


Figure 4.5 Taxonomy of Decoraction: categorization of smart materials and electronics enabling physical interaction to be seamlessly embedded into everyday decorative objects (shaded), and other sensing and actuating techniques (dotted).

In this sense, I developed a taxonomy of embedding interactive materials into decorative finishing materials through these three components. Figure 4.5 shows my taxonomy of interactive materials that can be embedded seamlessly in the material finish of interior decorative elements. I selected these materials based on the criteria that they are: 1) deemed embeddable (i.e. paintable, sewable or weavable), 2) can be electronically programmed and controlled, and 3) offer substantial potential for making objects interactive while keeping their aesthetics and utilizing their natural deformability and affordances. Interactive materials such as tactile sensing, colour-changing and shape-changing were covered in the literature survey (see Section 2.4) and discussed in terms of their capabilities and limitations towards prototyping and building decorative OUIs.

4.3 Exploring Crafting Techniques

In this section, I explore different making and crafting techniques of embedding interactive materials into decorative material finish. As the majority of interior decorative elements are textile-based objects, typically referred to as *soft furnishing* (such as cushions, throws, linens, curtains, rugs, table runners and cloths), it is crucial to understand and learn how to embed interactive materials into fabrics as means of seamless interactivity with OUI Interiors. Therefore, I pay particular attention to fabrics in most of my experimentation and material exploration. However, it is important to highlight that my research agenda is tangential to but not incorporated within the field of e-textiles, which focuses only on fabrics. Moreover, recent work on e-textiles (Hamdan et al., 2018) defined it as fabrics of stitched circuitry with electronic components, which may use digital tools but still produce applications that activate LEDs or vibration motors, often based on electronic sensor input.

Alternatively, I look into crafting the sensors and actuators themselves from OUI materials through a range of crafting techniques that extend previous work.

4.3.1 Crafting Sensing

Crafting methods have been used in previous relevant work, including hand-sewing soft sensors (Vogl et al., 2017; Parzer et al., 2016), hand-embroidering copper wire (Posch and Kurbak, 2016) and crocheting conductive thread using chain stitches (Kettley, 2016). Recently, research has looked into machine-sewing sensing yarns (Parzer et al., 2018), machine-embroidering conductive thread for e-textile connections (Hamdan et al., 2018) and machine-sewing copper wire as a safe on-skin electric connections (Kao et al., 2018).

Herein, I discuss the different crafting methods that I have employed and developed to embed sensing into soft interior elements, from machine-sewing, knitting and felting to beading and embroidering.

Machine-Sewing Conductive Fabric

The first straightforward technique to explore soft-sensing was to machine-sew touch-sensing fabric. Conductive fabrics (discussed earlier in Chapter 2, Section 2.4) can be used for adding seamless sensing into interior elements and furniture (in the form of upholstery lining) such as backs of bed headboards, or bottoms and arms of chairs and sofas. Although some conductive fabrics (such as the woven conductive silver-plated nylon) are easier to machine-sew than others (such as stretchy knit conductive fabrics) due to their relative stiffness, most types can be used with sewing machines under appropriate thread tension and stitch. In this sense, I machine-sew conductive fabrics to regular lining fabric using normal cotton thread as an extra layer beneath the upholstery. Then, I sew conductive thread from the fabric to a microcontroller that is programmed to respond (in any desired manner) to the proximity or soft-sensing input (e.g. stroke, stretch or poke) of the upholstery hiding conductive fabric underneath or the embellishment and adornment sewn using coloured-conductive fabric. For example, I have made two overlapping sensors by

Figure 4.6 Two Soft sensors (using silk and cotton-based conductive fabrics) machine-sewn into a double frill.

machine-sewing a double frill (out of black silk and pink cotton-based conductive fabrics) that can detect touch, stroke, stretch or flip. (see figure 4.6).

Knitting and Felting Sensors

I have also experimented with other crafting techniques borrowed from crafting wearables (Perner-Wilson and Buechley, 2011) to make e-textile sensors. I've tried felting and knitting, despite being a beginner, and found such techniques to be relatively easy and efficient in making soft sensors that are both aesthetically pleasing and electronically efficient (although not quite robust). Using the dry felting technique, I've created soft sensors by needle felting, using conductive wool (80% wool, 20% stainless steel) felted onto base synthetic felt of a colourful material. Any felted shape can be achieved with such a mixture and result in aesthetic shapes that can be soft sensors detecting either pressuring or squeezing of the conductive wool. Figure 4.7.a shows a 'flower sensor' I have felted using a mixture of Bekaert conductive wool with red synthetic fibre using a felting needle.

Figure 4.7 Two soft sensors using a) felting conductive fibre with synthetic red fibre in a floral shape, and b) knitting conductive yarn with a shimmering green yarn.

Using conductive yarn on a knitting machine or tool can help craft soft sensors. The tool I had in hand was a knitting mill, which helps create tubular knit of 10-15 mm diameter with its four needles. The end result is a soft stretch-sensor that can be pulled away and lowers its resistance across the two ends as it gets stretched. Figure 4.7.b shows a sensor I have knitted using both conductive yarn (80% polyester and 20% stainless steel) and a bright shimmering green non-conductive yarn. Being knitted tightly this sensor does not stretch but is squeezable, so I used it as a soft-pressure sensor. Figure 4.8 shows another stretch sensor that I knitted using only conductive yarn (80% polyester and 20% stainless steel) of which the resistance falls from 120KΩ to 800Ω when fully stretched.

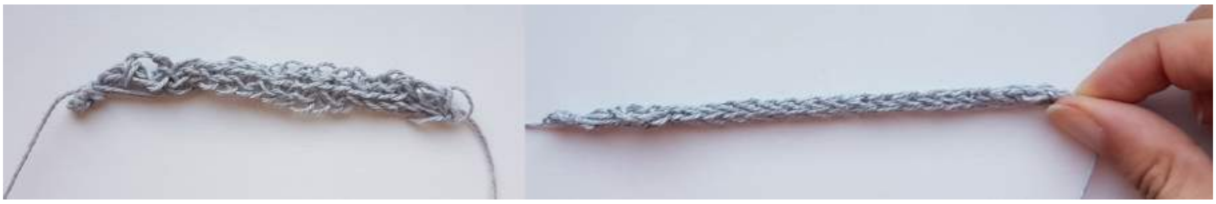


Figure 4.8 Soft stretch sensor using knitting conductive yarn in a 4 needle knitting mill.

Beading Conductive Crafting Materials

Metal and glass beads are commonly used in decoration and adornment of soft artefacts. I found a way to incorporate beads in wearables sensing (Perner-Wilson and Buechley, 2011) and I thought of reappropriating this crafting technique for interior furnishing as well. The technique basically resembles the basic contact switch that detects if two contact points are touching or not. By extending one of the contact points with conductive thread and a metal bead as a dangling weight, a soft sensor can be crafted to detect the tilting direction. The (conductive) thread can be embellished with colourful glass/plastic beads appropriate for the design aesthetics. The metal bead swings with gravity and touches different pieces of conductive fabric with open contact as it tilts. Figure 4.9 shows my tilt sensor designed in a floral pattern using copper conductive thread and copper conductive fabric.

Figure 4.9 Soft tilt sensor using beads, conductive fabric and thread.

Hand-Embroidering Conductive Thread

As discussed in the literature review (see Section 2.4), using off-the-shelf conductive thread to hand-stitch circuits is currently widely taught and practised in e-textile workshops and online tutorials (Satomi and Perner-Wilson, 2019). However, I have used their guidance to add interactive embellishment and decorative details to interior elements. By using conductive threads to add embroideries to soft furnishing, I was able to make aesthetically-looking soft switches to control any desired program. For example, an embroidered motif on the corner of the bed's headboard (matching the motifs on the linens, wallpaper and curtains) can be a soft switch for the lighting of the bedroom or control the A/C. Such thoughtful hand-stitched embroideries can be soft-switches for near-future smart home automation systems.

As a proof-of-concept, I made several hand-embroideries myself and connected them to touch-sensing electrodes of Arduino microcontrollers, and used them as different inputs to control different programmed outputs. Figure 4.10 shows my hand embroidered soft switch designed in a floral pattern using teal-coloured conductive thread. In this example, I used three basic embroidery stitches of which tutorials are plentiful online: the chain stitch, the daisy chain and the French knot. Other stitches can be potentially employed to achieve different embroidery designs. Coloured conductive thread can be prepared (Devendorf et al., 2016) and is also available at habutextiles.com in silk, wool or linen yarns mixed with 31% stainless steel, making them both conductive and colourful, unrestricting design choices.

Figure 4.10 Hand embroidered sensor using teal conductive thread.

Machine-Embroidering Conductive Thread

Conductive thread is used to replace electric wires in wearables (Berzowska and Coelho, 2005) and malleable interfaces (Follmer et al., 2012) in soft furnishing, creating seamless embedded soft circuits. Relevant work that has used a sewing machine with conductive thread for connecting their soft circuits to the PCB boards is quite limited (Berzowska and Bromley, 2007). For capacitive sensing though, if conductive thread was used in machine-stitching entire seams in fabric, it will mean that the entire seam will be ‘touch-sensitive’. Alternatively, I thought of a rather *seamful* interactive use of conductive thread by embedding it in specific areas or textured embroidery. This also adds tactility, softness and 3D texture to the ‘touch’ input. I used conductive threads in the bobbin of a ‘digital embroidery-machine’ to automatically embed interactivity into fabrics using capacitive-touch sensing (of conductive thread in the back side of the fabric) into embroidered patterns (using normal threads in the front of the fabric) that are digitally-designed and machine-automated. Conductive thread types that were soft and delicate (such as silk yarns) failed to withstand the embroidery-machine’s pull and were soon cut and unthreaded causing errors in the machine’s running embroidery design program. However, I succeeded to embroider with thicker stainless steel conductive thread that proved to be more efficient in terms of bearing and resisting the machine pull-force of the thread. Figure 4.11 shows samples of this work on touch-sensitive digitally-designed machine-embroidering.

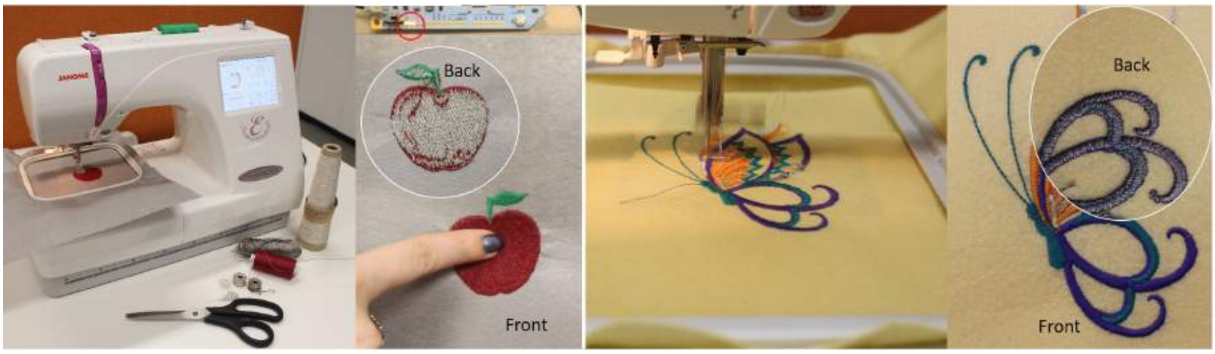


Figure 4.11 Digital machine-embroidering using conductive threads (in the bobbin) to make touch-sensitive embroidered patterns.

4.3.2 Crafting Colour-Change

As discussed in Section 2.4, embedding colour-changing actuation within fabrics can be achieved using thermochromic (Devendorf et al., 2016; Orth, 2009), photochromic (Taylor and Robertson, 2014), hydrochromic (Berzowska, 2005) and electrochromic inks (Wakita and Shibutani, 2006), leveraging digital technology beyond the *neon* era. Thermochromics, in particular, can be electronically controlled used a heating agent (e.g. conductive thread, copper wire and nichrome). In this sense, some used thermochromics for designing fabric animations using conductive thread (Song et al., 2018; Orth, 2009), while others dyed the conductive thread with thermochromic pigments to achieve sensing-actuating textiles (Kuusk, 2015; Devendorf et al., 2016). However, the drawbacks of conductive threads include its high resistance, fraying and being uninsulated, potentially causing short circuits.

Herein, I explore the use of thermochromic pigments and experiment different methods to embed colour-changing actuation in soft materials, including: painting, tie-dyeing, knitting and machine-sewing.

Painting with Thermochromics

The first technique to explore thermochromic paints is to paint with them. Brush-painting on paper is straightforward and the colour-changing effect can be instantly seen using a heating device such as a hair dryer or an iron. Off-the-shelf thermochromic paints usually disappear in such heat (above 37°C), but it could also change from one colour to another if mixed with other acrylic paints. I mixed thermochromic paints with different acrylic colours to explore a palette of colour-change that can be used to create morphological paintings, see figure 4.12. Then, I explored fabric painting using thermochromic paints using different brushes, from pointed round to angular flat. Fabric painting allowed me to explore the interplay between the pattern-changing print I make and the fabric's original pattern, see figure 4.13.

Tie-Dyeing with Thermochromics

A common crafting technique for creating organic patterns on fabrics is the 'tie-dye'. Tie-dyeing is considered a popular DIY technique and is facilitated by affordable kits with fabric dyes of vibrant colours. However, these fabric dyes are manufactured to be permanent and do not change their colour, at least after the first wash. I was intrigued to try this technique with thermochromic pigments and examine the results. Figure 4.14 shows the process in which I have done that. First, I prepared a 40x40 piece of white cotton fabric and started to fold it iteratively in halves until it was ready to be tied. Meanwhile, I prepared thermochromic pigment and ice cubes (the latter being commonly used in tie-dyeing to allow gradual colour absorption). Using rubber bands, I tied the folded fabric tightly then started adding the different colours of thermochromic pigments then added the ice cubes on top and left to soak overnight. The result was not as expected, as thermochromic pigments are not inherently fabric dyes, but it still made a creative and interesting colour-changing pattern. I then placed the fabric in a wooden hoop and hanged it as a decorative piece i.e. as a dream-catcher, or a wind chime. Conceptually, it could actuate and change its pattern in different phases if each individual thermochromic colour had a different activation threshold. In this sense, interior ambient heat or wind breeze by the door once opened can trigger pattern-changes. Using a 5V heating pad underneath, I was able to control and experience the interesting materiality of a pattern-changing tie-dyed fabric.

Knitting Thermochromic-dyed Yarn

Another fabrication method that can be used in the same sense is knitting with yarn that is thermochromically-dyed, either using a knitting machine, tool (e.g. knitting mill) or knitting needles (see Figure 4.15). After dyeing wool or cotton yarn with thermochromic pigments, it can be used as normal yarn to knit or crochet any desired soft object such as a cushion or a throw. Devendorf et al. (2016) used a similar technique before, where they have dyed conductive thread with thermochromic paint. A drawback for their approach is that large scale designs created will inherently be of very high resistance as conducive thread is knitted or crocheted throughout the soft object. To overcome this dilemma, I have dyed normal yarn (non-conductive) to enable any scale design freely, then embedded conductive thread in longitudinal lines (seamlessly through

Figure 4.12 Experimenting brush-painting with thermochromic pigments on paper to make colour-changing paintings.

the knit) to achieve seamless colour-change with the least amount of conductive thread, thus an adequate amount of resistance to the circuit.

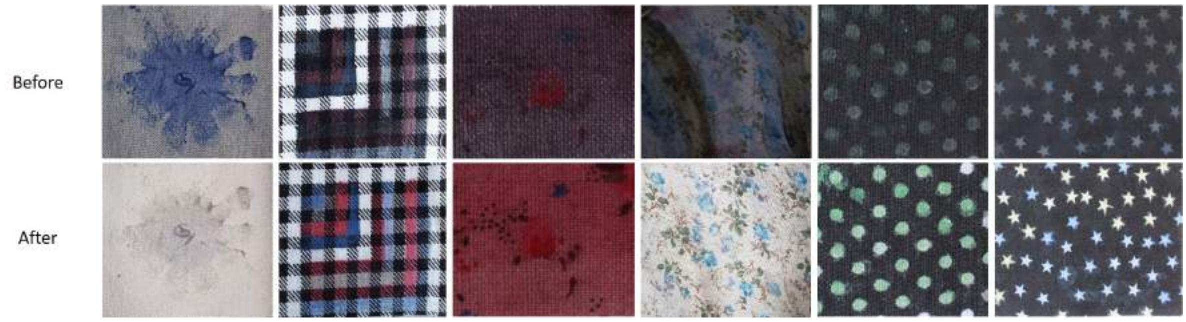


Figure 4.13 Swatches of my pattern-changing fabrics using brush-painting with thermochromic pigments on fabric. Photos of swatches in room temperature (top) and heated to 31°(bottom) using a 5V heating pad.

Figure 4.14 Tie-dying using thermochromic pigments to make pattern-changing textile.

As a proof of concept, I created a set of soft interactive objects to decorate an interactive interior space commissioned for the AMR Pharmacy installation at the London Design Festival 2018, in collaboration with Napper Architects, UK (see Section 5.8).

Machine-Sewing Copper Wire

Copper enamelled wire with 0.1 mm diameter is as thin as thread and can be used for embedding actuation in e-textiles in various ways. For example, Posch and Kurbak (2016) used copper enamelled wire to embroider coils creating a few logic gates as 1-bit displays using electro-magnetic shape-change. Their approach was delicate and interesting, yet unique and difficult to replicate. I wanted to develop a simple technique to help anyone sew their own actuation. After realizing how hand-stitching copper wire can have its complications in terms of time and breakage, I believed using a sewing machine could be a simpler idea.

Figure 4.15 Knitting with yarns dyed in thermochromic pigments.

Copper enamelled 0.1 mm wire can be easily used for loading the bobbin case of a sewing machine and can be threaded smoothly through the sewing machine's needle. Any normal thread spool can then be used to stitch the copper. I tested different stitches and found the basic straight stitch to be perfect for thin feeds, while the tight satin stitch (resembling embroidery) was ideal for thick covering.

My first method was to stitch directly onto thermochromic fabric (see figure 4.16). In the second method, I used a thin mesh fabric underneath thermochromic fabric to reveal its hidden pattern and achieved different results, see figure 4.17. Once connected to a 3V power source, the thermochromic fabric glows around the stitched seams revealing another colour. Once disconnected, the fabric slowly returns back to its monochromic colour. In my third method, I used normal fabric (not thermochromic) to machine-sew copper wire in the same way. After stitching through, the fabric can be screen-printed along the seams with thermochromic paint, then activate the copper wire after allowing it to dry. The fabric seams should change colour around the screen-printed pattern along the dyed seams, revealing the fabric's original pattern underneath.

Machine-Sewing Thermochromic Thread

Given that neither conventional fabrics are thermochromic, nor painting fabric is easy, I developed a much simpler solution that achieves the same previous results: machine-sewing thermochromic thread. Similar to any normal yarns, thermochromic thread can be machine-sewn. In order to do this, I dyed some light-coloured cotton threads with darker thermochromic pigments, as thermochromic thread is not available off-the-shelf, *yet*. Following the standard usage of thermochromic pigments (described in the user manual of most suppliers) where all inks are accompanied by a binder, the dye is prepared by mixing the binder 50/50 with the ink, to produce the desired amount of usable dye. The dyeing process is best described by the photographs shown in figure 4.18 documenting the process which begins by soaking thread for 30 minutes in a shallow bath of mixed shades of different thermochromic dyes (Figure 4.18.a). Then, thread is taken out and dried overnight on layers of tissue paper (Figure 4.18.b). Afterwards,

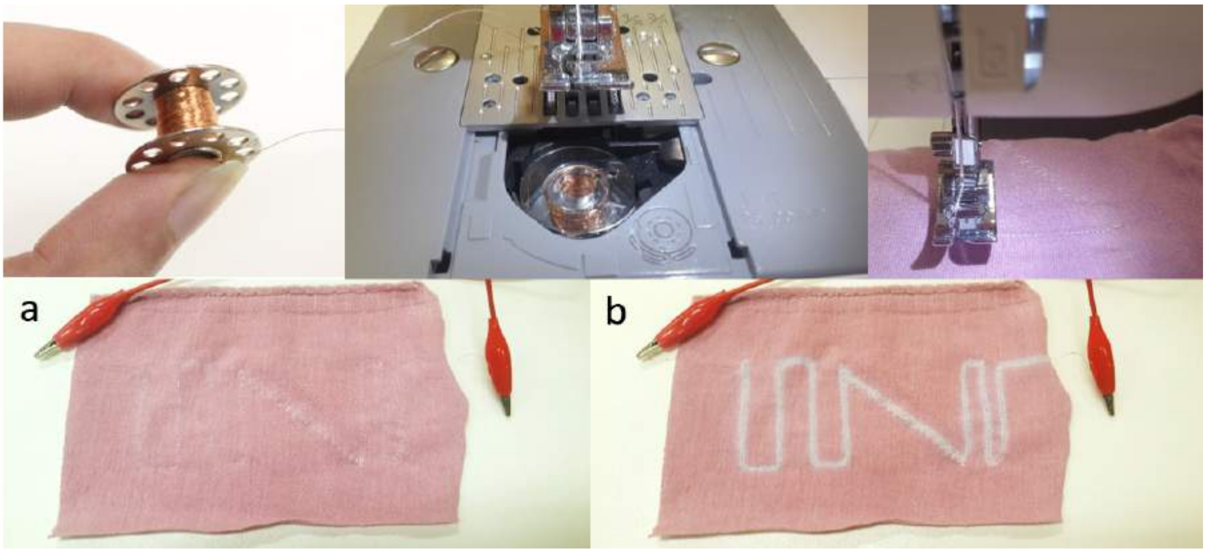


Figure 4.16 Machine-sewing Copper enamelled 0.1 mm thread (in the bobbin) directly to thermochromic fabric. b) Connecting 3V power source reveals/ glows around the stitched pattern.

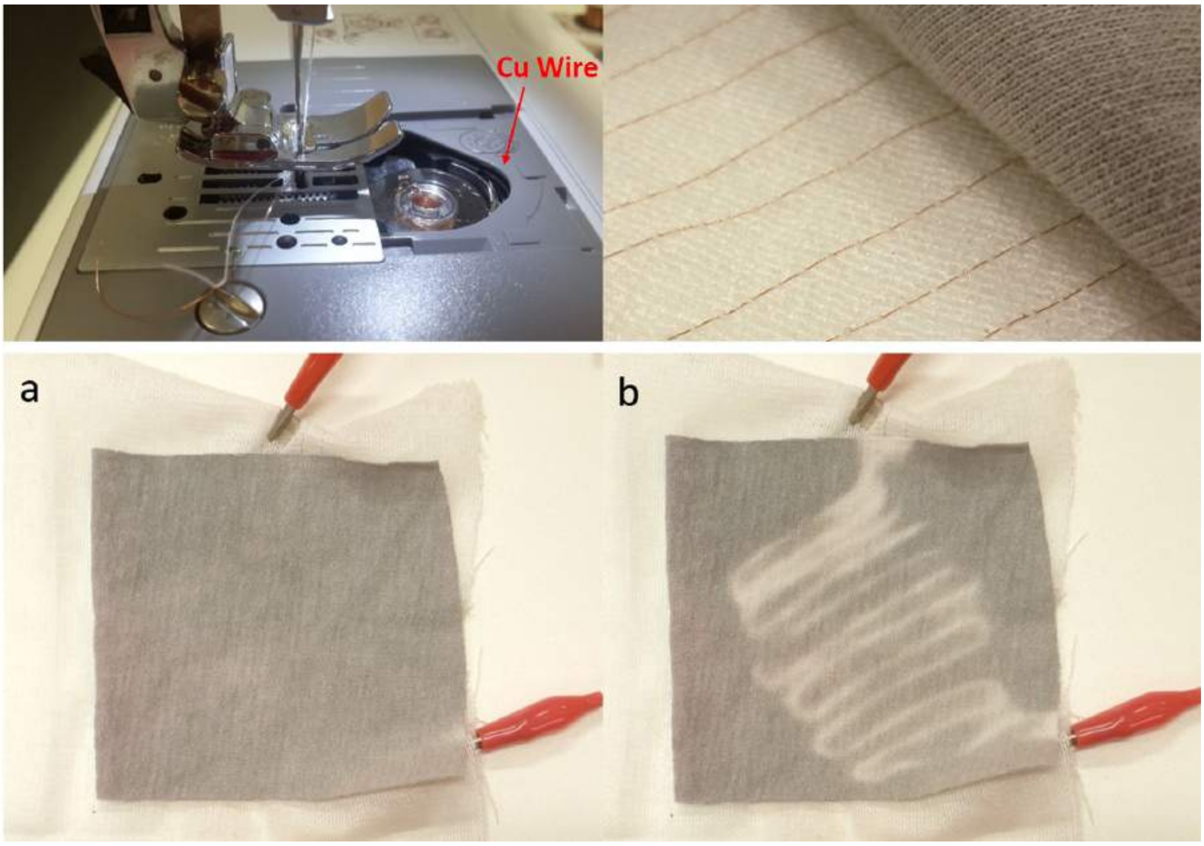


Figure 4.17 Machine-sewing Copper enamelled 0.1 mm thread (in the bobbin) to light weight soft mesh fabric (top). a) Having a Thermochromic fabric layer on top. b) Connecting 3V power source reveals the stitched pattern.

thread is subjected to bobbin winding for use with the sewing machine (Figure 4.18.c). Finally, thermochromic-dyed threads on bobbins can be tested using heat, changing back to their original colours (Figure 4.18.d). When thermochromic thread is ready on the bobbin, it can be simply

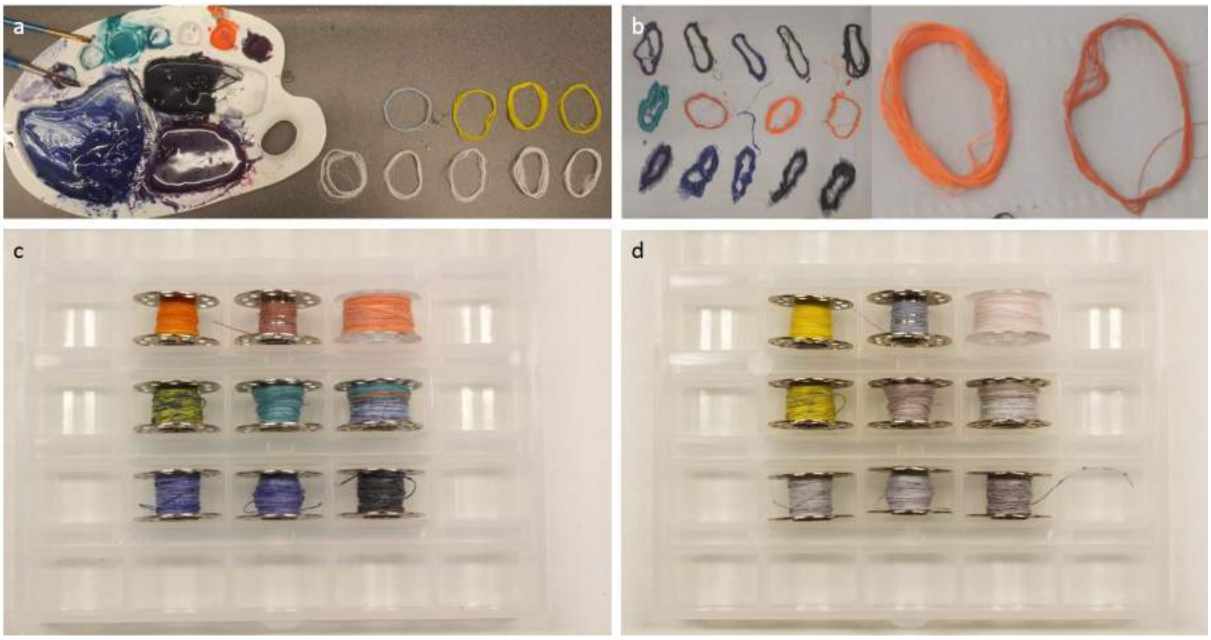


Figure 4.18 a) Dying light-coloured cotton threads with dark saturated thermochromic pigments, b) drying threads after dying, c) thermochromic-dyed threads on bobbins in room temperature, d) thermochromic-dyed threads on bobbins when heated (changing back to their original colours).

used in the sewing machine as any normal thread, while filling the bobbin with copper thread, as a heating agent. Interestingly, while sewing, the warmth generated on the presser foot from the sewing machine's LED causes the thread colour to instantly change on the part being sewn, then reveal again as the sewing machine's presser foot moves away from that part, creating -what I felt to be- a magical repertoire between the thread and myself. In this technique, the sewing machine was stitching colour-change directly into any kind of fabric. Once connected to a battery, the fabric seams transition from one colour to another. Apart from colour-change, and to demonstrate further effects, two approaches were tested: hiding and revealing. When using dyed thread with a matching colour to the fabric, seams seem seamless, but reveal once actuated. Alternatively, stitching fabric with thread that has a matching 'original' colour causes the seams to be contrasting/visible, then hidden once activated, see figure 4.19.

4.3.3 Crafting Shape-Change

The majority of previous e-textile research focused on activating LEDs or motors (Kao et al., 2017; Kono and Watanabe, 2017; Buechley and Qiu, 2014), creating *robotic* fabrics (Yuen et al., 2014). Although some have explored crafting sensors (Perner-Wilson and Buechley, 2011; Post et al., 2000; Zeagler et al., 2012), investigating controlled shape-changing fabrics has been limited and difficult to replicate. Taking this work further into realizing self-morphing fabrics using replicable methods has not been investigated before, aside from online tutorials and blogs stating that machine-sewing shape-changing wire (i.e. SMA) cannot be done (XSLabs, 2018) and therefore such e-textile applications are not yet ready for mass production and consumption (V2_Lab, 2018).

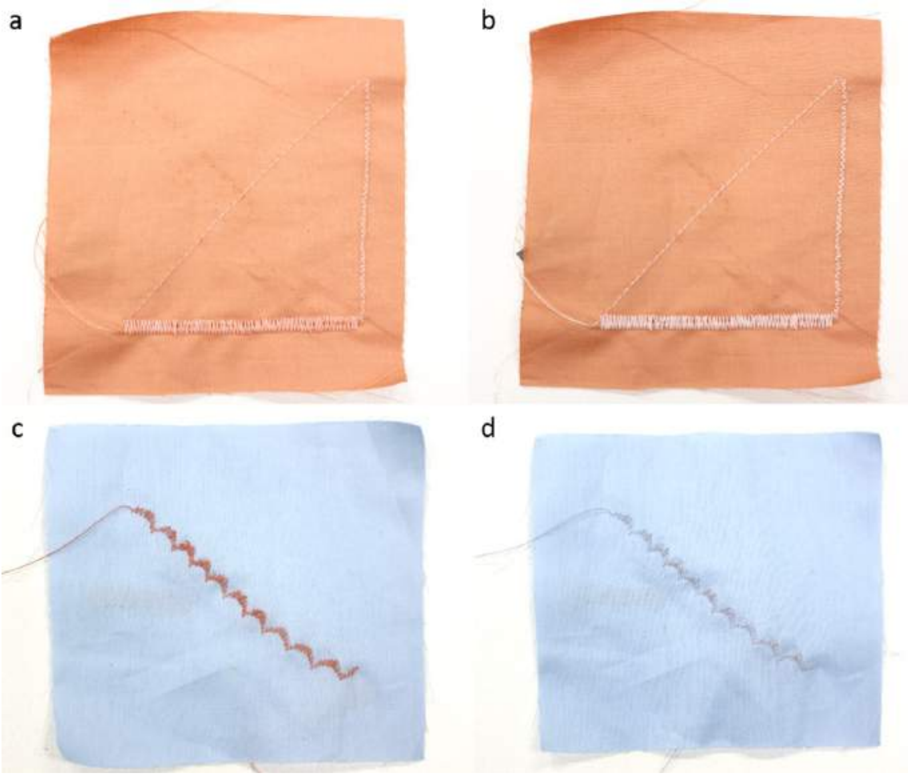


Figure 4.19 Machine-sewing thermochromic-dyed threads (in the spool) with copper enamelled 0.1 mm thread (in the bobbin). Left: fabric swatches in room temperature (default state) where stitched pattern is hidden (a) or visible (c). Right: fabric swatches after connecting 3V power source converting the seams into visible (b) and hidden (d).

Unlike servo-motors and stepper-motors that create a disturbing sound, weight and rigidity for everyday materiality, other shape-changing techniques can create morphological effects that are calm, quiet and appropriate for everyday use. Shape changing materials such as thermal-responsive SMA wire can be an alternative solution for creating interesting deformations (Dierk et al., 2018; Zhu and Zhao, 2013), not only because of its subtle shape-changing effects, but also due to its light weight, experiential transparency, silent operation and organic expression (Bodanzky, 2012). Examples of previous work that explored the use of SMA wire with fabrics include the Kukkia and Vilkas actuating dresses (Berzowska and Coelho, 2005), wrinkling trousers (Ueda et al., 2016), the Textile Mirror (Davis et al., 2013) and the Shutters curtain (Coelho and Maes, 2009), which all used hand-stitching to fix SMA wire to their fabrics. Alternatively, Vili (Vili, 2007) proposed ‘yarn-spinning’ for creating actuating textiles by *incorporating* SMA strands within fabric yarns to enhance both the functionality and aesthetics of interactive textiles.

Machine-sewing techniques have been used for textile actuation in very limited work. For instance, Bern et al. (2017) envisioned the design of actuating plushy toys, but only *simulated* them and stated that “this actuation complexity is clearly well beyond current fabrication capabilities”. Animating Paper (Qi and Buechley, 2012) vaguely used “sewing” SMA –mentioning no machines– and Kono and Watanabe (2017) proposed using strings and “sewing methods” to make shape-changing fabrics, but still actuated the fabric deformation using rotating servo-motors to pull the strings.

Sprout I/O (Coelho and Maes, 2008) has briefly introduced SMA to textile techniques not only by hand-stitching SMA wire to felt fabric but also intertwining SMA spun yarn with Teflon to curl a fur strand down taking advantage of its soft properties and textural changes (rather than light emitting techniques). Other previous work that explored SMA wires, or springs, fixed both ends only to the soldered connections of the circuit without any sewing to the fabric (Coelho et al., 2008; Ueda et al., 2016).

Herein, I explore additional methods to previous work by weaving SMA into the material itself and machine-sewing SMA wire to the fabric like threads. These two techniques are presented below:

Weaving SMA into materials

Experimenting with firm and sturdy fabrics such as linen is interesting yet challenging. I tried different patterns of threading the wire within the linen swatch but most of which did not actuate due to relatively loose bends and ends, which prevents the wire from giving a sensible actuation effect. Eventually, this pattern (systematic snack shaped) achieved a subtle wrinkling effect within the fabric itself which is not significant yet could be useful and desired in some cases. As an unusual technique, I also explored how lace can be embedded with SMA wire (without any stitching or gluing) and fixed through the lace web-like pattern itself. Although expected to be loose and lame, it turned out to be very unusual and unique as it swirls and sways in a snake-like continuous motion in random non-uniform behaviour which appeared to be alive!

A bead thread was similarly inspiring, What if it could be alive and possess self-morphing capabilities as well? By threading SMA 0.010" wire into the beads, then fixing the thread on a soft surface, the bead thread started swirling back and forth as if it was a living snake, with its curves moving closer and further from one another in an organic behaviour. Figure 4.20 shows snap shots from the video footage that recorded the actuation of woven SMA within linen, lace and beads. Other materials may also be appropriate and more interesting for weaving SMA within. However, not all soft materials enable weaving wire within due to their tight or stiff nature, nor materials with loose and relaxed composition would likely express any visible shape-change or any movement at all. For example, when trying to weave SMA wire within a knitted object, no visible actuation was observed as the wire contracts and elongates within the spaces between the knit.

Machine-Sewing SMA Wire

In the same way of filling the sewing machine's bobbin case with copper wire, I explored machine-sewing SMA wire, mostly using Flexinol HT 0.006" and 0.010" muscle wire as the Shape-Memory Alloy (SMA) actuators. Such SMA wire is pre-trained to flatten and shrink by around 4% of its total length when adequate current flows through and heats it up (around 0.4A and 1A respectively) causing the wire to usually erect (lift and bend outwards) the material it is fixed on. Figure 4.21 illustrates machine-sewing SMA wire and the fabric deformation after applying 5V and 0.4A. Alternatively, SMA springs retract significantly causing compression or

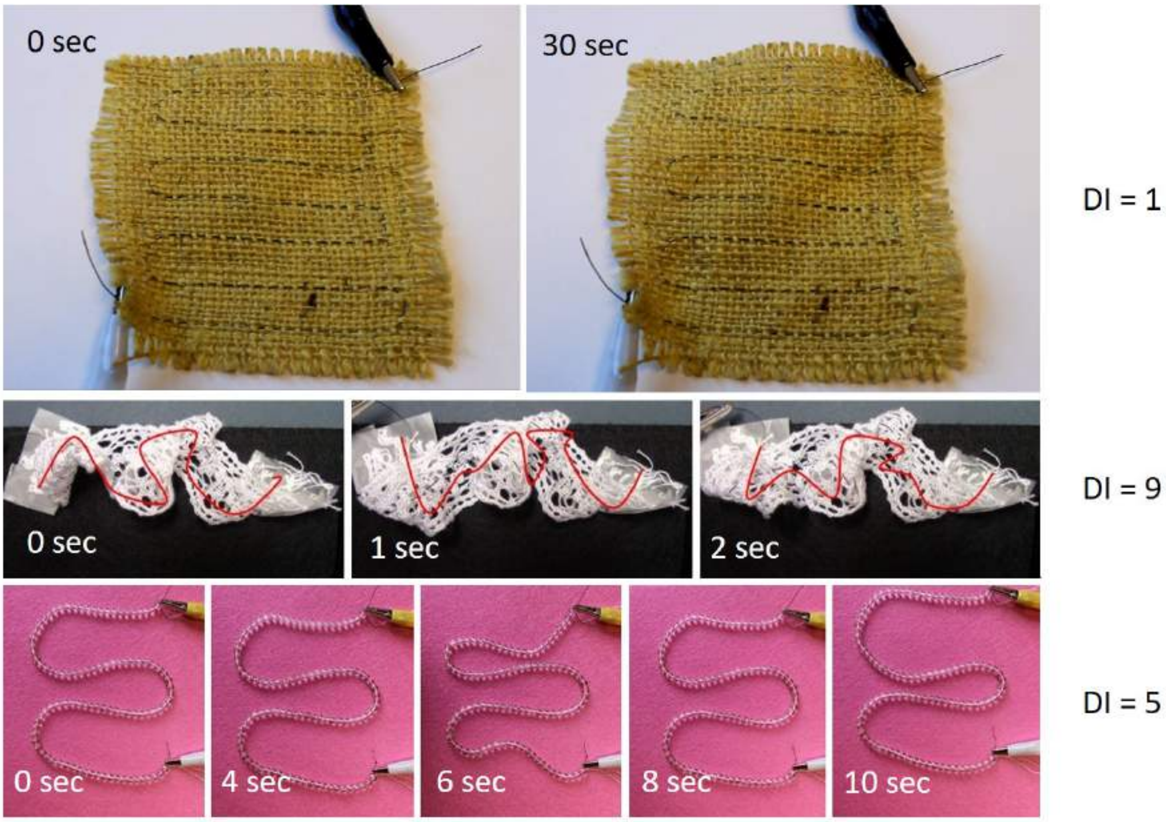


Figure 4.20 Weaving SMA shape-changing wire within different materials: hessian burlap, lace and beads. Deformation is indicated on a scale (i.e. Defomation Index [DI]) from 0 (none) to 10 (max).

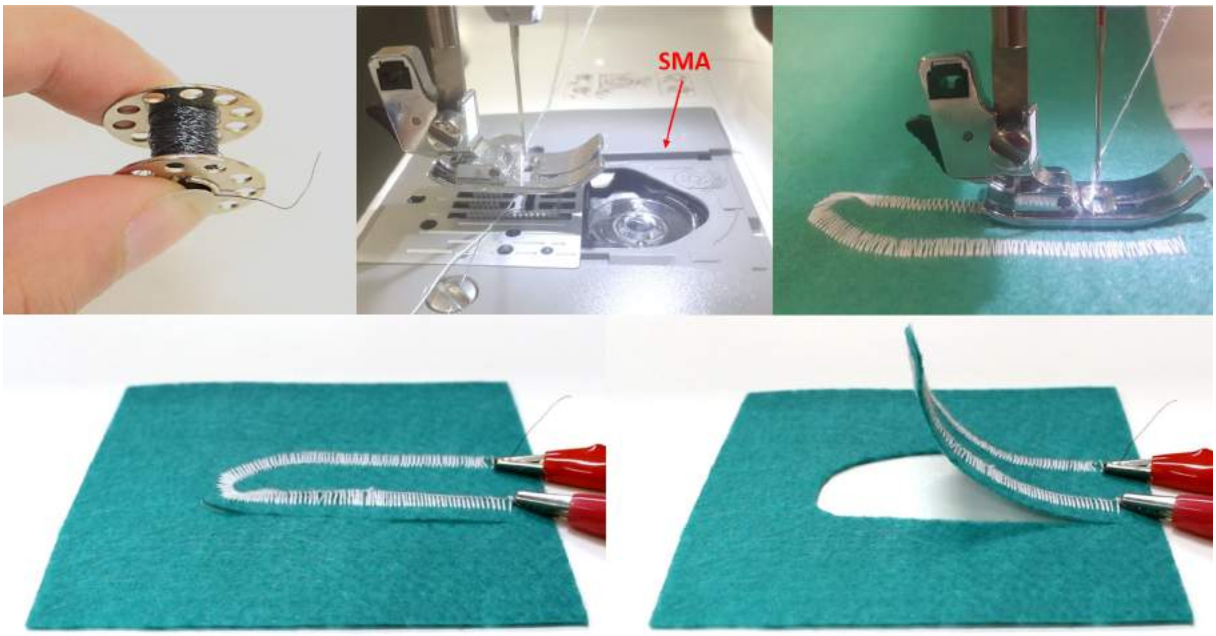


Figure 4.21 Technique 1: Machine-sewing SMA wire (in the bobbin) to felt fabric. The fabric swatch in default state (bottom left). Connecting 5V power source actuates the shape-changing stitched pattern (bottom right).

creasing deformation of the material to which they are affixed depending on its affordance. SMA wire can also be retrained to actuate in any desired form by heating it on a fixed mould of that required shape up to 400-500°C for a few minutes then immediately quenching it in cold water to *remember* that shape. Figure 4.22 illustrates retraining SMA wire to different shapes. Once the electric current flows through the SMA wire, it begins to reveal the deformation effect it is trained upon and this essentially causes the fabric to undergo physical movement according to the applied stitching form and sewn stitches. The material behaviour then relies on a number of factors/parameters and can be enhanced and controlled using a range of techniques, all detailed next in Section 4.4.

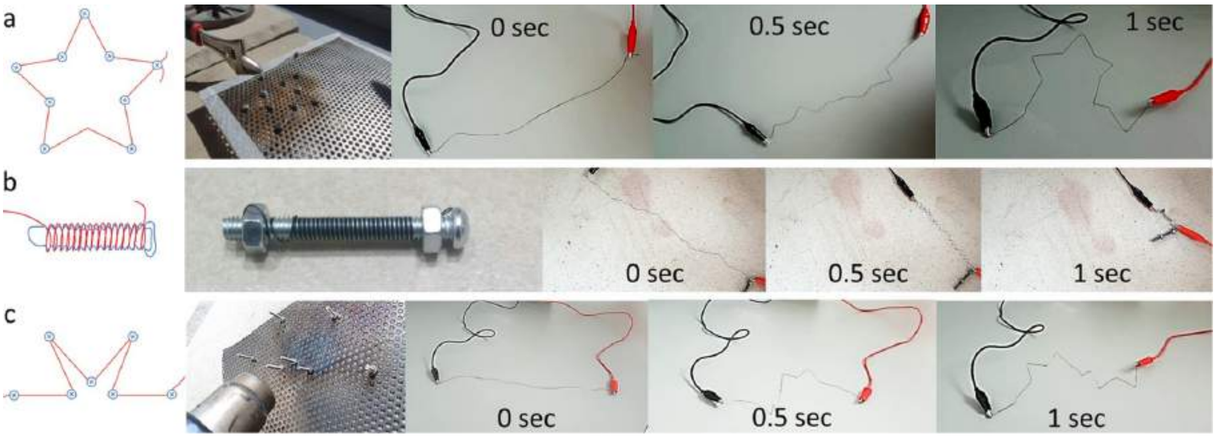


Figure 4.22 Training SMA on a) star shape and b) spiral/spring shape and showing the timelapse of connecting 1A power supply.

4.3.4 Crafting Circuitry

Microcontrollers

Off-the-shelf microcontrollers are either multi-purpose non-specialized, or e-textiles branded boards. The former either offer very limited features (few inputs/outputs) or are rather bulky, rigid and not aesthetically pleasant (such as the Arduino Uno, Leonardo and Genuino). The latter boards are more appropriate for e-textile projects with their minimalist design as purposely made for use with fabrics, wearables and soft circuits, and most importantly introduced the 'sewable holes' useful feature (such as the Gemma, Flora and LilyPad). However, such boards can not drive circuits of high-power (more than 5V) as required to control shape-changing SMA wire or heating materials for colour-change. Briefly, I had to choose between either thin elegant and sewable boards but incapable of controlling high voltage circuit, or unconcealable large and bulky microcontrollers powered with MOSFETs (i.e. high-power transistors).

I started to tinker with both types but soon realized that my circuits were not reliable or robust enough without soldered MOSFETs. However, the idea of having numerous wires and rigid electric components such as electronic transistors and resistors was (for my approach) not appropriate for claiming soft, aesthetic and morphological decorative designs. To achieve this goal, my circuits evolved to reduce the dimensions (length, width and thickness), possess some aesthetic qualities or less intrusive appearance. Finally, I invented a new microcontroller board that attempts to bridge the two worlds. With the help of my research colleague Jan Kučera, the MuscleMuffin was born. Figure 4.23 shows the evolution of my circuits to control OUI Interior objects, moving away from wires and rigid bulky electronic components as much as possible. Table 4.1 also shows a comparison between these different boards in terms of maximum number of sensors, actuators, dimensions and voltage.

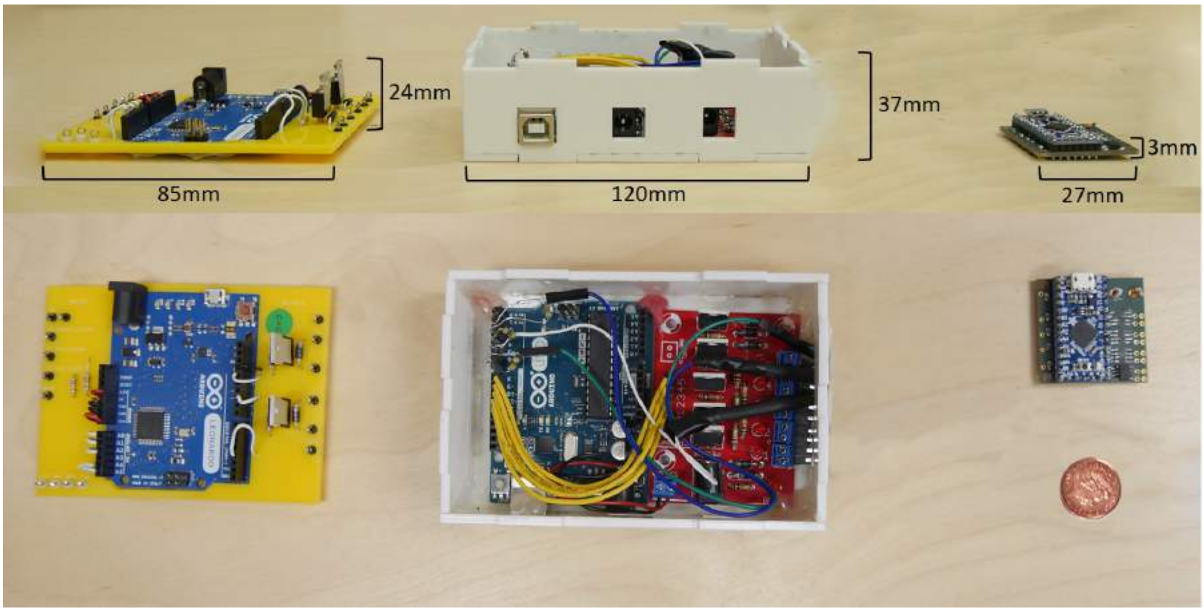


Figure 4.23 The evolution of my circuits to control OUI Interior objects and designs, from bulky rigid microcontrollers to the MuscleMuffin: a sewable custom-made PCB with miniature SMD transistors and resistors.

	Board 1	**Board 2**	**Board 3 (MuscleMuffin)**
Length (mm)	85	120	27
Width (mm)	60	80	27
Height (mm)	24	37	3
Sensors	2	3	5
Actuators	2	5	8
Volt up to (V)	5	5	16
Sewable	No	No	Yes

Table 4.1 Comparing boards' dimensions, maximum number of sensors, actuators and voltage.

The MuscleMuffin v1.0 (followed by v1.1) is the smallest PCB that can generate high-power enabling the control of shape-changing and colour-changing circuits, with the least compromisation towards affordance and aesthetics of decorative artefacts and interior elements embedded with interactivity. This design meant upgrading the Arduino Uno plus MOSFETs, to a sewable custom-designed PCB board with a tiny Arduino ItsyBitsy processor and miniature SMD (Surface Mount Devices) resistors and transistors. This MuscleMuffin custom-board can be simply programmed using Arduino coding and its standard libraries (e.g. CapacitiveSensor.h) through a mounted USB serial port connected to its processor. The MuscleMuffin also supports up to 5 proximity/ touch-sensing inputs (to be connected to soft sensing conductive fabric, thread, paint or paper) and up to 8 high-power output that can control shape-changing SMA wire or colour-change through heating materials. This circuit supports up to 16V and therefore can be safely used with high-power LiPo batteries providing up to 1050mA for driving both SMA wire and thermochromics' heating materials. In addition, its surface mount 3mm resistors enable plug and play for any touch-sensitive material used on the OUI interactive object or surface.

Machine-Sewing Resistors

To maintain a calculated amount of current flowing through the circuit, one has to ensure a precise amount of resistance in the used materials (whether heating or shape-changing materials). For example, if an 11.1V LiPo battery is used to power a circuit, then the connected SMA wire with a resistance of 55Ω/m and a recommended current of 410mA will need to have a length of 49 cm. If we want a shorter shape-changing wire, then we will need to add this extra resistance in another form. It is a common practice in electronics to add resistance to the circuit to maintain the flowing current according to Ohm's law (V= IR). However, this means (for my approach) adding bulkier and more rigid components to accommodate the needs of each individual circuit. Resistors come in different shapes and sizes but most of them might negatively affect the material experience and affordance to which it has added undesirable rigidity. For solid objects (such as a painting canvas, a mirror frame or a vase) this might not be a problem, but for malleable objects (such as cushions, throws and rugs) this might have a serious impact on their malleability and material affordance.

To solve this dilemma, I created a way to make small 'soft resistors', by machine-sewing conductive thread to fabric patches and stitch them directly to the interactive soft object. Different resistor values can be machine sewn on fabric pieces using different stitches such as the zigzag and satin stitches. For testing, I have used 1 mm felt fabric due to its relative sturdiness compared to other types of thin and delicate fabrics. Another tip that I found useful, was to skip the thread from the thread 'hook' by the needle clamp to avoid extra tension and tear of conductive thread that is usually thicker than normal thread.

Soft resistors can also be sandwiched between or covered with another layer of soft fabric using the sewing machine as a cap to insulate from the remaining circuit. Also, different available conductive thread yarns and bobbins have different resistances from 10 to 100Ω/m depending on the yarn thickness, number of ply threads and the conductive material within (e.g. copper, silver, stainless steel). I experimented with 3-ply silver nano-plated conductive thread from Kitronik.co.uk, that was at hand. First, I used the bobbin winder to fill the bobbin with conductive thread before using it on the spool pin. Then, any non-conductive thread can be used in the bobbin case (I used white cotton thread). Different machine stitches give different resistance due to their varying amount of thread used and the pattern they are stitched into. A trick I found useful is to use a multimeter device concurrently while machine sewing the soft resistors to realize the ohm value increasing as the seam length increases.

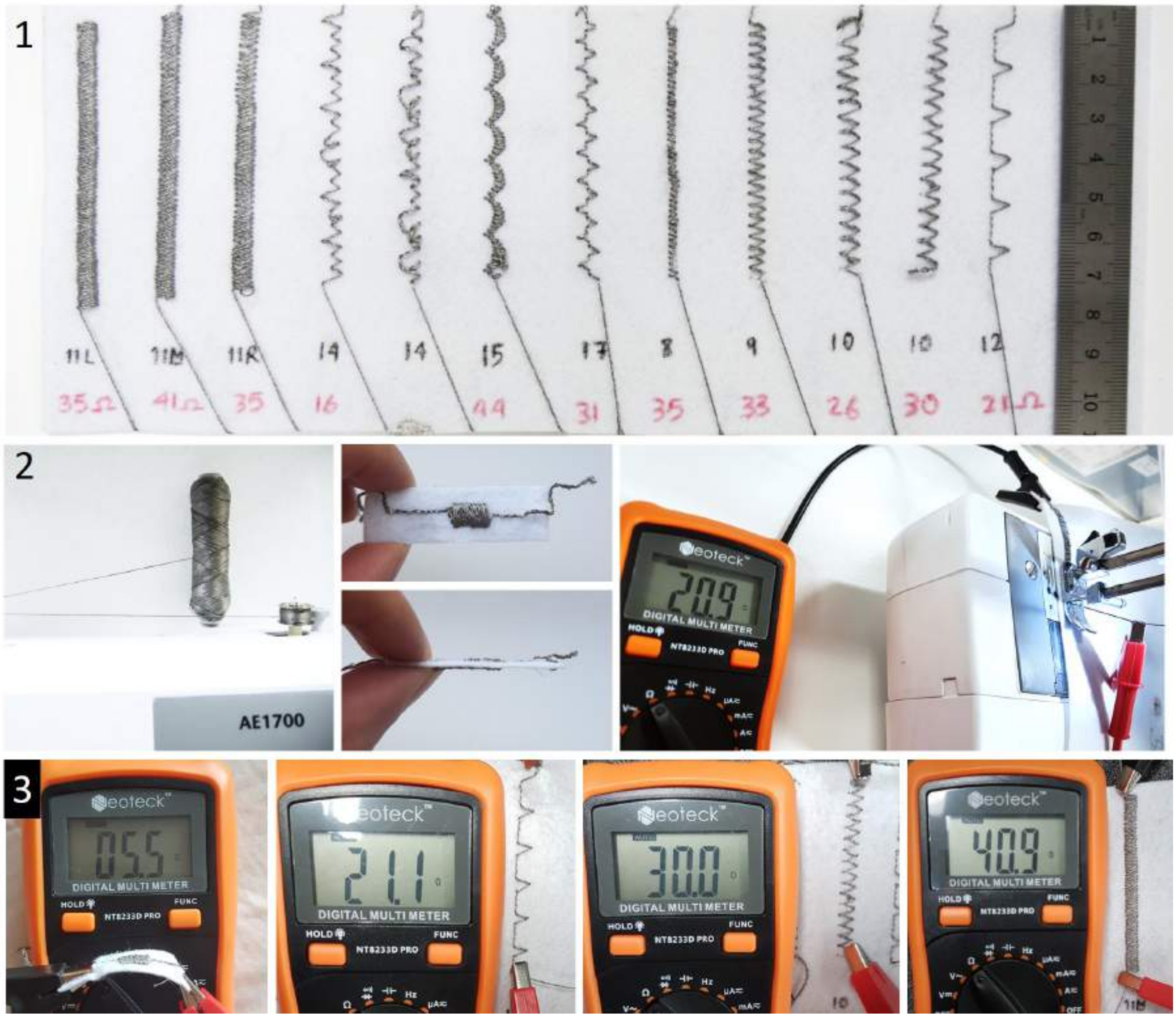


Figure 4.24 Machine-sewing soft resistors while measuring their value concurrently using a multimeter.

Figure 4.24 shows this process and some of the ‘soft resistors’ that I have created using this machine-sewing technique to complement the resistance in the circuit to the desired value. I have experimented with over 40 samples of 10 different sewing machine stitches sewn in varying lengths. Figure 4.25 shows a graph of how the measured resistance of my soft resistors changes with the length and type of the machine-sewn stitch.

A drawback of this technique is that soft resistors vary in their value when being bent or squeezed considerably. However, this can be utilized to create sensing parts in a voltage divider technique (see Section 4.3.1) or can be minimized with care of placement in least-manipulated areas of the soft interactive object. Another limitation of some non-coated conductive threads is that their resistance changes over time and with frequent friction, sun light or humidity. Solutions to these issues include using corrosion-proof conductive thread when sourcing. Still, this technique provides soft objects with the required resistance without compromising its softness, malleability and thickness as in the case of solid resistors.

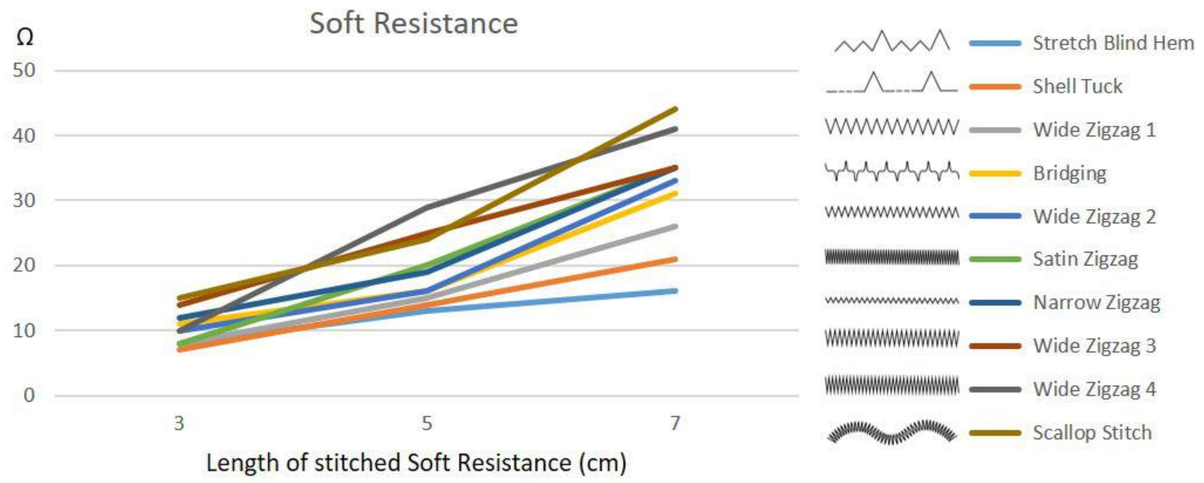


Figure 4.25 Graph showing the relationship between soft resistance and length of stitch for 10 different sewing machine stitches.

Crafting Soft Speakers

Inspired by paper-speakers (Coelho et al., 2009) and their e-textile version (Satomi and Perner-Wilson, 2019), I wanted to experiment crafting a soft speaker as yet another means of interactivity that can be embedded seamlessly in soft artefacts. I crafted a soft speaker using the couching embroidery technique in a coil shape, see figure 4.26. The fabric speaker is then placed on top of a magnet (placed in the centre of the stitched coil) and connected to an audio amplifier or an Arduino board equipped with an MP3-player IC. The embroidered speaker is as thin as the fabric it is stitched to and can be used in everyday soft decorative artefacts which will then double as a speaker. For better sound quality, the thread used should be of high conductivity and very low resistance, such as the Karl-Grimm.com copper conductive thread, cushioned using any cotton thread on (non-conductive) opaque fabric of choice that suits the aesthetics of the desired decorative artefact. It is worth mentioning that if the fabric is too stiff, it will not allow the sound to vibrate, and if it is too soft , it will absorb all the vibration. The drawback of this technique is that it is both time consuming and needs exquisite precision to hand-stitch the conductive thread neatly in a spiral path close together but without touching each other. The tighter the conductive thread is embroidered together, the more turns can fit in a smaller area and the louder the speaker will be (Kobakant.com).

Taking this technique further, soft fabric speakers can also be crafted using a digital sewing machine. By designing the coil shape on a digitizer illustration software, and uploading the machine's bobbin case with conductive thread, we can obtain precise stitches that create better quality soft speakers custom-made to the size and sound volume we need in a more efficient and easier technique. Figure 4.27 shows how this can be done.

Figure 4.26 Hand-stitched soft speaker.

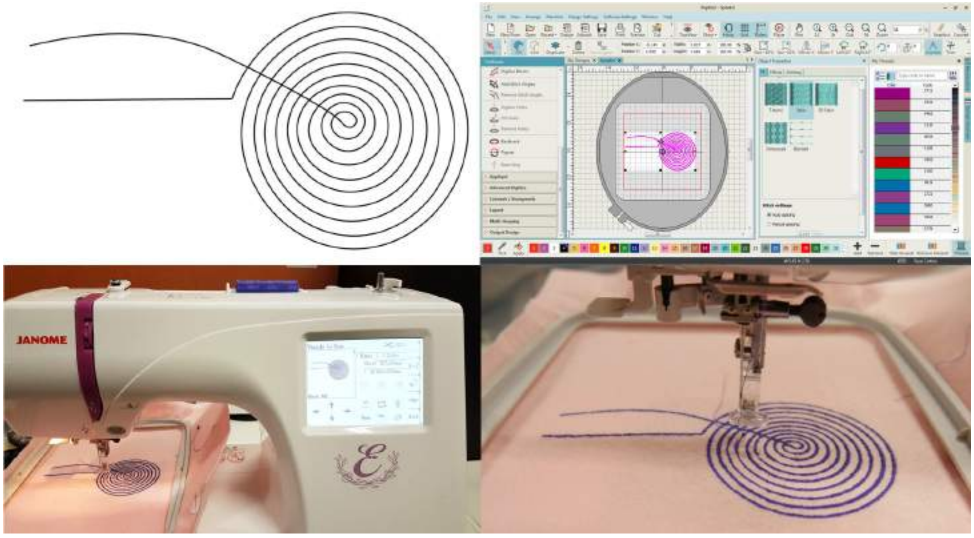


Figure 4.27 Machine-stitched soft speaker using a digital sewing machine.

4.4 Experimenting Material Behaviour

Through 32 months of exploratory learning-through-making, I carried out more than 120 experiments of embedding interactivity into a wide range of materials, noting observations in my annotated portfolio, documenting, analysing and comparing results of both successful and failed experiments. About 100 experiments focused on ways of embedding SMA onto fabrics as the most promising (organic, subtle, calm and dramatic) actuation effect, and the least fully-realized method of actuation in both literature and practice. As a result of these exploratory experimentation (documented in my swatchbook portfolio, see Appendix A) of material behaviour, similar results were collectively gathered for valuable insight, and 10 different techniques were developed, which are described as below:

4.4.1 Technique 1: Basic Machine-Sewing SMA wire

In general, SMA wire is much harder to control as it physically tends to loosen and wobble due to its unique alloy, so it cannot be firmly bent or tightened. However, by using thin 0.006"

Flexinol wire, firmly gripping the ends in one's fingers to avoid its unrolling, working quickly and accepting that the wire will somewhat loosen, it is applicable to achieve neat seams using SMA wire. Figure 4.21 shows how SMA wire was rolled around the bobbin and loaded into the bobbin case of the sewing machine underneath the presser foot. Then, the bobbin wire stitched the spool thread neatly on a tight zigzag stitch through a U-shape pattern. Once stitching was done, both the wire and thread are cut, leaving 1-2 cm of the wire to allow electronic connection. In this example, a 20 cm long wire that has 55Ω/m was consumed, giving 11Ω for this piece. When applying 410mA (the recommended current for this wire) using 4.5V, the wire couldn't move as the fabric around the pattern forced too much weight, pressure and stiffness beyond the pull force of the wire (321 grams). The pattern needed to be free, so a cut-out was formed around the pattern and a new test was made. This time, the stitched pattern could move freely by bending upwards when connected.

4.4.2 Technique 2: Parametric Machine-Sewing SMA wire

To investigate the relationship between different stitches and the shape-changing actuation effect, I held systematic experimentations of almost 60 swatches with various combinations of the different factors that impact the deformation to understand their effect. Various parameters played a role in the equation of fabric actuation resulting in different deformation effects. These parameters are:

1. **Type of fabric**: The more malleable it is, the easier it is for the wire to deform the fabric. However, the type of fabric (determining its stiffness, rigidity/elasticity and weight) is correlated with the type of desired actuation e.g. firm fabrics can bend, while lighter ones can twist, (un)roll and crumple. Rigid fabric should be chosen for controlled actuation, while light-weight fabrics can support organic deformation. Flammable fabric should be avoided when sewing SMA.

2. **Type of thread**: Certain types of threads may have different impacts on the tension of the wire fitted on the fabric and therefore the deformation effect when connected. I found that loose thread minimizes deformation while tight-able thread maximizes wire pull-force and thus amplifies fabric deformation. For precaution, the thread type used should not be flammable to avoid catching fire if the wire gets unexpectedly heated too much.

3. **Type of stitch & its tightness**: the shape and tightness of the stitch that fits the SMA wire to the fabric is of significant importance. In general, the wire needs to be held tight to deform the fabric when actuated. However, if it is too tight it will not allow any deformation to take place. On the other hand, loosely fitted SMA wire will deform between stitches without causing visible deformation in the fabric.

4. **The pattern of stitching**: The most significant parameter that affects resultant deformation is the shape of the wire traces when stitched onto fabric. It has been agreed between practitioners that one of the most successful patterns that cause visible shape-change is a U-shape pattern (Satomi and Perner-Wilson, 2019). This pattern maximizes the pull-force

SMA Product		**Diameter (mm)**	**Resistance (Ω/m)**	**Current (mA)**	**Pull-Force (g)**
TOKI BMX	BMX750	0.075	1600	100	5
Muscle Wires	Flexinol Wire 0.006" LT	0.15	55	410	321
Light Stitches	Muscle Wire with terminals	0.15	55	410	320
Muscle Wires	Flexinol Wire 0.010" HT	0.25	18.5	1050	891
Smart Wires	Nitinol Wire	0.5	4	4000	3560
Rapid Education	Smart Niti Spring	0.75	2	3000	500

Table 4.2 Examples of SMA wires commercially available.

of the wire causing the material to bend upwards when the wire actuates, acting like an arm muscle that can lift objects upwards by contracting. Other patterns can cause the wire's pull-force to be distributed in uneven loads minimizing its actuation capability.

5. **Type of wire**: SMA wires are commercially available as Nitinol, Flexinol, muscle wire or smart wire, and can be as malleable and thin as normal thread (e.g. 0.15 or 0.25 mm) with pulling force ranging between 320 and 900 grams at 410mA and 1050mA respectively. If high current (than the recommended by the manufacturer) is applied for more than 10 seconds, the wire may burn. Thicker SMA wire usually has a much higher pull-force which can deform fabric more intensely, even when it's heavier. However, thicker SMA wire requires significantly higher power. Accordingly, thicker wire increases the deformation boundaries but simultaneously adds rigidity and stiffness to the fabric that might affect its malleability, affordance or texture.

6. **The austenite form** (trained shape): The *memory* shape that the SMA wire has been trained (i.e. heated up to 400-500°C) to remember when activated by 40-90°C is called the austenite form/state. The austenite default shape of off-the-shelf SMA wire is a straight-line; that is, it flattens unfolding itself and often slightly shrinks by 4% of its length when heated or connected to electric current. This shape can be changed as required if the wire is retrained to remember a new shape. Most SMA actuates repetitively for millions of cycles, but if high stress or strain is imposed, the actuation only lasts for a few hundred cycles. This parameter can dramatically change the SMA wire actuation behaviour resulting in different deformation effects for each different austenite form (i.e. trained shape).

7. **The martensite form**: SMA wire is malleable and hand-deformable in room temperature (when no electric power or heat is applied). This malleable state is called the martensite state. In this idle malleable state, the wire accepts any physical deformation applied to it. Once the wire is connected or heated, it returns back to its memorized austenite shape. However, the deformation is not always consistent and is often affected by the martensite form. That is, the shape-change is affected by the manipulation applied to it earlier. In other words, if the wire is bent, rolled or twisted by force, then actuated, it will unbend, unroll or re-twist itself back. This allows a variety of interactions between people and actuating soft artefacts in the form of a conversation where physical input affects output.

8. **The fabric orientation**: As the pull-force of thin SMA wire is relatively not high enough, the fabric deformation is significantly affected by the seam orientation. The fabric might not be able to actuate vertically, but could on a horizontal surface, where it's not working against the gravity. Also, non-spring SMA can only deform the fabric towards the side it's stitched on, not the other way. Gravity can also be used to work with the design (rather than against it) if utilized as the reverse mechanism, pulling the contracted SMA back down while cooling achieving a two-way actuation.

9. **Length of wire**: Although used as thread in this technique, the length of consumed wire determines its resistance, which determines the amount of electric current it draws according to Ohm's Law ($V = I \times R$), consequently affecting the deformation effect that occurs. For example, a 20 cm long pattern circumference of a 55Ω/m wire forms 11Ω requiring 4.5V for its recommended 410mA. However, a 50 cm long pattern stitched with the same wire forms 27.5Ω requiring 11V to be able to draw its recommended current.

10. **The distance between the seam (SMA wire) and the edge of the fabric**: The same combination of all previous parameters may work if the pattern is stitched by the edge of the fabric, but may not work if placed in the middle of the fabric, as more weight will be applied on the wire beyond its pulling-force. This is the reason why, in most cases, a cut-out around the pattern is essential to allow the deformation to take place.

For instance, by altering two variables (the type of stitch, and the pattern of stitching) and fixing other parameters, insights can be drawn on how to optimize the SMA machine-sewing technique. By experimenting with different stitches, I found the straight stitch, the satin stitch and the zigzag stitch to be efficient, with tighter stitches causing more dramatic deformations. Through testing different patterns, I found that the more curved the pulling end is, the more the pulling-force of the wire is maximized. Figure 4.28 compares the four combinations of two patterns (triangular pointy peak, round curved peak) and two stitches (wide zigzag and tight running stitch).

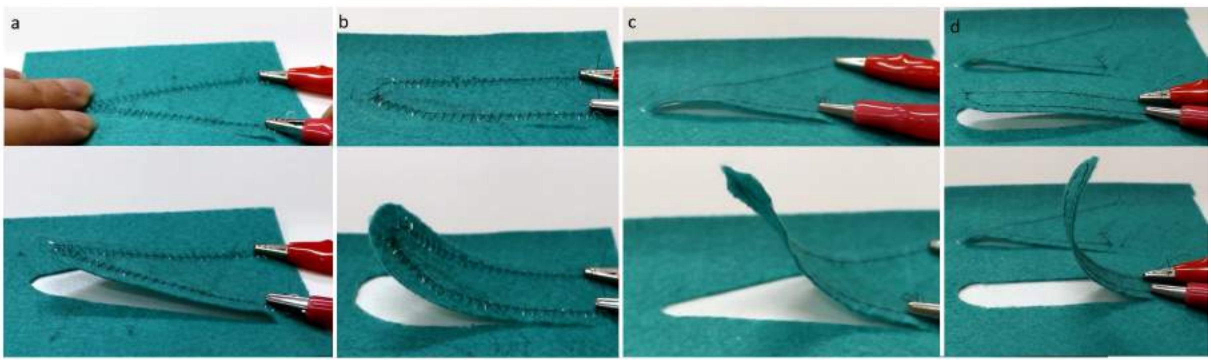


Figure 4.28 Technique 2: Machine-sewing SMA wire (in the bobbin) to felt fabric over a U-shape pattern using a loose zigzag stitch (a: pointy, b: curved) and a tight running stitch (c: pointy, d: curved).

4.4.3 Technique 3: Sewing-Patterns for Machine-Sewing SMA

The great benefit of using a sewing machine rather than hand-stitching SMA wire is the ability to replicate, evaluate and rapidly create different shape-changing effects. We can now machine-sew actuation directly into fabric and systematically compare different patterns and shapes. Using *paper patterns* is an old traditional sewing method for cutting fabric to desired sizes and is a natural step to learn when sewing garments and soft artefacts. Consequently, it is reasonable to utilize and reappropriate this same technique of using a paper pattern to enable the creation of complex shape-changing patterns (see figure 4.29). This technique enabled me to simply follow the lines while machine-sewing SMA wires into various curves easily. Figure 4.30 shows some paper patterns have been machine-sewn using SMA wire, including a star shape, a hexagonal inner shape and again a U-shape. Comparing the resultant actuations of different stitched patterns yielded a conclusion that the latter pattern is most effective in terms of visibility of deformation.

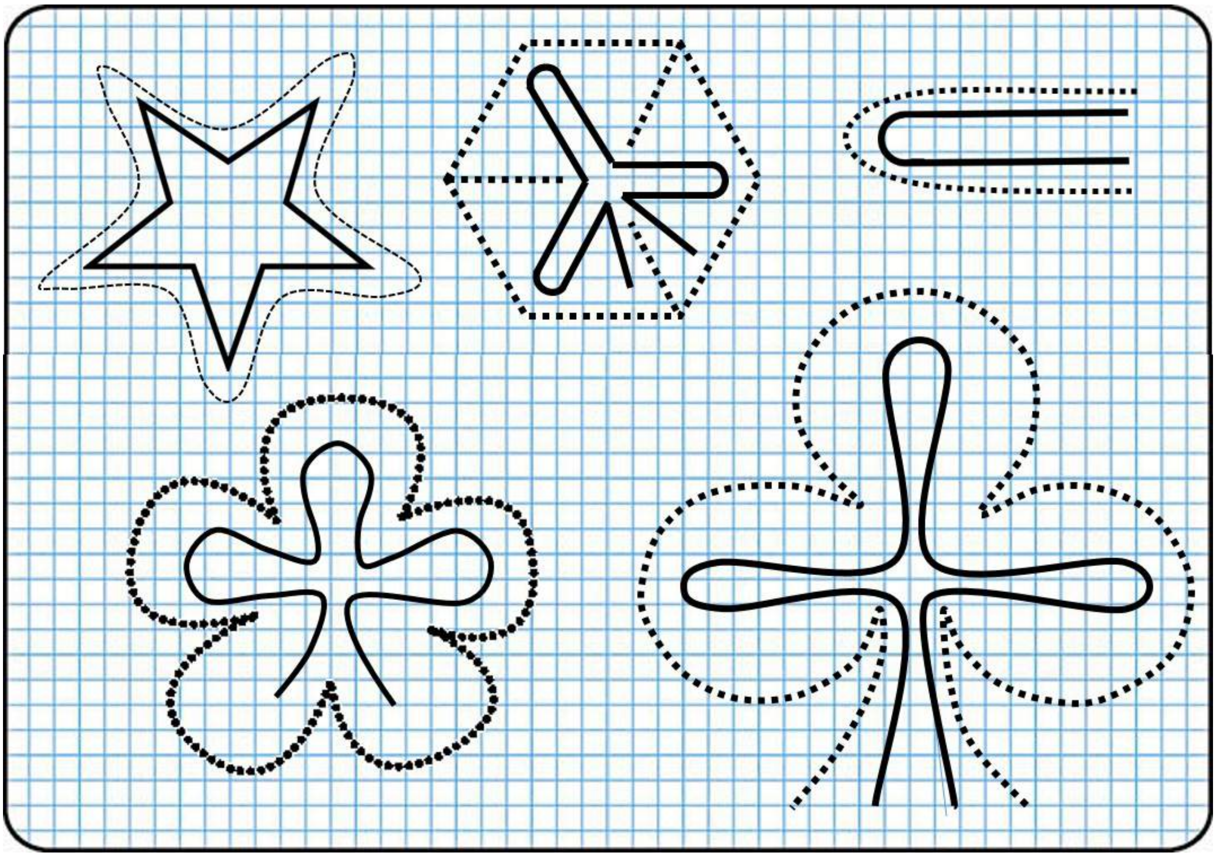


Figure 4.29 Examples of paper patterns for machine-sewing SMA wire (solid lines) on fabric pieces (dotted lines). Feel free to scissors-cut, pin down to your fabric and stitch. Follow the pattern while sewing then tear out your paper pattern from the fabric after machine-sewing is finalized.

4.4.4 Technique 4: Controlling Fabric Deformation

Learning from Technique 3 how the U-shape pattern worked nicely, I went on to try different versions of this pattern. I learned that by changing the size of the pattern to a narrower width

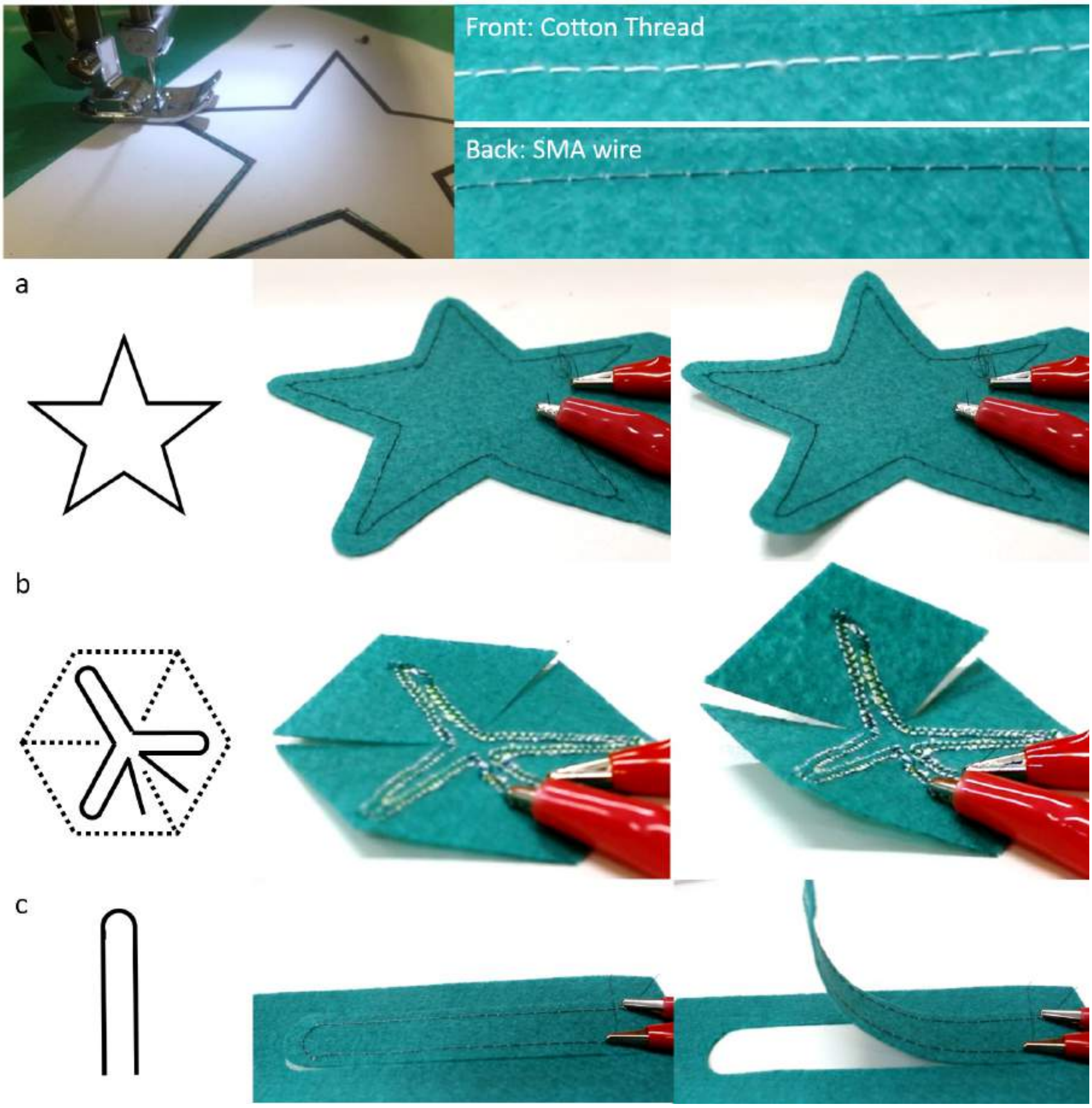


Figure 4.30 Technique 3: Machine-sewing SMA wire using paper patterns to create complex shapes (top). The stitching paper patterns (left), fabric swatches in default state (middle), and after connecting 9V power source triggers the deformation of the stitched pattern (right).

and longer length, we can achieve more visible variations of shape deformation. I learned, by coincidence, that a bend can be controlled at a particular desired part of the fabric through less weight at this part. Figure 4.31.a shows a scrap that actuates in a right angle bend at the point where less fabric strain is found. Figure 4.31.b shows how the pull-force is maximized (compared to figure 4.28.d) when the pattern gets narrower, allowing more grip. By changing the parameter of the martensite state (i.e. twisting and untwisting figure 4.31.b by hand), the same piece deforms in a different way by twisting itself -instead of swirling- as shown in figure 4.31.c. In this technique, the fabric relaxes back and obeys gravity once no electric current flows through the wire. However, the deformation is repetitive and the resultant actuation is the same every time. Such techniques can be used when the actuation output needs to be designed and performing in a specific constant way to achieve a certain task or display a specific message to a user. For

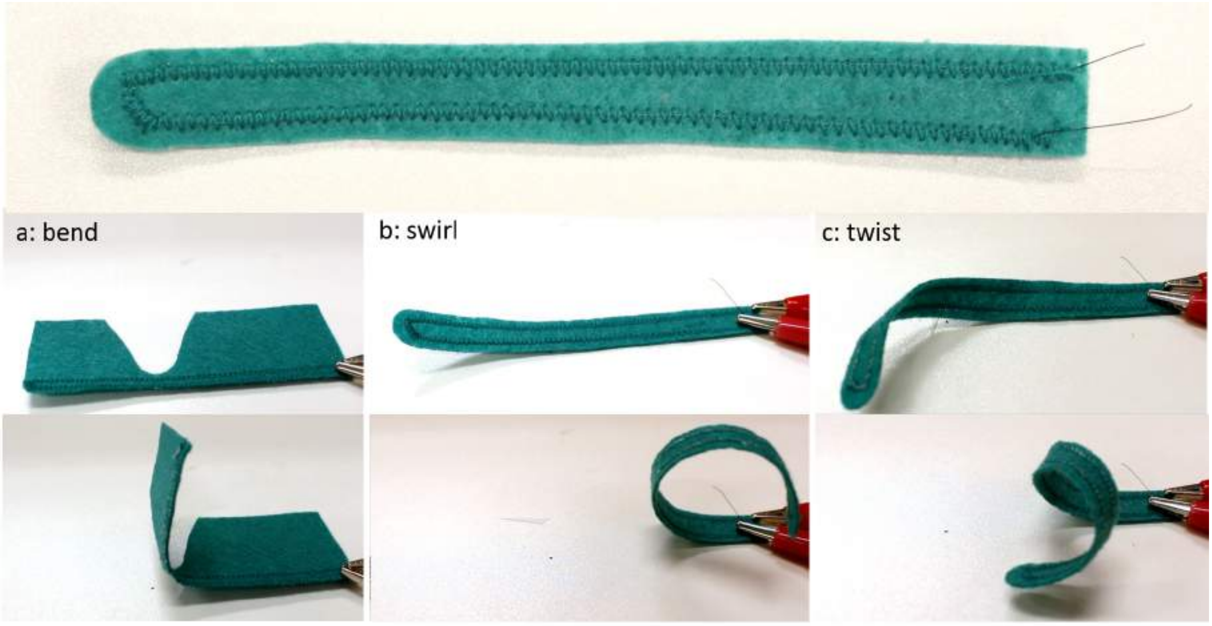


Figure 4.31 Technique 4: Machine-sewing SMA wire in the bobbin and cotton thread in the spool over a finger-outline pattern using a tight zigzag stitch (a: bend, b: swirl, c: twist).

example, a cushion's corner can bend twice notifying one that something has happened. Such actuation needs to be consistent and can thus be achieved in one of these controlled deformations.

4.4.5 Technique 5: Manipulated Fabric Deformation

Rather than controlled actuation, I was interested in the unexpected ways SMA wire deforms the fabric in a non-controlled but more organic behaviour. To allow such free-style actuation, the martensite state parameter (i.e. hand manipulation input before actuation) can be manipulated and light-weight fabrics can be used to avoid rigid repetitive deformation. In this technique, other parameters (such as the stitch, pattern and wire) are fixed to the most effective ones found so far. Figure 4.32 shows deformations resulting from a) swirling, b) rolling, and c) folding hand manipulations of the fabric. Results informed how autonomous behaviour of SMA actuated fabrics can often yield more interesting forms and organic shape-changes depending on user direct manipulation as opposed to programmed consistent outputs. This technique can suit applications around home decor where people deform their soft furnishing in different (free-style) and unique ways.

4.4.6 Technique 6: Machine-braiding retrained SMA wire

To achieve a crumpling fabric deformation, the wire needs to significantly contract (not just bend, swirl or twist). Relevant previous work in material science has looked into training SMA wire to remember a certain austenite shape (Sun et al., 2012). Therefore, SMA wire can also be customized into remembering a specific desired shape by training the wire in a mould, fixing it to that shape and applying 500°C of hot air for a few minutes (Sun et al., 2012), or a naked

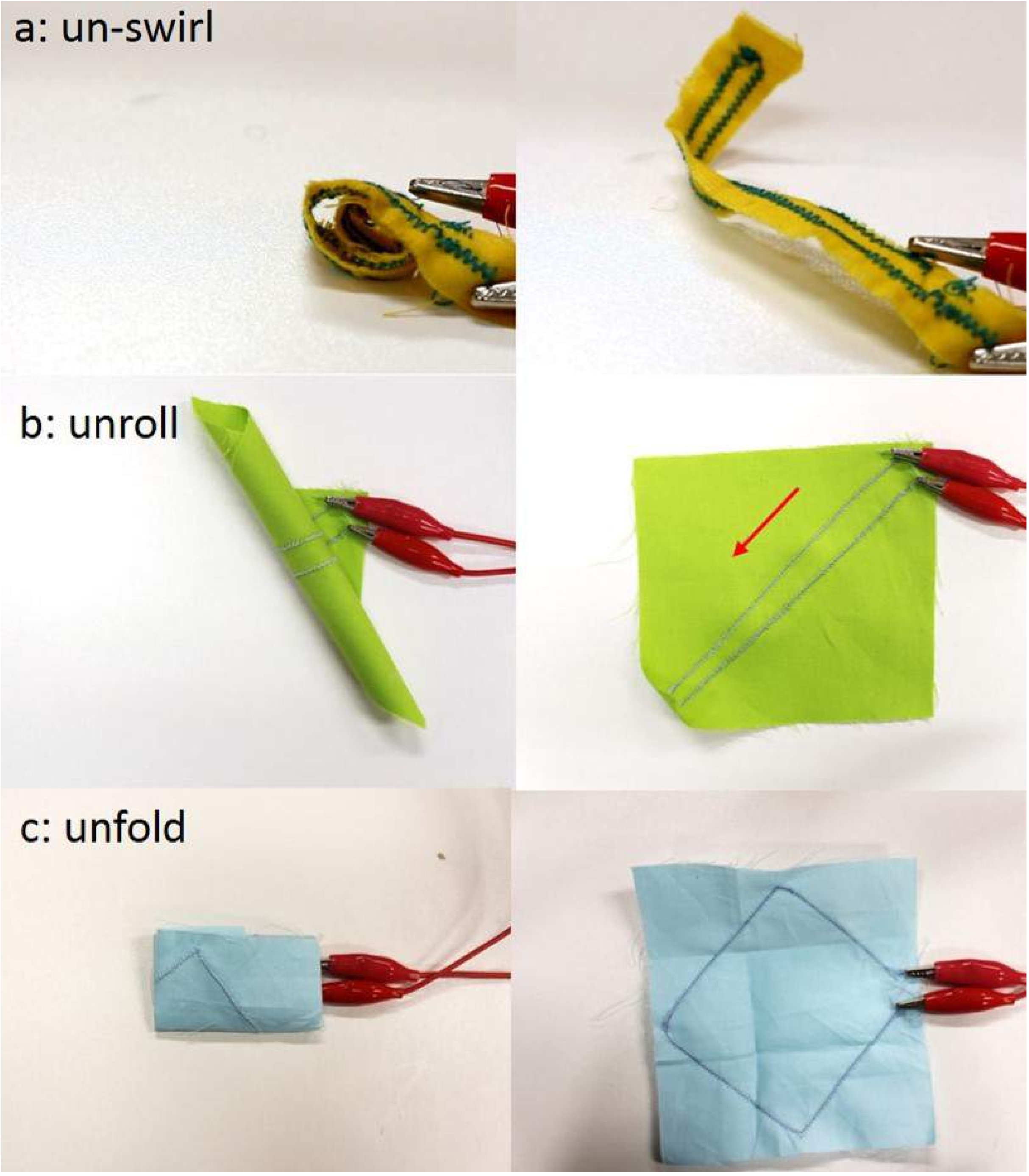


Figure 4.32 Technique 5: Machine-sewing SMA wire in different patterns. The fabric swatch in the malleable martensite state (left), and after actuation (right).

flame for a few seconds. For this technique, the wire is retrained to remember different austenite shapes then machine-braided on top of the fabric. For example, a wire actuating into a spring shape can be achieved by rolling the wire around a screw (to achieve a spring coil shape) then heating the wire using a hot air gun for 5 minutes in direct contact, while taking safety measures such as wearing fire-resistant gloves and goggles. It is required to throw the wire immediately afterwards in cold water in a process called ‘quenching’ for the training to take effect. Some have recommended repeating this process numerous times to train the wire, but I found that it does remember from the first time.

Once the wire is physically-programmed to remember this spring shape, it can be stitched to the fabric. However, it is difficult now to roll the wire around the bobbin as it has bends of a different diameter (from the screw). To machine-sew this wire, I used the conventional machine-sewing technique called ‘braiding’. Similar to adding decorative embellishments to fabric such as ribbons and thin braids, I used the spring-trained wire on top of the fabric to be fixed using the sewing machine’s tight satin stitch. Although using a braiding or a couching foot would be suitable for this, I used the basic presser foot which worked fine. I stitched the wire to the edge of firm felt fabric using an embroidery tight satin stitch. However, the wire could not deform the fabric at all, as the fabric swatch was too heavy and firm to be deformed. Then, I cut the fabric from around the wire, leaving some fabric attached to half of the wire length to compare the results. Figure 4.33 shows how the fabric transformed into a soft spring once connected to electricity, while the part with fabric that was still attached became wavy.

Figure 4.33 Technique 6: Heat Training SMA wire on a screw to a spring shape (left). The fabric swatch with machine-sewn SMA wire (by top braiding) to the felt fabric (middle). Connecting 9V power source deforms the fabric into a spring shape (right).

4.4.7 *Technique 7: Machine-Sewing zigzag-trained SMA wire*

As an alternative austenite memory-shape to train SMA wire (than a spring coil), I used zigzag-trained muscle wire to investigate the shape-change pattern that will result. On the swatch in figure 4.34 the 16 cm zigzag-trained SMA wire was machine-braided on top of a cotton fabric swatch. When connected to the electric current, the fabric deforms in a wavy creasing form creating a different shape-change deformation than all the previous techniques.

4.4.8 *Technique 8: Machine-Sewing bobbin-trained SMA wire*

Based on previous techniques, the idea can be developed to investigate a new possibility: why aren’t SMA wires pre-programmed directly on the machine’s bobbin? In other words, training the SMA wire while rolled on the bobbin, using the bobbin as its mould, then placing the bobbin (with the spring-trained wire) directly inside the sewing machine. This technique was much easier than braiding the wire on top of the fabric and resulted in new kinds of deformations. To hold the SMA wire from jumping out of the bobbin, I carefully closed the two ends with an adjustable wrench tool, then used the hot air gun over the bobbin for 5 minutes, quickly quenched it in tap water, and the bobbin was ready for sewing. Using this technique with different stitches and sewing patterns achieves different results. For example, when using this bobbin to machine-sew a tight zigzag-stitched square pattern, the SMA -once actuated- crumpled the fabric swatch in 1 second, see figure 4.35. However, when machine-sewing the bobbin-trained SMA

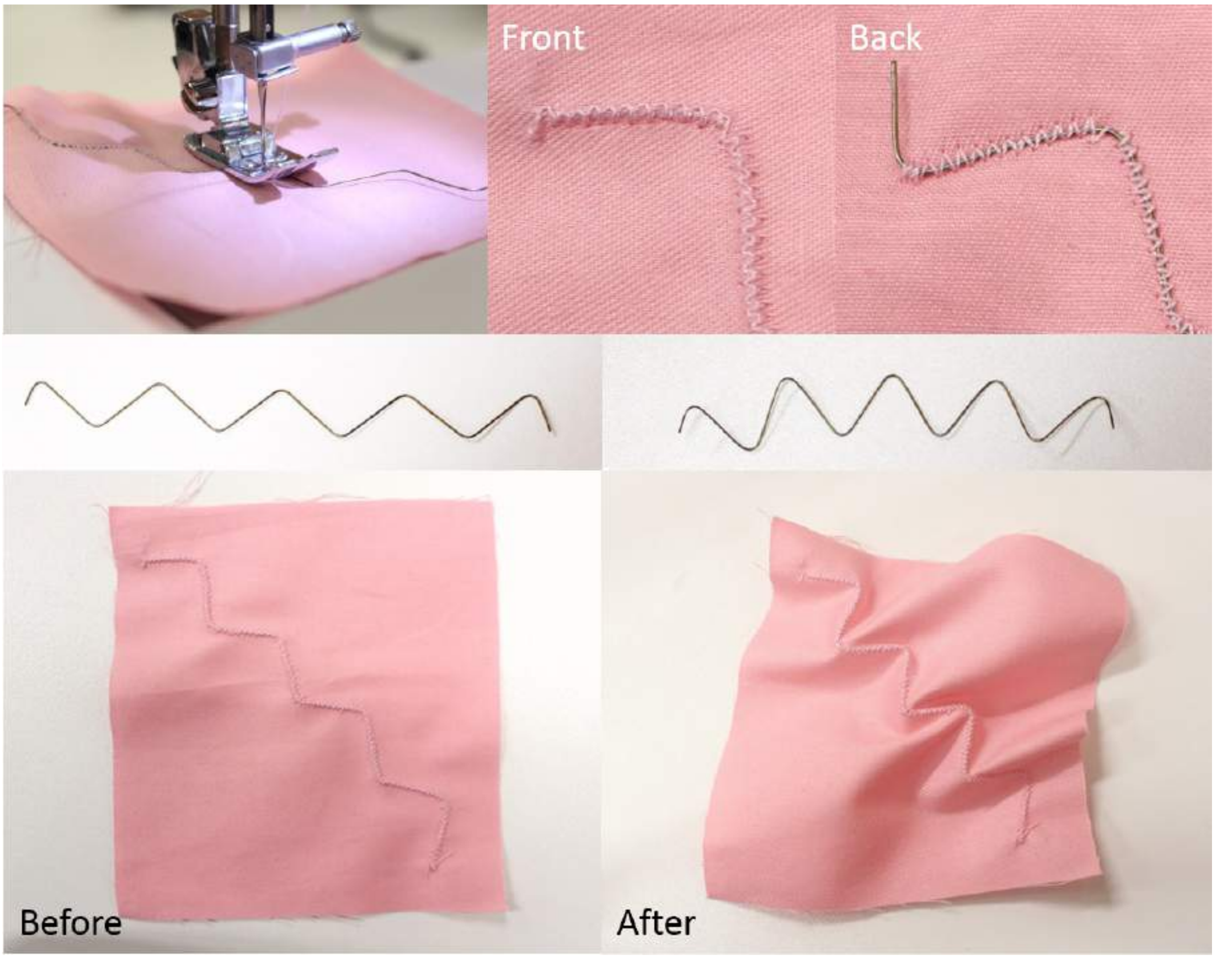


Figure 4.34 Technique 7: Machine-sewing zigzag-trained SMA wire and close-up to the tight zigzag machine stitch (top). The fabric swatch with machine-sewn SMA wire after connecting 9V power source crumbles the fabric inwards (bottom).

wire in a narrow U-shape pattern using a satin stitch, the fabric swatch rolled around itself once connected, see figure 4.36. In all these examples, the SMA wire is intertwined with the normal thread, causing the fabric deformation at the *seam*, only visible from the back, and is entirely *seamless* from the front of the fabric.

4.4.9 Technique 9: Machine-Sewing shape-colour-change

By combining Technique 7 with machine-sewing thermochromic thread, colour-change and shape-change can both be achieved simultaneously. In this technique, thermochromic-dyed thread is used on the top spool pin, all the way through the thread guide, the take-up lever and the needle. On the other hand, the bobbin is filled with SMA wire that can be retrained in a spring austenite shape for a contracting actuation. With a tight zigzag stitch, to hold both threads in place, and prevent excessive thread consumption (as with the satin stitch), I experimented this technique on different fabrics and threads. As with Technique 2, using matching colours of fabric and thread, will hide and reveal a contrasting seam that swirls, bends, rolls or crumples once actuated, according to the SMA trained shape, as in Technique 8. Figure 4.37 shows one of

Figure 4.35 Technique 8: Heat Training SMA wire in the bobbin to a spring shape (top left and middle). Close-up to the tight zigzag machine stitch (top right). The fabric swatch with machine-sewn SMA wire (in the bobbin) to cotton fabric (bottom left). Connecting 9V power source crumbles the fabric inwards (bottom right).

the samples in a vibrant coral colour fabric and teal thermochromic dyed thread, that changes both shape and colour simultaneously once connected.

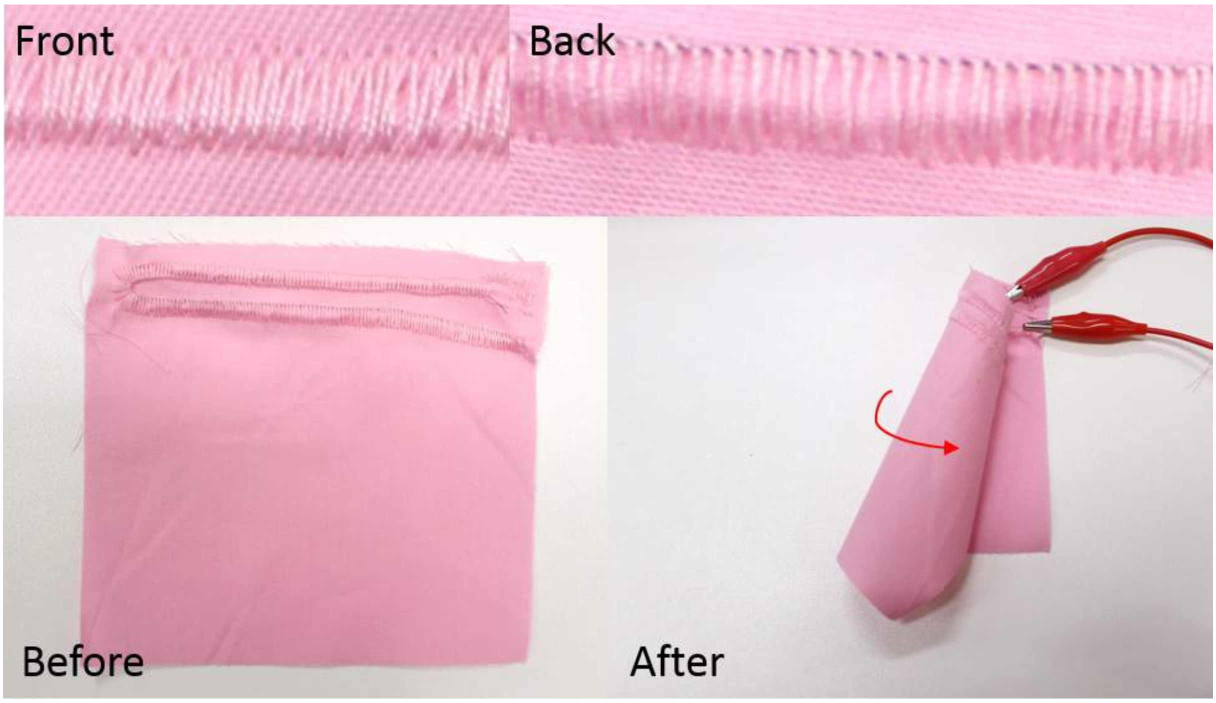


Figure 4.36 Technique 8: Machine-sewing bobbin-trained SMA wire in a narrow-finger pattern using an embroidery stitch. Top: Close-up to the machine-stitched seams from the front and the back (where SMA wire is intertwined with thread). Bottom: The fabric swatch with machine-sewn SMA wire after connecting 5V power source rolls around itself.

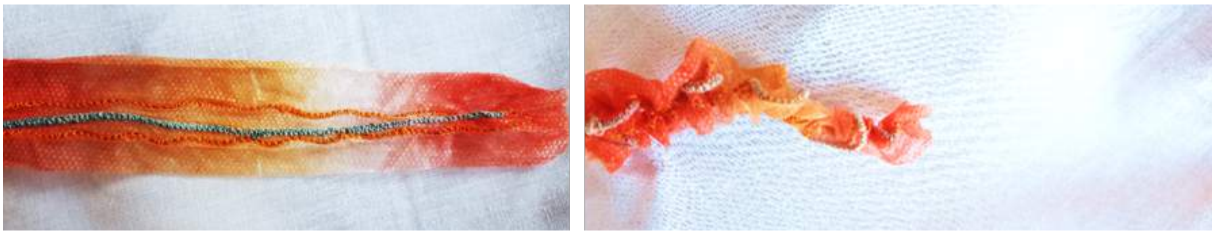


Figure 4.37 Technique 9: Machine-sewing bobbin-trained SMA wire with thermochromic thread. After actuation, the fabric seam changes both its shape and colour.

4.5 Evaluation and Observation

After almost 100 experiments of different combinations between the 10 identified parameters (fabric type, thread type, stitch type, sewing pattern, fabric orientation, wire type, wire austenite, wire martensite, wire length, distance to edge) resulting in different deformations, I decided to use them as a data set for training a machine-learning model to enable evaluating and predicting the result of any further sample. With the help of my colleague Dr. Yu Guan (Machine Learning Lecturer) I found an open-source data-mining software, called WEKA, to be helpful for this task with its tools for data preparation, classification, regression, clustering and visualization. Using the WEKA software, I generated class distribution in terms of different features (i.e. parameters) after converting numerical values into nominal ones for simpler input to a Logical Regression classifier. I collected more data samples (by machine-sewing them) and used the WEKA software as a data mining and visualization tool to understand which attributes are the key factors for a high drama index. Accordingly, I was able to detect how some features are crucial, quantifiable and controllable for creating a successfully deforming/positive pattern i.e. the length of the wire and the distance between the stitched wire/seam and the edge of the fabric, for different austenite SMA wire forms.

In this sense, such numerical values were converted into nominal features (e.g., the length of the wire (in cm) is classified as *short* (<10), *medium* (11 to 60) and *long* (>60), which is more intuitive for visualization. Also, the distance (in cm) between the stitched wire and the edge of the fabric (affecting its pulling-force) was classified as *close* (<3), *far* (3 to 10) and *too far* (>10). Finally, the changes observed, or the shape-change intensity/effect was measured by observational evaluation of the resultant deformation as a 'Drama Index' scale from 0 (i.e. no deformation happened) to 10 (i.e. significant dramatic deformation). For eliminating subjectivity, the drama index was then categorized into two classes, *high* (>=5) and *low* (<5), from which we can understand how to design a "good pattern".

Figure 4.38 provides the plot where we can see, for the spring austenite form, the length of the wire should not be too short for a more visible and dramatic actuation. Also, for the flat austenite, the length of the wire should be neither too long nor too short (ideally medium between 10 and 60 cm long). Clearly, we can get the following knowledge from the aforementioned data analysis: to design a good pattern (i.e. with high Drama Index), we should stitch the 'seamless seam' with *medium* length wire that is not *too far* from the fabric edge with distance values set at the range of 0 to 3 cm.

In general, data visualization showed the 10 parameters (i.e. features) in different charts distributed based on feature quantization throughout the data set (i.e. swatch samples). These features were then narrowed down to the most impacting values, particularly 3 features: 1) the length of the wire/thread, 2) the distance between the wire and the fabric edge, and 3) the type of sewing stitch. By fixing other parameters (such as fabric type, thread type and wire type), the most significant features were then plotted in a 3-dimensional chart in relation with the drama index using data visualization tools. Figure 4.38 shows graphs of the relationships between the 0.5 mm Flexinol data set and different deformational parameters represented in the Drama Index. Results show how the ideal length of SMA wire for the best deformation results is a *medium* length i.e. from 10 to 60 cm long, and that better results are achieved with tight stitches close to the edge of the fabric i.e. distance to edge is less than 3 cm. Moreover, higher drama indexes were achieved with light cotton fabrics and felt using custom-trained austenite wires than with heavier fabrics and standard wire.

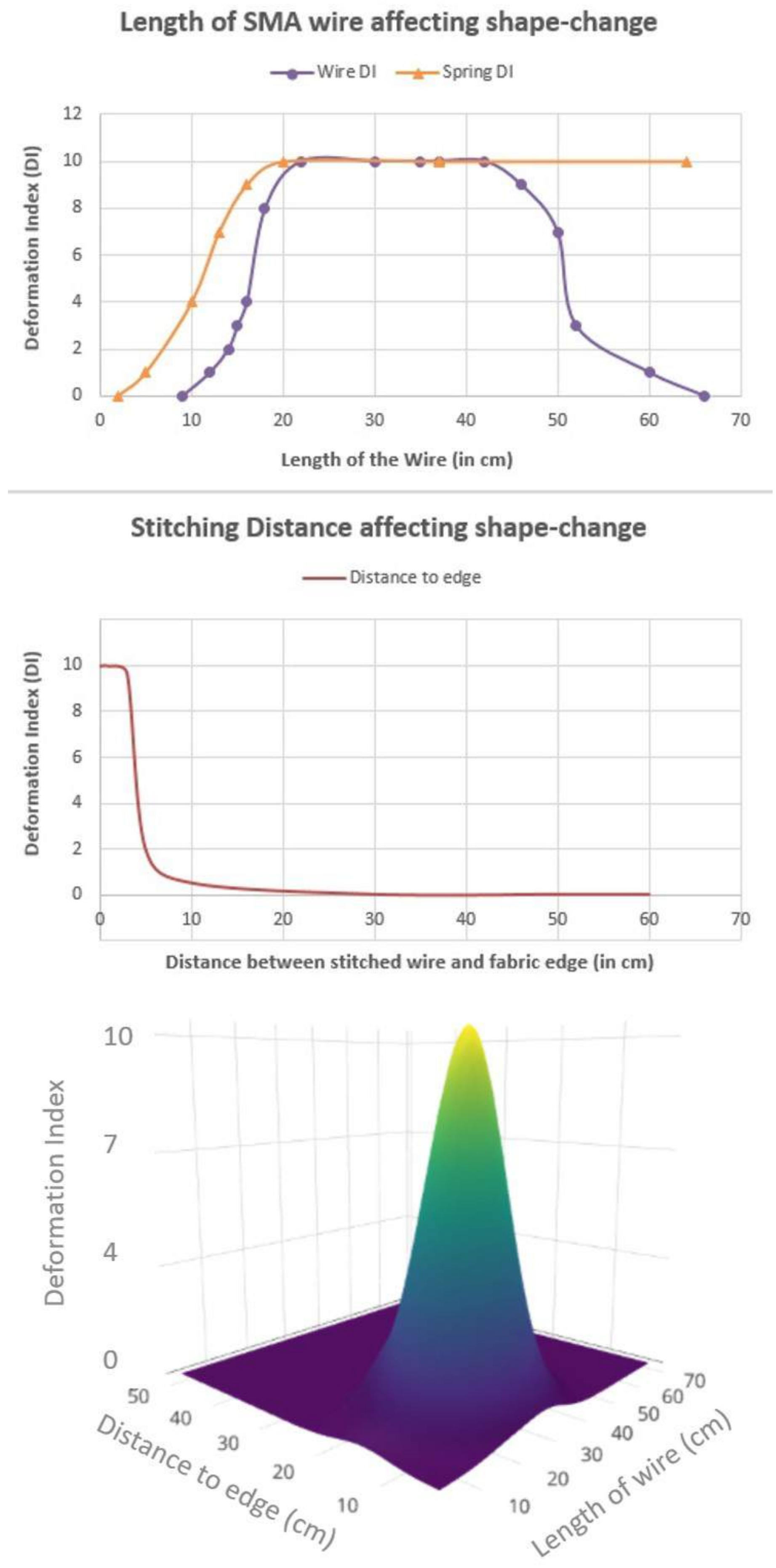


Figure 4.38 Graphs representing the observed relationship between the Drama Index and impacting parameters (length of wire and distance between stitched seam and edge of fabric).

4.6 Summary

This chapter is an exploration of the territory of weaving technology seamlessly within everyday finishing materials (such as fabrics, textiles and paper) through capacitive sensing, colour-changing and shape-changing actuation with a particular focus on sewing and textile practices. Despite the extensive experimentation, the results drawn only scratch the surface of what could be achieved in tackling the appropriating and retrofitting of OUI Interiors. Nevertheless, I have introduced a range of novel techniques for machine sewing and embroidering actuating threads/wires to fabrics, opening the door for seamless interactive soft furnishing. While previous work (Berzowska and Coelho, 2005; Coelho and Maes, 2009; Perner-Wilson and Buechley, 2010a; Davis et al., 2013) has relied mainly on hand-sewing, my machine-sewing techniques enabled an array of reproducible soft actuations (i.e. colour change of seams and soft shape-changes such as bend/unbend, swirl, twist, roll/unroll, curl, crumble and crease).

Emphasizing on retrofitting soft furnishing as the majority of interior decorative elements, this chapter brought material science innovation of actuating *wires* to a new context and appropriated practices, as *threads*. This merge between technology and crafting enables *smart* or interactive materials to have new encounters with other materials (such as fabrics and textiles), other tools (such as needles and bobbins) and other machines (such as sewing machines or embroidery machines). This approach broadens the accessibility of technology prototyping and has the potential to enable new previously unrealizable possibilities. For example, it allows any person to sew for themselves a shape-changing garment or make a colour-changing cushion gift without much of the common paraphernalia of digital technology development. Recent research in interactive e-textiles using servomotors and LEDs (Kono and Watanabe, 2017; Mennicken et al., 2014a) sits in opposition to notions of 'ubiquitous', 'seamless' and 'everyday use'. However, stitching threads, that alter their appearance and/or interactively deform constituent fabric, making the *seams* hide and reveal new aesthetics might also be thought of as a productive play on the idea of seamless and seamful interaction (Chalmers and MacColl, 2003).

While embedding colour-change was more artistic and elaborate, techniques required for embedding shape-change were more sophisticated and unintuitive. Therefore, I have paid particular interest to resourcefully experiment numerous samples and develop new scalable and reproducible techniques of embedding shape-change into soft materials. From observations of experiments sewing SMA to fabrics, 10 parameters were realized as the impacting factors that control the drama index: fabric type, thread type, stitch type, sewing pattern, orientation, wire type, wire austenite, wire martensite, wire length and its distance to the fabric edge. Further data analytical findings of these parameters as features' analysis revealed the relationship between different lengths and distances of wire/seam and the resultant drama index on a quantitative scale. Data visualization helped revealing the deformational scope of such techniques (sewing SMA wire as thread) in a 3-dimensional plotted graph showing "medium" lengths of wire/seam that are "closer" to the fabric edge using a "tight zigzag" stitch gives the most visually dramatic shape-changing effects.

I have also experimented some paper patterns (see figure 4.29), that I encourage others to scissors-cut and stitch to fabrics using a sewing machine, to test the fabric actuation. Further work should take it forward to systematically investigate the range of different textiles, threads and sewing patterns. With more sewn samples and collected data of the given attributes, we can build more robust systems of soft actuation prediction using machine learning techniques. This should inspire machine learning projects to predict which parameters/features can result in various material deformations. Alongside, this should also inspire crafting and tech-making designers and researchers equally to develop "sewing books" of different *seamless seams* that can change their colours or shapes using various sewing patterns in an array of real-world artefacts. Once designers learn and understand how smart threads can be sewn into their designs (not just wearables, but also interior elements such as a chair arm or a pillowcase), this might bring us to a world with new rituals, practices and interactive possibilities.

This work facilitates further research on actuating everyday soft objects, and expand on previous work that generally focused on either novel computational composites or motorized-actuation. My learning through making was presented in several techniques that each evokes design opportunities that can pave the way for a vast amount of future work. Machine-embroidering sensing patterns and machine-sewing actuating threads will change the topology of how garments, soft furnishing and other textile artefacts are designed, crafted and manufactured, on a scalable level. Designers, crafters and practitioners can now use such techniques to create predictable, replicable and scalable rapid fully-functioning prototypes and interactive designs of everyday interior objects.

The objective of my critical making was to find aesthetically-seamless ways to embed subtle and silent organic movements and actuations that do not disturb people or require constant attention as with other interfaces such as light emitting displays (Nabil et al., 2018a). Rather than developing bespoke technologies, utilizing OUI materials (that can embed interactivity within existing artefacts) is the means of creating interactive decorative objects. This work contributes a set of appropriations and retrofitting exploits that can be adopted by others to support the making and crafting of decorative OUI for calm-computing contexts.

Nevertheless, a number of challenges would need to be addressed before claiming such potentials. For instance, how can such materials and techniques be used on a large scale? how can they be seamlessly embedded and controlled within everyday objects? As for the scope of this thesis, such learnt techniques were developed in parallel to the work presented in the next two chapters utilizing *OUI materials* to design and prototype *OUI artefacts* (Chapter 5), and studying situated deployments of *OUI Interiors* (Chapter 6). In the next chapter, I present a number of inspirational artefacts that I have developed throughout my research using the crafting and making techniques that I have exploited and developed concurrently (presented in this chapter). In doing so, I express the practicality, replicability and scalability of my presented making techniques to produce interactive interior artefacts of different types, materials and scale.

Chapter 5. Prototyping OUI Decoratives

Following my research-through-design approach, and while experimenting with OUI materials (presented in Chapter 4) and exploring how they can be used to craft interactivity and stitch sensing and actuation, I frequently moved up and down in scale from *swatches* to *objects* to verify my experimentation and techniques and develop my understanding further through making. This chapter presents the design space I explored through a range of *inspirational artefacts* I have developed throughout my research. These prototypes tackle challenges of scalability and retrofitting of OUI materials to everyday interior elements.

In interior settings, decorative elements that complement the space design, aesthetics and style are everywhere. As a design space, there are a range of interesting elements that can/need to be explored. Most pieces of furniture (e.g. sofas, tables and drawer chests) have enough volume to seamlessly hide electronics within their textile upholstery or opaque hard-surface materials, due to their scale. But what I found as a more challenging terrain and was motivated to explore was the smaller sized interior elements. Some lay on horizontal surfaces such as floors, tables, counters and shelves (e.g. rugs and tablecloths), some are hung on vertical surfaces such as walls and windows (e.g. paintings, mirrors and curtains), some dangle from the ceiling (e.g. chandeliers and light pendants) and others are 3D objects (soft or rigid) placed around the space for interior adornment (e.g. vases, cushions, blanket throws and objets d'art).

To embed such interior elements with *controllable* sensing and actuating capabilities, a number of practical technical challenges need to be addressed. From the softness and small/thin volume of some, to defying gravity in others, obstacles of no small magnitude arose when ideating or sketching them as OUIs. Previous relevant research has prominently focused on horizontal tabletops, e.g. (Gaver et al., 2006), where the actuation is not working against gravity, the hazard and breakage is minimized and most importantly the electronics and hardware equipment can be hidden underneath. Therefore, I decided to take off from this point and move forward with my critical making and OUI prototyping. In this chapter, I present a number of exemplary artefacts that each explore an alternative dimension and/or a different material or interaction modality in addressing **Research Question 2**: "What can we design and build using OUIs in interior decoration?". Several OUI decorative artefacts (see figure 5.1) have been designed and prototyped, including: an actuating table runner, an interactive wall-art, pattern-changing wall-tiles, an actuating furry throw, a shape-changing vase, a colour-changing cushion and matching painting, a shape-changing rug, interactive objets d'art and curtain with tactile-sensing tasselled fringe. As an output of this design process, I have created an Ikea-like catalogue that envisions near-future everyday decoration products and interior elements with seamless interactive capabilities (see Appendix B).

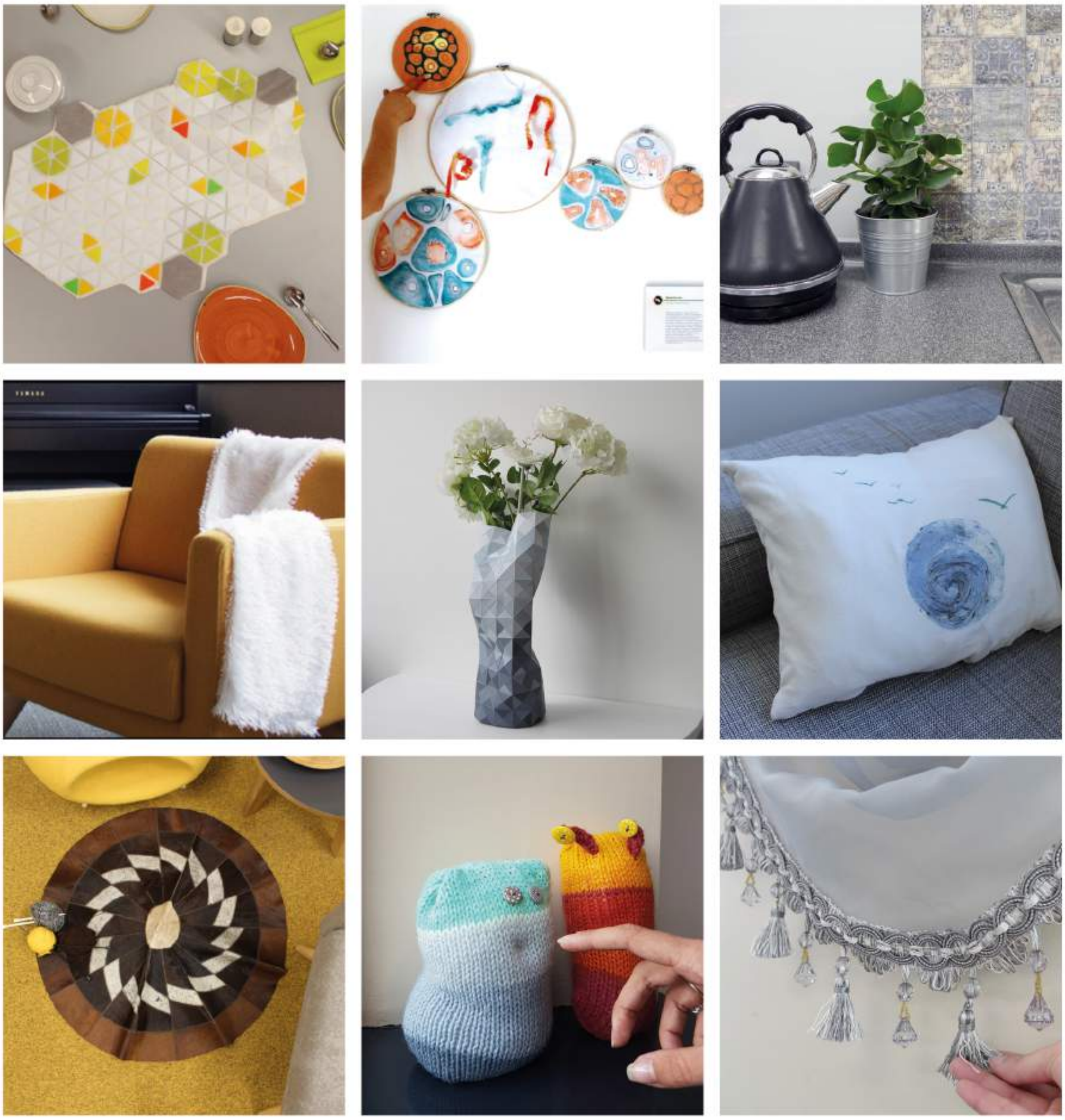


Figure 5.1 OUI decorative artefacts that I have designed: an actuating table runner, an interactive wall-art, pattern-changing wall-tiles, an actuating furry throw, a shape-changing vase, a colour-changing cushion and matching painting, a shape-changing rug, interactive objets d'art and curtain with tactile-sensing tasselled fringe.

5.1 ActuEater

5.1.1 Designing ActuEater1

Building on previous relevant literature, most notably horizontal tabletops (Gaver et al., 2006), my first artefact was a table-runner that lays horizontally and can shape-change on top of a table. As an initial prototype, I have found inspiration in John Hardy's ShapeClips (Hardy et al., 2015) to create a rapid working prototype of an actuating table-runner. ShapeClips are prototyping toolkits for creating interactive shape-changing displays using vertical actuators (stepper-motors) animated with photo-sensors using any computer display/monitor. PolySurface (Everitt and Alexander, 2017), a shape-changing tabletop, used ShapeClips to deform a semi-flexible tabletop surface as a means of tangiblizing digital data in a 3D form.

5.1.2 Making ActuEater1

The process of 'making' ActuEater1 involved 5 steps: 1) Sketching ideas and designing the interactions, 2) Developing the software and hardware of ShapeClips, 3) Designing the table-runner's pattern, 4) Making the ActuEater and covering the table with a nice wooden layer for an aesthetic appeal, and 5) Preparing the dining table, see figure 5.2. Inspired by PolySurface (Everitt and Alexander, 2017), I repurposed the ShapeClips to build a dynamic and customizable shape-changing prototype that fits on a dining table as a traditional table runner. As ShapeClips vary between 8 and 18 cm in height, I had to find a way to fit them inside the middle of a dining table and allow them to actuate the table runner through an opening. By cutting a rectangular piece in the centre of an abandoned table, I was able to embed the hardware within the table itself to ensure an initially flat surface of the runner. The initial prototype was a 30x20 cm felt fabric used to realize the affordance and limitations of the ShapeClips underneath this flexible material and specific pattern. After the software was reprogrammed and the hardware electronic components were restructured in the desired arrangements, a full-length table runner was made as ActuEater1. Similar to PolySurface (Everitt and Alexander, 2017), I designed ActuEater1 from white stretchable Spandex fabric and a uniform custom-designed pattern laser-cut on 0.8 mm thin white polypropylene sheets to give it a controlled semi-flexible moving capability. Although my initial hope was to create it all in soft fabric, I realized that these thin polypropylene pieces give the ActuEater just the desired ratio between being flexible and deformable in addition to a textured pattern. After fixing it together, I lined the edges with a satin golden-beige ribbon as a finishing touch to give it an original look and an aesthetic value similar to contemporary table runners. The final runner was 93×35 cm consisting of 10 ShapeClips in a 2×5 grid to control its inner body.

ActuEater1's ShapeClips was then controlled using a remote Wizard of Oz (WoO) interface, a prototyping tactic that allows the developer (i.e. myself as the wizard) to simulate the full functionality of the interface behind the scenes, as if it was sensing users interactions and responding to the socio-physical activity around the dining table by changing its shape. ActuEater1 could change its shape on top of the dining table in an array of different actuations: 1) Default state

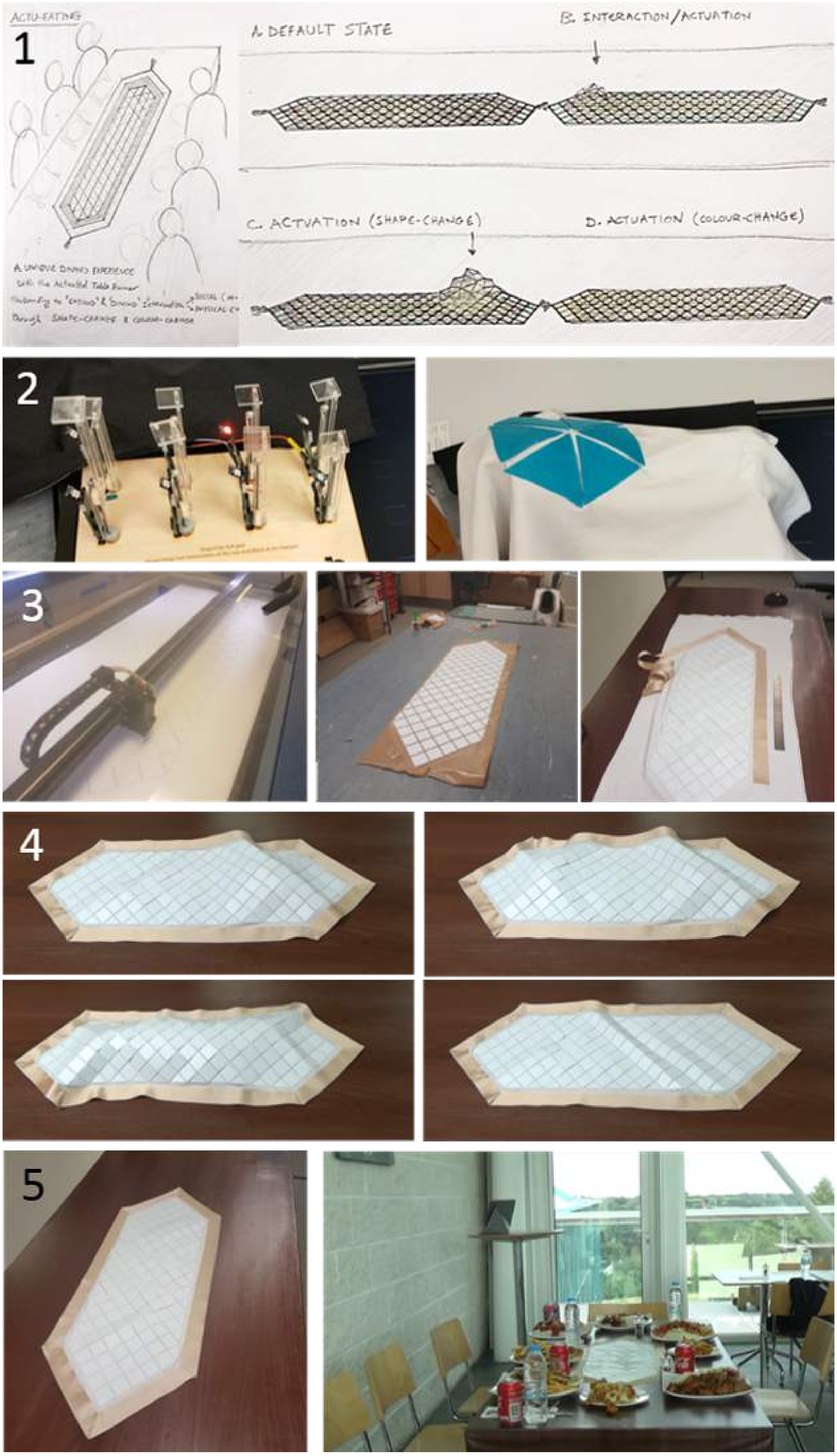


Figure 5.2 Designing and Making of ActuEater1. i) Ideation and Sketching. ii) Prototyping the Software and Hardware.iii) Designing the Pattern. iv) Creating the Actuations. v) ActuEater is ready and ‘dinner is served’.

(sleep mode); 2) Located actuation (using a single bit/actuator i.e. discrete area of movement in front of a certain diner) that either moves upwards and stays for a while or vibrates up and down slowly or rapidly; 3) Two located actuations (two bits away from each other interacting with users on both sides of the table); 4) Sequential deformation from one end to the other; 5) An animated wave motion moving across the table runner; 6) All-up and all-down. Height and speed are both controlled variables that allow variation in the resulting actuation. During testing, I noticed that when ActuEater1 returns to the default state, it does not become flat, but leaves 'history wrinkles' i.e. traces of previous actuations, in the form of fabric bends. Although these traces were not intentional, it was an unexpected yet interesting feature of ActuEater1, showing a 'history' of actuation which I saw as an interaction richness rather than an irregular performance.

I developed ActuEater1 with capabilities to enable controlling single clips or 'physical bits' in real-time without affecting the remaining parts of the grid. This feature was not only an enhancement (over ShapeClips) to support an array of actuations needed on-the-fly in response to user interactions, but it also supported multi-single-user interactions. That is, ActuEater1 can respond to two or more users individually, separately and simultaneously, and still support a multi-user engagement event with this flexible method. I can then use cameras to track the social and physical interactions of users (with each other, with the table runner and with other objects on the table) in real-time to enable controlling (via WoO) the corresponding designed animations/ actuations of ActuEater1. The eventual actuations performed by ActuEater1 were prototyped, live, in a situated study (detailed later in Section 6.1).

5.1.3 Evolution of the ActuEater

As an SCI (Shape-Changing Interface), ActuEater1 had a number of limitations, both technical and experiential. To develop an OUI (Organic User Interface) version of it, a set of criteria needed to be addressed:

1. **Control**: not be remotely-controlled and be legible (not randomly actuating because WoO human control meant that actuations were not always immediately responsive to user interactions).
2. **Interaction**: be responsive to user physical interactions (e.g. touch and physical objects).
3. **Hardware**: not to have such a bulky structure, loud noise or create a hole in the table.
4. **Aesthetics**: blend more with the surrounding space and be more colourful.
5. **Capabilities**: potentially colour-change to complement and enrich the shape-change.
6. **Experience**: be entertaining/ dancing, autonomous (have agency of its own), and interact with the surrounding space (e.g. music, objects).

5.1.4 Designing ActuEater2

In response to ActuEater1's limitations, I developed ActuEater2 to have more organic actuations (rather than mechanical ones), direct physical interactions (rather than WoO), and richer capabilities (colour-change as well as shape-change). The redesign also shifted away from demanding, bulky and noisy hardware (requiring a big hole in the table). Broadly speaking, ActuEater2 was intended to not be a radical departure from the design of ActuEater1, but build upon what I had learnt in terms of design, making and observing its operation. ActuEater2 presented an organically-actuating soft decorative object which could be used to further study how multi-aesthetic interactions from a decorative OUI could impact people's experience of a given interior space/activity over time.

5.1.5 Making ActuEater2

ActuEater2 (see Figure 5.3) is a 60×40 cm cotton fabric envelope, that changes shape using a set of SMA (Shape Memory Alloy) wires sewn inside using Technique 2 and Technique 6 of parametric machine-sewing retrained SMA wire to spring austenite forms (see Section 4.4). The fabric envelope has a stretchable spandex top holding the deformable pattern, sandwiching a silicon rubber layer in between, holding the stitched SMA wires. This layering technique was inspired by the HotFlex (Groeger and Loo, 2016) technique for making interactive printed objects, which proved to achieve better results allowing ActuEater2 to be malleable enough to deform yet firm enough to relax again. Moreover, the layering acted as an insulating cover for the SMAs (a useful safety feature). The nine SMAs used were each 1-inch pre-trained shape-changing 'Nitinol' shape-memory springs from Kelloggs Research Labs that actuate at 'standard temperature' (45°C) or equivalent 5V and 0.7A drawn from a MOSFET/transistor, pulling it back to its 1-inch spring shape from any malleable form. ActuEater2 also had capacitive sensing parts (green flowers) using 10×10 cm concealed knit conductive fabric to enable soft touch and proximity sensing through $1M\Omega$ resistors. I used an Arduino Uno microcontroller to program ActuEater2 and control the behaviour of its interactions.

As Nitinol SMA springs are not solderable, I used the crimping technique where I have carefully attached to both ends of each spring a conductive (silver) crimp bead to form a connection with an insulated copper wire. Through this crimping, I was able to connect and control SMA springs through the Arduino, which was sleeved and concealed out of user sight. I found that stitching the ends of SMA carefully to the fabric gives it better grip force to 'pull' it upwards without moving freely elsewhere. As SMA 'one-way' springs work by shrinking with heat or current, it crumples the fabric in between both ends it is stitched to creating deformations. The weight of the runner and force of gravity then brings it back slowly to the table. Working out a perfect material weight that could be light-enough to deform with SMA, but still be heavy-enough to return to flat, was key to achieving a 'two-way' actuation. However, this meant that the most perceivable deformations were the ones stitched to the edges of the runner, not in the centre, where the weight is maximum, preventing visible deformation. Finally, to entirely conceal ‘technology’ from visibility, ActuEater2 was carefully finished using a sewing machine where I enclosed all its core components.

Similar to ActuEater1, I designed ActuEater2 with a uniform custom-designed pattern laser-cut on 0.8 mm thin polypropylene sheets to give it a controlled semi-flexible moving capability. This time I optimized the pattern into triangular tessellation (instead of squares) to allow more organic deformations in different orientations. ActuEater2 was also designed to be more colourful. Thermochromic ‘grey’ fabric was used in some parts to add the capability of colour-change. By embedding a heating wire underneath, the thermochromic fabric was controlled to reveal a hidden pattern as an ambient display and means of richer interactivity.

ActuEater2 changes shape more subtly, slowly and silently than ActuEater1, making it appear far more organic and less mechanical. Different parts of ActuEater2 behaved in different ways according to the affordance, stiffness and weight of the material at differing points i.e. edges deformed more freely than the centre. Touch-sensitive ‘green’ parts acted as ubiquitous sensing that triggered actuation of parts beside it. Agency was also enabled in the algorithm of ActuEater2 to display autonomous actuations if ignored for some time. Similar to ActuEater1, during the testing phase, I realized that when ActuEater2 goes back to the default state, it also does not return entirely flat, again leaving unintentional traces showing a potentially interesting/useful ‘history’ of interaction.

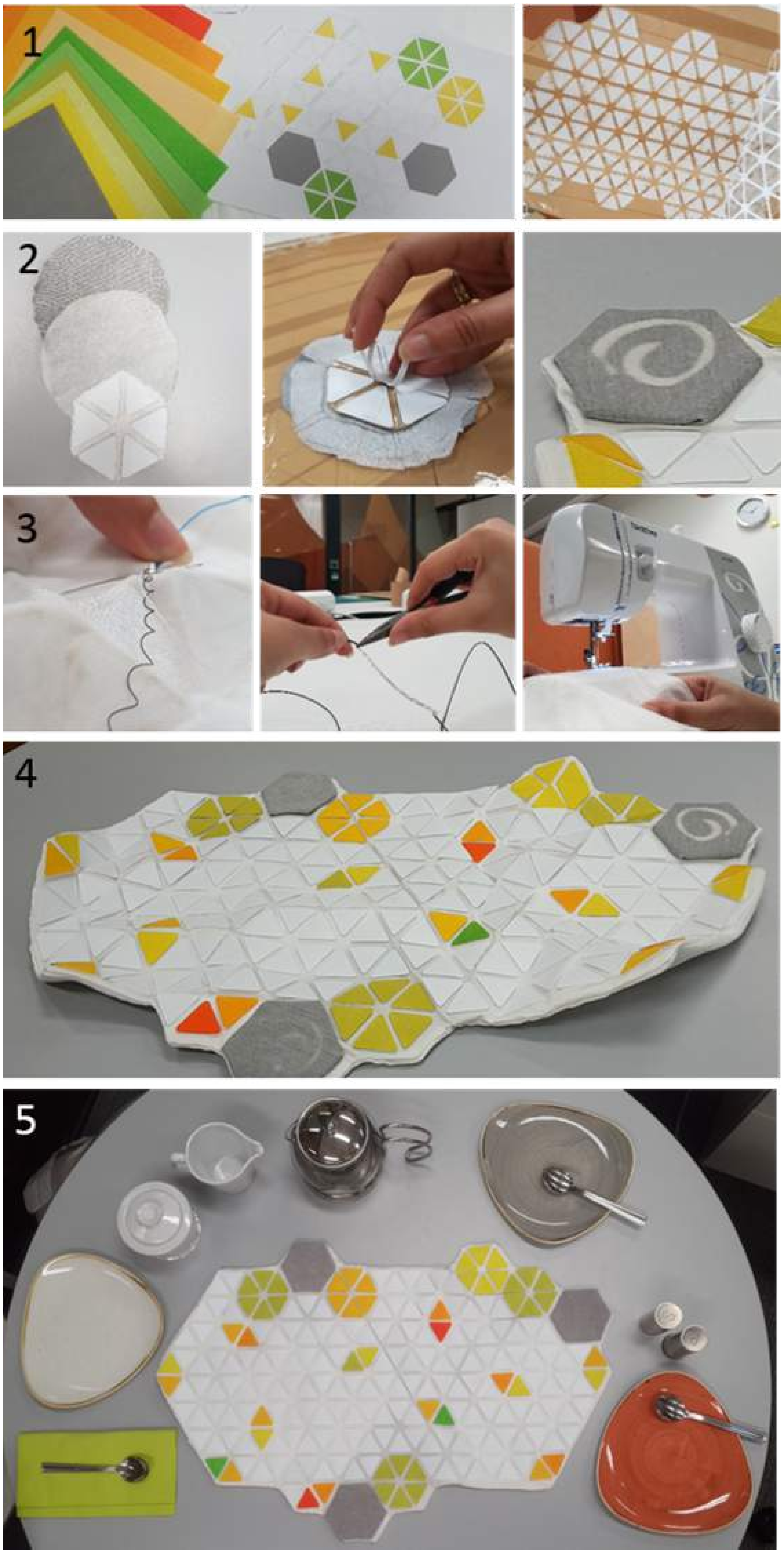


Figure 5.3 Designing and Making of ActuEater2. 1) Designing the Pattern. 2) Making the Colour-changing parts. 3) Stitching, Crimping and Sewing. 4) Creating the Actuations. 5) ActuEater2 is ready.

5.2 BacterioChromic

Moving forward from the horizontal surface to the vertical dimension, I then designed and crafted a piece of wall-art to utilize morphological fabrics and demonstrate the use of the techniques developed through Chapter 4. Herein, this section describes the design process and making of BacterioChromic, another inspirational artefact that is an interactive wall-art designed with morphological capabilities changing its patterns, colours and shape. With this piece, and to put them into practice, the crafting techniques I used include machine-sewing SMA wire, machine-embroidering thermochromic-dyed threads, fabric painting with thermochromic pigments and bobbin-training SMA wire.

5.2.1 Design Concept

Inspired by the patterns of bacterial growth in Petri dishes, I designed the BacterioChromic wall-art piece as part of the 'Living with Adaptive Architecture (LWAA) Exhibition 2018'. The concept behind BacterioChromic is to be a fabric tapestry that changes its patterns to raise awareness of antimicrobial resistance of microscopic members of our ecology, thus revealing the unseen. Using the previously-mentioned crafting techniques, I made this piece to envision future interior spaces that can be artfully dynamic and adaptive by highlighting changes in a realm outside our senses. This artefact speculates how future interior spaces can be dynamic and adaptive, not necessarily for structural/ functional purposes, but for revealing the hidden and visualizing the unseen.

5.2.2 Crafting & Making

I embedded shape-change in loose strands of thin colourful fabric resembling a type of resistive bacteria, by machine-sewing Shape-Memory Alloy (SMA) wire to the fabric. Learning from all my experiments (see Section 4.3), I utilized the parameter values that were recorded to achieve the best results in terms of deformation intensity. That is, thin light-weight fabric was used to help reduce any additional weight hindering the pulling-force of the SMA wire. Then tight zigzag stitches were used for machine-sewing the SMA to the fabric using thermochromic-dyed thread that changed colour simultaneously as the SMA actuated and heated to change-shape (Technique 10). Through manipulated martensite (Technique 7) and austenite (Technique 8) forms, machine-braiding the SMA wire directly on top of the fabric, achieved organic actuations that are seamlessly stitched into the fabric. The U-shape sewing pattern was used to realize the desired form and deformation of the bacteria-like fabric strand. Colour-changing embroidery patterns were realized with the digital embroidery machine using digital design illustrated on its digitizer software, see figure 5.4.1,2,3.

I embedded colour-change through dyeing threads with thermochromic pigments, machine-sewing and machine-embroidering them to the fabric (Technique 2) in bacteria-driven patterns that react to user input. I used a digital embroidery machine to embed different morphochromic shapes on plain white cotton fabric, see figure 5.4.4. The *digitizer* software of the digital

Figure 5.4 Crafting BacterioChromic: 1) Learning illustrations of stitches, 2) Experimenting digital embroidery, 3) Designing embroidery on Thermochromic Fabric, 4) Designing Colour-changing fabric and threads, and 5) Machine-sewing shape-changing fabrics.

embroidery machine allowed illustrating the designs then automating the embroidery onto the fabric. As an alternative effect, I also used thermochromic fabric with the digital embroidery machine to achieve colour-changing digitally-designed microbial patterns on the fabric itself rather than on the embroidered patterns. To compensate for any skipped stitches by the machine due to any errors in its program, I hand-stitched them with the same thread to fill these minor gaps and obtain a neat finish.

To achieve two-way shape change, SMA wire that is pre-trained as *straight* was machine-sewn to one side of the fabric, while another SMA wire piece that is bobbin-trained (Technique 9) as a *spring* was machine sewn to the other side of the fabric. The choice of the wire was also carefully made, as thin 0.006" SMA was used for bobbin-trained retracting spring side, a thicker 0.010" SMA was used in its default straight austenite, to have a stronger pulling-force (891 grams) enough to unfold the strand again from the other side. As a result, when each side is controlled in sequence -in response to user touch input- the fabric strand appears to be living, blossoming and unfolding and then rolling itself back, crumpling in organic imprecise patterns and forms, see figure 5.4.5.

Sensing was achieved using conductive fabric sewn and layered underneath the top fabric layer, utilizing capacitive-sensing in close proximity, achieving seamless interaction, with no visible electronic components at all. Crumble microcontrollers (Redfern Electronics, 2018) were used to control each *Petri dish* individually due to their thin small size and high current outputs which were reprogrammed to control the thermal-responsive actuation of shape-changing and colour-changing materials in response to capacitive-sensing. High-current MOSFETs were used to allow enough power to be drawn from the back-mounted batteries to the SMA and heating wire. With most of the circuit being threads on top of the fabric wall-art, the rest (the microcontroller, transistors and battery) was just less than 9 mm thick, and was therefore *stitched* to the back of each hoop and hung on the wall with absolutely no external cables or power source needed. This enabled BacterioChromic to be perceived as a normal crafted wall-art, not a digitally interactive device.

5.3 TacTile Tiles

To explore other materials (than fabric), I wanted to experiment with ceramic tiles, as a common contemporary interior finishing material in walls and floors, mainly used in spaces such as kitchens, toilets and bathrooms. As an interesting material to work with, ceramic has unique aesthetic and textural qualities that intrigues me as a *designer*, urging me to hack as a *maker* and motivates me as a *researcher*.

5.3.1 Design Concept

TacTiles are heat-responsive tiles that change colour with ambient heat from smokey monochromic dark blue to Ottoman floral and arabesque patterns. TacTile are also *tactile* in that they can also respond to touch-sensitivity. The square-shaped tiles act as large buttons that one can activate one after another to turn on and off different patterns. Thus, people can play with the endless combinations of plain and patterned tiles on their walls. The unique texture of ceramic and its aesthetic appeal should also play an important role in the experiential effect of TacTiles. Figure 5.5 shows my design concept of TacTiles as part of my design catalogue.

Figure 5.5 TacTiles: Decoraction Catalogue page 9.

5.3.2 Crafting and Making

I wanted to create thermochromic ceramic tiles, but due to the unavailability of the equipment needed (such as a furnace) to work with actual ceramic, I created a mock-up using acrylic plastic. The idea is to use thermochromic paints for the colour-changing actuation and Nichrome wire as a heating material. As acrylic is laser-cut friendly, I designed an engraved path on the back of my 10x10 cm acrylic tiles to give space and depth for the Nichrome wire. This design allows each separate tile to be individually controlled as desired, and allows the flexibility of having other static tiles in the same design (if needed) reducing cost and effort. Figure 5.6 shows the design and crafting of my TacTiles in different steps: 1) digital design, 2) pattern design, 3) laser-cutting, 4) weaving Nichrome wire, and 5) programming.

Figure 5.6 Designing and crafting TacTiles: 1) digital design, 2) pattern design, 3) laser-cutting, 4) weaving Nichrome wire, and 5) programming.

Then, I added a blue and white Ottoman tile pattern for a traditional aesthetic look. I painted the tiles' pattern with a layer of black and blue thermochromic paint. Finally, I connected the Nichrome wire to the Arduino microcontroller and programmed its software to respond to capacitive sensing by activating the Nichrome wire, that in turn causes the pattern change. However, this process takes a few minutes to heat and then to cool down again to be ready for another actuation. Still, the result was not only thermochromic-painted tiles that respond to ambient heat, but electronically-controlled pattern-changing tiles, as never realized before. Moreover, I demonstrate, using TacTile, how technology can be literally *woven* through decorative artefacts as means of interactivity, by weaving Nichrome wire through my TacTiles as means of interactive pattern-change.

I imagine TacTiles deployed in the splashback of a kitchen, interacting in three different modes: 1) responding to touch, allowing users to play with its pattern and add a new eye-catching focal point every while; 2) responding to ambient heat while cooking, revealing the unseen and (often) unfelt smoke and heat; and 3) autonomously actuating changing its patterns over time for a dynamic environment.

5.4 Furry Throw

Moving from flat surfaces to 3D objects, I wanted to make fluffy and furry fabric object that is soft, malleable and can be thrown on any piece of furniture taking its shape. Thus, I created the Furry Throw with interactive capabilities as described below.

5.4.1 Design Concept

The Furry Throw is a throw blanket that has a unique furry texture which (in addition to being a normal throw) has 'living qualities'. The Furry Throw has the capability of moving, swirling and swaying calmly in wavy motions as if it is alive, see figure 5.7. As a throw blanket, it adds a cosy and luxurious taste to a living room on a sofa or an upholstered chair. Moreover, it is equipped with seamless touch and stroke-sensing that causes the actuation. The throw comes in pairs, where one is activated when the other is stroked, wirelessly through the internet via Wi-Fi. In this sense, friends or family members can send tactile pokes that would 'display' in the homes of their apart loved ones.

Figure 5.7 TIKALIQ: the furry throw in my Decoraction Catalogue.

5.4.2 Crafting and Making

Since the wireless communication between two interfaces is already electronically feasible, my focus was on the seamless tactile sensing and the calm and soft actuation. As a proof of concept, I made one Furry Throw as both a sensing and shape-changing soft throw that is 125×32cm and made of furry off-white fabric. It actuates using SMA thin wire sewn to the inner layer of the fabric that contracts causing its furry texture to swirl and sway calmly. I used Flexinol 0.006" SMA wire and retrained it myself, then stitched it to the fabric in star shapes to achieve the desired organic actuation that also relaxes easily back again. Stronger SMA wire or pre-trained types would have: 1) required high current in the circuit, 2) caused stiffness to the soft fabric or 3) contracted entirely without relaxing. Figure 5.8 shows the SMA wire stitched inside the throw in organic (star) shapes. SMA was then crimped to machine-sewn conductive thread that is connected to my MuscleMuffin Arduino and powered with an 11.1V LiPo battery drawing 0.4A. SMA gives the throw's actuation a silent, organic, subtle and slow behaviour. The malleability of the SMA does not affect the softness, affordance and texture of the throw, so it can be folded or thrown as a normal throw. The soft furry texture of the fabric created the feeling that I wanted to convey from my concept; that technology need not be in solid boxes, but could be in softness and cosiness. I also chose the off-white fabric purposely to blend and coordinate with most styles and colour schemes, as a coloured throw would add a vibrant pop to a room, and I want it to be completely ubiquitous in the background and not stand out, especially as a piece of technology. It also gives it a semi-transparent look that one does not expect that it conceals *more* inside.

The whole throw is then neatly finished with machine-sewing and I also sew a 22 inch invisible zipper to the side for easy access troubleshooting. Stroke-sensing is detected through capacitive touch using conductive fabric that is machine sewn to its inner layer. This physical interaction can be perceived more emotional and sincere through a soft interior decorative artefact more than either 'mechanistic' devices or touch-screens GUI apps, proving the OUI interiors concept to be more amenable.

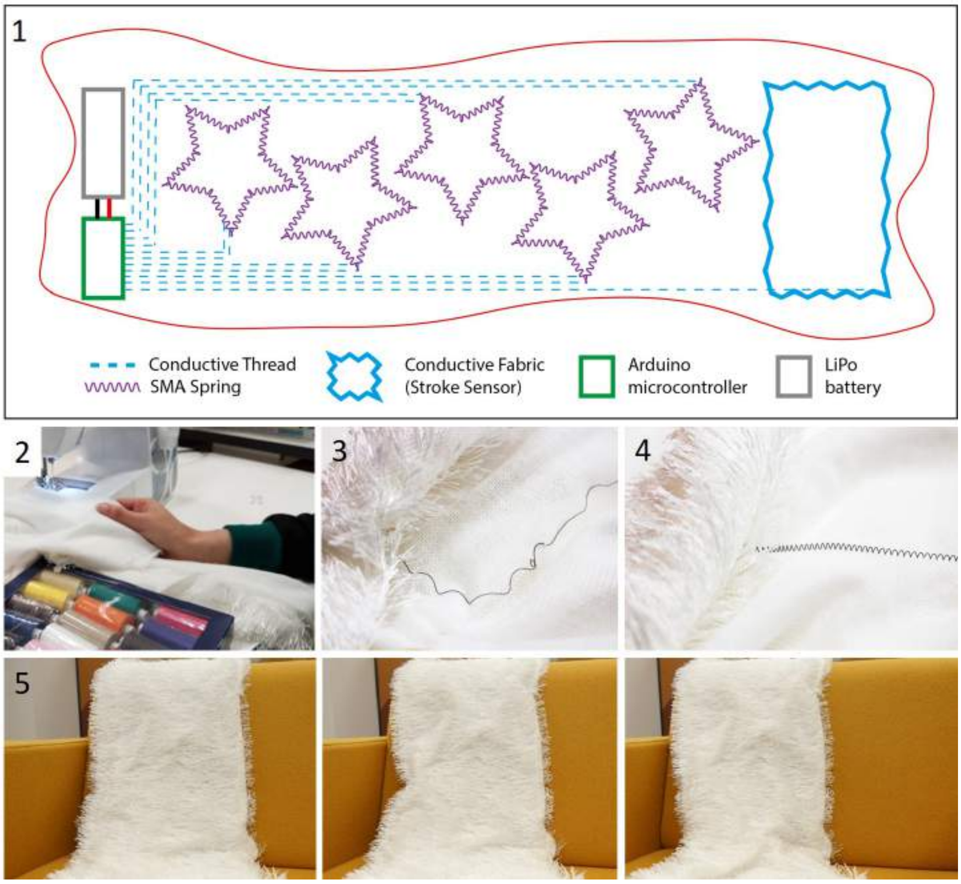


Figure 5.8 Furry Throw's making: 1) Designing the soft circuit; 2) Machine-sewing the fabric and the SMA; 3) inner body with SMA in relaxed; 4) SMA contracted; and 5) Programming and testing sensing and actuation. The Furry Throw actuating slowly, silently and subtly.

5.5 Morvaz Vase

Morvaz is another common decorative 3D object, a vase that changes shape in response to user manipulations and interactions. I wanted to design a shape-changing vase from a very early stage, but was always stranded with the practicality of this idea. Most materials that are used to make decorative vases (such as glass, porcelain and acrylic) are too hard to allow dynamic shape-change. Moreover, how can water be poured into a container that houses electronic components?

5.5.1 Design Concept

MORVAZ is a morphing vase that changes its shape in response to interaction with it via touch, proximity or placing flowers. MORVAZ is different than traditional vases that are static in shape and behaviour, in that one can perceive it as if it feels what is happening around/to it and bends itself in an origami-like structure reflecting context-awareness and autonomy. Figure 5.9 shows the Morvaz in context and visualizes its morphing behaviour.

Figure 5.9 Morvaz morphing vase changing its shape in response to hand manipulation and interaction.

5.5.2 Crafting and Making

To overcome the challenges of making a shape-changing vase, I resorted to a layering solution. The idea was to have a glass container for the water and flowers, and another external façade that is malleable. While visiting the Arts Rijksmuseum in Amsterdam, I found an interesting laminated cardboard material with an origami design -in the gift shop- that I can use as the external vase to give it both an aesthetic design and flexible structure that can be manipulated. Then, I started thinking how can I attach SMA springs inside to control the actuation electronically. My solution was to fit anchors to the inner body and attach each SMA spring between two anchors. In this sense, the shape of the vase can be altered from different sides at various angles, depending on the shape it was in last (martensite) and on the overall bent origami form. I designed and laser-cut the anchors from two pieces of clear acrylic sheets, then glued them to the inner body of the Morvaz after attaching metal rings to each for strong grip of the SMA springs. Figure 5.10 shows an internal view of the Morvaz showing the SMA springs attached to the fitted anchors and rings.

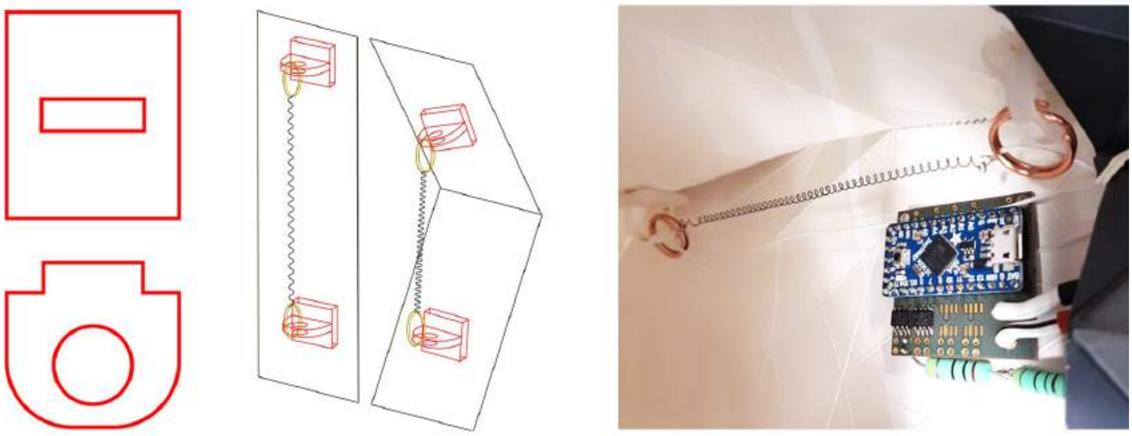


Figure 5.10 Morvaz's inner body with SMA springs attached to fitted anchors and rings.

Although I have resorted to a relatively-flexible material to make MORVAZ, I tried different SMA types that were not strong enough to deform it. Finally, I used the 1-inch smart springs by Kelloggs Research Labs that gave the best results due to their stiffness. The SMA springs are connected to my MuscleMuffin Arduino microcontroller that also has the proximity sensor connected to detect user interaction when (re)placing flowers or approaching its top opening. Morvaz also enables hand manipulations to its flexible origami structure allowing people to actively change its physical shape as desired.

5.6 WaterFall

As an example of two decorative artefacts that are matching and can potentially communicate together and respond to one another, I designed the WaterFall and the WaterDrop. WaterFall wall-art is a colour-changing painting that features 'water' and WaterDrop cushion is the matching pair of the WaterFall painting and a soft version of it.

5.6.1 Design Concept

The idea behind this dynamic wall-art is that it changes the amount of visible water in the painting in response to the water consumption rate in the household. By accessing smart-meter online readings or uploading the meter reading into a mobile-app, people can realize how much water is being consumed over time, not through numerical figures or even graph charts, but through multifaceted aesthetics that is part of their interior decoration. This multifaceted painting relies on an impressionistic approach that is better suited to interior aesthetic experiences. With this design, I hope that people may appreciate running water and become more self-conscious of their usage once they find the cushion birds with no water left in their world. Figure 5.11 shows both the WaterFall wall painting and the WaterDrop cushion in a situated context in my design catalogue.

Figure 5.11 WaterFall painting and WaterDrop cushion colour-changing matching pair.

5.6.2 Crafting and Making

I painted the WaterFall using blue and black thermochromic paint on a conventional acrylic painting canvas. Similarly, in a plain white cotton fabric, I also painted the WaterDrop cushion to literally feature a single drop of water in various shades of blues (that also resembles our planet earth), plus some flying birds far away. Then, I machine-sewed the cushion, hiding the 5V heating pad that controls the colour-change, after stuffing it with a fibre 'pillow insert' for comfort. Theoretically, once the WaterFall activates, with the increase of water consumption, it sends a wireless signal to its sister cushion to activate as well, causing the (thermochromically-painted) water to begin slowly disappearing, see details in figure 5.12. Whilst they are matching, the idea is that the cushion will still work simultaneously with the WaterFall painting even in another room through Wi-Fi signal. Occupants can 'see' the change wherever they want in their home, and thus realize how every drop matters. I have not implemented the connection to meter readings, which can be programmed in several ways, but have proved the concept by focusing on the colour-changing actuation of the decorative artefacts.

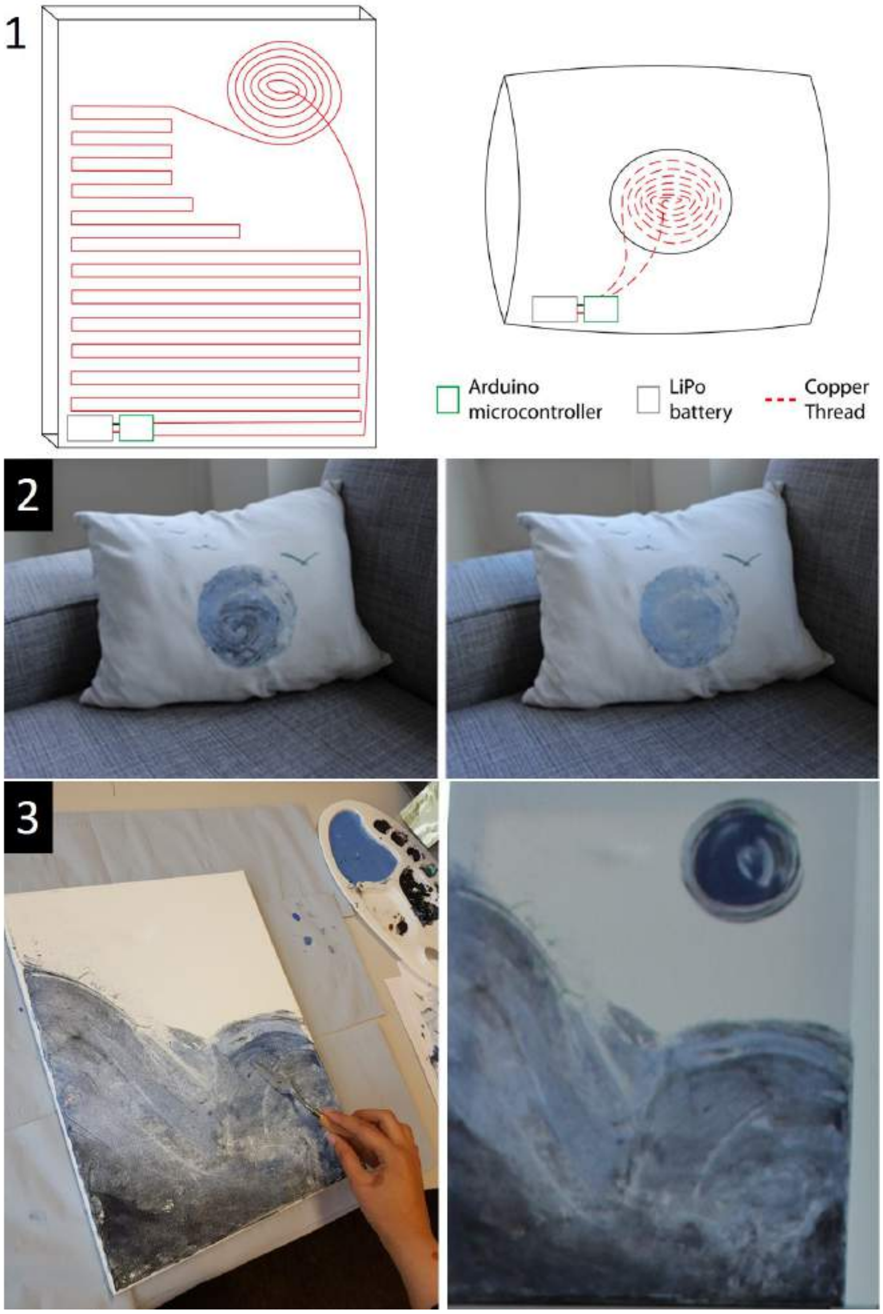


Figure 5.12 1) Designing the WaterFall and WaterDrop; 2) Crafting the WaterFall painting; and 3) The WaterDrop Cushion off (left) and on (right).

5.7 LITHER Rug

Another challenging idea is to make an interactive rug, with difficulties including: 1) a rug is a too heavy object to be actuated using SMA; 2) wires should be entirely eliminated; and 3) tripping or stepping on electronics can cause a hazard. Due to all of these obstacles, I was even more motivated to win this battle, but it was not an easy task to design LITHER, the shape-changing rug.

5.7.1 Design Concept

The LITHER rug is a shape-changing rug that responds to 'ambient sounds', specifically high pitches of loud voices or noises. Every time LITHER rug detects such a loud voice, it deforms as a whole (using SMA sewn underneath) then relaxes leaving behind small parts that are kept deformed, see figure 5.13. To un-deform the rug, one would have to physically manipulate it or control their noisy behaviour. LITHER also employs 'Slow Interaction' where over-time it deforms rather more and does not return entirely back to its default state if surrounding noises persist (e.g. a screaming parent, quarrelling couples, noisy children). Therefore, LITHER expresses aesthetic interaction, encourages self-awareness and imposes self-reflection on one's behaviour and attitude, not just instantaneously but over time as well.

Figure 5.13 LITHER: the moving rug from my design catalogue.

5.7.2 Crafting and Making

I brought a custom hand-made circular rug (⌀110) made from different intersecting natural leather materials from the Middle-East, to realize my design concept of the shape-shifting LITHER. I tried different approaches and techniques to make LITHER interactive according to my rationale presented above. However, all of my trials have completely failed. I tried a range of SMA wire types with different diameters and thus pull-forces, but they none of them was able to lift the heavy leather off the ground. I also tried retraining the SMA wire in several (austenite) shapes, and in different diameters of spiral forms to get the leather to morph, but it did not. Moreover, I changed the sewing machine's stitch type and changed the sewing pattern to which the SMA is fitted to the back of the rug. Figure 5.14 shows these different sewing patterns, of which none was able to cause visible deformation due to the material weight, stiffness and horizontal orientation towards the ground. Eventually, I resorted to a faux leather light material that does not overload the SMA with such weight and resistance to move. Once I machine-sew the SMA to the light material, it actuated as desired changing its shape, but the aesthetics and qualities of the leather LITHER rug were missed.

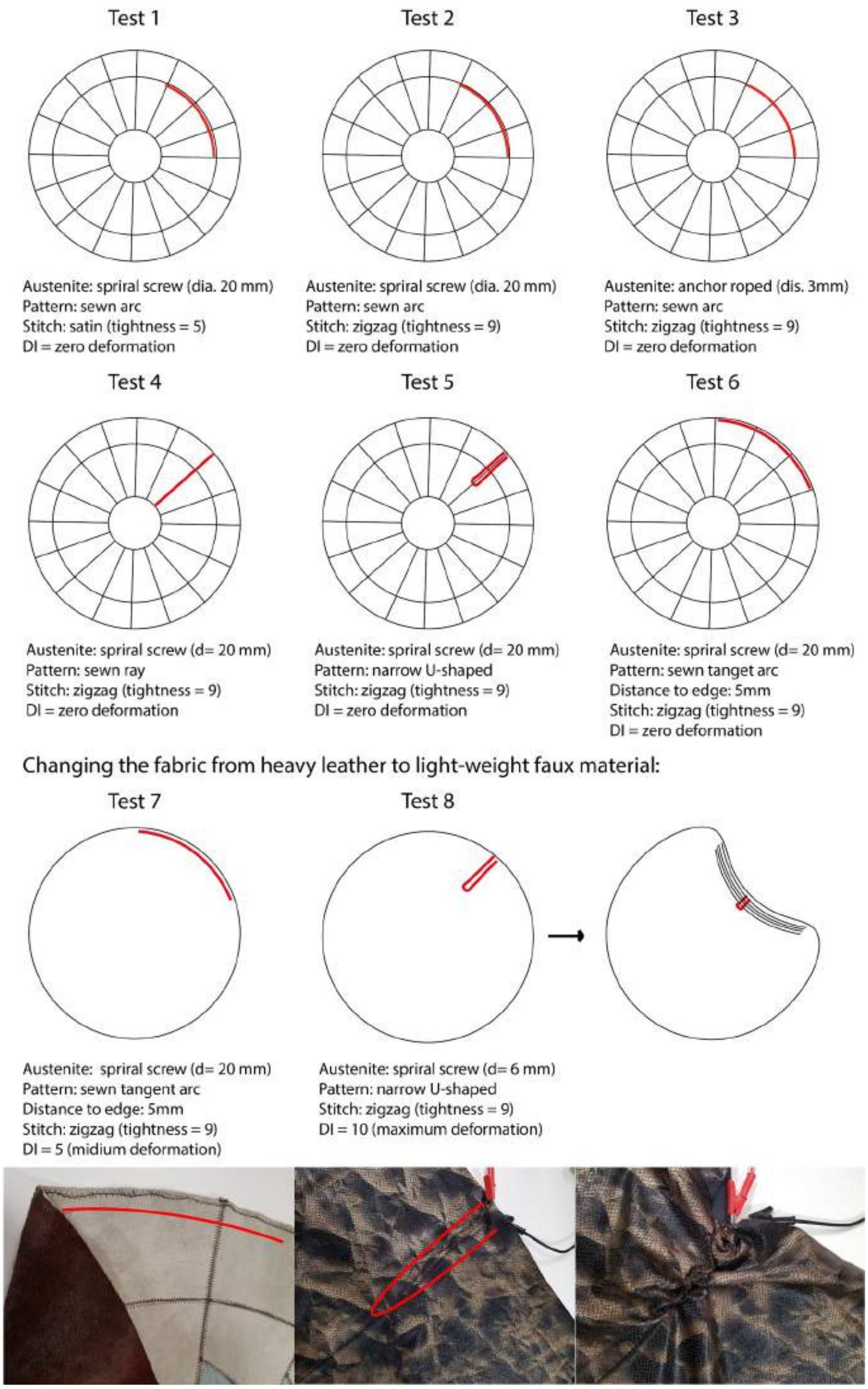


Figure 5.14 Different trials for making an SMA actuating rug.

5.8 AMR Bugs

To work with a different interesting material, I found knitting to be unlike other previous inspirational artefacts and I was intrigued to weave technology through its unique texture, again literally. As part of the Persuasive Pharmacy Space project for the Day Lewis Pharmacy, and through collaboration with Napper Architects design office, I created interactive knitted decorative artefacts: "Thermo Bugs" and "Talking Bugs". Then, these soft artefacts were embedded with soft touch-sensing in different part of their bodies and responded by both colour-change and voice output, respectively.

This allows visitors to the new Day Lewis Pharmacy installation to engage with the interactive artefacts that provided information about tackling common infections and ways to avoid unnecessary overusage of antibiotics in an aesthetic and user-friendly cartoon story format. The project is the work of a team in Reading University and pharmacists at Day Lewis, to consider how pharmacies can be used to inform the public about major health issues. My contribution brings the expertise of Interioraction Design with these artefacts as seamless interactive decorative elements in the space, introducing how future interior spaces can be dynamic and interactive, not necessarily for structural/ functional purposes, but for informative and engaging purposes, revealing the hidden and visualizing the unseen. Finally, by interactive artefacts were exhibited at both the “London Design Festival 2018" and the ‘Persuasive Pharmacy Space’ Installation in Reading, UK.

5.8.1 Design Concept

The concept behind this crafted artwork was to simulate the interaction with bacteria in the surrounding space, to help stimulate awareness and discussion around Anti-Microbial Resistance (AMR). My bacteria-resembling design attempts to draw our attention to the microbial world, which develop antimicrobial resistance to survive despite our ever-evolving antibiotic treatments. Designing tactile and *living* artefacts that respond to such environmental stimuli is key to raising people’s awareness in both public and private spaces, particularly in an aesthetic form as decorative artefacts i.e. part of the interior space, rather than charts and graphs.

Figure 5.15 Talking bugs: my interactive decorative artefacts resembling bacteria.

5.8.2 Crafting and Making

I made two sets of soft artefacts resembling bacteria: talking bugs and thermo bugs, two each, four in total. For the talking bugs, I used conductive threads and fabrics to make them respond to touch, stroke and squeeze input interactions by 'talking' about harmful and useful bacteria. The audio feedback is totally concealed and embedded inside the knitted bacteria through a BareConductive Touch Board microcontroller, a micro-speaker and a 3.7V LiPo battery. Thus, no cables or external power sources are required, see figure 5.15. This allows people to perceive the interactive artefacts as normal everyday soft objects and not as 'technology' or interactive devices. By applying the techniques I developed in Section 4.3.2, I also made the thermo bugs. With the help of my colleague architect and textile designer Nikoletta Karastathi, my soft 'bacteria' were knitted with white and yellow yarn both dyed with blue thermochromic pigment. Then I stitched conductive thread through the front face of each and connected it to my MuscleMuffin Arduino microcontroller powered by an 11.1V LiPo battery, of which was controlled through my machine-sewn conductive fabric lining inside as the touch-sensitive switch input. Once touched, the woven conductive thread starts heating, causing the knitted yarn to gradually change colour from blue to its original colour (i.e. yellow or white) for the set time in the program (40 seconds), then gradually cools again causing the soft yarn to gradually change-colour again and turn back to blue, see figure 5.16.

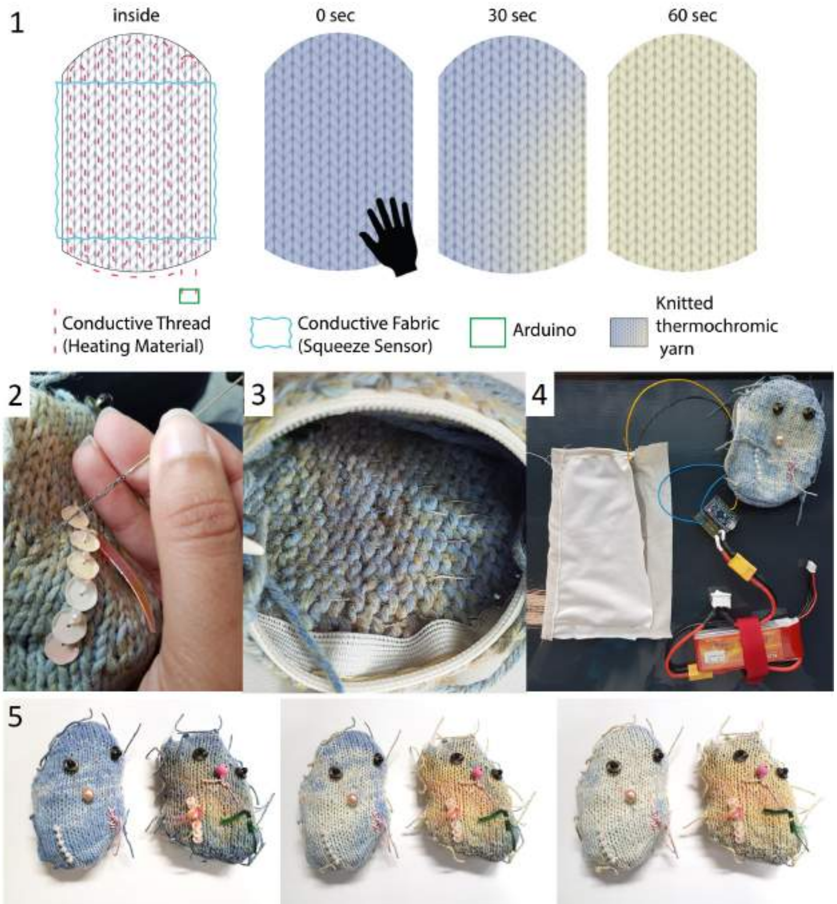


Figure 5.16 Thermo bugs: my colour-changing soft artefacts responding to squeeze.

5.9 STARA Curtain

STARA is a shape-changing curtain that responds to touch and tactile manipulation to its soft tasselled fringe. In essence, tassels are crafted into sensors in this artefact.

5.9.1 Design Concept

STARA is a crystal beaded voile curtain swag that is made of ‘sensing’ tassels fringe and actuating light voile fabric that creases itself when the fringe is ‘touched’. STARA has an Arabic style, and an advanced seamless interaction, with no perceived electronic components or wires. With its tassels being sensors and its voile being the actuator, STARA demonstrates how technology can be seamlessly embedded in interior elements, even in the most soft, delicate and traditionally-aesthetic materials, see figure 5.17.

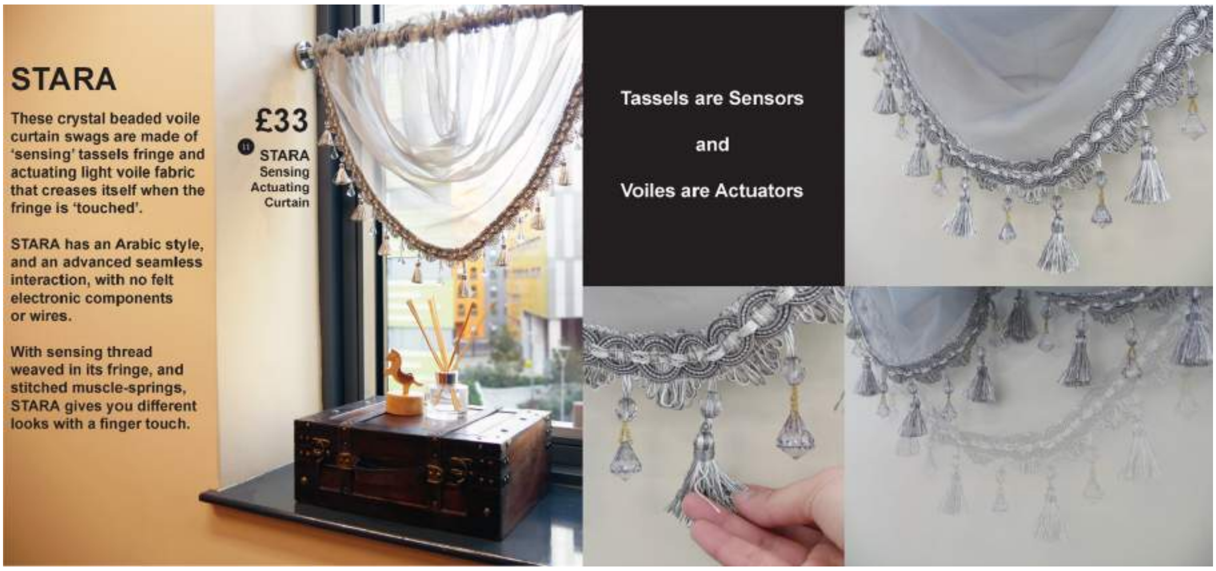


Figure 5.17 STARA shape-changing curtain in my design catalogue.

5.9.2 Crafting and Making

I designed STARA so that the fringe and tassels are the sensors. To achieve this I used conductive thread to machine-sew the tasselled fringe to the curtain voile, after pinning them together. The conductive thread in this case served as both the sewing thread that attaches the fringe to the curtain and as the embedded sensing material at the same time. As I machine-sew the conductive thread (filled in the bobbin case), I purposely pulled out extra thread from the bobbin at each tassel. Then, after sewing, I used that extra thread pulled earlier to embed it inside the tassels using a sewing needle. Then used the needle to embed the end of the conductive thread to the Arduino sensor pins. For STARA, I used my MuscleMuffin microcontrollers to program the SMA springs that pulls the voile upwards based on touch and stroke-sensitivity of the tassels and fringe. As STARA hangs vertically, it relies on gravity to bring the SMA along with the voile back down. This crafting and making process is best described with photos and illustrations in figure 5.18.

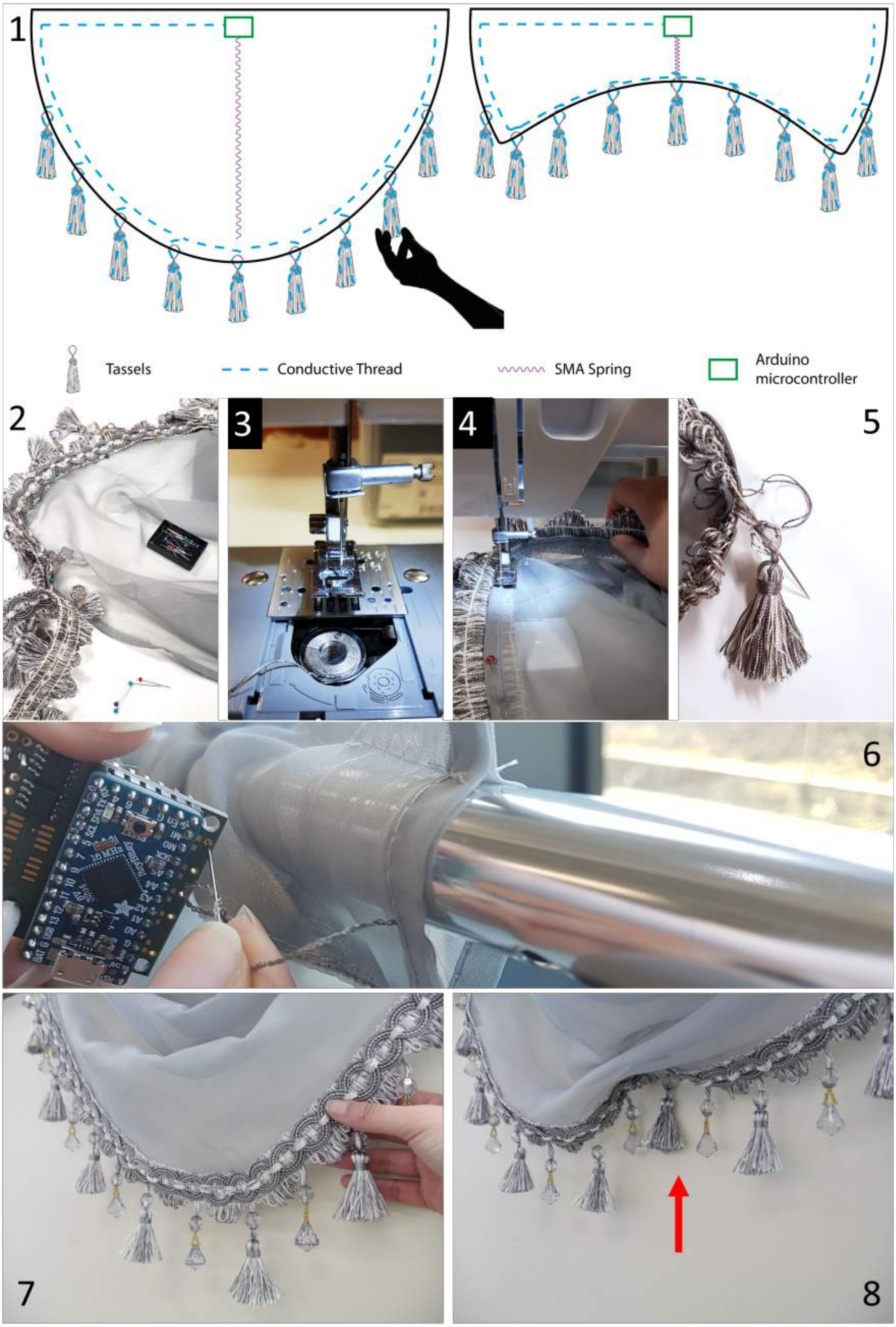


Figure 5.18 Crafting and making STARA: 1)Designing STARA; 2) Pinning the tasselled fringe to the voile fabric; 3) filling bobbin case with conductive thread; 4) Machine-sewing fringe to fabric using conductive thread; 5) Weaving conductive thread through the tassels (i.e. sensors); 6) Sewing conductive thread through MuscleMuffin input pins; 7) Programming tactile-sensing; and 8) Testing SMA actuation.

5.10 Summary

Following my exploratory research, this chapter leverages my series of design explorations from ‘swatches of materials’ to ‘decorative objects’. While learning how to use OUI materials (presented in the previous chapter), I was also crafting and making OUI decoratives (presented herein), to exemplify how contemporary interior elements can be embedded with interactivity, animation and morphological capabilities. My ideas and designs of OUI objects in such an interior setting were realized in the form of a design catalogue (see Appendix B). This chapter presented my catalogue including a number of inspirational artefacts which each uses OUI materiality and interactivity i.e. either seamless soft-sensing, shape-change or colour-change.

In this chapter, I also explained the crafting and making process of my inspirational artefacts, that are both interactive and decorative, designed throughout my research.

1. ActuEaters: two actuating table-runners and interactive tableware for social dining events.
2. BacterioChromic: an interactive wall-art for antimicrobial resistance awareness.
3. TacTile: heat-responsive and pattern-changing Ottoman wall tiles.
4. Furry Throw: an actuating soft throw for exchanging tactile emotional messages.
5. Morvaz: a morphing vase that interacts with hand proximity when (re)placing flowers.
6. WaterFall and WaterDrop: impressionistic pair of colour-changing cushion and wall painting for household water-consumption awareness.
7. LITHER Rug: shape-changing leather rug responding to noise in the interior space.
8. AMR Bugs: interactive knitted decoratives for pharmacy AMR awareness.
9. STARA: shape changing curtain with its tasselled fringe being its soft sensor.

My design catalogue including these inspirational artefacts together addresses my second question “What OUI decorative artefacts can we create?" (Research Question 2). While utilizing the materials and making techniques that I’ve learnt from experimentation with OUI materials (Chapter 4), I was critically examining the potential use of seamless soft-sensing, shape-change and colour-change in the design of interactive decorative elements (in this chapter) on a scalable level. Not only does this work provide grounds supporting my iterative Research-through-Design to situated deployments of OUI Interiors (Chapter 6), it also supports others who might wish to design and develop actuating decorative artefacts for different contexts, cultures and interior styles.

Through ideation of the design concepts, to the crafting, making and implementation phases, each developed prototype produced valuable and contributive insights. Exploring the design space of interiors in different planes (horizontal, vertical, diagonal and 2-dimensional) allowed me to think of solutions and alternative approaches to different challenges. Some of these objects would be eaten on, sat on or walked on, while others are too soft and others must afford certain functionalities (like holding water). Such properties enriched the concurrent learning of crafting and making techniques of OUI materials (presented earlier in Chapter 4).

Moving from the lab to the field and showroom (Koskinen et al., 2011) (a methodology detailed earlier in Section 3.3), I have also carried out a number of situated studies in the wild to capture how people would perceive, interact and respond to such design interventions. In the next chapter, I introduce and discuss these concurrent studies of situated deployments of some of my OUI designs (including, but not limited to, ActuEaters (Nabil et al., 2018a) and BacterioChromic) in relevant settings (both in the real-world and in the design practice). Qualitative data (field observations, photographs, video/audio recording, design crits and interviews) are collected and analysed to gain insights helping my research forward. The intention isn't studying the user experience in itself, but to address my third and final question "What can we learn *for design*?" (Research question 3). In this sense, I run a number of case studies of deploying OUI decorative elements and OUI interior spaces to explore the experience, materiality and aesthetic qualities of such technologies in-situ and gain a deeper knowledge into designing interactive decorative objects and spaces.

Chapter 6. Situating OUI Interiors

In parallel to the experimentation with OUI materials (Chapter 4), and prototyping of OUI decorative artefacts (Chapter 5), a number of situated studies for OUI interiors (discussed in this chapter) were carried out concurrently. Utilizing the research-through-design experience gained from crafting and developing making techniques in addition to knowledge and insights gained from inspirational artefacts discussed earlier, I advanced my practice and design exploration towards interactive interior spaces. This chapter presents and discusses OUI in-situ deployments through five case studies, presented in two main parts. The first part discusses three situated studies in real-world deployments: 1) *'ActuEating'*, 2) *Adaptive Architecture*, and 3) *'Immersive Hive'*. The second part discusses two situated studies in design practices: 4) *'Enchanted Architecture'* and 5) *'Interactive Theatre'*. To bridge the gaps identified earlier (in Chapter 2) between HCI researchers and design practitioners, the latter two situated studies have been in collaboration with design practitioners and students from architecture and interior design disciplines respectively.

The first part of this chapter focuses on deploying my OUI designs in real-world settings to evaluate how potential users, viewers and audience may experience them. The second part is situated in practice, looking on how designers may use OUI materials themselves to improve their own design practice, engaging them in interaction design. Working with designers in this sense can be through a number of ways. First, I can design for designers, respond to their brief or demo an OUI to them, so that they can realize the potentials. Then, I can give them the materials and techniques to design OUIs themselves and examine the ideas generated, the design uptakes and the built interactive space.

In this process of engaging other disciplines, I had to create some design tools (e.g. a tactile palette, a design concept jigsaw, and an interactive beehive demo) to reach a common ground with each of them and bridge between 'what could be' and 'what is', given the tangible tools and/or metaphors of different practices. Using OUI materials (seamless sensing, colour-changing and shape-changing materials), interactivity was embedded into different interior elements of the interior space (e.g. wallpaper, wall panels, furniture, tableware and decorative elements). By designing and building these interactive interior spaces, new insights were gained towards the capabilities and limitations of such materials.

By opening my OUI Interiors to the public, new insights were gained towards the aesthetic experiences and people's reactions and perceptions of the materiality and interactivity of such spaces. This chapter elaborates the design concept, building and situating of each case study. Each situated study then allowed me to observe and interview people engaging with my OUI

Interior designs. The analysis of these observations and interviews addresses **Research Question 3**: “What can we learn *for design* by situating OUI interiors?". Moreover, the collective analysis of all five in-situ studies also supports reflecting back on all of them as an overall design space (presented next in Chapter 7).

Part I

Situated Studies in the Real-world

6.1 ActuEating

The first situated study took the OUI decorative table-runners and tableware that I have designed (ActuEaters, see Section 5.1) into the wild. Extending on previous work of situating interactive shape-changing furniture in both public (Gronvall et al., 2014) and private (Gaver et al., 2006) spaces, I wanted to study the *ActuEating* experience (i.e. eating around actuating decoratives) in both settings. In this sense, both ActuEater1 and ActuEater2 were interactive shape-changing decorative artefacts than can be embedded within complex social settings. Extending typical duration of user interaction to over an hour (instead of an average of 2 minutes in the case of coMotion (Gronvall et al., 2014)) allows people the time to observe, practise, learn and develop a variety of interactions. Also, enabling physical change in the fabric form of the soft object instead of illuminating patterns in a table-top in the case of the History Tablecloth (Gaver et al., 2006) extends on previous relevant work. Moreover, a richer interaction repertoire can be designed using a wider range of seamless sensing, colour-change and shape-change actuations (than controlling one parameter/dimension in previous work).

6.1.1 Studying ActuEater1

Since my goal was to observe people's experience around a dynamic decorative piece as an integral part of their interior space, not as a separate or independent one, I wanted to investigate in-the-wild how people perceive and interact with such technology embedded within an everyday artefact that is conventionally just static, non-functional and otherwise blends into the background of the perceived space. This would allow unpacking the potential of such interactive decoratives when developing interactive interior spaces in different contexts. In addition, it would allow investigating what interesting interactions users might understand, develop and adopt.

Location: The initial study took place in a carefully chosen restaurant that was about a 20x10 m open dining space in a roof terrace floor occupying the edge of a modern building with all glass windows on both sides allowing full natural lighting and spectacular views of green fields to the horizon from its lofty location. The restaurant also had a neutral colour-scheme design that ActuEater1 matched and fitted nicely within. The tableware in that restaurant consisted of plain white square-shaped plates that inspired the square-patterned design of the table runner ActuEater1. In addition, I added a wooden finish to the dining table of ActuEater1 instead of the cold metal frame to match the aesthetics and style of the restaurant. Deploying ActuEater1 in such a space setting enabled investigating a close-to-realistic experience and explore the consequences, potentials and limitations of 'hiding' technology within the furniture woodwork, blending it into the fabric of the interior space, and capture users' interactions as natural and comfortable as possible.

Participants: This initial evaluation study (A) took place in this restaurant with a group of 6 friends to each other (P1-P6), with mixed genders (2F / 4M), age-groups and backgrounds (Media, Design, Economics, Computing, Chemistry and Psychology) who signed up to participate in the study. In addition, there were 3 HCI researchers (including myself as the lead researcher) working as a team to facilitate and orchestrate the study. Participants were not briefed as to what to expect beyond their voluntary participation in a study over a dinner meal, as I intentionally wanted them to realize and interpret themselves what was happening.

Setting: I planned for a complex dining experience with a long set of details to fully test interactions with the table runner and cover a variety of cases as possible. For example, aside from the six main meals that were ordered for the participants, the table setup included: two side dishes, three water bottles and two salt shakers to be shared among the six participants as means of exploring the functional and experiential possibilities of ActuEater1 when for instance passing the side dishes, reaching for the salt, or grabbing the water bottles. Nothing was placed on the ActuEater itself in the initial table setting to allow for free actuations and to explore participants' possible alterations to that setting. Dinner menus were sent out to participants to select their personal preferences in terms of main courses, non-alcoholic drinks and side dishes prior to the study day. The formal dinner setting included background music, silverware cutlery and porcelain tableware plates. Before participants' arrival, a series of tests to different actuations were run and once the ActuEater was actuating reliability, dinner was served. Participants started enjoying their dinner with minimal social interaction on both sides of the table. I planned for 10 minutes to allow participants to start their dinner normally and comfortably as well as allow us to realize their un-intervened social behaviours together on a dining table (e.g. who are talking/ engaging together, who are isolated or silent) before ActuEating. After 10 minutes of beginning their meal as usual, the ActuEater started actuating, responding to social and physical interactions with different deformations, or autonomously to attain one's attention or reaction.

Interaction Repertoire: The eventual actuations performed by ActuEater1 were controlled live, in this situated study, where ActuEater1 was deployed. Table 6.1 below shows how I responded to emerging interactions and developed the following pattern of responses to users: when one participant was engaged with ActuEater1 or touched it, it vibrated (low actuation) the part in front of her/him by moving up and down in a small scale with limited height. When two participants were both engaged with it (talking about it with each other), it would vibrate in front of both of them. If two people touched it with their hands or used an object, it rose all up. Then if they tapped it, it went all down. If two or more people kept touching it, it animated in an organic wave motion going up and down from one end to the other. I was able to improvise actuations at some points to initiate interactions with one (or more) of the participants to explore the effects of this on their reactions to ActuEater1 and interactions with each other. For instance, a sequential low actuation can train from one end to the other if ActuEater1 'got bored of people ignoring it'. To allow for discoverability, I controlled the height of actuations to increase over time and usage, to see whether people will relate their interaction with the increase of deformation.

Method: The meal was audio-video recorded from two different angles to capture as many of the users' expressions, interactions and conversations as possible. The dinner lasted about an hour, then I joined participants for a post-study 'design crit', a group discussion, lasting 30 minutes where participants had the opportunity to express their reflections on their experience and provide me with critical feedback on my design and further design opportunities. This group discussion was of great significance to the reflections and findings later discussed in this

Input		Output		
Name	**Description**	**Actuation**	**height**	**size**
hello world	single user touch interaction	in front of them	medium	single
coupling	two users engaged (talking about/pointing at it)	in front of both	medium	two
togetherness	two users touching it with their hands or an object	rise all up	max	all
calming	users tap/pat it	goes all down	zero	all
petting	2+ users keep hands on it	animated wave motion across all of it	spectrum	all
boredom	no interaction for >5 minutes	sequential actuation	medium	single

Table 6.1 Mapping input and output interactions in ActuEater1's WoO Study.

section. Moreover, individual questionnaires were also filled out by participants collecting basic demographics and backgrounds of participants in regards of such social events as well as similar technologies.

Initial Findings

This initial study of ActuEater1 (Study A) suggested a number of user-desired potential developments to ActuEater1: 1) Control: not be remotely-controlled and be legible (they assumed it was randomly actuating because human control (WoO) was not always immediate and consistent to all 6 participants); 2) Interaction: be responsive to their physical interactions (e.g. touch and physical objects); 3) Hardware: not to have such a bulky structure, loud noise or create a hole in the table; 4) Aesthetics: blend with the surrounding space and be more colourful; 5) Capabilities: colour-change was suggested to complement and enrich the shape-change; 6) Experience: be entertaining/ dancing, autonomous (have agency of its own), and interact with the surrounding space (music, objects); and 7) Meaning/ value: reveal/support further values (believing ActuEater1 had a hidden agenda of some good intention and meaningful purpose). Therefore, I designed ActuEater2 to be a silent stand-alone fabric runner (with no motors required beneath the table) that is touch-sensitive and still has some agency designed to be more colourful with colour-changing capabilities (as well as shape-changing). Then further studies complement the understanding of how these changes affected the user experience and what meanings and values would people draw from their interaction. These further studies are detailed below and analysed altogether to give more insights on deeper findings i.e. social engagement, interaction repertoire, physical manipulations, and seamful/seamless sensing beyond interaction boundaries.

6.1.2 Studying ActuEater2

ActuEater2 was also studied in-situ, using methods and settings consistent with Study A (ActuEater1). I successfully ran 3 sessions with a total of 13 participants. In all three studies, participants were not briefed about the ActuEater, or that it was an interactive artefact to give them the chance of having their meal as usual and discovering the ActuEater themselves. Although I purposely recruited participants from diverse cultures, backgrounds and age groups, clear consistencies were observed in most people's behaviour around ActuEater2 across groups.

Location: I varied location for the meals to enhance the ecological validity of my exploration. For instance, the situated deployments included a home, a café, and a restaurant. In each case study, a complex experience with a long set of details was carefully planned and organized, to explore embedding technology in a real-world experience as much as possible. For instance, while the restaurant of Study A had a neutral colour-scheme design that ActuEater1 matched, the interior spaces where ActuEater2 was deployed included vibrant colours and other contemporary decorative elements that matched the interior style and decorative scheme. White square-shaped plates were chosen for the tableware around square-patterned ActuEater1 runner, while coloured triangular-shaped plates were chosen to complement triangular-patterned ActuEater2 runner in the same colour palette. Minor details were taken into consideration, from the fabric of the chairs and the shape of the plates to the colour of the napkins. For example, in study C the pattern on the floor tiles matched the colour-changing pattern of the ActuEater, and in study B the triangular shapes of the ActuEater2 were also engraved on the glass tabletop of the restaurant's dining table. These criteria helped ActuEaters to blend into the background of the environment and create a ubiquitous spatial experience. Why bother so much with such details? the answer is twofold: 1) because designing interior spaces is about designing every detail and choices of colours, patterns, form and material, and 2) to enable investigating in-the-wild experiences and explore the consequences, potentials and limitations of 'hiding' technology within the furniture woodwork, blending it into the fabric of the interior space, and capture users' interactions as natural and comfortable as possible.

Participants: I specifically aimed at recruiting participants who are friends of each other for every study and are unlikely to be familiar with such OUI technologies. The first (Study B) took place in a Lebanese restaurant over an evening meal among a group of four Middle-Eastern friends (1F, 3M) studying fields of in Psychiatry, Health-care, Business and Biotechnology (P7-P10). The second (Study C) took place in a university café over lunch among a South-East Asian group of five female friends studying fields of Business, Computing, Architecture (2) and Dentistry (P11-P15). Finally, the third (Study D) was a dinner party at home, where a group of four mixed international friends (2F, 2M) professionals in fields of Education, Social Work, Business and Civil Engineering (P16-P19) met at P18's home. Table 6.2 shows a summary of all my ActuEating situated studies in terms of which ActuEater was used, the location and participants.

Setting: In-situ deployments of a self-actuating table runner meant that participants would enjoy a more authentic (self-governed) experience. The three locations that were chosen for studies B, C and D were selected with an interior's style that would fit with ActuEater2 in terms of the interior decoration, lines, patterns and colour-scheme to achieve a sense of harmony, unity and coherence. In both study B and C, the 'waiter' and 'waitress' were unintentional participants, where the ActuEater responded to them whilst placing appetizers in the centre of the table (on top of ActuEater2). In study C, I added the ActuSet (i.e. interactive tableware, see Section 5.1) by adding a conductive layer to the plates, sugar pot, cinnamon and chocolate powder shakers,

	ActuEater	Location	Participants				
			Total	M	F	Alias	Cultural Background
Study A	1	Restaurant	6	4	2	(P1-P6)	European
Study B	2	Restaurant	4	3	1	(P7-P10)	Middle-Eastern
Study C	2	Café	5	0	5	(P11-P15)	South-East Asian
Study D	2	Home	4	2	2	(P16-P19)	Mixed International

Table 6.2 The four ActuEating situated studies.

and the teapot, either using conductive paper (aluminium foil) bottom layer, or stainless steel frames, and therefore interacting with ActuEater2. In study D, the home owner (i.e. host) dealt confidently with ActuEater2 in which she replaced objects and plates on top of it as she pleased, and lifted the ActuEater and repositioned it on her dining table. Figure 6.1 shows different photographs taken during the four situated studies.

Figure 6.1 ActuEating interactions in study A using ActuEater1 and study B, study C and study D using ActuEater2.

Method: As in study A, meals were audio-video recorded from multiple angles to capture users' expressions, interactions and conversations. After each meal a design crit group discussion was held to critically evaluate the design of the ActuEaters in terms of:

1. Sense-making and interpretation: how did participants understand ActuEater? Does ActuEater look, feel and sound right?

2. Interaction and emotional engagement they had with ActuEater, and with each other in relation to it
3. Complex scenarios and interactions beyond expected legible interactivity.
4. Proposing possible enhancements: in terms of visual design, interaction, purpose, meaning/value and/or context in light of constructive feedback about the design itself.
5. Materiality: evaluating the material quality and finish.
6. Pros and cons: what is bad and what is good about the design.

Data from ActuEater1 (Study A) was subjected to initial analysis including participants' speech and behaviour from the audio-video recording, before deploying ActuEater2 (Study B,C,D). Our observations of participants behaviours that were captured in the recorded video were eventually compared to their comments and feedback in the design crits and analysed accordingly to help us understand more clearly the position of each participant. The collected video and audio data are also supplemented by photographs to help capture and analyse participants impressions, interventions and interactions during dinner. Both the study (video material) and the post-meal design crits (audio material) were subjected to a process of Thematic Analysis (Braun and Clarke, 2006). A sample of the codes generated from quotes and observations are shown in Appendix D. From a total of around 31,170 words, the transcription of the video and audio data fed our thematic analysis to derive initial codes that were then iteratively refined into four main themes: 1) the evolution of interaction, 2) the experience sense-making, 3) the complex behavioural repertoire, and 4) design explorations. These themes are unpacked below to discuss the overall experience participants had, their sense-making of what was happening and why, the scale of interaction and its evolving, and their proposed expected enhancements to enrich this experience. We describe these four main themes in the below findings.

6.1.3 Findings

This sub-section discusses the results of the thematic analysis drawn from all four in-situ studies (A-D incorporating both ActuEater 1 and 2). The orientation to use a 'situated design crit' as an evaluatory mechanism means that the emphasis of the results is less on the 'dining experience' and more on a critical reflection on the design of the ActuEaters. Accordingly, the themes discussed unpack the ActuEating experience, exploring how users made sense of both ActuEaters, and how they imagine they could be better designed, used and employed.

Experience Sense-Making

Describing the Experience: People made sense of my actuating decoratives in various ways. While ActuEater1 was described as *"an attention seeker, not distracting in a bad way, it's more of an interesting distraction."* (P4), ActuEater2 was more *"subtle, it can take the attention, but not all the attention."* (P7), and described *"like a cherry on top, just a nice part of our conversation,* *but not focus demanding"* (P10). Variously, the ActuEaters were seen as conversation-starters, e.g. *"an ice-breaker* (P13) and *"an interesting talking piece"* (P5). But some focused more on its enigmatic qualities framing it as *"very creative and interesting"* (P8), *"revolutionary"* (P7), *"mysterious, quite alive"* (P19), *"unbelievable"* (P17) and *"an object of curiosity"* (P16). However, it is understandable how this was largely driven by its novelty effect. Nevertheless, some saw immediately entertaining qualities in the ActuEater suggesting it was playful like a *"treasure box"* (P12), a board game and generally *"fun and entertaining"* (P11). Whilst others saw it as something more meditative *"like a water fountain"* (P1) and *"calming like ocean waves"* (P8), and *"great to meditate or gaze at, like a fireplace"* (P7). When describing some of the deformations and interactions of ActuEater1, participants used more mechanical terms like *paused, rested, nudging, popping and poking, all go up, moving across and slow down*. Whilst, ActuEater2 was defined in perhaps more fluid terms as *changing, moving, crumpling, dancing* and *"it's almost like breathing!"* (P18).

Understanding the WHY: Understanding interactions with the ActuEater had clearly occupied a great portion of the conversation among participants over their meal. Some discussed how it might be proximity/motion sensing, and not any touch, but the way they touch it *"that's why when I touch it, it goes brighter than when you touch it, you have to calm down P12, see, if you're gentle to it, it responds"* (P13). Also, sound-sensing was frequently suggested and tested with its different versions: *voice*, *volume* or *conversation engagement*, *restaurant music*, *cutlery sound*, *noise in the environment*, or even *keywords*, all assuming it is *"physicalizing it (sound)"* (P2). Although it responded to their touch and physical interactions, some suggested further para-sensing beyond that, wondering if it picked up their *"heat, or energy"* (P19), *"mood"* (P12), *"stress"* (P13), *"brain waves or heartbeat"* (P16). To validate their theories, participants tested their ideas in different ways: group D gathered around it covering it up to warm it with their hands in a spiritual manner, group B and C 'clicked' it together on different parts simultaneously, while group A patted it together like a pet.

Perceiving the Meaning & Value: Besides its entertaining aspects, participants were keen to give ActuEater further values believing it had a hidden agenda of some good intention and meaningful purpose. Group A questioned *"Was it to do with how engaged you are in the conversation?"* (P2), *"or is it kinda 'stop eating' and 'talk to people'?"* (P1), *"It did try to nudge me because I was so focused while eating."* (P6), *"or maybe it's just trying to bring us all together"* (P2). Likewise, group B suggested how it could be a good conversation starter if people are not quite friends, group C also expressed it is a way to help people interact with each other, and group D argued that *"it could be interactive with people who speak the most or speak the least, because I finished my food, that's why it is reacting more on my side"* (P19). Through conversations, participants were building assumptions that ActuEater was a resource for social engagement. Participants' responses implied how they thought ActuEater 'wanted' them to engage with each other and sought to develop a deeper social interaction amongst them.

Envisioning the Concept: The overall experience of ActuEating can be drawn from participants' comments about the ActuEaters in the design crits as an abstract concept for interactive decorative artefacts in general, not specifically a table runner. For instance, participants' thinking about the broader relevance and use of decoratives was described in study C as *"the fun part of the boring life"* (P11) elaborating on how such aesthetic interaction allows people to have fun with objects that they might not actually take notice of on a daily basis. In study B, P7 also ensured that the ActuEating experience changed his perspective about decorative objects, furniture and aesthetics in general. Moreover, in study D, P16 highlighted how *"the best value is the merge of technology where everyday objects can do more things and react to our presence and actions"*. In this sense, we need to start exploring other decorative objects and investigate ways they can be of further purposes, meanings and values to people beyond their static aesthetics.

Evolution of Interaction

Users' Roles: Participants' desire to interact with the ActuEater ranged from reluctant to frequent. During the 4 studies, participants created similar scenarios, engaging with ActuEaters through three different roles: 1) the 'explorer' role who was actively engaging and frequently interacting (9/19 participants); 2) the 'observer' closely watching in a spectator role and occasionally interacting with ActuEaters (6/19 participants); and 3) the 'bystander' role of those who rarely touched it and were reluctant to take part in 'physically' exploring it (4/19 participants). Particularly one in each group was a bystander/reluctant to touch it or look at it, yet still reflecting on it and analysing its behaviour. Observers analysed every interaction and assumed meanings and interpreted its actuations. Despite their different roles and positions, all participants at some point during the 4 studies attempted to explore ActuEaters either physically, by finger touching, poking, hand patting, lifting up the fabric off the table, or looking down under the table to realize what is causing the shape-change.

Social Engagement: The way participants responded to and interacted with the ActuEater varied over time and for different situations, bringing opportunities for rich social engagement. They frequently exchanged eye-contact when it moved, especially those adjacent to the moving part, expressing it felt as a personal message for them, while exchanging smiles, laughs and jokes about it, acknowledging their amusement, surprise and enjoyment of its unexpected behaviour. Four female participants were observed taking photos of their ActuEating experience using their smart phones to share on social media. Three or more participants often physically explored the ActuEater together, which made them establish social engagement around it. For example, both P2 and P5 kept their hands on ActuEater1, together, while smiling for a while, as it was actuating, enjoying the feeling of it going up and down. With ActuEater2, several participants touched 'similar' parts simultaneously to explore it together imitating each other's interactions from gentle touches to firm pressing strokes. As actuations varied, participants were developing interactions together in a self-learning exploratory process, learning from each other in playful ways, collaborating and exchanging techniques. For example, *"wait, if we touch one by one together, what will happen?"* (P13) and *"let's press it together at the same time"* (P10 to P7).

On a few occasions, some would interact on behalf of others when they felt that the ActuEater needed to be responded to but was being ignored.

Physical Manipulations: Once ActuEater1 had gained users' attention it attracted their touch interactions (first fingertip touch, then hand and palm touch), initially passive (responding to) then active (initiating) interaction. Then interactions went beyond touch into more physical 3D manipulations according to the shape, material and its affordance (such as grasp, pat, squeeze, bend, etc), see figure 6.2. After thoroughly exploring direct physical interactions, participants became more creative. For instance, P1, P3 and P5 used water bottles, salt shakers and mobile phones to place onto ActuEater1 to explore its response. Further exploration with ActuEater2 brought richer physical manipulations to the table. For example, many participants frequently touched the coloured 'felt' parts with a brushing stroke on its soft texture, although these elements weren't sensitive. 'Hover' hand gestures above seamless sensing parts were used by all groups when proximity-sensing was realized. Some covered up thermochromic parts with both hands to 'feel the heat'. Some lent forward or backwards in their seats to test proximity. Some repositioned physical objects (that were initially placed randomly) precisely on particular parts of ActuEater2 to test them. Many were observed 'tracing' the colour-changing pattern with one finger in a continuous satisfying way.

Figure 6.2 Interactions with ActuEater1 (left) and ActuEater2 (right)

Physical interactions were quite directly proportional with actuations in terms of scale. That is, it was noticed that they responded to located (small) low actuations of ActuEater1 by one fingertip, higher ones with their three middle fingers, and when it was all up, they used their whole palms. ActuEater2 was definitely manipulated more intensely, it was flipped over or pulled off the table, bent, felt and squeezed, and perceived more like a 'fabric' runner than as a shape-changing device like ActuEater1. This reflects how people develop their own interactions based on their own perceptions, interpretations, backgrounds and instincts. Yet, people learn together and from each other, developing their ideas, perceptions and engagements with a certain artefact.

A Complex Behavioural Repertoire

Beyond the Boundaries: Several participants had an irresistible urge to 'tidy up' both ActuEaters after actuations by flattening the 'history wrinkles' that were created by its actuation, which triggered more actuations thereafter. Observing how participants took extra effort to interact with it (e.g. stretch out their arms to reach it or put down cutlery) shows their 'willingness' to physically engage with it. Interacting blindly with it (without even looking at it) shows 'expertise' and confidence. Participants not only interacted with the actuating parts of ActuEaters, but they tended to explore the boundaries of sensitivity to discover the edges of 'seamless and seamful' interaction, evident by manipulating even the satin ribbon edge of ActuEater1 and the plain senseless petals of ActuEater2.

'Interaction Boundaries' were even crossed to explore other potential means of engagement. For example, ActuEater2 received several 'voice commands' to test speech as possible input interaction: *"Hi" (P12, P13), "Move" (P13), "By the power in me, rise!" (P8)*. At the end of study B, P10 held its edge with a firm grip and shook hands with ActuEater2 saying *"nice to meet you"*. Participants often felt an urge to initiate interaction with ActuEaters deliberately, when they were not actuating, driven by an inner desire to have fun through playing and to find out more about how it works. This creates space for contradicting scenarios where they want to stop it when it's up/active, and yet they wanted it active when it sleeps. Such complicated behaviour resembles typical interactions with pets or children: when quiet, we want to play with them, but when they are manic, we wish them calm. It can also explain participants' tender 'pat' interaction, as their way to calm it down, revealing a zoomorphic interpretation of the actuations. *"Stroke it carefully, it's like your pet!"* (P13). Others showed further 'empathy' towards it: *"You should just touch it, not squeeze it like that"* (P7 to P10).

Curiosity and Mystery: Curiosity was evident in all four studies, where participants explored and talked about how it works, and sneaked a peek underneath. Every participant at some point picked the table runner up from the table, pressed it to feel its inner body, or bent downwards to look underneath the table. ActuEater1 obviously had the shape-changing mechanism under the table and participants commented on how it would be more practical not to have a hole in the table *"and keep all the mystery alive, because you look under the table and oh no, it must be in the runner!"* (P4), *"what kind of sorcery would this be!"* (P6).

Accordingly, ActuEater2 was designed to be self-actuating using SMA wires which caused participants to flip it, bend it and pull it off the table to ensure there is nothing underneath, then squeeze it and press it to feel what is inside. P10 put his hand underneath the table below ActuEater2 testing if the capacitive sensing would work through the glass downwards. P17 'rolled' it firmly to realize its affordance and materiality when others wondered whether there was something inside it. Participants expressed a mysterious aspect not just in the movement but also in the colour-change: *"Notice those colouring spirals again, it doesn't look like an electrical light"* (P18), *"It is totally unexpected, it would never cross my mind that a table fabric can actuate like this. I wonder how it changes? What causes the colour-change? and how does* *this pattern reveal?"* (P7). This shows how people think about inter-weaving technology into everyday objects in a hidden way and how it is more 'magical' from a user perspective.

Discoverability and Legibility: During the initial study, participants criticized ActuEater1 for not having an immediate consistent response to their actions. Although there was a specific pattern mapping inputs to outputs, participants expressed how they still require an explicit cue to fully understand. ActuEater1 made participants of study A feel unconfident about its illegible and discoverable interactions, when some autonomous interactions were perceived as random. Participants not only expressed how legibility is easier to relate to, but also how a level of control over ActuEater1 was desirable.

As a result, ActuEater2 was designed to be both sensing and autonomously reacting at the same time, which was appreciated in the design crits: *"It's nice to have some control of it and it is also nice that it does its own thing by itself as well"* (P18). In addition to direct and immediate input-output relationships, participants' view of the artefact's behaviour that evolves with their interactions over time and usage was also explored, instrumenting discoverable interaction as an adventure: *"was it moving that much from the beginning?"* (P10), *"as we talk about it more, it moves more"* (P9), *"we'll keep playing with it and at the end we'll find out it's a Jumanji!"* (P13), *"or find the treasure"* (P12). *"it could evolve more over our dinner party and break out a dance at the end to celebrate!"* (P16). This shows how people were readily orienting to a world where objects known to be static cannot only change over time, but can change unexpectedly and in an adventurous manner with different paces, taking various forms, that could be ultimately rewarding.

Design Explorations

During their group discussion in the design crits, participants suggested many enrichments to both ActuEaters and proposed other functional and aesthetic possibilities. They also proposed different artefacts that could be similarly interactive and suggested other types of spaces where they believed it might be interesting to interact, adopt and utilize such technology.

Proposed Functions: Participants focused their suggestions of potential functions on three main themes: 1) extending, 2) engaging, and 3) entertaining. 1) 'Extending' decorative objects by augmenting them with further capabilities was suggested as an alternative to smart devices and gadgets, e.g. *"now we're getting into an era where we expect objects to be that smart and you can just talk to them and tell them what to do"*, *"so Alexa should be part of my decor and have more interactive capabilities than activating heating or obeying commands"* (P16); 2) 'Engagement' was frequently mentioned for i) bringing people together and provoking social engagement, or ii) occupying people waiting for something or feeling lonely, iii) engaging children in different situations such as doctors' waiting rooms, and iv) creating an ice-breaking object for those meeting for the first time; and 3) 'Entertainment' and stimulating was also discussed as a useful purpose for such an object as: *"it is great for an absent mind to meditate or gaze at"* (P10), *"gives a sense of calmness.. I can keep looking at it for hours"* (P7), *"it reduces* *stress, like a fidget-spinner"* (P12) and *"stimulating curiosity of children, how is it moving and changing colour?"* (P7). P13 expressed a similar functional quality of keeping children entertained without a digital screen i.e. a display-less display, and P18 suggested a changing wall-art that entertains, but unlike a TV set, is not focus demanding. All these functions represent the value of non-demanding and non-disrupting technology (people aspire for) that keeps the essence of social quality time and adds a bonus dessert to it.

Proposed Artefacts: As they perceived it as a gaze-drawing object, some participants suggested other artefacts that could be similarly (or more) interesting. Some suggested other flat surfaces such as *"colour-changing coasters or placemats that entertain me until the next course, or warms my plate"* (P10), *"a mat or a rug on the floor that we sit on and crumples when one moves away"* (P11), *"a seat that changes colour the more you stay sitting down too long then moves urging you to get up"* (P15) and *"a mirror or a painting"* (P4). P7 imagined wall-art that gives different shadows or shapes responding to proximity and an entire wall that autonomously reveals and moves parts such as butterfly wings decorating the wall to actuate his home decor. Moreover, others suggested 3D objects such as *"a playful sculpture"* (P16), *"a moving vase"* (P9), *"a pillow to help my neck problems"* (P11), *"a lampshade that starts dancing like this when I'm in a 'dancey' mood"* (P7), *"a coffee table itself"* (P18, P5), *"a blanket that crumples around you would be great to give you warmth"* (P7).

Proposed Interactive Aesthetics: A crucial aspect of decorative artefacts is their need to blend in to complement an interior style and are usually matching other objects in the same space. Therefore, I was keen to choose settings where the ActuEaters could fit-in and complement those spaces with matching objects, such as matching tableware, interior colour-scheme and style (as much as possible): *"I didn't notice anything weird at first as it had the same colours of the restaurant chairs and napkins, and petals shape are the same as the table glass engravings."* (P7). However, more tailored design for all details has to be carried out for each individual space, e.g. *"It looks elegant and the colours are matching but the shape has to be round because the table is round"* (P13), while some saw it as a *"futuristic design"* (P10, P17) preferring more traditional aesthetics.

Although I carefully eliminated any LEDs from ActuEater1 to keep it as normal and traditional as possible, 4 out of the 6 participants expressed how they expected/wanted ActuEater1 to have 'lights'. This indicates how they do not entirely perceive it as a (normal) table-runner, but as a 'digital' object. When they were asked about colour-changing capabilities instead of lights (e.g. using thermochromic inks), they showed excitement and suggested that colour-change could complement and enrich the shape-change, adding *"a more interesting layer"* (P3). Whilst enabling thermochromic colour-change in some parts of ActuEater2, they suggested that all petals should change colour and recommended hydrochromics as well *"if it responds to water or spilt liquids, it would turn an embarrassing bad situation into an interesting conversation re-starter"* (P9). Other richer multi-aesthetic interactions suggested that petals could move freely and blossom in 3D, or it plays music and amplifies itself with the volume to *"hit as many senses as possible"* (P16).

Proposed Environments: In terms of spaces, participants proposed different environments in which they envisioned such technology. Restaurants and silent spaces such as libraries, museums, clinics, waiting rooms and specifically waiting areas at the doctors' surgeries to entertain people while waiting, were proposed by several participants across the 4 studies. Other proposed environments, included classrooms as a board that *"attracts focus of students"* (P12), toilets *"instead of reading the shampoo ingredients if you forget your smart phone"* (P6) and office spaces *"to distract from work, to refresh, take a breath and de-stress"* (P12), but *"not in a formal setting as meeting rooms, it becomes distracting"* (P11). Alternatively, having them in homes was debatable. Some expressed their worry about the finite number of actuations that wear its novelty out too quickly for home occupants, but still found it exquisite and delightful for their guests. So careful design should create actuating capabilities that make it 'sustainably interesting'. Others saw it *"as a creative or a special object that you'd like to display"* (P8) and saw opportunities in which a domestic artefact can change colour based on ambient temperature or display household data such as water or energy consumption.

6.1.4 Critical Reflections

This situated study presented a series of design explorations, critically examining the potential use of shape-changing materials in the design of interactive decorative elements or OUI artefacts. This work provides a helpful case-study supporting others who might wish to design and develop actuating decorative artefacts for different contexts and cultures. The ActuEating study offered an open-ended set of observations in terms of users' behaviour, interpretation, reactions and expectations. The intention wasn't studying the dining experience in itself, but to explore the design of interactive artefacts and how people may perceive, interact with and experience such technologies in relevant settings and to gain deeper knowledge and insight into designing interactive everyday objects as decorative artefacts.

As with both coMotion (Gronvall et al., 2014) and the History-Tablecloth (Gaver et al., 2006), the improvised interactivity and often confusing behaviours, added value and richness to the ActuEating experience in ways that had not been anticipated, allowing for complex interpretations. While controlling ActuEater1 from behind the scenes, I learnt how participants collaborated to realize how to control it themselves, not just theorizing what triggers it, but by testing different input interactions beyond my expectations. I then designed ActuEater2 to be both physically-interactive and autonomous. From voice commands, knocking on the table and observing music patterns, to stroking, patting and using other objects (e.g. teapots, salt, sugar and phones) on top of it, participants developed interactions themselves through social engagement to explore its potentials, interaction boundaries and limitations. Despite the 'engaging' and 'entertaining' benefits realized by the ActuEating studies, I understand the limitations in terms of the effect of 'novelty' on user experience.

The challenges I faced to conceal technology within an everyday fabric artefact ubiquitously, were aimed at experimenting how hidden interactivity in objects (that blend into the space design) could be of value, meaning and significance to space occupants over an in-situ social event (in a restaurant, a café or at home). By emphasizing on how weaving technology into real-world objects, specifically decorative ones, we can deliver a rather richer 'spatial experience' in a given contextual setting.

By taking previous work further, I was able to explore new territories of this design space. However, the design constraints set herein included studying only actuating table runners in dining settings. In my further research, I explore other artefacts, in other contexts, to realize the latent and intrinsic potentials of extending their capabilities, seamlessly. Although ActuEaters were designed as non-functional artefacts, their aesthetic qualities as decorative objects are rather useful as they don't need constant attention, which aligns well with slow and calm technology concepts (Odom et al., 2012).

6.2 Adaptive Architecture

Moving from the horizontal (table runners), to the vertical (wall tapestry), I was able to hold a new situated study using one of my other prototyped OUI decoratives (BacterioChromic, see Section 5.2). This situated study took place in the "Living with Adaptive Architecture" (LWAA 2018) Exhibition (www.lwaaexhibition.uk/). This exhibition was concerned with architectural elements that are specifically designed to be adaptive to their surroundings and to their inhabitants. The selective process of exhibition curators included only installations that lie within the scope of adaptive architecture, spanning from materials and prototypes to paradigms and conceptualizations. To cover the wide range of architectural elements on different scales, the exhibition was presented in three zones: 1) "Materials and Mechanisms" for building components with adaptive or morphological capabilities; 2) "Connection to the City" for exterior facades and wider urban spaces; and 3) "Home" for interactive furnishing, art, and interior design.

Figure 6.3 The residential corner of the 'Living with Adaptive Architecture' Exhibition, with the BacterioChromic wall-art in the middle.

6.2.1 Methodology

Setting: The LWAA 2018 Exhibition took place in the Lakeside Arts Gallery in Nottingham, UK. Around 1285 members of the public were reported to have visited the exhibition during this period. Over the span of 6 weeks, my interactive BacterioChromic wall-art was displayed in the exhibition's "Home" zone. Throughout the exhibition, there was a total of 16 installations, only 5 of which were interactive to the exhibition visitors, including the BacterioChromic. Inside the gallery, BacterioChromic was placed in a residential décor setting (see figure 6.3) with Scandinavian-style furniture and an inviting atmosphere (natural lighting, neutral base hue and pops of vibrant colours) including a sofa, some cushions, a coffee table, a small dining table and a couple of chairs. Within that zone, the BacterioChromic was placed beside other actuating interior artefacts, but those which rely on mechanical actuation i.e. using rotating servo-motors. This gave visitors a useful context on differing forms of actuated interior spaces.

Methods: I was present for some days (during the 6 weeks exhibition) and took field notes, made video recordings, observed visitors' interactions, and spoke to them about their experiences. The exhibition was visited by a diverse audience (age, gender, background, family groups, individuals) which helped give a wider perspective on the engagement with my artefact than inviting participants to a lab setting. Through their questions, comments and reflections, visitors provided insights into designing similar artefacts, highlighting how such interactive approaches are useful for raising community awareness of various issues. In addition, this engagement gave a better understanding of the potentials and limitations of the crafting techniques employed. Further, informal interviews were audio recorded with six visitors who were happy to discuss this research further. The interviews were audio transcribed in full and subjected to Thematic Analysis (Braun and Clarke, 2006). A deductive iterative process of assigning codes and deducing themes resulted in four main themes: 1) sense-making, 2) user-behavioural repertoire, 3) aesthetic qualities and value, and 4) design explorations.

Participants: The exhibition was visited by a diverse audience (age, gender, background, family groups, individuals) which helped give a wider perspective on the engagement with my artefact than inviting participants to a lab setting. A few visitors were happy to discuss this research further in audio-recorded unstructured interviews during my field observation. The six gallery visitors who participated in such a way were 2 females and 4 males, who I refer to as P1 to P6. Most of their expertise were self-expressed as spanning over fields of Architecture, Design and Art, in either practice or research.

6.2.2 Findings

Based on observations, field notes, video recording of public engagement and audio-recorded informal interviews, I was able to gather data and insights into potential value and impact of using my crafting and making techniques to produce both seamless sensing and morphological actuation in interactive interior elements.

Experience Sense-Making

The *organic* and *slow* morphological transitions of patterns and movements were described by many visitors as being more *natural* versus the *mechanical* actuating objects placed beside BacterioChromic. Although the silent and slow actuation of BacterioChromic made it look as if it was *"alive"*, it also caused it to be, at times, unnoticeable and gallery visitors passed it by whilst it actuated and failed to grab their attention. Several people were observed advising their friends or family members to *"wait and see"* as it slowly morphed after a user interaction. Whilst some walked away perceiving this actuation as too slow, others described it more poetically, articulating its morphological actuation as *"the breeze of the air"*, suggesting that it might *"remind us of sea waves"* (P5), or that it *"looks like a sea creature"* and reminds one of *"sitting in the woods, where everything is moving around you"* (P6). Most likely, these *organic* interpretations would not be drawn from motor driven actuators or LED e-textiles, not only because of their sound and flashing light, but also due to their rigidity and lack of naturalness.

User Behavioural Repertoire

Many visitors expressed curiosity about what was causing the shape-change, how the fabric was shifting its colour and where the batteries were (if any). Also, video recordings showed unexpected proxemic user behaviour, ranging from gently touching, pointing, poking, stroking, pulling strands, warming up with hand palms and even blowing at it. Blowing, in particular, is an unusual interaction with a wall-art piece, yet at least 5 visitors were observed using it as a playful and unusual interactive experience, happily enjoying the colour-change their breath caused and the gradual fading back of that colour-change in the embroidery afterwards, see figure 6.4. I also noticed that interestingly, small-sized circular shapes in the pattern received a lot of pointing/ clicking as if they are mentally associated with *buttons* that afford pressing. Pulling the shape-changing free fabric strands was particularly unique in the fact that every interaction manipulated its martensite state, therefore, changing the resultant deformation. These interactions caused the output actuations to vary in form and intensity, depending on the exerted input. While some visitors were amazed by unexpected organic deformations in the fabric itself, others were disinterested and impatient to wait for a few seconds to perceive a visible output.

Aesthetic Qualities & Value

Most of the visitors commented on the *meaningfulness* and *aesthetics* of BacterioChromic as the main factors for describing it as "interesting" and "intriguing". That is, they acknowledged and thoroughly discussed the design concept presented, but mostly valued the fact that no 'demanding' technology was used to convey it. They thought that the expression of AMR (Anti-Microbial Resistance) is a hot topic of great interest that is often (mis)represented by charts, graphs and scientific signage. However, upon encountering BacterioChromic and its gentle patterns of revealing and hiding colours and moving fabric, participants felt that it was communicating a message about AMR, and generating an experience that was pointedly different from normal health communication. People appreciated the interactivity of an aesthetic object, that does not appear to have any 'offensive' technology, as a means of communicating a serious medical problem of public concern. For example, one visitor stated that *"as an aesthetic object, you can live with it without having to live with lots of offensive looking warning signs."* (P1) which points to how we should potentially design technology that avoids the appearance of digital devices, if we need and/or want people to enjoy 'living' with them. Another visitor highlighted how this seamless interaction of a non-device-looking object gives it its value: *"you could get carried away of putting more and more technology into it.. it does not have sensors and wires, it's got simple interaction"* (P3).

Figure 6.4 Interactions with the BacterioChromic wall-art through different tactile manipulations e.g. touch, stretch, and blow.

Design Explorations

The *crafted nature* and *making* of the BacterioChromic was a conversation topic among some visitors, who expressed these qualities upon visually examining it prior or after interacting with it. Most were surprised by how the fabric itself changed its shape or colour, based on their presumptions of how interactive objects operate. Yet the behaviour of the different elements of the piece presented new possibilities to them, away from mainstream product design. A designer who visited the gallery reflected on how she realized that the actuation was stitched into the fabric itself, and that this made it -unlike any other interactive object- *"move naturally, depending on where and how you touch it."* (P5). This reflects the quality of crafting methods as techniques for embedding actuation in soft artefacts as opposed to the previous work on shape-changing interfaces. Other visitors suggested different soft artefacts that could be embedded with actuation like BacterioChromic, including garments, cushions and gorilla knitting in public spaces. All these examples emphasize the value of crafting when designing interactive actuating artefacts. Similarly, some verbally compared it to IKEA products to point out the apparent differences between its crafted individualized and bespoke quality versus *"mass production and mass design"* (P6).

6.2.3 *Critical Reflections*

The Adaptive Architecture exhibition was a good opportunity not only for showcasing BacterioChromic as an interactive interior element, but to provide context to this situated study in a designed setting among other surrounding installations. This contextual presentation in the "Home" zone provided a view of near-future interactive interior spaces in a residential setting, gathering the work of architects, artists and researchers together, that could have been difficult to achieve otherwise. This overall context of the Adaptive Architecture space directly influenced and framed visitors' perception, reflection and sense-making of BacterioChromic. This is what my interviews and field observations focused on and this is what constitutes the majority of the contribution in this situated study. In exploring people's engagement and reflection on an interactive wall-art on-site and in such a situated study, a deeper layer of this research about interactive interior spaces is exfoliated. Although such a study is not to be accounted for as an (ideally) domestic long-term study, still it provides more than a prototype demo in a lab setting where the 'device' would be separate from the surrounding and potentially out-of-context.

Moreover, deploying the BacterioChromic opened a new opportunity for the exploration of a design created through my crafting and making techniques including machine-sewing actuation seamlessly and the impacts of doing this. Using a range of the novel techniques of machine sewing and physically programming actuating threads/wires into fabrics, this piece of wall-art was crafted on wooden sewing hoops using colour-changing and shape-changing threads and fabrics. My SMA sewing techniques also enabled the movement of free fabric strands on the piece of wall-art in an organic and soft behaviour perceived by people as if it were alive. In this sense, BacterioChromic extends previous work on shape-changing interfaces by manipulating the deformational parameters affecting the fabric's morphological effect.

Finally, this situated study designed, exhibited and evaluated by members of the public, who interacted with it, shows the potentials of creating aesthetic artefacts with colour-changing and shape-changing capabilities, crafted in seamless ways, moving beyond intrusive technology and mass-produced devices. These findings evoke design opportunities that pave the way for a vast amount of future work on actuating decorative elements, contrasting previous notions that argued the need to create novel computational composites and peculiar materialities. In my further research, I explore other interactive interior elements, in other contexts, incorporating more sensory experiences, beyond colour and shape.

6.3 Immersive Hive

The third situated study not only brings my research to a new context, but also takes it to a new level where interactivity is embedded into the walls, and the OUI is the interior space, rather than a single decorative artefact. Through this study, I wanted to design and build an interactive *space* and explore more sensory experiences than shape and colour-change (such as sticky touch, smell and taste). In addition, it was a great opportunity to observe how would people interact with/in an interactive space in yet a new context.

This study was held in collaboration with Barbara Keating (Digital Artist and Chair of Tyneside Beekeepers Association) and Michael McHugh (Curator and Event Producer at Tyne and Wear Archives & Museums). This project was funded by the Tyne and Wear Archives and Museums' TNT 2018 (Try New Things) Action Research programme and kicked off as a result of a collaboration opportunity that arouse during a Newcastle University's IdeasFest event. Several meetings and brain-storming sessions/discussions took place between the collaborators to allow us explore and ideate the options of making and materiality for achieving a great audience engagement whilst on the tight budget of the TNT funding.

6.3.1 Activity 1: Design Tool

To bring my ideas closer to my collaborators, I first designed the 'Hive Demo' (see figure 6.5) as a design tool to demonstrate embedded capacitive-sensing and seamless audio feedback in the form of a physical wooden hive demo that belonged to the TBK (Tyne & Wear Beekeepers) which contained 10 frames of honeycombs. I have used some copper adhesive tape as a conductive material for rapid prototyping and a BareConductive touch-board to make a quick and interactive demo of how a beehive might be *physically* interactive. Once the frame was touched, bees can be heard buzzing from the microspeaker connected to the touchboard microcontroller. This 'Hive Demo' was an efficient design tool in bridging between the two worlds, the digital and the physical, research and design, it formulated a middle language and created a new dialogue afterwards among collaborators who can all now touch, hear and see seamless interaction embedded as I had in mind.

Figure 6.5 The interactive 'Hive Demo' as a design tool to tangibilize the idea of a seamless sensing physical hive with audio feedback.

6.3.2 Activity 2: Ideation

The design concept was inspired by the fact that bees are sometimes maligned, but without them our world would be a very different place. Honey bees are the world's most important pollinator of crops. It is estimated that one-third of the food we consume relies on bee pollination and in addition, bees are thought to contribute over £500m to the UK economy each year (Keating, 2018). The idea was to hold an event where visitors can have the opportunity to discover more about our relationship with bees and how important they are for the food we eat. Visitors can meet beekeepers, take part in a treasure hunt and walk into a prototype 'hive' installation that uses seamless sensing, informative output, thermal imaging and sound to imagine the hidden aspects of life inside a bee colony.

6.3.3 Activity 3: Design & Making

With the aim of creating an interactive immersive experience of the inside of a beehive, my idea was to have an enclosed space where visitors would enter to find a human-size hive-like dark space with real-world hive photos printed (not projected) on the wall panels themselves to trigger a feeling of being miniaturized inside a real beehive. To achieve this, I sourced the best quality photos with the highest resolution possible of matching-scale front-faced to actual "brood frames" of different hive activity (e.g. working bees, eggs and larvae, honey and pollen, the queen bee and her retinue). Due to the tight budget, only two photos -with the desired quality- were purchased from Nature Photographer Simon Croson (copyright acknowledged). Then, these photos were printed on 3 mm foam boards in a human-scale (183 cm wide and 110 cm high) then mounted on wooden frames to hold and elevate them in the reach of both adults and children to touch different parts of them, and be accessible from behind -for troubleshooting- as well. There was also an intention to leave the bottom part of the frames open and accessible to allow and encourage children to crawl underneath them and move freely beneath and among the panels, but that was discarded due to safety concerns.

Figure 6.6 Making the Immersive Hive: 1) printing hive photos on foam board; 2) painting the wooden frames of the wall panels; 3) making the back circuit using conductive paper; and 4) Soldering the microcontroller.

The wall panels were then augmented with seamless touch-sensing from the back using inexpensive capacitive paper (i.e. aluminium foil sheets) and tactile interactive elements from the front using conductive thread and conductive paint (see figure 6.6). For an immersive input, 3D laser-cut wooden hexagonal shapes were also fixed to the panel front to hold burlap mesh soaked in local honey wax. Another hexagon held a soft colourful fringe yarn of 8 cm in diameter representing a magnified pollen grain as those typically gathered by bees and stored in the hive as food for their colony. The tactile sensing was added to the honey wax using capacitive touch sensing behind every bee in the wall panel, and behind the *real* honey wax hexagon, and threaded within the pollen's yarn using the conductive threads (see figure 6.7.a and b). All the sensing input on each panel was connected to an Arduino BareConductive Touch-board that is embedded with an MP3 decoder IC to give audio feedback in the form of recorded educational narrations about life in the hive.

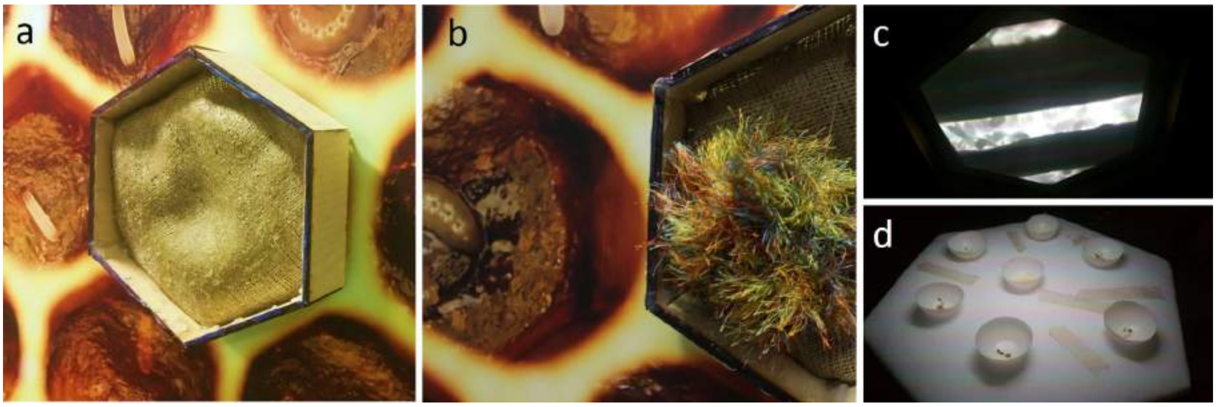


Figure 6.7 a) The touch-sensing honey wax hexagon, b) The soft-sensing pollen yarn, c) Thermal imaging hive display, and d) The Bees-Buffet plinth.

For an immersive output, I chose a first-person narrative for the space to talk about itself and space elements (bees, honey and pollen) to present who they are and their roles inside the hive. Special care was taken into consideration prior to recording these narrations to enhance the user experience and create a sensational impressiveness. For example, female adults were recruited to record the voice of worker bees (as they are scientifically categorized as female bees), while Geordie male adults were recruited to record voices of 'local' pollen and honey wax. On the other hand, a toddler narrated a two-days-old egg, a child played a larva, while an elder woman narrated the queen's voice. In response to user touch input, the output narrations they hear (see figure 6.8) were as follows:

1. I am an egg that the queen bee has laid, and I'm only two days old.
2. I am a larva, just a bit older than my sister egg. This gluey stuff around me is delicious royal jelly to make me grow big and very strong.
3. I'm a big larva and I grew fast because my sisters fed me royal jelly and brood food. Soon it will be time for them to cover my cell over with wax so I can hide away until I have grown into a proper bee like my big sisters.
4. I am pollen, collected from trees, flowers and shrubs by the forger bees. Bees bring me home to mix with nectar. I'm then fermented, a bit like bread or yoghurt, then stored. Everyone in the hive eats pollen, it's so good for them.

5. I am wax. A whole group of bees have to work together to make me. Some bees shape me by chewing me, while some make me warm enough to mould.

6. We look after the queen very well and spread a special scent around the hive to let every bee know that mother is happy and well.

7. We're the queen's retinue, the bees surrounding our mother, the queen. The youngest one's feed her and the others stroke her because she's too busy to get her own food or groom herself. We even have to take her pooh away!

8. I am a young worker bee. I am stroking and grooming my mum, the queen. When I do this, I pick up the lovely scent she has and I pass it on to my sister worker bees who carry it around to let everyone know that mum is safe and well, and laying lots of eggs to make new babies.

9. I am very young, but I can carry royal jelly on my tongue, to my mother, the queen of the hive. I will stay with her for a few days then I will learn other jobs in the hive.

10. I am the queen, so I am the mother of all the bees in the hive. In summer, I lay lots of eggs day and night, up to fifteen hundred in one day!

11. Watch out! That's my bottom. It's where my stinger is. I don't sting, unless I think that my sister bees or my mother are in danger, or someone is steeling our honey.

6.3.4 Methodology

Setting: This situated study of the interactive interior space "Immersive Hive" was held at the Great North Museum (GNM) in Newcastle upon Tyne, UK as part of the Bees Exhibition. During this weekend event, the Immersive Hive was deployed in the Clore Suite, an interior space at the back side of the museum's permanent gallery hall. Within this interior space where the Immersive Hive wall panels were installed, the work of Barbara Keating was also displayed in the form of video projection and bees buffet. The video projection provided a unique footage of thermal imaging captured from a beehive displayed in a hexagon acrylic upside-down projector to provide an unusual view of life inside a bee colony (see figure 6.7.c). The bees buffet was underneath the video projection, on a hexagonal-shaped plinth displaying wax stripes and edible bowls filled with bee food and made of hive-sourced materials (see figure 6.7.d). On the way to the Immersive Hive, the museum was themed in bees, where members of the Tyneside Beekeepers Association and Newcastle University Students' Union BeeSoc, alongside researchers from both Newcastle and Northumbria universities and other community groups and makers were there to greet visitors, provide guidance, raise awareness, and man stalls and bees-themed activities.

Participants: The Bees! Exhibition at the GNM museum was a well-attended event with around 700 recorded visitors from the public (see figure 6.9). Visitors showed wide engagement with the Immersive Hive in particular and the event organizers reported great positive feedback within the local community and the local printed media (The Northern Echo, 2018). My gathered

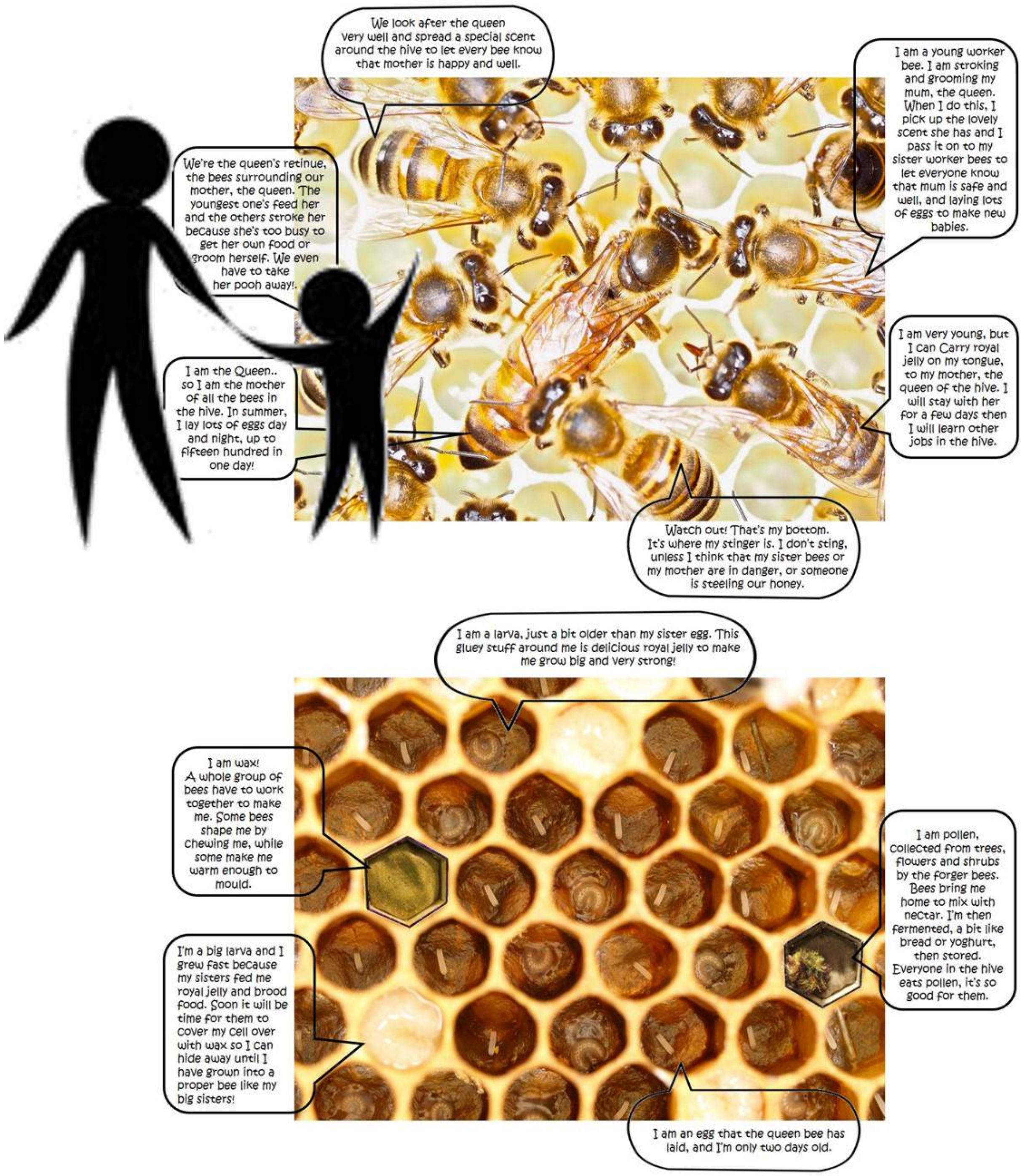


Figure 6.8 A pictorial of the two touch-sensitive wall panels with the audio feedback.

data consisted of five hours of field observations and notes recorded during the exhibition. In addition, five unstructured interviews with participating visitors (4F, 1M) who are referred to as (P1 to P5), were audio-recorded during the event, after their consent.

Method: The research goal was to explore not only designing an interactive interior space in yet a different context using conductive sensing materials embedded seamlessly within the physical elements of the designed space, but also to capture user feedback and *test* the design in an in-situ deployment with members of the public (from different backgrounds, age groups, etc) to get helpful insights on how people perceive and engage with such an interactive interior space. Therefore, I stood in proximity to the interactive walls of the Immersive Hive for the entire event to document field observations. The collected data was supplemented by photographs of user engagement captured throughout the exhibition event. I also interviewed people who were willing to discuss this design further to capture deeper insight on user sense-making and interpretation to this design. Interviews were fully-transcribed and subjected to Thematic Analysis (Braun and Clarke, 2006), were codes led to five main themes: 1) Immersive experience, 2) tactile sensing, 3) sensational audio output, 4) education and playful application, and 5) potential future enhancements. These key themes are unpacked below with some evidence of grounding quotes.

6.3.5 Findings

Immersive Experience

There was a theme in the data around how the experience of being in and interacting with this space was perceived as immersive. Visitors who participated in my feedback interviews described their experience as *"really exciting"* (P1), *"a fantastic experience"* (P4) and *"brilliant.. very very striking visually"* (P2). Several people were sincerely impressed by the seamless hidden interaction e.g. *"that's amazing! I haven't seen anything like it before"* (P3) and several were observed sneaking a peek behind the wall panels to figure out how it works. A ten-year-old boy insisted on wearing the beekeepers head-to-toe costume with its white fencing veil and suit -provided by one of the neighbouring activities- while entering the Immersive Hive because he felt that he was inside a real hive. The multi-sensory experience of touch, sound, smell, taste and texture altogether created a unique experience for people who were immersed into that interior space beyond the conventional 3-dimensional design. For instance, one of the museum visitors (P4), who also happened to be an architect by profession, expressed his view of the Immersive Hive as *"I felt I'm in a 4D experience"*.

Tactile Sensing

As with the ActuEater, the scale of interactions varied. Some people touched it with their finger tips by taping or poking, mostly with eggs, while others used their whole hand palm in hovering over bees' bodies and big larvae, as the latter were about the same size as a hand palm. One was observed attempting to hug the panel from its top right corner, while a few visitors were aggressive and would hit the wall panels hard forcing me to advise them to hover gently, breaking my uninterrupting observation. Generally, people would carefully listen to what the bees say then proceed to glide their hands on the panel again to explore more interactive media. The soft texture of the wall panels and the seamless hidden interaction behind them appeared to have a satisfactory effect upon people smiling while gliding their hands gently on the surface pursuing more engagement. Children were trying to reach up high while adults would even bend downwards to touch new -unexplored- areas of the wall panels. Several people were curious about how their interactions were being *seamlessly* sensed and tracked with no tracking cameras. Alternatively, *seamful interaction* was incorporated as well in two hexagons carrying the pollen-like yarn and the honey wax respectively. The softness of the pollen was perceived in pleasing, tactile and unusual metaphors. People not only touched it but stroked, pulled away and squeezed it. It was indeed designed to be stroke and squeeze-sensitive, but not to be pulled away, causing it to fall off place in a few incidents. This raises attention to unexpected user behaviour towards unexpected tactile sensing interfaces, leading to (unintentional) damage.

Figure 6.9 Capturing visitors' interactions with the Immersive Hive at the Bees! Exhibition.

On the other hand, once they touch the honey hexagon, they get struck by the fact that it is indeed real sticky honey revealing facial and bodily expressions of surprise e.g. a sudden step backwards, an oh! in the face, a little disgust and mild discomfort, which all quickly turns into smiles and attempts of smelling and even licking their finger tips to taste it, asking themselves *"Is that real honey?"*, while they simultaneously listen to the wax talking about itself. The initial puzzled response that most people had with the striking texture of the honey indicates how people primarily expect interaction with technology to be *faked* and jump head-first without anticipating genuine feel and texture or authentic experience. This paradigm bridges the gap between both the physical and the digital worlds, opening the door for innovating real-world experiences through interaction with technology as opposed to virtual or augmented digital realities.

A vast amount of feedback -from interviewed participants- towards what they liked the most in the Immersive Hive tackled the *materiality* of the design having different textures. For example, *"I loved the fact that it.. had the textures, different things to feel"* (P1), *"touching it and getting that immediate response which is so good, and the stickiness of the honey!"* (P2) and *"I loved the wax and that [pollen] that I touched. It was an amazing experience."* (P4). Another participant elaborated explaining that *"a lot of people when they think of pollen and wax and things like that they don't think of how it feels, they just think of how it looks! And I think it's good to be able to feel it"* (P3). This clearly highlights the benefits of tactile sensing and the missed opportunity of incorporating different materialities and soft sensing in my designed user interfaces, at no (significant) extra cost.

Sensational Output

During field observations, it was easy to tell if someone was hearing audio feedback in their headphones as their facial expressions immediately express surprise, excitement and joy, showing smiles and laughter once the audio is played. Voices of eggs and larvae, in particular, triggered the most delightful sensations in the feelings and behaviours expressed by most -if not all- people who encountered them. These interactive areas received the most repetitive engagement where people not only returned to them again, but also brought their accompanying loved ones to specifically try them *"Come! Try touching this little egg!"*. I also had an audio cable splitter so that each panel would be heard by two people simultaneously through two headphones in response to the input of either of them. Parents shared this experience with their children as well as friends, couples and other group visitors.

Children paid particular interest and excitement towards children's voices of eggs and young larvae, of which they intuitively associated with their young selves. An excited child kept interrupting an interview with his mother repetitively saying *"The voices were so cute!"*. It was a common theme between all the transcribed audio data how people expressed their appreciation of *"different voices"*. Although I was initially suspicious towards displaying the hive-activity sonification audio in background speakers, as it may disrupt the informative narrations in the headphones, but it actually supported the immersive experience as people felt inside a busy hive, and entertained those with no headphones on.

Educational & Playful

The informative narrations written by the beekeeper expert collaborator, which I recorded in different funny voices were perceived by visitors as both *informative* and *playful*. Visitors were observed smiling and laughing together through the Immersive Hive, then most carers were heard asking their young ones about what they *learnt* as they walked out. *"For children, it's perfect, because you can actually get an immediate response and they're like answers to your questions, it's hands-on, it's very informative, you want to know more about it and it's just a very* *different way of finding out that information"* (P2). Friends and family members were observed grabbing each other towards the Immersive Hive to share the novel excitement with them as trying out a new taste of food or playing a new game.

A few visitors expressed how the playfulness and the overall design of the Immersive Hive allowed them to 'conquer their fear of bees' allowing them to enter what felt like a real hive but without being afraid of real bees. A mother revealed that she brought her apiphobic 10-year-old son who suffers from 'fear of bees' to the exhibition hoping he would experience therapeutic fun and he ended up -unexpectedly- happily touching every single bee in the Immersive Hive to learn about what bees have to say to him. One visitor said that she had never thought she could touch a bee and talk to her. Most people stated that it is an effective engaging and novel educational tool for both children and adults, as well as some people with learning difficulties. One participant revealed: *"I am an aesthetic learner, so I actually have to touch things, so being able to touch it and then it tells you what it's about, I think that that's the best thing about it. It's good to be able to feel it. I think it tells you more than just reading about it"* (P3).

Future Enhancements

In addition to studying how people perceived and interacted with the Immersive Hive, it is equally important to question the limitations and potential enhancements that could benefit the Immersive Hive, in particular, as well as an interactive space in general. Although seamless interaction was magical and exciting to people, leveraging discoverability and curiosity, it still holds frequent questions of "What should I do?" and "Where should I touch?" plus suspicions of what would happen in response. The Immersive Hive was designed to have a mix between both seamless and seamful interaction to reduce such confusion. Still, people find it unusual to interact openly without specific boundaries. Most of the visitors were confused at first of what they *should* do, or how they *should* interact which was observed during the exhibition and raised during the interviews: *"I wasn't sure which one to press, so maybe the colour scheme or the graphics itself, as it wasn't very informing"* (P4).

This can be explained through the current GUI paradigm we are still living in and the contemporary WIMP interfaces imposed on all desktop, web and mobile applications where people expect visual clues such as buttons and menus to be clear and finite. However, this is contrary to many art and design disciplines where it is perfectly acceptable that some work might be ambiguous and unclear in part or in whole until viewed from a specific distance or angle, in specific lighting, or within a specific context. Moreover, seamless interaction is increasingly becoming acceptable in -ironically- VR (Virtual Reality) and AR (Augmented Reality) systems, where users interact more freely discovering the almost-boundary-less space. Perhaps the expectations of physical interactive technology will change as well in the near future as people get more accustomed to a new paradigm of interfaces embedded within their surrounding environment, surfaces and objects. In this sense, interactivity will be unwrapped over time and during engagement, revealing more as people discover new sensing and actuating elements of the interior space.

Other enhancements suggested included adding a translation option to support different languages for non-English speakers. Also, a few people commented on the lack of 'user identification' where the Immersive Hive had two headphones for each panel responding to any sensed input on that panel. Users expected that their personal headphones would play output in response to their own touch input while playing another output in their partner's headphone in response to their touch input 'on the same wall panel'. Although this is an understandable request, it is technically unachievable yet with the current technology to achieve such user identification seamlessly, even with multi-user multi-touch displays responding in audio output through headphones to distinguish and separate the input/output interaction from the same display.

6.3.6 Critical Reflections

During this situated study, I had the opportunity to: (1) design and create an interactive interior space using OUI materials; (2) investigate how people engaged with OUI Interiors; (2) examine their views on a large-scale interactive element (i.e. walls); (3) unwrap new ideas and opportunities of such OUIs; and (4) discuss and raise new challenges and considerations.

The collaboration with a digital artist and an event curator, on a completely different context, only scratches the surface of opportunities in which upcoming situated studies unwrap. This minimal intervention helped imagine what is possible and created a motivation for the deeper exploration in the rest of this chapter (see Sections 6.4 and 6.5).

This designed honey-sticky interaction and multi-sensory experience (including visual, audio, tactile plus honey-wax smell and taste!) yielded great feedback and huge engagement from museum visitors who got to interact with the touch-sensitive human-size hive-like wall panels, soft squeeze-sensing pollen and honey sticky hexagons reacting in sensational and informative audio feedback about the mysterious life inside the hive in bees' voices. This can be seen as a new form of interactive spaces, where the space is not only capturing our explicit commands, but is also talking to us, telling us about itself, in the first-person narrative.

New interfaces should challenge traditional perceptions. For example, touch input of the future does not necessarily have to stay in rigid (or bendable) glass emissive displays, but could take any shape or form, even that of a sticky honey wax. Soft sensing as well is quite appreciated by people, can be very easily stitched into fabrics and soft objects, and should, therefore, replace many current electronic sensors that we still try to embed in our designs and interfaces. It is understandable that the limitations of such a design involve a lot of novelty, whilst an everyday space would not involve such excitement and playfulness, and should be designed in dissimilar ways. Nevertheless, such designs offer helpful insights on new materialities, expectations, user perception and engagement.

Part II

Situated Studies in Design Practices

6.4 Enchanted Architecture

In this situated study, I brought the OUI design space to the field of Architecture in a week-long hands-on workshop. By engaging architects (both practitioners and students), I was able to unwrap with them different ways of utilizing and embedding OUI materials into the building fabric as a means for designing interactive interior spaces.

6.4.1 Method

This study was with the School of Architecture at Newcastle University, UK in which there were 9 participants (3 final-year undergraduate students, and 6 postgraduates in different programs: MArch and MSc in Experimental Architecture) out of which there was 1 male and 8 females. The workshop was held over a week (five full days) and was located within my research lab (i.e. OpenLab), facilitated by three HCI researchers including myself as the lead researcher and investigator, and participants signed up willingly as a part of a pre-teaching 'Design Week'.

The objective of this study was to explore through architecture students three main aspects (which correspond to my overall research questions): 1) What OUI materials can be used? and how? 2) What can we design as an OUI? and 3) What can we learn by situating OUI Interiors?

Therefore, my method included three activities: 1) meeting OUI materials and hands-on exploration, learning and programming followed by an audio-recorded group discussion; 2) ideation using cards and sticky notes, where the ideas generated form part of the data set analysed; and 3) design challenge where a design concept is developed and built as an OUI interior space that is opened for the public, and observed. Although these activities were planned to be sequential and distinct from one another, addressing the main questions/objectives of this study was entangled and overlapping, as with my PhD research. For example, some ideas were generated during the first materials exploration activity, while further validation of the making techniques and choice of OUI material was mostly investigated during the design challenge. Several group discussions and brainstorming sessions took place in between these activities to allow them (and myself) to evaluate and critically reflect upon concepts of OUI Interiors.

The gathered data consisted of 8 hours of audio data, recorded during the workshop week, to which selective audio transcription was performed on 2.5 hours that formed the entire length of group discussions and presentations after each group activity. These transcriptions were then subjected to Thematic Analysis bringing out codes and themes in the data. The collected data was also supplemented by video recordings of the making process and the exhibition visitor interacting with the Enchanted Architecture space in addition to participants' sketches, schematic architectural drawings, textual written descriptions of their ideas and designs, and most importantly my observational notes taken throughout the sessions.

6.4.2 *Activity 1: OUI Materials Exploration*

Prior to this first activity, participants were briefed about the concepts of OUI Interiors and interaction design, then introduced to the array of OUI materials (discussed in Section 2.4), and taught how to control them using Arduino programming. The materials that I provided them in this activity included seamless sensing (conductive paint, thread, fabric, paper, metal powder and copper tape) in addition to flexible sensors (bend, pressure, tilt and accelerometer) and actuating (colour-changing thermochromics and shape-changing SMA wire) in addition to LEDs. They were also taught how Arduino can be controlled through a network feed (capturing online data, Wi-Fi remote sensors and environmental stimuli e.g. temperature, humidity or wind speed). The reason behind providing them with this variation of options (such as LEDs, Wi-Fi data and electronic sensors) was because I wanted to observe their preference versus OUI materials.

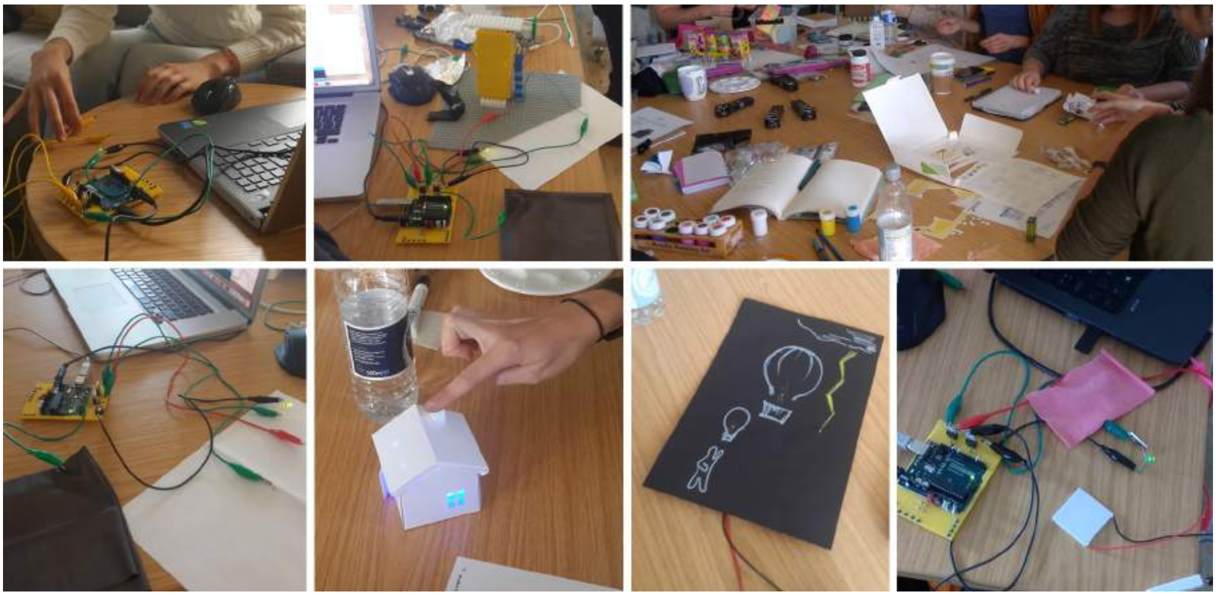


Figure 6.10 Crafting and programming during the Material Exploration activity.

Participants had the opportunity and time to not only examine the materials but to use them by themselves in crafting and making. To enable their exploration, I also provided them with other making materials and tools such as acrylic paints, brushes, play-doh, LEGO, origami-paper, fabrics, sewing tools, laser-cutting acrylic sheets and plywood. I have also given them complete orientations on using the laser-cutting machines in case they needed to use them. Moreover, I had prepared the Arduino microcontrollers in shield-like kits including two MOSFET-powered output pins and two capacitive-input pins. First, the basics of Arduino electronics and programming were introduced to them to facilitate their hands-on prototyping of different interactive OUIs. Then, they connected different combinations of inputs and outputs together. They wired the different capacitive materials and flexible sensors as input, and shape-changing SMA (Shape-Memory Alloy) muscle wires and controllable heating pads for colour-changing thermochromic paints as actuators (see figure 6.10).

6.4.3 Activity 2: Ideation

After exploring and playing with materials, participants were asked to work in groups discussing different applications of sensing and actuating interior architectural spaces on four different categories: spaces, surfaces (walls, floors, ceilings, windows, etc), furniture and decoratives. To aid the ideation activity, each group was given a random set of cards that show inspirational photos of architectural, interior and product designs. These inspirational cards acted as design probes facilitating imaginative thinking of 'what could be?' Eventually, few ideas were generated for both the 'spaces' (the whole) and 'decoratives' (the detailed), but rather participants focused on both the 'structural surfaces' and 'furniture'.

Figure 6.11 During the Ideation group activity with inspirational cards.

The ideation activity led to 37 different applications ranging from the simple obvious "window regulating indoor ventilation according to weather or pollution" to the creative and immersive "show warmest place in the house using thermochromic wall-paint" or "lighting sculpture that glows more the more the number of users connected to the Wi-Fi in the building". Table 6.3 and table 6.4 together show a summary of these ideas as inspirations for what could be designed as interactive interior elements from their (architectural) perspective. This ideation activity (see figure 6.11) helped unwrap the inherited features and attributes these applications incorporated. Their ideas were equally distributed among four types of interaction:

1. **Explicit Deliberate Interaction:** hand manipulation i.e. touch, press, in-air gestures, speech control.
2. **Implicit Motion:** motion (proximity/ moving around), posture (i.e. sitting down/ laying/ standing) and displacement (i.e. moving/dropping objects).
3. **Ambient and Autonomous:** surrounding environment (weather: temperature/ humidity), ambient conditions (sound, light, time, heat).
4. **Network-based Feed**.

	Category	What	Sensing		Actuating		Interaction Type	Purpose
			Literal	Meaning	Literal	Meaning		
1	Surface	wall	Air Pollution	Weather/ Pollution	Indoor Ventilation	Indoor Ventilation	Environmental	Functional
2	Surface	wall	Acoustic	Sound	actuates	shape-change	Environmental	Experiential
3	Surface	façade	Passing-by people	Proximity	changes ground floor façade	skin-change	Implicit	Experiential
4	Surface	window	smart glass	Weather/ light	opacity/shade	colour-change	Environmental	Functional
5	Surface	ceiling	movement	Proximity	brightness control	Lights	Implicit	Both
6	Surface	floor/ pavement	walking	Pressure	lights on/off	Lights	Implicit	Both
7	Surface	wall	Press Tile	Touch	Tile on another wall lights up (maybe overseas)	Lights	Explicit	Both
8	Surface	window	Humidity	Weather/ humidity	Indoor Ventilation	Indoor Ventilation	Environmental	Functional
9	Surface	floor	dropped object	dropped object	lights on/off	Lights	Explicit	Experiential
10	Surface	space	show warmest place in the house using thermochromics	Weather/ Indoor ambient temperature	thermochromics	colour-change	Environmental	Both
11	Surface	deck/ ceiling	Humidity/ water	Weather/ humidity	water-repellent but opens up with humidity	Indoor Ventilation	Environmental	Functional
12	Surface	floor	Proximity	Proximity	lights on/off	Lights	Implicit	Experiential
13	Surface	facade/ wall	Proximity/ motion	Proximity	lights on/off	Lights	Implicit	Experiential
14	Surface	floor	Pressure	Pressure	switches small lights at night	Lights	Explicit	Functional
15	Surface	space	fully sensible	Proximity/ Motion	Heat follows user	Indoor Heating	Implicit	Functional
16	Surface	window	CO2, temperature, humidity	Weather	Indoor Ventilation	Indoor Ventilation	Environmental	Functional
17	Surface	stairs/ floor tiles	pressed	Pressure	play music notes or glow LEDs	Lights & Sounds	Implicit	Both

Table 6.3 OUI design ideas generated by Architecture students (1 of 2).

6.4.4 *Activity 3: Design Challenge*

Through a multidisciplinary group of 9 architects (professionals and students) in addition to 3 HCI researchers, including myself as lead researcher, we moved from design experiments to designing for the real world. With the aim of designing and building an interactive interior space, we chose a gallery room around 6m x 4m (see figure 6.12). The design concept developed was: creating a playful experience in the form of an 'enchanted' interior, a cave-like dark room with hidden maze-like qualities, themed as 'Alice in The Wonderland', and augmented with

	Category	What	Sensing		Actuating		Interaction Type	Purpose
			Literal	Meaning	Literal	Meaning		
18	Surface	wall	touch cubes	Touch	Moves other cubes in playful wave but rests at night	skin-change	Explicit	Experiential
19	Furniture	chair	sit on	Pressure	turn on computer	Turn on device	Implicit	Functional
20	Furniture	door	when opened or closed	Movement of Door	detect people close by		Implicit	Functional
21	Furniture	sofa	sit on	Pressure/ Touch	ergonomics	shape-change	Implicit	Functional
22	Furniture	Toilet seat	stand up	Pressure release	flushes when done	Turn on device	Implicit	Functional
23	Furniture	bins	when full	Pressure	lights-up the night before they need to be put out	Lights	Autonomous	Functional
24	Furniture	plant pot	soil dryness or sun need	Weather/ humidity	regulates water or moves to stay in the sun	shape-change and Turn-on device	Autonomous	Functional
25	Furniture	chair	body temperature	Temperature (localized)	heats/cools and gets softer the warmer it gets		Implicit	Functional
26	Furniture	chair		controlled	unfolds from table to chair	shape-change	Explicit	Functional
27	Furniture	table	placing objects of dining table	Pressure	surface lights up	Lights	Implicit	Experiential
28	Furniture	sofa	sit on	Pressure	turns on TV	Turn on device	Implicit	Functional
29	Furniture	chair + Lamp	sit down	Pressure	checks light level around and regulates surrounding light if needed		Implicit	Functional
30	Accessories	lamp	dimmer switch	controlled	thermochromics shade	colour-change	Explicit	Experiential
31	Accessories	curtain		controlled	thermochromic fabric get opaque	colour-change	Explicit	Experiential
32	Accessories	light-ball	when pass by	Proximity	lights-up	Lights	Implicit	Experiential
33	Accessories	umbrella box	outdoor humidity	Weather/ humidity	lights-up	Lights	Autonomous	Functional
33	Accessories	kettle	water temperature	Temperature (localized)	tell if water is still hot from across the office	colour-change	Autonomous	Functional
34	Décor	wallpaper	daytime	Time	wallpaper colour and fairy lights	colour-change	Autonomous	Experiential
35	Décor	wallpaper			responds to sound		Environmental	Experiential
36	Décor	painting	heat sensitive	Weather/ Temperature	transforms from hot summer colours to cold winter colours	colour-change	Environmental	Both
37	Décor	sculpture	WiFi-connected number of users	External Feed	light glows more	Lights	Autonomous	Both

Table 6.4 OUI design ideas generated by Architecture students (2 of 2).

interactive installations and clues leading to the location of a treasure (a magical object). Based on the sensing and actuation techniques learnt, the team split into smaller groups to design and build six interactive installations to augment their interior walls with interactivity.

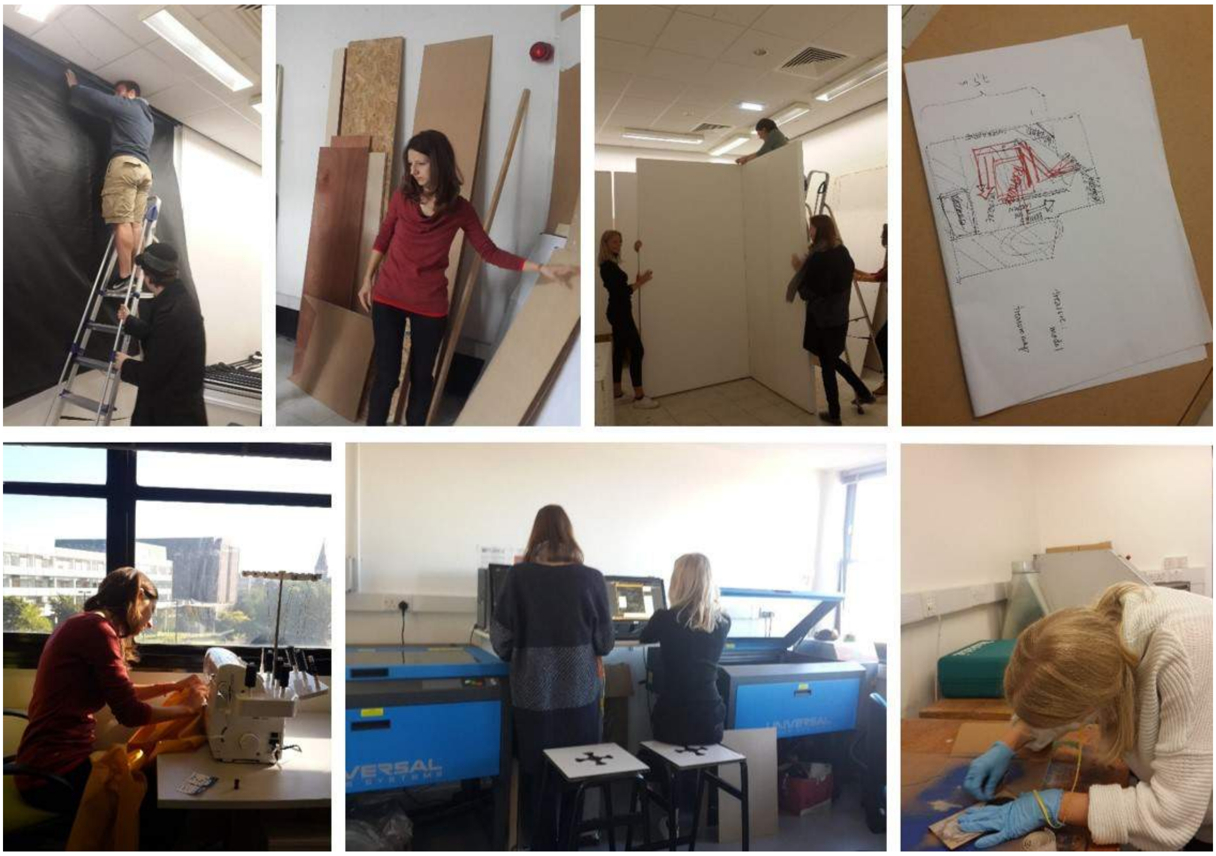


Figure 6.12 Designing and Building the Enchanted Architecture interactive space.

The six interactive interior elements were (see figure 6.13):

1. A tactile wallpaper/poster that used conductive fibre and paint to display audio feedback for users playing with it.
2. A touch-sensitive wood wall-panel using capacitive paint manipulating LED lights that shows an arrow for the right way in the maze.
3. A 2D cardboard light switch based on conductive paint, that activated a far away lighting sign showing users what to do next.
4. A hidden clue painted with thermochromic paint on a wall that only revealed the invisible treasure code when a connected corresponding pressure-sensitive chair was sat on.
5. A haunted (actuated) curtain that moved flipping cut-outs using SMA reacting to proximity sensing.
6. A treasure (i.e. actuated decorative centre-piece) designed as a mushroom model that activated (bounced cap using SMA wire and lights up LEDs) when a user entered the right code by dipping a finger in capacitive connected tea cups.

All designs were then installed and the room was opened for public visitors as part of a bigger architecture gallery evening event. The event was publicized around Newcastle University attracting visitors mainly from the School of Architecture, including academics, students and their friends.

Figure 6.13 The Making of interactive artefacts for the Enchanted Architecture interactive space.

6.4.5 Findings

The results of the data analysis can be articulated in three main themes, describing the unwrapped ideas, potentials and challenges of OUI Interiors. For anonymity, participants are referred to as P1 to P9.

Spatio-Autonomy & Context-Awareness

Participants mainly ideated around different context-aware functional uses for interactive interiors, rather than their aesthetics. For example, *"proximity activates lights leading the way to get*

Figure 6.14 Capturing visitors' response with the interactive wall-paper at Workshop 1 Exhibition: 'Enchanted Architecture'.

somewhere" (P4), *"curtains change opacity whether it was heated up or it was brighter outside, the curtains' back would become more or less opaque so the space would be more comfortable inside"* (P4) and *"if you walk by, chairs pop out so it reacts to you wanting to sit down"* (P5). Other functional purposes were also proposed for OUI artefacts such as furniture with context-aware ergonomics such as *"more comfortable furniture that shape your body"* (P3), *"reading chair checks and regulates the surrounding ambient lights"* (P6) and furniture responding to noise in the space or supporting space comfort: *"chairs would heat up or become more comfortable and soft the colder you are and then also get rather sturdy and colder if you're too hot"* (P5). Throughout the sessions, designers started thinking of and referring to interior objects as living things that have minds of their own e.g. *"when bins feel full they can tell us they need to be put out at the night before"* (P6), and *"plant pot that moves to stay in the sun"* (P6).

Playfulness vs. Calmness

Temporarily Playful: participants expressed how they feel OUI Interiors can be more appropriate for non-permanent installations (e.g. museum seasonal exhibits, shows, tourist sculptures/ attractions, retail stores, temporary entertainment). For instance, *"a lot of this is about the novelty, it's great when you've never seen it before and it's the first time, fantastic, but if that's on your wall forever, it kinda loses its novelty."* (P2) and *"it has to be things that are consistently useful rather than being sort of transiently entertaining"* (P6). So for exciting engagement, sequential interaction was discussed as a journey in discoverable scenarios. For example: *"you would touch something then it would tell you something to do next and then that does something else, for example it lights up and when you touch it, it tells you to jump around then when you jump around something else happens"* (P2).

On the other hand, architects suggested residences and permanent spaces should be designed with *calmness* in mind i.e. designing for permanent settings should be carefully considered to avoid boredom and/or frustration through creating hidden and/or calm interaction scenarios. Alternatively, participants pointed out how interior interaction can not only be pleasurable but provoking as means for promoting physiological well-being: *"what else could get people moving, for example, if you sat too long on a seat it would get really cold or really warm so that it would help you move like a little provocation somehow so not always pleasurable"* (P1).

Still, the design challenge showed how participants kept considering these two paths as an interaction 'double-edged sword' where designing a simple logic is too obvious, unimpressive and therefore not quite playful, while the complicated scenario is unintuitive and often incomprehensible to users. In the end, however, they succeeded in designing their enchanted exhibition in a way where visitors were observably enjoying the playful experience, commenting how it was a *"curious"*, *"surprising"* and a *"wow"* experience (see Figure 6.14). Although, unexpected user interaction behaviour for exhibit visitors was not uncommon, for example, some visitors were observed repeatedly touching everything as if playing a musical beat with interactive sounds and lights.

Design Constraints and Limitations

Scalability issues bring limitations to some designs: *"probably anything that is out in the rain but needs to be controlled by an electric current would become way more difficult to construct it and also would break much easier"* (P5). Other aspects such as the expectations of users were also raised: *"you don't want to make people lazy, you still want them to want to interact with things, but if everything is constantly being done for you, if you have sensors that tell you what the weather is like outside"* (P2), *"what if you want it to be brighter, what if you want to sit in the dark"* (P6), *"when you want the design to stop being intuitive and for you to then as the user to take over that"* (P2). Designs were also constrained by the simple but delicate materials that are quite easy to use and prototype with but lack the resilience required for a public installation, so careful considerations needed to be taken such as transparent coating of conductive paint, tight fixing of materials and soldering of electronic components.

6.4.6 Critical Reflections

Collaborating with architects yielded a productive framework to design interactive spaces. During this study, I had the opportunity to address my research questions with architecture students and to:

1. Investigate how they experimented OUI materials and examine their views on the appropriation and applicability of OUI.
2. Explore new ideas and potentials of such OUIs and discuss and raise new challenges and considerations arising from scalability.
3. Design and implement six different interactive artefacts using OUI materials to create an OUI interior space with an enchanted theme.
4. Capture visitors' user experiences (in a situated deployment) with the OUI interior developed and observe their interaction behaviour with OUI artefacts.

Although not structurally dynamic or adaptive, the space designed and constructed was context-aware with embedded interactions within the walls, furniture (sensitive seat) and interior objects (enchanted treasure: cups and center piece) using Arduino microcontrollers controlling motion sensors, tactile conductive, shape-changing and colour-changing materials.

What slowed down the design process at the beginning was their need to visit and check the physical location, which wasn't ready from Day 1. A lesson learnt is how the site visit is a crucial starting point for interior architects to be able to conceptualize any design. This should be considered by interaction designers wishing to collaborate with architects to create an interactive space i.e. having the physical space ready beforehand and scheduling the site visit at the very beginning. Another lesson learned from this situated study regarding the visitors' reaction and behaviour within the exhibit: not all people should be expected to act in the same normal way. Similar to the Immersive Hive situated study, some visitors were overly cautious while gently touching the touch-sensitive walls, while others were too intense and rough (consumption of wine was involved!). A good interaction design should therefore take such variation of user behaviour into account.

6.5 Interactive Theatre

This final situated study brought OUI materials and artefacts to the field of Interior Design in a studio-based workshop to explore designing OUI spaces in different interior settings designed for disparate contexts.

6.5.1 Method

This situated study took place in the School of Interior Design, Faculty of Arts and Design in Northumbria University where 36 final-year undergraduate students (7 male and 29 female), participated in a full-day workshop in their own studio space, together with 3 HCI researchers to facilitate the planned activities, including myself as lead researcher. The research goal was to explore with them the potentials of OUI materials in Interior Design as a means of designing interactive interior spaces in different contexts and using different contemporary finishing materials.

Similar to the 'Enchanted Architecture' method, my aim from this final study was to address my research questions through the interior design students. Therefore, my workshop schedule was planned in three activities: 1) OUI material exploration; 2) developing OUI ideas; and 3) designing OUI Interiors for a specific situation. These three activities (similar to the Enchanted Architecture) correspond to my three research questions.

Between these activities, audio-recorded group discussions provided rich data consisting of 1.5 hours of audio data, transcribed in full including the entire length of group discussions and presenting back after each group activity. The collected data is also supplemented by participants' sketches, schematic architectural drawings and textual written descriptions of their ideas and designs. Again, my field notes and observations of different activities constituted a significant part of the gathered data. Such data was then subjected to a process of Thematic Analysis (Braun and Clarke, 2006).

6.5.2 Activity 1: OUI Materials Exploration

Unlike the 'Enchanted Architecture' workshop which was stretched over a full week, this workshop was planned to run for a day. To compensate for this lack of time and get a head start, I created a set of design probes with different OUI materials instead of providing students with the raw materials. For demonstrating OUI materials to interior design students who are accustomed to material samples from different suppliers, I prepared four OUI artefacts that would show tactile input, colour-change and shape-change output each embedded in standard interior design materials that students may be more familiar with.

For example, I designed the 'Tactile Palette' as a design tool to demonstrate to designers a variety of possible embedded capacitive-sensing in the form of a physical wooden palette, including sensing wood sheet, wood engraving, fabric, leather, fibre, thread, paint, glass, acrylic and ceramic tile, using flexible conductive materials underneath such as capacitive paints, fabrics

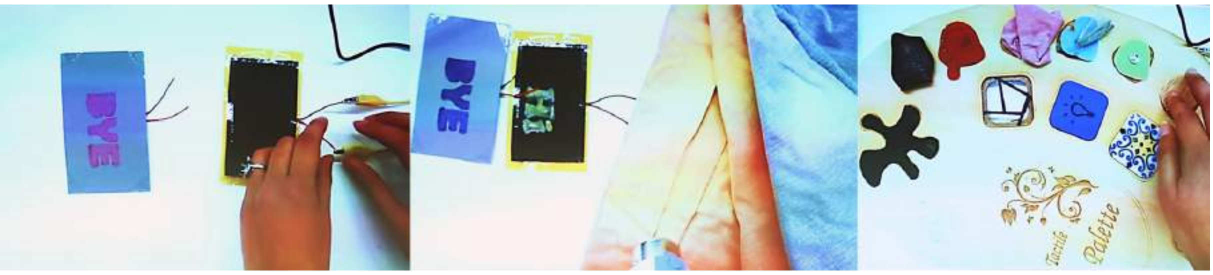


Figure 6.15 Exploring OUI materials in the form of design probes and OUI artefacts.

and metal powders (see figure 6.16). Other probes included shape-changing fabric using SMA wire and colour-changing cards using thermochromic paints and embedded heating pads (see figure 6.15). In this activity, students were divided into groups, each exploring one of these interactive design probes on a table, then rotating to take turns, exploring all of them. These prepared OUI artefacts helped in rapid learning, exploration of physical interaction and how such materials can be embedded into their normal interior designs.

Figure 6.16 Tactile Palette: a design tool for introducing seamless-sensing embedded within different interior finishing materials (e.g. wood, fabrics, leather, glass, acrylic, ceramic).

6.5.3 Activity 2: Ideation

This group activity was designed in a way that is closer to how interior designers work. Their methodology is mainly about how a design concept would be developed based on a series of fixed

Space Context	*Finishing Material*	*Sensing*	*Actuation*
Education	Acrylic	Surrounding (Sound/ Smell)	Change Shadow
Clinical	Glass	Motion Sensing	Change Skin (Colour/ Pattern)
Entertaining	Fabrics	Environment (Temperature)	Activate Sound/ Light
Retail	Wood	Bio-sensing	Change Physical Shape
Residential	Metal	Seamless Sensing	Change Skin (Style)
Eatery	Paint	Pressure Sensing	Change Skin (Texture)
Historical	Paper	Environment (Humidity/ Rain)	Activate Motion
Office	Tile	Environment (Wind/ Sun-Light)	Activate Vibration

Table 6.5 Design Concept Jigsaw parameters: interior contexts and finishing materials with sensing and actuations.

constraints such as space or building typology, in addition to a set of parameters which allow for creative exploration. As I wanted to explore designing different interactive spaces, I had a set of space contexts (educational, clinical, entertaining, retail, residential, historical, office and eatery). I also wanted to explore the possibilities of embedding a variety of the normal interior finishing materials (wood, metal, paint, acrylic, glass and fabrics) with sensing and actuation capabilities. Data sensing include seamless sensing, implicit motion or pressure, bio-sensing, environmental conditions, and ambient sounds or lights, while actuation may include change in physical shape, colour, skin, style, pattern or texture, and activating feedback such as sound, light/shadow or motion.

Table 6.5 shows the parameters of the 'Ideation Jigsaw' as an array of interior contexts and finishing materials with sensing and actuation interactions. Consequently, I designed the 'Ideation Jigsaw', a design tool in the form of a six 3x3 jigsaw puzzle (i.e. 9 pieces). Each Ideation Jigsaw contains four pieces (from the set of space contexts, finishing materials, data sensing and actuation effects) that are pre-defined as a means of constraining the design with some boundaries, and four other pieces left as variables they can decide: (*who* are the users, *what* is the interactive surface or object, *when* will it transform or trigger reaction, and *why* will it do that).

With these four constraints and four variables, plus a middle piece for the design concept, each group would have nine random pieces to help define their interactive interior idea (see Figure 6.17). This method resulted in a variety of ideas with different combinations of interaction attributes (users, inputs, outputs, context, usability and user experience).

The result was impressive as using this technique proved to be a rapid ideation method allowing creativity yet bounded to some constraints. After a few minutes, each of the six groups developed a creative idea of an interactive interior design as following:

1- 4D Cinema: a cinema hall that changes colours and patterns of sound-proofing fabric covering walls and floors based on ambient sounds and/or light of the movie scenes creating immersive story moods for enhancing people's movie experience, plus seats that could have glowing seat numbers for late audience.

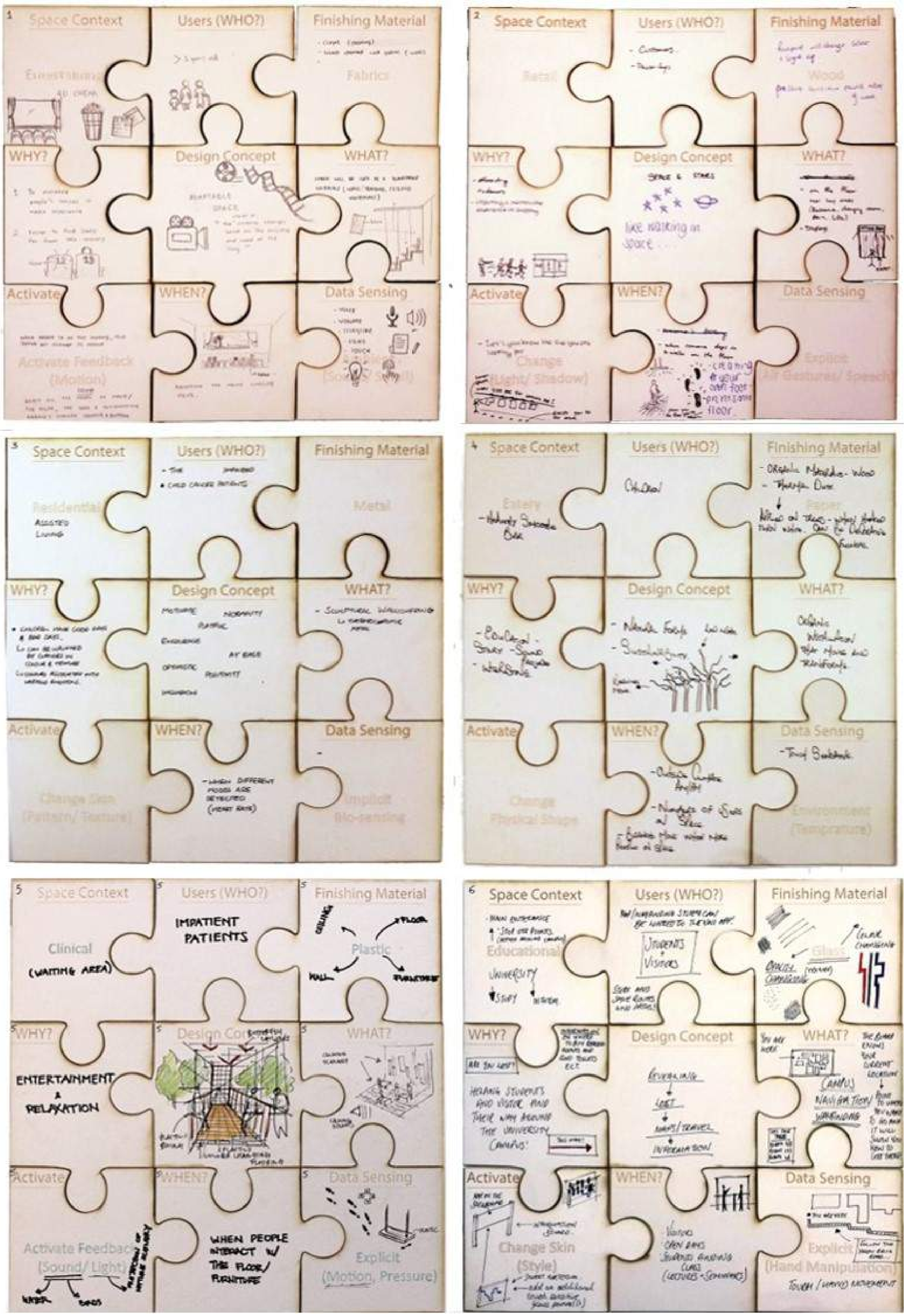


Figure 6.17 Ideation Jigsaw: a design tool for supporting the development of design concepts to OUI Interiors.

2- Shopping in Space: glowing footprints of retail customers would appear on the pressure-sensitive wood floor near key areas (entrance, stairs/lifts, changing rooms) visualizing their flow as they step-in and wander in the shop, could also direct them to the area they want, then fading over time. Hangers could also glow to direct customers to their size reacting to speech, all for creating a memorable experience in shopping.

3- Sensory Assisted Living: texture-changing (uplifting) and colour-changing (associated to emotions) residential object (water cube sculpture/ wall covering/ floor/ toy tunnel) responding to bio-sensing and facial expressions of special needs (impaired/ blind/ child patients) when different moods detected (through heart rate and biometric measurements) by kinetic changing patterns and textures to turn their bad days into good ones, motivate, encourage positivity, optimism, inclusion, normality and playfulness.

4- Healthy Smoothies Bar: an eatery for children designed with organic installations (i.e. trees) that move branches, glow LEDs and transform colour when heated based on busy rate and day/night temperature, for educating kids (healthy nutrition awareness, sustainability) and adding an interesting feature that -when moves- unleashes a story.

5- Butterfly Clinic: a clinical waiting area designed as a butterfly garden for impatient patients where pressure-sensitive floor panels (hanging bridge), walls or furniture could produce nature sound effects (birds, grass stepping, waterfall) and display calming nature sceneries, responding to user interactions such as moving around and sitting on motion-sensitive swings and passing underneath ceiling butterflies will move their wings, for relaxation and entertainment while waiting for their turn or stressful waiting for their relatives.

6- Campus Navigator: an interactive wayfinding/ outdoors map navigation system embedded across a university campus that stores and shows students and visitors different routes and paths on opacity-changing glass panels that are touch-sensitive to allow users to point to where they want to go and it shows the path on the interactive glass panel in front of the map background board offering information for lost visitors or students on open days directing them to classes, refreshments, toilets, etc.

6.5.4 Activity 3: Design Challenge

During this final activity, I was looking into situating the ideation and design of students with a specific design concept. They were given a design brief earlier in their module study situated around designing for the 'Pan's Labyrinth' theatre setting. I incorporated their brief into this activity with a design challenge to use OUI materials to create interactive theatre settings. Participants were split into five groups where they worked on theatre set designs to achieve two main goals: 1) immerse the audience within different scenes and 2) create changing scenery through OUI materials (shape-changing SMA and colour-changing materials). The five groups discussed different ideas of turning the Pan's Labyrinth theatre set into an *OUI interior space*. In order to do so, they utilized an array of *OUI materials* into the design of different surfaces and *OUI decoratives*. As a result of this activity, five different interior designs emerged and were sketched down to present as potential OUI interior designs in the given context, see figure 6.18, responding to the lead character in the play (a girl) and her surrounding environment (supporting actors, animals, audience, etc):

Group1 (War Scene): Use conductive fabric integrated in a sandbag to trigger different effects within the scene such as explosions and light effects, creating an integrated way of performing. Using light and photochromic fabric to change atmosphere of the scene from colourful to dark dingy scene or descending mist on stage activating hydrochromic fabric changing colour of the uniforms from crisp clean to military style gear which is important within that scene. Trees in the scene would actuate using SMA wire instead of being static elements. Use photochromic foot prints illuminating way-finding within the dark theatre. Back-seat panels to produce special effects like smells and gust-air to simulate different senses.

Group2 (Death/Last Scene): Use revealing concept to create a scene of stages where the prominent circular back window that lets a lot of light in would react to the death of the lead character by turning dark once she's shot, colours would be dark, gloomy and dingy. The back wall will use SMA to crumble like rocks break away piece by piece then the wall would reveal another appearance for the next scene, then colours would convert to reveal the golden heaven kingdom. Ink that appears when she opens the book with narrative aspect could be a giant book that reveals the story using thermochromics when pages flip, and footprints of different characters (e.g. fairies) would appear to make it magical.

Group3 (Opening Scene): When she enters and steps on the grass, it will react to produce sound and spotlight to shine on her and follow her as she walks in through the stage, and hidden pressure-sensitive buttons activate the curtain rolling down. The scene where she draws a doorway with chalk will reveal the perspective view through thermochromics. Similarly, when she reads the book, it reacts by revealing pictures of her future when she touches it.

Group 4 (Labyrinth Pit Scene): when she enters and moves across the stage it will look like she's descending into the pit without actually moving down, using two interlocked circular slanted structures start off both inline then create focus-transition effect between two spaces. SMAs hanging from the ceiling creating moving leaves of the forest, and change the shadows behind them as they move, as if the sunlight is coming through. Pressure-sensors on stage spark the noise of the forest at night.

Group 5 (Crawling under Tree Scene): getting the audience to make assumptions on what will happen in advance. Create a tree that had dead leaves and flowers that would come to life and open up using SMA to open and close thermochromic fabric flowers and leaves so that when it opens it starts slowly changing colour as well. As she crawls, the sensitive floor will glow beneath her in the dark stage, reflecting the frog scene, creating that sense of mystery. Mapping what is on the stage sets off another response in the cafe or box office, such as glowing footprints of actress, frog and fairies.

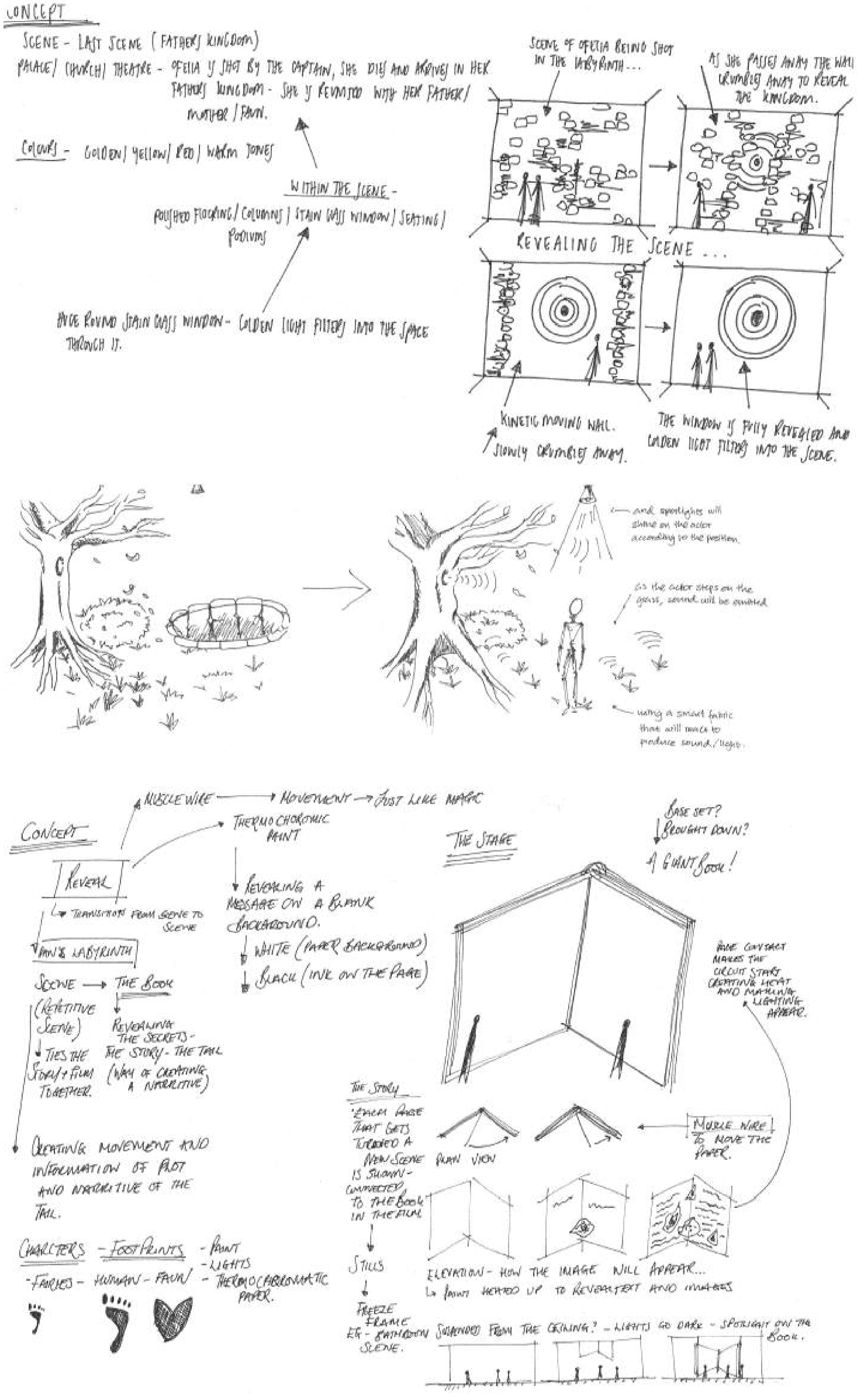


Figure 6.18 Some sketches from the Interactive Theatre situated study drawn by participants during the Design Challenge.

6.5.5 Findings

The result of thematic analysis process was four main themes described in detail in this sub-section.

Special Effects: Light/Shadow, Sounds and Smell

One of the main themes that was clear throughout the data gathered was how designers focused on embedding special effects when asked to design for interactivity. Four out of the five groups used sound and light as means of output feedback/ interaction. Other effects such as smoke and smell (odour) were also used for a more immersive experience. Light was used in the form of both spotlights and illuminating objects and floors as means of grabbing attention and/ or changing focus from one area or action to another. Personal light was also created to follow the user e.g. *"to shine on her and follow her as she walks"* (G3). Sound effects were often triggered by implicit actions such as walking, stepping and approaching something or somewhere as means of immersive experience engaging different senses. Controlling both sound and light together was a clear theme across different designs with response to motion and other implicit user input, and were considered a bold mix of actuation effects that instantly captures user attention. Shadow was also manipulated with light to create a sense of depth as per *"as if the sunlight is coming through with a dappled shadow-lighting effect"* (G4). Sound and light were also used separately as inputs to trigger other actions e.g. *"once she's shot.."* (G2), not just an output interaction. In this sense, one interaction can open the way to another, allowing the interior space to conceal and reveal interactions, unfolding as the user digs up embedded sensation/ interactivity and get exposed to hidden discoverability within the space.

Exploring Materiality through Tactile Sensations

All six groups were clearly enthusiastic about embedding sensation within the fabric of their interior design, using both capacitive materials and pressure sensors. Pressure-sensitive floor tiles appeared popular as four groups designed them in different ways considering them a form of *"hidden buttons"* (G3) that can control or activate some interactive features in seamless ways. Apparently, they all wanted their interior to have motion detection as a means of implicit input that is either deliberate or not, such as walking, approaching or entering somewhere e.g. *"when she enters and steps on the grass"* (G3), *"when she gets to the centre"* (G4), and *"as she crawls on the sensitive floor"* (G3). Others embedded pressure-sensing seamlessly within the fabric of soft decorative objects e.g. *"conductive fabric integrated in sandbags can trigger explosions and light effects of the war when stood on creating an integrated way of performing"* (G1). Other designs of embedded sensing included manipulating interior objects such as: *"when she holds it"*, and *"when she touches it"* (G3). Another interesting code was found as OUI Interior would not only reveal *living* qualities, but *dying* as well: *"would react to her death by turning dark"* (G2) meaning that death can be sensed and can trigger the 'aesthetic death' of the interior space of its owner for a mourning time.

Communicating Through Colour-Change

Realizing their disparate properties, participants used a variety of colour-changing materials in their designs to be triggered at different conditions/inputs. Using photochromic footprints murals (triggered by light in the dark) on the floor was repeatedly thought of as means of immersiveness leaving a glowing mark behind to be faded over time, even that of imaginary or distant characters/users who do not necessarily exist within the same space e.g. *"creating that sense of mystery"* (G5) and *"would appear to be magical"* (G2). Hydrochromic dyed fabric was used to respond to mist, and thermochromic paints and dyes were used on walls, fabrics and decorative artefacts. Two main reasons were behind using colour-changing interaction in all designs: 'revealing' and 'reversing'. 'Revealing' a hidden story, text, picture or view was a noticeable objective behind embedding colour-change in different interior elements and composed an essential part in designing discoverability within the space. For instance, *"ink that appears to give a narrative aspect to the hanging book that reveals the story using thermochromics when pages flip"* (G2), *"it will reveal the perspective view through thermochromics"* (G3) and *"it reacts by revealing pictures of her future when she touches it"* (G3). On the other hand, 'reversing' was the aim of integrating colour-changing materials to change the atmosphere, the feeling and appearance of the space between three states normal/default, cheerful/colourful, and dark/gloomy on both the background (walls) and the foreground (objects) accounting on the psychological effects and social-norm interpretations of different hues of colour schemes. For example, *"to change the atmosphere of the scene from colourful to a dark dingy scene"* (G1) and *"once she's shot, colours would be dark, gloomy and dingy.. then colours would convert to reveal the golden heaven kingdom"* (G2). During the discussions, colour-changing materials were considered appropriate to show the unseen such as mapping distant unseen actions or conditions.

Shifting Focus Through Shape-Change

SMA was mainly used to add dynamics to decorative objects that already exist in their designs and was explicitly justified by adding automated vibrance to the interior. For example, *"trees in the scene are actuated using muscle wire instead of being static"* (G1) and *"The back wall will use SMA to crumble away like rocks break away piece by piece without anyone moving anything"* (G2). Kinetic actuation, in general, was also used to allow a focus-shifting effect between two spaces, scenery transition and revealing a hidden appearance. Another usage of kinetic actuation was to create an illusion of spatial movement: *"it would look like descending into the pit without actually moving down"* (G4). SMA muscle wire was not just used for shape-change but to activate ambient subtle motions that could manipulate light shadows underneath: *"as it [SMA] moves, it would change the shadows behind it, as if sunlight is coming through with a dappled shadow/lighting effect"* (G4). However, SMA was mostly considered for an organic actuation effect due to its linear lift and bend nature that resembles a subtle breath motion, so most groups embedded SMA within artificial flowers and tree leaves for ambiance. When integrated within thermochromic fabric the combined effect of shape-change with colour-change attributed to creating a living scenery: *"dead leaves and flowers would come to life and open up using SMA to* *open and close thermochromic flowers and leaves so that when it opens it starts slowly changing colour as well"* (G5). This technique actually utilized the same energy source/ wiring that heats up the SMA to implicitly heat up the thermochromic fabric triggering colour-change as well, so a flower would blossom and brighten at the same time, as if alive.

6.5.6 Critical Reflections

As much as they succeeded in designing with the concept of 'Revealing', other findings included the difficulty of designing for 'Reflection, Speculation, Legibility (Indirectness) and Para-Engagement (Extra-involvement)'. For example, G5 mentioned that during their brainstorm: *"we thought getting the audience to make assumptions on what will happen next in advance"*, then they tried to frame it in other ways *"like mapping, so what is on the stage sets off another response in the cafe or box office"* and even *"get the audience to be part of the play, so what they do reflects on the stage or what actors perform can be projected around the audience, reflecting what happens in the scene"*. These 'para-engagement' types of designs create a deeper meaning of involving the users within a public space and takes engagement and interactivity to a level that is beyond the traditional direct interaction that is obvious, discoverable and legible. However, they did not actually design much of these insightful preliminary ideas. Perhaps due to their complexity, deepness and unconventional nature.

While designers in the previous situated study (Enchanted Architecture) expressed more elaboration and interest on the 'structural' scale of surfaces (walls, floors, ceilings) and furniture, designers in this case study (Interactive Theatre) had a perspective of the 'ambient' scale, joining both ends of the holistic view of the 'space' and the decorative details/ accessories that essentially contribute to their conceptual design identity and experience. This is because architects more naturally consider building related aspects, and interior design students more naturally consider decorative aspects, in addition to the 'theme' at which each particular case study was framed upon. Therefore, clear and careful consideration of the setting and subject of collaboration with interior architects and designers is highly recommended to yield both 'functional' and 'experiential' applications and domains to enable the emerging of a new generation of interior designs.

6.6 Summary

This chapter finalizes my entangled research activities of material explorations, artefact prototyping and situated studies as the ultimate objective of this project is to explore the design space of OUI Interiors in terms of materials, designs and contexts. In this chapter, I have presented my five situated studies of OUI Interiors. Three of which were real-world deployments evaluated by members of the public and volunteering participants, while two more studies placed OUI materials and artefacts within situated studies with architects and interior designers.

These situated studies generated knowledge for OUI interiors, their design and critique on several levels, in both real-world deployments and design practice settings. Not only did situated studies in different contexts contribute to a stronger understanding, but also the different interior decorative elements designed had an evolving rationale and explorational terrain. For instance, both ActuEaters mostly employed shape-changing interaction, BacterioChromic (predominantly) utilized colour-changing interaction, while the Immersive Hive focused on seamless-sensing. During the ‘Enchanted Architecture’ and the ‘Interactive Theatre’ studies, all these OUI interaction paradigms were mixed and intertwined together in the same design ideas in richer spatial contexts. Each study added a new understanding aspect and another exploratory layer of this investigation:

1- The *ActuEating* studies took interactive decorative elements (table-runners and tableware) into four in-situ deployments in two restaurants, a café and a real-world home, exploring the sense-making, complex interaction repertoire, users’ roles and social engagement with and through OUI decoratives that blend into the interior space, but do more, such as generating humour and supporting rapport.

2- The *Adaptive Architecture* gallery situated BacterioChromic with other interior elements in a ‘Home’ display setting, allowing me to explore with people the interactivity, materiality and aesthetics of a crafted piece of interactive artwork, that can do more, such as raising awareness and public engagement in health-related topics.

3- With *Immersive Hive*, I advanced my designs into the scale of a space (rather than an object) and added more sensory interaction, such as texture, smell and taste, in addition to employing sound and light, to explore people’s engagement in an ‘immersive experience’ of an interactive space, that could have a playful-educational application.

4- The *Enchanted Architecture* brought my research to the field of Architecture and, during a whole week, engaged, taught and collaborated with post-graduate Architecture students in hands-on workshop sessions on designing OUI Interiors using raw OUI materials. Finally, we built an interactive space, with several interactive elements (i.e. wallpaper, furniture and decorative objects) opened to the public, observed and analysed.

5- The *Interactive Theatre* took this paradigm to the field of Interior Design, through interactive artefacts and design tools that I created (e.g. Tactile Palette and Ideation Jigsaw), teaching interior design students about OUI materials, artefacts and spaces, supporting them to develop novel design concepts. The result was a rich set of ideas in addition to designs of interactive interior spaces in a wide range of space contexts.

These latter two inter-disciplinary studies were held in collaboration with individuals in relevant design fields, all wishing to engage in and realize innovative designs with high fidelity but with seamless interaction, bringing technology closer to people's everyday lives. When redefining interior spaces as user interfaces, and when the interface disappears into the materiality of our real-world objects and environments, we need to start reconsidering many interaction design fundamentals. In this sense, user interaction is immersive rather than focused, when interacting with spaces rather than devices or wall-sized interfaces rather than screen displays.

Moreover, the collaborations with relevant design practices were aimed at addressing radical interdisciplinarity and challenges of 'immersiveness of interaction' by bridging the gap between involved parties as an essential requirement for realizing the vision of OUI Interiors. This also helped to create and evaluate new arrays of interaction techniques that are scaled to room size or entire interior space, but are still tangible and enchanted, an interaction that is immersive and playful but at the same time not hidden or perceived as completely random.

The following final chapter (Chapter 7) provides a detailed discussion of such findings from all the situated studies held throughout my research, binding and tying up the threads of this thesis and presenting the interconnected and interrelated insights and knowledge gained throughout.

Chapter 7. Discussion & Conclusion

In the previous chapters, I have presented my body of research work in terms of: 1) the experience of making with OUI materials (Chapter 4); 2) crafting an array of inspirational artefacts to show designers what can they make (Chapter 5); and 3) a number of situated studies in both real-world setting and design practices (Chapter 6). Herein, I finalize my thesis with a critical commentary on the future of interactive interiors with the knowledge gained from all of this collective design research work.

This research aimed to explore the design space of interactive interior design framing this exploration in terms of future opportunities and challenges. More specifically, I have shown in previous chapters how smart materials can be utilized to support new interactions in interior designs in the following ways. First, I introduced the aims and objectives of my investigation, the three key research questions and the motivation for exploring Organic User Interfaces as a paradigm for interactive interior design (Chapter 1). Following this introduction, I contextualized my area of enquiry by examining and reviewing relevant previous work in both research and practice in interactive interior design and decoration as well as interactive materials (Chapter 2). This grounding of the state-of-the-art of OUI design and development constitutes an understanding of interactive spaces and decorative artefacts, and begins a voyage towards my research aim to "*Explore the design space, potentials and challenges of creating interactive spaces with OUIs?*". After this theoretical positioning within the wider practice and scholarly context, I then outlined the key research methods I used throughout my PhD research. Within a research through design approach, I discuss my methods in three methodological strands: critical making, critical engagement and critical speculation (Chapter 3).

Addressing my first research question of "*What interactive materials and making techniques can be used to design and build OUIs?*", I then introduced the body of exploring an array of OUI interactive materials in addition to developing a range of crafting techniques explored over the course of this research, with a specific focus on seamless-sensing, shape-changing and colour-changing materials, as individual threads (Chapter 4) which contributed to the development of interactive interior design practice of this thesis.

During this hands-on exploration, I concurrently designed a number of interactive decorative artefacts that range from an actuating table runner, an interactive wall-art, pattern-changing wall-tiles, an actuating furry throw, a shape-changing vase, a colour-changing cushion and matching painting, a shape-changing rug, soft objets d'art and curtain with tactile-sensing tasselled fringe. Each of these interactive decorative elements is described from the ideation and design concept to the crafting and making process in terms of materials and techniques. This work (presented in

Chapter 5) directly responds to my second research question "*What OUI decorative artefacts and interior elements can we create?*". By introducing such design work in a decoration catalogue format, I presented inspirational artefacts for designers who wish to explore OUI Interiors and unwrap its opportunities.

Then, I introduced situated studies that were held in parallel to this design research together to tackle my third and final research question "*What can we learn for design by situating OUI interiors?*" (Chapter 6) exploring different aspects of OUI Interiors from user sense-making, interpretation and engagement to the materiality, interactivity and multifaceted aesthetic qualities. In this sense, I was looking at the bigger picture of designing interactive spaces, holding five case studies, engaging with users, architects, interior designers and digital design, bringing design disciplines into collaboration with HCI to scaffold interior designs with OUI materials, whilst designing interactive interior spaces. In each case, I utilized my developed techniques and created design tools/ probes for supporting their understanding and exploration (of OUI materials) to design OUI spaces and artefacts.

This final chapter continues by revisiting the case studies and tying the threads of this research together in an overall critical reflection on designing OUI Interiors. In doing so, I revisit the previous literature and present a critical commentary on my work in relation to the context of the state-of-the-art. By doing so, I have reached my initial aim to **explore the design space, opportunities and challenges of creating interactive spaces with OUIs**. Section 7.1 explores this *design space* in deep reflection and thorough discussion. Then, both the design *opportunities* (Section 7.2) and *challenges* scoping future research (Section 7.3) are discussed before articulating the conclusion (Section 7.4) of this research.

7.1 Overall Reflection

Looking back in retrospect, I revisit my research questions, in this section, and present the key findings in my research that tackle each question respectively, in light of the previous work, showing how it was further extended and advanced.

7.1.1 What interactive materials and making techniques can be used to make OUIs?

To address this research question, I have surveyed interactive materials that are: 1) deemed seamlessly embeddable (i.e. paintable, sewable, weavable), 2) can be electronically programmed and controlled, and 3) offer substantial potential for making objects interactive while keeping their aesthetics and utilizing their natural deformability and affordances. Consequently, I was able to develop a taxonomy (see Section 4.2) of OUI materials that can be embedded seamlessly in the material finish of interior decorative elements, including tactile sensing, colour-changing and shape-changing materials that integrate with and complement the interior design scheme's texture, colour and form respectively.

Then, through critical making, I experimented with these OUI materials in different ways, exploring the potentials of creating aesthetic artefacts with calm and organic interactive capabilities, crafted in seamless ways, moving beyond intrusive technology. Through my extensive experimenting, I have developed a range of novel techniques for crafting sensing, colour-change, shape-change and circuitry components with soft OUI materials. My crafting techniques have productively built upon previous work (Perner-Wilson and Buechley, 2010b; Devendorf et al., 2016; Hamdan et al., 2018) by machine-sewing sensing, colour-changing and shape-changing threads/wires.

Moreover, my techniques extend previous work on SMA shape-change by examining deformational parameters affecting the fabric's morphological effect, enabling organic actuations such as bend/unbend, swirl, twist, roll/unroll, curl, crumple and crease. From observations of experiments machine-sewing SMA to fabrics, 10 parameters were realized as the impacting factors that control the deformation intensity: fabric type, thread type, stitch type, sewing pattern, wire type, wire austenite, wire martensite, fabric orientation, wire length and its distance to the fabric edge. This employs and reflects the quality of crafting methods as techniques for embedding actuation by stitching it directly to fabric finishes of *everyday* soft interior elements, contrasting previous notions that argued for a need to create novel computational composites and peculiar materialities.

The swatchbook that I have created (see Appendix A) is a physical representation of this contribution, including the range of experimentations of crafting and making with OUI materials that I have explored. This annotated portfolio collects the pieces of my evolving learning in the physical swatches that have been embedded with an OUI material as means of experimenting its interactivity. Every page of the swatchbook presents a certain (set of) sample(s) or swatch(es) with annotations of the material finish, the OUI material used, its dimensions and properties, the crafting technique used, its interactive behaviour, a drama index (i.e. rating the extent of

Related Work	**Intuitiveness** Sensing Method	**Calmness** Output Mode	**Situated Study** Research Environment
*ActuEater2 (Nabil et al., 2018a)	Physical Sensing	Peripheral	Real World
*BacterioChromic (Nabil et al., 2019)	Physical Sensing	Peripheral	Exhibition
FurryThrow	Physical Sensing	Peripheral	Showcase
ImmersiveHive	Physical Sensing	Focus-demanding	Exhibition
*Enchanted Architecture (Nabil et al., 2017a)	Physical Sensing	Peripheral	Exhibition
*Interactive Theatre (Nabil et al., 2017a)	Physical Sensing	Peripheral	Showcase
Stara Curtain	Physical Sensing	Peripheral	None
WaterFall Cushion	Physical Sensing	Peripheral	None
Morvaz	Physical Sensing	Peripheral	None

Table 7.1 Overview of implemented work in this research compared to related work in Chapter 2. Publications with * refer to full-length papers.

dramatic actuation) that I hence assign and finally potential applications in the design space of OUI Interiors. In the case of actuation, these records describing each sample are complemented by snap shots of videos of experiments, either transforming colour or shape.

7.1.2 What OUI decorative artefacts and interior elements can we create?

During my research, I have designed and implemented a range of interactive interior elements as inspirational designs, supporting designers wishing to engage with OUI Interiors. These inspirational designs provide a direct answer to this research question in terms of providing exemplary work of what else can be done. In doing so, I was alternating between different materialities, making techniques, and other practical challenges of making such as orientations (i.e. horizontal, vertical, diagonal and 3D) and usability concerns (i.e. folding away, sitting on, stepping over, hanging on the wall and pouring water into).

In addition, my inspirational artefacts of interactive interior elements extended previous work in terms of applying the OUI principles (Holman et al., 2006) of intuitiveness, calmness, seamlessness and robustness of withstanding situated studies (see Section 2.1). Table 7.1 shows how my work expands the design space of OUI interactive interiors based on these OUI principles in comparison to previous work shown earlier in table 2.1.

The decoration catalogue that I have created (see Appendix B) is a physical representation of this contribution, including the range of OUI interior elements that I have designed as inspirational artefacts for designers. To reflect back on my OUI designs, I review some of them below utilizing the four key design aspects: technical, aesthetic, experiential and rationale (see figure 2.2) that were used earlier to critically review previous work (Chapter 2).

The ActuEater (Nabil et al., 2018a): was an actuating decorative dining-table centre-piece (table runner) designed with the aim of studying the aesthetic experiences, material qualities and socio-physical engagement among people, through and around an OUI decorative artefact. Two ActuEaters were designed for this experiential purpose with shape-changing capabilities embedded within. While ActuEater1 had a minimalist design with white fabric and golden edge ribbon, used step-motors underneath the table-runner to actuate its shape and was remotely controlled in real-time, ActuEater2 was designed with more character in shapes, colours and autonomous interactive behaviour with its Arduino microcontroller, soft-sensing body, colour-changing fabric and embedded SMA wire stitched seamlessly within to -organically- morph its shape. Four deployments of the ActuEaters (in two restaurants, a café and a home) and subsequent 'design crits' showed insights into how people perceive, interpret and interact with such technology and pet it in interesting (and unexpected) ways, in addition to their reflection on a mechanical (SCI) and organic (OUI) interface in the two versions. The results of the 'ActuEating' studies provide evidence for how an actuating artefact that is seamlessly embedded in the interior spaces, matching its colour scheme and interior style, can be simultaneously a resource for social engagement, curiosity and playfulness, and an interactive decorative object.

ActuEater1 pushed the previous work of shape-changing tabletops (such as TRANSFORM (Ishii et al., 2015) and PolySurface (Everitt and Alexander, 2017)) into the interior design space of interiors with more focus on being embedded ubiquitously and aesthetically in the environment, as opposed to standing out as a separate *device*. ActuEater2 can be perceived as the evolution of the History-Tablecloth (Gaver et al., 2006) that couldn't be made in fabric at the time, and provides a deeper understanding from its situated studies (in hours as opposed to minutes, and in the form of design crits as opposed to short interviews) than the shape-changing coMotion (Gronvall et al., 2014). It was informed by the relevant work done on the DigitalLace (Taylor and Robertson, 2014) and TextileMirror (Davis et al., 2013), on soft, calm and seamless actuation, although neither were subjected to a situated user study. Moreover, I was inspired by the 'Interactive Decoration for Tableware' (Meese et al., 2013) study, and created the ActuSet tableware that complements ActuEater (both aesthetically and digitally), as physically interactive, not through camera code scan.

BacterioChromic (Nabil et al., 2019): was an interactive piece of wall-art with the aim of creating a tactile and living artefact that simulates interactivity with environmental stimuli presenting potential value for raising people's awareness towards AMR (Anti-Microbial Resistance), in an aesthetic form as part of the interior space. Inspired by the patterns of bacterial growth in Petri-dishes, BacterioChromic consists of six fabric elements individually controlled with Arduino that responds to touch-sensing and proximity via morphological capabilities, changing its patterns, vibrant colours and organic shapes using soft-sensing, SMA wire, colour-changing paints, threads and fabrics, all sewn together. This shows how a user interface with sensing-actuating capabilities can be crafted, designed and perceived as an art piece. Exhibited over 6 weeks, with 1285 visitors recorded, unexpected user behaviour was observed and people expressed curiosity, interest in its seamless sensing, living behaviour and craftness, aesthetic and artistic values as opposed to other electronic devices, in addition to reflecting on its organic actuation as opposed to mechanical actuation of other relevant work.

In this sense, BacterioChromic extended the 'living-like' capabilities of interactive homeware objects in previous work (Impatient Toaster (Burneleit and Hemmert, 2009), Escaping Chair (Oozu et al., 2017), the Earthquake Shelf (Selby and Kirk, 2015) and Thrifty Faucet (Togler et al., 2009)) to the design space of soft and delicate decorative elements such as a tapestry or a fabric wall-art. Moreover, it employed insights of embedding decorative art with colour-change (from AmbiKraf Byobu (Peiris et al., 2013) and Anabiosis (Tsuji and Wakita, 2011)) and embedding fabrics with shape-change (from MoodFern (Cheng et al., 2014) and Shutters (Coelho et al., 2009)) and extended their crafting techniques into replicable, predictable and scalable methods using sewing machines instead of hand stitching.

Immersive Hive: is another case study in which I moved from artefacts to walls, designing an interactive interior space that is themed as a beehive as part of a bees exhibition to raise the public awareness of pollinating bees and their mysterious lives inside the hive, through engaging and tactile ways. Capacitive touch-sensing and soft-sensing e-textiles were used to control the Arduino multi-sensory interaction (striking visuals, touch, smell, taste and sound) of human-scale wall panels showing adult bees, larvae and eggs in addition to soft pollen-like yarn, sticky honey wax, and their real-time audio feedback talking about themselves. The Immersive Hive aimed for not only designing an interactive interior space in yet a different context, but also to capture user experience and *test* the material and design potentials in a situated deployment with members of the public. Although not incorporating shape-change or colour-change, visitors of the exhibition reflected on their multi-sensory experience, the carefully designed bees' voice interaction, its potentials for playful education, the tactile and seamless sensing and the immersiveness of the space.

In this sense, the Immersive Hive extended the work of interactive walls that respond to sound, touch or hand manipulations in previous work (such as SmartWall (Farrow et al., 2014), LivingWall (Buechley et al., 2010) and LivingSurface (Yu et al., 2016)) and in practice (such as Hyposurface (Goulthorpe, 2000), EngagingSpace (Dalziel & Pow, 2015) and Light-Form (Rogers and Daniele Gualeni Design Studio, 2010)), by pushing the boundaries of the physical real-world environment through tactile playful interaction and socio-physical engagement in a situated well-attended study. In addition, the Immersive Hive employed new materiality, interactivity and tactility than my previous work, in the form of touch-sensing honey, smell, taste and sound.

Enchanted Architecture (Nabil et al., 2017a): was a 6x4 m gallery space designed (in collaboration with a group of 9 architecture practitioners and students) to create a playful experience in the form of an 'enchanted' interior, a cave-like dark room with hidden maze-like qualities, themed as 'Alice in the Wonderland', and augmented with interactive installations and clues leading to the location of a treasure (an actuating object). Again, using seamless sensing of conductive paints, shape-change using SMA and colour-change using thermochromic paints, six interactive interior elements were designed and deployed throughout the space to augment their interior walls with interactivity (i.e. touch-sensing wood panel, interactive wallpaper, pressure-sensing seat, colour-changing painting, shape-changing curtain and actuating decorative centre-pieces).

Although not structurally dynamic or adaptive, the designed space was context-aware with embedded interactions within the walls, furniture (pressure-sensitive seat) and decorative objects, building on previous work (such as EmotoCouch (Mennicken et al., 2014a), Long-Living-Chair (Pschetz and Banks, 2013) and Shutter Curtain (Coelho et al., 2009)). This design helped capture user experiences with an OUI interior space, and observe people's playful reactions and interaction behaviours with OUI artefacts. Nevertheless, it was aimed at bringing this paradigm to the field of interior architecture to yield new forms of interactivity with the interior space and develop ideas and designs for interactive interior spaces seamlessly using smart materials and crafting techniques. Through this case study, not only did I explore, with architects, the design space, potentials and limitations, but I also tackled new challenges inherently related to the larger-scale nature of this deployment, such as scalability, retro-fitting and multidisciplinary collaboration.

Interactive Theatre (Nabil et al., 2017a): was another situated study aiming to engage interior designers who wanted to go beyond the traditional direct interaction that is obvious, discoverable and direct/legible in their brief for designing a theatre set for a "Pan's Labyrinth" play. Interior design students (36 participants) discussed, ideated, sketched and pitched different designs embedding smart materials into different interior finishing materials such as wood, metal, paint, acrylic, glass and ceramic. This design challenge had two main goals: 1) immerse the audience within different scenes and 2) create changing scenery through dynamic shape-changing SMA, colour-changing materials and seamless sensing. Although the 'Enchanted Architecture' case study expressed more elaboration and interest on the 'structural' scale of surfaces (walls, floors, ceilings) and furniture, designers of the 'Interactive Theatre' had a perspective of the 'ambient' scale joined both ends of the holistic view of the 'space' and the decorative details/ accessories that essentially contributed to their conceptual design identity.

This collaboration between fields of interaction design and interior design created design opportunities and visionary ideas that could not have been foreseen by researchers and/or practitioners of a single discipline. For example, the idea that: *"as it [SMA] moves, it would change the shadows behind it, as if sunlight is coming through with a dappled shadow/lighting effect"*, or that *"once she's shot, colours would be dark, gloomy and dingy, [everything] would react to her death by turning dark, then colours would convert to reveal the golden heaven kingdom"*. In this sense, designers created five different interior designs for various scenes, incorporating smart materials to achieve revealing and reversing through colour-change, shift-focus using shape-change, explore materiality through tactile sensation, and achieve special effects by playing with shows/light, sound and smell.

7.1.3 What can we learn for design by situating OUI Interiors?

Finally, I address, herein, the third and final research question by pulling together the threads of all situated studies (presented in Chapter 6) and reflecting on all the research findings of these studies collectively. The intertwined findings are presented below in these overlapping themes arising from analysing the results of all situated studies collectively, articulating what I have learnt with respect to materiality, aesthetics, enigmatic qualities, interaction repertoire and social engagement.

Materiality Experience and Sense-Making

The overall experience of users (engaging with ActuEating, BacterioChromic, Immersive Hive) and designers (engaging with Enchanted Architecture and Interactive Theatre) helped to better understand how interior spaces and decorative artefacts, can uplift the state-of-the-art to a new level. The evolution of ActuEater2 (with its OUI organic actuation) from ActuEater1 (with its motorized actuation) is a clear distinction between the two paradigms, in spite of being the same type of object: a table runner, ActuEater2 was described as a pet, alive and breathing. The placement of BacterioChromic near decorative –but motorized– objects also shaped people's expression of it in terms of comparison as being 'natural' versus 'mechanic' and 'organic' versus 'robotic', making sense of it as being alive, having slow morphological transitions of patterns depending on where and how it is touched. This organic interpretation was also clear in how participants described the ActuEater as a *"dancing water fountain"*, *"gazing at a fireplace"* and *"ocean waves"*, and describing the actuation of the BacterioChromic as *"breeze of air"*, *"sea waves"*, *"sea creature"* and that watching it *"feels like sitting in the woods where everything around you moves subtly and slowly"*. Although both the ActuEater and the BacterioChromic were completely different objects and designs (a table runner and a wall-art), evaluated by completely different groups of participants in three cities, they were described with quite analogous terms. This is due to their materiality and interactivity being both designed as OUIs with seamless sensing, colour-changing and shape-changing materials, resulting in comparable experiences of people encountering them.

This learning suggests that OUIs should be designed to realize subtle, silent and slow non-focus-demanding interaction that can be perceived as organic and 'alive'. Similarly, the materiality experience of the Immersive Hive constituted a great deal of people's sense-making and their described value of different textures such as the soft pollen and the sticky honey, in addition to the multi-sensory experience of the *"striking visuals"*, *"cute voices"*, textures, smell and taste, creating what was described as *"a 4D experience"*. Such a spatial 4D experience was created using the materiality of which the space was designed, unlike contemporary 4D notions of entering a special simulator with motor-controlled chairs, wearing hi-tech headgear, or any special VR/AR equipment, but in the physical realm of our actual environment. Architects working with me on the Enchanted Architecture were thinking of and referring to interior objects as living things (that have minds and feelings of their own), and interior designers brainstorming ideas for the Interactive Theatre were keen on designing organic ambiance using OUI materials in artificial (dead) tree leaves and flowers to change their colours and shapes, and give them 'life'.

Aesthetic Qualities and Value

In all case studies, participant expressed that they not only changed their perspective about decorative elements, furniture and aesthetics in general, but they also elaborated on how such aesthetic interaction allows people to have fun with objects that they might not actually take notice of on a daily basis. Participants expressed how they would like to 'live' with such an aesthetic smart artefact as opposed to electronic devices and other forms of *"intrusive"*, *"offensive"* and *"demanding"* technology. The great potential and value of having decorative elements *"do more"* was highlighted during my different case studies. However, architects collaborating with me were careful not to take this as a means of full automation, avoid making people lazy and still giving them control over space smartness, intuitiveness and autonomy. Still, interior designers used my paradigm of OUI Interiors to visualize the unseen, reveal a hidden story, reverse the atmosphere, feeling and appearance of the space, walls and interior elements. In this sense, the aesthetic elements of the Immersive Hive ware appreciated for not only sensing people's input, but for talking to them, telling them about itself, in the first-person narrative. Similarly, both the ActuEater and BacterioChromic were described as having agency of their own.

This learning suggests designing OUIs that allow the interior space to conceal hidden appearances, and hidden personality of its own and be able to slowly reveal them through user interaction as an interesting aspect of an interactive interior. Although it is not necessarily always the case, a space that entirely transforms its interior elements together playing one symphony creates an immersive experience with its coherent dynamics. For example, colour-change and/or texture-change of an interior's wall paint, curtain, sofa cushion, flower vase, rug and wall art can create an impression of a whole new space or reveal a different feeling or mood. This can be achieved by wirelessly networking each of these soft decorative interfaces and playing with the options of appearance-changing in a coherent theme that can unfold together showing the veiled mystery beneath, designing for both the playfulness and aesthetics of interaction (Petersen, 2007). The value for this multifaceted interior design is not merely aesthetics in itself, but rather utilizes aesthetics as a vehicle for further potentials and benefits, accounting on psychological social-norm interpretations of different hues, colour schemes and textures to add dynamics and vibrance, support social engagement, public awareness and well-being.

For example, BacterioChromic showed the benefits of raising public awareness in an aesthetic artwork, a non-offensive form of communicating a health-related problem. ActuEaters were conversation starters, icebreakers and a material for social engagement even between old friends, in addition to being playful, fun and entertaining. The Immersive Hive was more informative still in a playful, hands-on and entertaining way, conquering one's fears and described as an effective engaging and novel educational tool. Alternatively designers of the Enchanted Architecture space were careful with designing for playfulness as they are aware of its novelty, wanting to create designs that are not only pleasurable, but provoking, and promoting well-being. Interior designers of the Interactive Theatre wanted the space to not only reveal the 'living' qualities, but the dying ones as well. Nevertheless, people interpret their overall experience in deeper meanings and give a purposeful value to the actuations often beyond what was designed for, in either positive or negative ways.

Enigmatic Qualities and Discoverability

All my designs were described by participants of their case studies of having *"mysterious"* aspects to their shape-change, colour-change and/or hidden embedded sensing. The ActuEater was perceived as an object of *"curiosity"*, *"makes one wonder"* and *"meditate"*. With ActuEater1, I explored how actuations can evolve with user interactions over time and usage, instrumenting discoverable interaction as an adventure. Most couldn't believe how BacterioChromic's fabric itself changed colour and shape based on the presumptions of how interactive objects operate. The Enchanted Architecture space was created with sequential interaction as a journey of discoverable scenarios, and the Interactive Theatre was also designed so that one interaction opens the way to another, allowing the space to reveal interactions, unfolding as users dig up embedded and hidden interactivity in the space. This created a sense of mystery, were all these designs were literally described as being *"magical"* to express the discoverability and illegibility from a user perspective.

This learning defines the discoverability of an interactive interior space or element as ranging from fully discoverable and understandable to being hidden. By discoverability, I mean the property or an interface that describes the extent to which a space is designed to express or hide its interactivity. That is, how quickly can people uncover interactive elements within a space and how an interior can unfold as users start interacting with it, either through implicit or explicit interactions. On the other hand, legibility defines how easily users can make a connection between the cause and effect i.e. input and output of interactions. Some spaces can be deliberately designed in a way that appears disconnected to urge users to systematically act within the space in order to reason what is happening. While we may not need or want to be reasoning about the legibility of some spaces, others should be designed in a way to reveal cause and effect relationships in dynamic environments.

In this sense, there is a clear relationship between discoverability (clarity of how to interact) and legibility (clarity of why it reacts). Table 7.2 shows how combining different ranges of discoverability and legibility can result in different space interactivity features and qualities. For example, a fully discoverable (flat) space that is fully legible (intuitive) with simple logic is understandable, obvious and consistent such as a regular light switch. An undiscoverable (unfolding) space that is also fully legible will be more playful (as it unfolds hidden interactions) depending on its learning curve as it still holds a 1-to-1 legible constant reaction, such as the BacterioChromic, the Immersive Hive, the Engaging Space (Dalziel & Pow, 2015) and the History Tablecloth (Gaver et al., 2006). On the contrary, a fully discoverable illegible interactive space is one that reacts to complicated logic/ scenarios that often use more variables in the

	Fully Discoverable	Undiscoverable *(Hidden Interaction)*
Fully Legible	Obvious and Consistent	Hidden and Playful
Not Legible *(Hidden Logic)*	Spatio-Temporal and Autonomous	Mysterious and Magical

Table 7.2 Discoverability and legibility of an interactive space.

interaction equation such as the number of users/tangibles, their position/ roles within the space as well as variable time, distance/proximity or a composition of more variables creating spatio-temporal responses, sequential or accumulative interactions over time. This combination results in an autonomously-perceived space or object with no clear idea of why it is changing or behaving in a certain way, such as the coMotion shape-changing bench (Gronvall et al., 2014) and the ActuEaters. Finally, a space that doesn't immediately show how to interact with it or why it is actuating creates a mysterious atmosphere and can –in the right circumstances– then be perceived as a magical object or an enchanted space, such as the 'Enchanted Architecture' space and the 'Interactive Theatre' design.

An actual immersive experience is the one that takes interaction into 4-dimensions (rather than just 3D) by adding temporality as a key player in the user spatial interaction. An interior element can change its appearance as a result of interactions done over a week, capturing all the dynamics of the space within that period of time rather than instantaneous reactions developed in previous work (Khoo and Salim, 2013; Yu et al., 2016; Buechley et al., 2010) that relied on a direct and prompt action-reaction approach. Once we design interactive spaces that can change over time or possess some autonomy of their own, our environment can start communicating 'self-expression' through their unfolding interaction.

Complex Behavioural Repertoire

Throughout my projects, capturing users' interaction and engagement was equally important. I observed how -in each situated deployment- users were one of three: an explorer (intensely interacting), an observer (watching others interacting and occasionally taking part) and a bystander (folding arms and/or suspicious of this technology). The seamless sensing (Immersive Hive), morphological actuations (ActuEater) and slow technology (BacterioChromic) I employed in my designs (colour-change and shape-change) caused some bystanders to be impatient and disinterested, while others would enthusiastically grab their attention to *"wait and see"*. Some explorers were overly cautious when gently touching, while others were intense and rough. Some people showed empathy towards my interactive designs (e.g. patting ActuEater1 to calm it down, shaking hands with ActuEater2 to greet it and hugging the Immersive Hive) as intimate, emotional and Human-Human interactions are spontaneous unique means of communication with OUI unprecedented with SCI and TUI.

This learning suggests designing OUIs with user input interactions that range in scale according to the material affordance, from fingertip touching and poking of small parts to hand manipulations such as bending ActuEater1 and stroking its felt fabric, pulling strands and stroking fabric of BacterioChromic, squeezing soft pollen-like yarn, hovering and swiping hands over bees in the Immersive Hive. User interaction also varied according to the aesthetic design such as tracing the hidden spiral patterns of ActuEater when revealed in the same spiral motion with fingertips, repositioning tableware on top of the ActuEater according to colour distribution, flattening its history wrinkles and stroking the satin golden ribbon edge. Small circles that I've painted in the pattern of the BacterioChromic received a lot of poking/ clicking as if they are mentally associated with buttons. Seamful hexagons of the Immersive Hive were finite, clear and focused, but hidden interaction behind the Immersive Hive caused people to glide their hands to explore more interactive points and pursue more engagement.

Other unexpected user behaviour included 'blowing' at the BacterioChromic (using breath as input interaction), 'licking' fingers after interacting with the honey of Immersive Hive, and 'warming' up the thermochromic parts of the ActuEater to change their colour. Curiosity led participants to wonder what was causing the actuation, expecting a device to be controlling it somewhere and wondering where the electronics and batteries are (if any), lifting the ActuEater off and sneaking a peek underneath the table, knocking on the wall on which the BacterioChromic hang and sneaking a peek behind the wall panels of the Immersive Hive to figure out how it works. Interior designers created their designs for user bodily interactions such as walking, entering and approaching something (i.e. motion and proximity sensing) in addition to physical direct touching and holding (i.e. hand manipulations) of interior elements in the space.

Resource for Social Engagement

My designs were observed to support and fuel social engagement around and through them. People were observed exchanging eye contact, smiles, laughs and jokes acknowledging surprise, amusement and enjoyment of unexpected behaviour of the interactive artefact or space elements. Not only did participants unfold the interactivity through self-learning, but they also collaborated, exchanged interaction techniques and explored different interactive elements together, learning from each other, when one discovered a sensing or actuating element. Moreover, my interactive designs were a rich conversation material between people theorizing together the sensing and actuating behaviour of ActuEaters, BacterioChromic, Enchanted Architecture and the Immersive Hive.

This learning suggests that OUIs should be designed to act as a valuable resource for such social engagement. With the ActuEaters, some friends interacted together simultaneously to see what will happen, and others interacted on behalf of each other when the actuation happened in response to one's input feeling the need to reply back and play with it. The ActuEater also interacted with the restaurant waiter and the café waitress unexpectedly creating an interested engagement between diners and their attendants. With the BacterioChromic and Enchanted Architecture, people encouraged their accompanying friends/loved ones to *"come, try touching* *this!"*. The Immersive Hive had audio cable splitters which parents and children shared to experience together as well as friends, couples and other groups to share the excitement. In the Interactive Theatre, the design included: 1) getting the audience to be part of the play, reflecting their interactions on the stage; 2) getting the actors' performance to be projected around the audience as well; and 3) reflecting what happens in one place (e.g. theatre) at other places (e.g. box-office or café). This shows how interactive interior spaces and artefacts can be a useful resource of rich social engagement beyond what we usually design for.

7.2 Design Opportunities

The previous section discussed my design research of OUI Interiors, substantially opening up a design space that offers new opportunities for Interactive Interior Design. Adopting this direction would emphasize how technology can support future interior design in a way that is beyond contemporary techniques of Computer-Aided Design (CAD) applications. My findings from different situated studies have suggested these key learnings which I highlight below in the form of a set of design opportunities to consider when designing interactive interior spaces and artefacts.

In this section, I present a 'manifesto' that summarizes the key opportunities and benefits of OUI for interactive interior design. Although previous work on OUI has mentioned art and architecture as interesting applications of OUI (Coelho, 2011; Holman and Vertegaal, 2008; Rekimoto, 2008; Vertegaal and Poupyrev, 2008), no systematic research has been undertaken investigating, questioning and discussing how OUI spaces and artefacts can be designed, perceived and lived with.

Through my thesis, I have highlighted the concept and use of *OUI Interaction*, the possibility of embedding this *interaction within interiors* (to which I have coined the term '*Interioraction*') and the potentials of embedding such *interaction within decoration* (to which I have coined the term '*Decoraction*'). Figure 7.1 shows how these three aspects form the pillars of my manifesto.

My '**manifesto**' below outlines these design opportunities for OUIs as a core technology underpinning my vision for interactive interior design, presented in these three aspects:

1. **Interaction**: OUI employs physical interaction with everyday real-world objects (Girouard et al., 2011; Holman et al., 2013) resembling more intuitive human-physical and human-human interactions (Rekimoto, 2008). Output interactions range from simple visual and haptic feedback such as light, sound or motion to richer sensory and morphological actuation, e.g., skin-change or shape-change. In this sense, people will engage effortlessly through their normal daily interactions with real-world objects and environment, and step into immersive experiences of a ubiquitous dynamic world.

    - Tactility: Evident by how my OUI interactive interior interventions attracted touch, hand manipulations and physical interaction through other objects, designers should seize this opportunity to design for tactility utilizing the intuitive affordance of different material textures and physical objects already in the space.
    - Seamlessness: People anticipate shape-changing interfaces that are portable, weavable and seamlessly hidden (instead of bulky, cabled and demanding machines), stimulating their sense of curiosity and mystery, believing it would be magical and more efficient in terms of everyday use in their normal environments. There is a great opportunity to augment existing artefacts with OUI materials instead of embedding mechanical solutions within them. If bio-sensors are machine-sewn into fabrics (like soft speakers and PCBs), OUIs can eventually replace current health sensor devices

Figure 7.1 The OUI Interior Design Manifesto briefly stated in three aspects: OUI Interaction, Interioraction and Decoraction.

in a ubiquitous and seamless implicit interaction. The simplest example could be a duvet cover or a blanket that can measure heart rate and blood pressure; or a sofa arm that senses stress levels. A bigger picture is where –through OUI spaces– architects can design buildings that are able to capture different neurophysiological and psychological data for both the analysis and better understanding of user behaviour and user experiences within interior spaces, buildings and landscapes. OUIs can be seamlessly sensing elements of the space, from pressing light switches and grabbing knobs, to stepping on staircases and pedestrian walks.

- Scalability: Users' interactions are directly proportional with the size and volume of the OUI element. The larger the actuating area, the bigger portion of the body people use to explore this actuation, its limits and capabilities. Small and subtle actuations usually only attract gaze, while the more dramatic the actuation gets the more it attracts physical interactions, ranging from fingertips to bodily interaction, according to the scale of the interactive part. This is an interaction feature that should be exploited.
- Discoverability: Systems that are not consistent and obvious, but enable actuations to evolve over time or usage can be misleading, incomprehensible, or perceived as random. However, careful iterative design and the use of situated studies (beyond minutes) can create opportunities for designers to explore new possibilities and unfolding interactions that promote discoverability in actuating interiors, to increase adventurous exploration of artefacts.
- Beyondness: Actuating decoratives are explored *beyond the boundaries* of the intended designed interactions, where people navigate away from observed sensors and cruise through new possibilities, from voice and gestures to shaking hands. Unlike robotic SCIs, when designing organic actuations (with living-like capabilities), people will tend to develop a notion of empathy and tenderness in their interactions with them, even with no designed zoomorphic shape, texture or sound, people still believe they have a body, mood and intentions.

2. **Interioraction** Interior Design consists of an array of elements with an interplay in their texture, colour and form, to achieve a certain atmosphere through their decorative style. Although people acknowledge that most of these interior elements are for aesthetic purposes, not necessarily functional, they still give them purpose in terms of meanings and values. This applies to OUI Interiors as well where people interpret their overall experience in deeper meanings and give a purposeful value to the actuations often beyond what was designed for (in either positive or negative ways), which is a key design feature to be exploited.

    - Significance: Designing interior elements that supports our well-being, creates a greater value to them. Through slow interaction and calm technology, we can (and should) make interiors with 'extended' functionalities, beyond their aesthetics, 'engaging' people together through their dynamic morphology and 'entertaining' them with their multifaceted aesthetics in diverse and novel ways.
    - Sociability: Social engagement in an actuating interior is rich in terms of the noticeable exploratory, collaborative and engaging nature of how people interact with such technology together. This should inspire designers investigating this design space, shaping how interactive interior elements might be dealt with to utilize and support sociability.
    - Playfulness: OUI interiors and artefacts have been found to be playful and enjoyable by users (Nabil et al., 2018a, 2019). Ubiquitous environments are believed to add a pleasure dimension leading to more user-friendly architectural designs (Mounajjed and Zualkernan, 2011). OUI interactions such as direct physical manipulations are not only intuitive but pleasurable as well. The pleasure factor of accommodating aesthetic elements in an interactive space influences the behavioural patterns of users (Mounajjed and Zualkernan, 2011). In this sense, interioraction accommodates pleasure as both a cause and an effect in which it encourages user participation and enhances the user experience in an enjoyable and pleasurable flow, influencing their emotions and visceral senses.
    - Expressiveness: the ability to express personalization -in some cases- is beneficial. When artwork and interior elements become OUIs that are digitally aware of occupants' presence, and perhaps identity, then profiling and real-time customization can be easily implemented so that the same artefact or room can look differently for different co-inhabiting occupants as they use a shared space. Moreover, interioraction can help transform the same space into different other personalized appearances that suit its owner/user.
    - Expand Creativity: Art and architecture are about inspiration, questioning and creativity, provoking people's curiosity and thinking differently. When augmenting interiors with actuating capabilities, allowing them to dynamically transform, creativity fosters conversations that alter meanings and aesthetics conveyed each time it generates a new form or appearance. Interioraction enables such creativity in different designs

not only in residential interiors, but also in public spaces such as museums, galleries and showrooms. Commercial spaces are also a candidate for designers who consider technology in their installations to incorporate tangible and tactile interactions to draw innovative, surprising, playful and engaging user interaction experiences (e.g. Dalziel & Pow (2015)). In this sense, technology should be promoted not only as a means of performing tasks, solving problems and improving efficiency and productivity, but rather as well support us to be human, expanding the unique human abilities of vision, creativity and imagination and thus enhancing our quality of living.

3. **Decoraction**: OUI materials that are tactile, change colour or change shape gives us new opportunities to design dynamic interior designs that are not necessarily static like most contemporary designs. OUIs can offer the flexibility of dynamically changing artefacts, either on demand (passively) or autonomously (actively). Changing tastes or decorative styles can therefore be accommodated. More importantly, decoraction allows technology to blend in the background of our environment, avoiding the distraction of other intrusive devices, shifting to the foreground of our attention only when needed.

    - Spatiality: When technology blends into our daily environment, people perceive it as part of their overall spatial experience and expect it to interact with the space, often relating its actuation to factors beyond their direct input such as the surrounding music, conversation topics, space occupancy and weather. This does not apply to digital devices that do not blend in, but stand out, requiring full attention of users.
    - Blending-in: Organic User Interfaces can enhance the social experience of a group of people in different environments. In a given context, when designed to blend into their environment (instead of standing out as a separate device), people can choose when to ignore it and when to use it together as a social probe, to talk about, interact with, and engage together through it.
    - Match-making: As decorative objects usually have other matching items in the same interior space (to blend and complement the space aesthetics and style), people relate these relationships intuitively. Therefore, when designing decoractives, we can utilize such relationships in developing spatial interactions (with different elements in the space) creating a rather richer experience. For example, a matching cushion and throw, or a curtain with a rug, can interact together or through each other.
    - Visualizing the Unseen: decoractives open frontiers for visualizing hidden data in new ways by translating the unseen data into visual, haptic and tangible representations in the interior space. For example, displaying energy consumption of a household can be visualized through colour-changing interior elements. Another application might be for office buildings where the interior space can visualize employees' satisfaction or engagement through sensing workloads, social interaction or stress levels and giving feedback through texture-changing decorative OUIs. Applications for healthcare spaces (e.g. patient rooms and senior homes) can be similarly designed to give biofeedback to certain health conditions and thresholds through decoractives.
    - Aesthetics: Concomitant with the third generation of computing is the desire to explore how computational devices can be made more aesthetically engaging. The rise of lifestyle brands such as Bang & Olufsen, Alexa and Apple demonstrates consumers' desires for aesthetically pleasing products. Decoraction provides a design space that allows both researchers and designers to collaborate and innovate around dynamic forms of decorative artefacts, harvesting the potential of creating aesthetic computers that can exist in any shape. These devices embed both digital technology -with all its capabilities- and decorative beauty -with all its artistic values- together in

one integral interface that can live, engage and influence people's lives over years. Using this paradigm, a lace tablecloth, a shaggy cushion or a Persian rug can become a computational device. Furthermore, aesthetic interaction -which is similarly important and impactful- aligns well with OUI interactions being more intuitive, familiar and manipulative than earlier user interface paradigms. Additionally, decoraction can provide a user-friendly interface alternative for complex embedded systems in simple metaphors. For example, power utilization trends can be tangiblized into colour-changing clouds hanging as decorative elements.

7.3 Challenges & Way Forward

The opportunities and benefits that OUI provides for developing interactive interiors were elaborated in the previous section in three aspects: interaction, interioraction and decoraction. Still, the vision of OUI as a key technology for interactive interiors requires substantial efforts to become a reality, which effectively define the future research agenda for the field. In what follows I outline what I have identified as the key challenges and the most important aspects that future research on OUI Interiors has to address, in each of the three aforementioned aspects.

1. **Interaction** Although OUI Interaction has shown opportunities of seamless sensing and morphological actuation (shape-change and colour-change) in OUI Interiors, challenges to such promises could stand in the way. In defining OUI Interaction for interactive interior design, we may need to (re)define the user(s) and consider various implications that may have ethical and behavioural shaping to such interaction. Moreover, how can we deal with the sustainability challenges that could arise from such interaction.

    - **Redefining the User**: As somehow different than usual interfaces, defining who would be users of OUI Interiors is rather vague and not straightforward. Traditionally, users of an indoor interface system are thought of as the space occupants, while users of an outdoor interface are considered as the public passing by. On the other hand, architects and interior designers may consider their users as the contractors, project owners or funding bodies of the designed building/space. For example, a design office would get its *brief* from the commissioning body whether that is Britain's NHS clinical division or a high-end retail store. In either case, rethinking who is the user is an important point to be tackled and explored by OUI research when it comes to entire buildings as an interface or a design space. This is crucial from both perspectives: HCI and design disciplines, both depend on building their 'design concept' on defining the users. More importantly, defining the actual users will essentially push forward a user-centric design and a post-occupancy testing or long-term evaluation of such designs/interfaces that can potentially constantly change, transform and react. However, as this paradigm becomes widespread, and shapes itself in everyday decorative objects, it will reach the other end of the design spectrum, gradually shifting from the professional designers and artists to the crafting and tech-maker communities. So, should we develop the tools and techniques for such designers or those? should there be a set of DIY toolkits for enthusiastic makers to produce their own OUI decoratives at homes, or maker spaces?
    - **Ethical and Behaviour-Shaping**: when spaces and objects surrounding us can dynamically transform their shape or appearance either autonomously or interactively, new challenges for ethics and security will emerge. Sensing environments, in general, are advanced systems that involve complex scenarios and thus are potentially be subject to 'hacking' activities as well. Special security procedures might need to emerge to protect one's wallpaper or moving furniture. An essential step forward

for OUI Interiors would be considering BMS (Building Management Systems) as a means of embedding security techniques into OUI software not only for creating anti-hacking systems but defining who has the rights to interact -thus change- the physical appearance and form of the interior space. Such implications are indeed applicable for any embedded system, yet it needs to be highlighted here as it would require new methodologies and considerations impacting people in their very own bedrooms. Another challenge is designing the appropriate skin-changes of the original architectural design and their possible emotional effects on residents. In theories of architecture, different colours, materials and textures have definite meanings, feelings and uses, thus consequently emotional effects on the space occupants and often the entire surrounding ecosystem. In OUI Interiors, the materials and methods of sensing, actuation and interaction will be an essential part of the interior design, requiring careful studies in each context to control and avoid any implications that might result on families either physiologically or psychologically. When designing for domestic spaces, more challenges emerge on different technical, social and ethical levels. Since some early challenges of domestic ubiquitous computing (Edwards and Grinter, 2001) have been resolved, it seems that it is a matter of continuous studies and research to find ways to overcome more. If OUI Interiors are the future designs of smart spaces where interactivity will be integrated within the fabric of interior elements and artefacts, responding to occupants' preferences, behaviours and seamless input interactions, we need to rethink a number of ethical, social and legal challenges, most notably inhabitants' privacy and the use of their personal data. A separate book chapter (Nabil and Kirk, 2019), that I have recently published, explores some of these implications and focuses on the challenges around the personal data that OUI Interiors will inevitably generate and use. I have written these design fictions (see Appendix C) of dystopian alternative interpretations to support a deeper reflection on the potential pitfalls of increased interactivity in our habitable spaces.

- **Sustainability**: Although OUI Interiors promise less need for re-design or refurbishment, if interiors are able to change their appearance (e.g. colour, shape, pattern and texture), the challenge remains to find low-power alternatives and energy-efficient ways to control them without compromising sustainability. Currently, sustainability research predominantly focuses on exploring means of building resource-efficient, energy-conservative and environment-friendly architecture through Green Building and Sustainable Architecture practices. Can OUIs contribute to sustainable buildings through 'modularity' where component-parts can be replaced easily? Can organic actuation and shape-change contribute to energy-harvesting? We need to research ways that allow micro-scale energy production to support self-sustainable buildings. Not only buildings, but rather smaller units from lobbies, rooms and partitions to lifts, cubicles and capsules. Together they form the urban glue in which indeed shapes our daily lives, and is a rich space for OUI, converting them from mute spaces to possible 'urban actors'. Yet, creating new urban actors would raise more sustainability challenges and opportunities. OUI materials that sense and react to changes in humidity, light or heat requires zero energy consumption and can be physically programmed to solely act as sensing, processing and actuating complete systems of adaptive architecture. But, would we accept having no control over them if they are not electronically programmed and powered? Finally, we have got a missed opportunity of utilizing wasted energy sources that are pouring, facing and blowing towards every architectural structure. Such natural resources can be either directly utilized as actuating stimuli (Ned Kahn Studios, 2016; Menges and Reichert, 2012) creating natural behavioural patterns or employed in more complicated processes. Nature powers of wind, sun radiation, wasted rainwater (storm drain) and even grey-water drains are all considered nature's gift to sustainable architecture researchers and should inspire interaction designers as well.

2. **Interioraction** The two main challenges facing the opportunities of interioraction reflect the entanglement of the concept. It is between two (or more) disciplines and is spatial rather than focused, enveloping special considerations that need to be addressed.

   - **Radical Interdisciplinarity**: Bridging the gap between involved parties (e.g., computer scientists, material physicists, architects, interior designers, OUI researchers) is an essential requirement for realizing interioraction. More than in any other domain truly interdisciplinary collaborations are essential, meaning that where researchers and practitioners from different core subject areas need to go out of their way and work together on creating what eventually will turn into an entirely new research area. Such radical interdisciplinarity needs to be formalized and -more importantly- 'lived' in everyday practice of researchers and practitioners. Staying in -certainly comfortable- silos of core disciplines will not lead to the realization of interioraction. Although it may sound obvious to some, this challenge has been identified as a key problem for the development of this research area: many architecture and HCI researchers work separately from one another, yet with the same vision. What is ultimately necessary is that, for example, classical architects not only utilize new materials and technologies but rather also actively contribute to their research and developments. Conversely, core technical research disciplines need to engage in thinking like architects and appreciate interior design from a UX and general user perspective. As such a new generation of researchers and practitioners will be able to develop and employ radically new methods, tools, and materials and thus be able to transform both interior design and interaction technologies. To adequately explore these new design landscapes, Chapter 6 presented my final two studies that support multidisciplinary collaboration with architects and interior designers respectively. Through engaging relevant design communities, these studies aimed at exploring how design disciplines can productively collaborate together and engage with OUI materials as a design resource, using an evolving set of techniques, to design and build interioractive spaces.
   - **Immersiveness of Interaction**: as much as interioraction sounds revolutionary and promising, it also triggers the need for essentially a new generation of interaction

design. When redefining interior spaces as user interfaces, we need to start reconsidering many interaction design fundamentals. User interaction will be immersive rather than focused, when interacting with spaces rather than devices or room-sized interfaces rather than tabletops. Crowd interaction would replace the traditional 'multi-user' notion, and would require creative methods and tools to study and evaluate. Even with small interior elements, HCI research needs to create and evaluate new arrays of interaction techniques that are immersive, playful and engaging, together with designers. Several challenges require careful design for OUI interactions that would need to be ubiquitous and ambient but not entirely hidden, intuitive but not basic or mundane, surprising and enchanted but at the same time not -perceived as- completely random. Moreover, as interioraction is realized, opportunities for social actions in these interactive spaces would also become an important topic in HCI. But what are the consequences of shifting users' expectations for their surroundings? When would embedded OUIs be appropriate? When would interaction be needed? How can we design long-term interactions? Most importantly, how would people perceive this new paradigm of seamless and immersive interactions with things and places they encounter on a daily basis? And how would this affect their spatial and social experiences on the long-term? Many questions that need wide discussions, debates and studies -before answers- are essential if we are to unwrap the potentials of such a field. Some of which were tackled in my case studies presented in Chapter 6, which brought people around and inside OUI artefacts and interior spaces respectively.

3. **Decoraction** Challenges facing decoraction lie mostly within the techniques of embedding OUI materials in decorative elements. I have explored herein a number of these crafting techniques (in Chapter 4). Other alternative ways of appropriation and retrofitting such technology seamlessly within real-world objects need further research. Scaling-up from swatches and crafted samples to real-world decoractives also raise many challenges.

   - **Appropriation and Retrofitting**: An interesting design space emerges not only for designing new interior spaces or artefacts with embedded OUIs, but also for retrofitting existing interior spaces and decorative elements. This requires less structural intervention and allows new OUI layers to cover entire pre-existing interior surfaces. Considering that furniture, decorative accessories and soft furnishings can be appropriated as interactive elements through decoraction, there is a broad space through which interior designers and OUI researchers can come to collaborate. The design space for decoraction is unique in the sense that it bears an intrinsic conflict of conceiving, designing, and developing new objects that effectively implement Organic User Interfaces versus the need for altering, adapting and extending existing objects that are not necessarily straightforward to modify. Especially the latter is the predominant case for existing spaces, which requires retrofitting and approaches of opportunistic modification. Embedding walls, furniture and objets d'art with seamless sensing in interesting, useful or playful ways without disrupting their inherent features, usages and expectations can all be quite challenging. What input and output modalities should we use? Which electronic components would best fit soft furnishing? How should these interactive capabilities be embedded without compromising texture, affordance and user perception? Tackling these challenges needs careful selection of OUI materials that could replace/ reduce the largest amount of electronic components possible, then find ways of embedding sensing and actuation seamlessly, along with extensive experimentation and exploration of crafting and making techniques that could be useful in this sense. This essentially requires thinking of both aesthetics and electronics in a concurrent approach. Chapter 4 focused on tackling this particular agenda utilizing research-through-design methods. That is, retrofitting and reappropriation of everyday existing materials with sensing and actuation through i) an array of smart materials, b) the experimentation of their behaviour, and c) the exploration of innovative techniques to achieve this.

- **Tackling Scalability**: Addressing scalability of decoraction is a fundamental challenge for the field. Scalability hereby refers to moving on from samples and swatches (crafted to explore a material or experiment a technique) to large-scale uptake of decoractives in everyday scenarios. Scalability of large interfaces, e.g., wall panels, is less challenging than small-sized interior elements. Designing OUIs in ways to be seamlessly hidden in real-world objects requires many different considerations and functional testing than just lab research. Such considerations are required due to the large-scale, robustness and reliability required for everyday use in addition to surviving different environmental conditions. As any newly introduced building material, OUI materials must prove durability in terms of sun, rain, wind and fire resistance. If designed as a structural material (holding some building weight), it needs to be tested for load resistance as well, as architecture is non-risk tolerant. Other considerations that require further research and testing are lifespans, vandalism and maintenance approaches of such subtle materials. Once OUI materials are proved to stand such testing and be produced into building components with qualified and quantified specs for architects and interior designers, pioneers can start using them with confidence and we can start witnessing a new era of OUI Interiors as reality. This also applies to decoraction but on a more achievable scale. Furniture and decorative elements augmented with interactivity on a real-world scale raises problematic practicalities that are probably unforeseen in samples and swatches that result from early experiments. Folding, handling and washing soft furnishing can turn to complex tasks once they are embedded with electronic components. What if multiple sensing points are embedded in the same piece of furniture, would they interfere with each other? or with their everyday use? What if different actuations are embedded together, how would they perform in unison? Would one override the others? How would people perceive a $6m^2$ actuating rug and how would they interact with it? What if numerous interactive threads are sewn in one wide curtain? Chapter 5 tackled some of these questions, discussing prototyping smart artefacts where interactivity is embedded in 1:1 scale decoratives, stepping away from swatch samples and elementary experimentation into real-world applications.

After a deep discussion in the overall reflection presented in Section 7.1, I introduced my manifesto for highlighting the opportunities of OUI interior design in Section 7.2. In this section, I discussed the key challenges that need to be addressed in future research. In doing so, I have reached my initial research aim to "explore the design space, opportunities and challenges of creating interactive spaces with OUIs". The next final section comes to the conclusion of this thesis and articulates the results of all my research on OUI for interactive interior design.

7.4 Conclusion

Interior Design (re)defines an interior space to suit occupants' needs and realize its design concept and decorative style in terms of texture, colour and form (i.e. shape). Organic User Interfaces (OUIs) provide an interaction paradigm where everyday objects of any physical shape can become interfaces that employ physical sensing and morphological actuation. Using the OUI paradigm, we can realize 'Interactive Interior Design' as a new generation of interior spaces and artefacts that have seamless sensing, colour-changing and shape changing capabilities. In this sense, OUI Interiors can embed interactivity within the fabric of interior elements using a range of OUI materials. Interactive Interior Design will soon be studied and practised towards extending both the capabilities and aesthetic qualities of interior objects (such as soft furnishings, objets d'art and vases). Through interactive interiors, real-world environments will be appearance-changing (i.e., shape, colour, pattern, texture) in response to occupants' behaviours and implicit input interactions.

This research project was initiated with the aim to **explore the design space, opportunities and challenges of creating interactive spaces with OUIs**. In order to do so, three main research questions have been defined for this thesis concerning: 1) What interactive materials and making techniques can be used to design and build OUIs?, 2) What OUI decorative artefacts and interior elements can we create?, and 3) What can we learn *for design* by situating OUI interiors?

To tackle the first research question, I explored a range of 'smart materials' that have interactive capabilities, are deemed embeddable within interior finishing materials and are increasingly available 'off-the-shelf'. For example, conductive materials and e-textiles provide sensing threads and fabrics that can be used for seamless sensing, while Shape-Memory Alloys (SMA) and thermochromic pigments can be used for shape-change and colour-change respectively. These interactive materials are either physically programmable, sewable or paintable. In addition, they afford hand manipulation and/or could change physical appearance as a means of input and output. I used critical making methods to explore different crafting techniques for embedding these materials into different finishing materials, innovated new ways of achieving this, experimented the material behaviour and found a number of parameters that affect their actuation. A physical representation of this contribution can be found in my swatchbook (see Appendix A).

For instance, I presented the exploration of machine-sewing sensors, resistors, speakers, shape-changing and colour-changing actuators seamlessly in unprecedented ways and the impacts of doing this. I have introduced a range of novel techniques of machine sewing and physically programming actuating threads/wires into fabrics. My SMA sewing techniques enabled both colour change of seams and soft shape-changes such as bend/unbend, swirl, twist, roll/unroll, curl, crumple and crease. From observations of experiments sewing SMA to fabrics, 10 parameters were realized as the impacting factors that control the deformation intensity: fabric type, thread type, stitch type, sewing pattern, wire type, wire austenite, wire martensite, wire length and its distance to the fabric edge. In developing 10 techniques for machine sewing actuation, I have productively built upon the relevant work of e-textiles (Perner-Wilson and Buechley, 2011; Kettley, 2016; Hamdan et al., 2018) that generally focused on LEDs and motor-based actuation by sewing conductive threads. Thus, my techniques for machine-sewing shape-changing and colour-changing threads represent an evolutionary step towards the ultimate goal of providing a high-fidelity experience to users, designers and researchers. This research project also extended previous work on SMA shape-change (Berzowska and Coelho, 2005; Coelho and Zigelbaum, 2011; Davis et al., 2013) by examining deformational parameters affecting the fabric's morphological effect.

I have purposely chosen to innovate new techniques to move beyond the UI design prototyping strategy to a craft and design-led practice-based research as I argue it has greater utility in raising issues of seamlessness, calmness and aesthetics in inspirational ways. In doing this, I have responded to the second research question by showcasing some of the design ideas that I have developed through my design research engagements with the materials I have explored. Starting off from previous work with prototyping a motor-based shape-changing table-top (ActuEater1), I showed how it could be designed as an OUI interior element entirely from fabric with stitched SMA for shape-change (ActuEater2), achieving a soft, slow and calm aesthetic decorative table-runner that blends in the interior space and interacts with the surrounding tableware as opposed to a stand-alone device. Moving from the horizontal to the vertical, I designed an interactive piece of wall-art with pattern-changing fabric (BacterioChromic) that morphs and fades with seamless soft sensing. To explore other materials, than fabric, I looked into ways of making electronically-controlled ceramic wall tiles that respond to ambient heat or tactile touch (TacTiles). Moving from horizontal and vertical flat surfaces, I explored 3D objects of different materialities and interactivities such as an actuating stroke-sensing blanket throw (Furry Throw), a shape-changing vase (Morvaz), a colour-changing pair of wall painting (WaterFall) and cushion (WaterDrop), a faux leather rug that deforms (LITHER), four interactive pieces of objets d'art (AMR Bugs) and an actuating curtain voile (Stara).

Playing with scale, materials, dimensions and orientations, this series of design explorations presented in this thesis shows how critically examining the use of sensing, shape-changing and colour-changing materials (as opposed to electronic sensors, motors and LEDs) is of great potential to the design of interactive interior elements and decorative artefacts. The challenges I've faced to conceal technology within everyday decorative artefacts ubiquitously, were aimed at experimenting how hidden interactivity in objects (that blend into the space design) could be of value. By taking previous work (Khoo and Salim, 2013; Buechley et al., 2010; Meese et al., 2013; Taylor and Robertson, 2014) further, I was able to explore new territories of this design space. A physical representation of this contribution that takes on a critical speculation approach is in my product design catalogue (see Appendix B) that contextualizes my inspirational artefacts for other designers. The time restrictions of this research required producing this limited number of designs in specific settings. More design ideas can be also found in my design fiction stories (see Appendix C) that I wrote to mitigate any technical limitations. Further research should explore other artefacts, in other contexts, to realize the latent and intrinsic potentials of extending their capabilities, seamlessly.

To evaluate these designs with both end-users and other designers, I used methods of critical engagement and in-situ deployments. This helped understanding the meaning and significance of such designs to space occupants in the wild over situated social events. Through situated deployments in different contexts (in restaurants, galleries and at home), members from the public and volunteering participants reflected on their sense-making, perception and interaction with OUI interior elements and spaces. Insights and findings from qualitative analysis of such deployments and post-study design crits emphasized on how weaving technology into real-world objects, specifically decorative ones, can deliver a rather richer 'spatial experience' in a given contextual setting. After three real-world studies, I held two other case studies within relevant design practices. With architecture and interior design students, I was able to put OUI materials in the hands of space designers and bridge the gap between interaction design and interior design. These collaborations generated new ideas, design uptakes and concepts for interactive interior spaces. Not only did all my situated studies extend previous work (Gaver et al., 2006; Gronvall et al., 2014; Mennicken et al., 2014b; Yu et al., 2016) but it also generated knowledge for OUI interiors, their design and critique on several levels, in different contexts (both real-world deployments and design practice settings) and contribute to a stronger understanding towards OUI interior design. This effectively addressed my third and final research question of "*What can we learn for design by situating OUI interiors?*".

A final overall reflection and deep discussion that ties all my research work together clarifies the entire design space of OUI interior design in light of previous work. After characterizing the design space and delivering the promises of my initial research aim, I came to a conclusion that framed a manifesto for OUI interior design. My manifesto defined a set of opportunities of this design space in terms of: i) OUI interaction in general; ii) blending such interaction in interiors (i.e. interioraction); and iii) blending such interaction in decorative elements (i.e. decoraction). By coining these new terms, I lay out the opportunities that designers should seize and *design for* in the intersection between those design disciplines. My manifesto includes opportunities of seamlessness, discoverability, social engagement, playfulness and spatial experience among others.

Nevertheless, this paradigm comes with a number of challenges that need to be addressed in future research. In terms of OUI interaction, we ought to *(re)define the user(s)* and consider various implications that may have *ethical and behavioural shaping* to such interaction, in addition to *sustainability* challenges that could arise. In terms of interioraction, the two main challenges reflect how this design space needs *'radical interdisciplinarity'* and a vision for the *'immersiveness of interaction'*. Finally, embedding interactivity in decoration, or decoraction, is different than electronics prototyping in that it emphasizes on aesthetics, affordance and materiality. Therefore, the challenges facing decoraction mainly focuses on finding alternative ways of *appropriation and retrofitting* such technology seamlessly within real-world decoratives and scaling-up from swatches and crafted interactive samples to real-world decoractives which raises challenges of *'scalability'*.

There is also a wide scope for future design research that should address the materiality of these interactive possibilities raised herein. With this motivation, we need to raise awareness amongst those who may wish to design for interactive interiors, about these materials and the opportunities that they offer. The potentials of interior spaces and elements changing their colours, forms and patterns mean that the need of having a fixed interior style for each space -until refurbished- can soon be relegated to history. In this sense, interaction designers, on one hand, need to revisit their prototyping techniques and evaluation methodologies, shifting more towards both real-world materialities and in-the-wild deployments. On the other hand, interior designers need to rethink their spaces in more dimensions than just the traditional 3D, considering not only the usability and flow within the space but the changeability of the space and its temporality as a response to user activities and needs, and ambient environmental conditions. Once interior elements are perceived as possible user interfaces that can sense and/or react, we can start imagining them communicating as well. Consequently, a wireless network of decorative artefacts could help achieve the dream of ubiquitous environments more quickly, easily and dramatically than ever perceived. The ultimate goal is inspiring and motivating others to design and create engaging, useful and beautiful OUI interior spaces and artefacts.

In conclusion, through this thesis, I argue that we should design and build OUI Interiors, explore what we can use (OUI materials) and how we can do it (Chapter 4), present 10 different inspirational artefacts (OUI decoratives) with their ideation and making processes (Chapter 5), and discuss how people (both users and designers) evaluated this paradigm (Chapter 6) in 5 situated deployments. In practice, people enjoyed interacting, engaging and playing with all deployed designs, and loved the seamless interaction, the socio-physical engagement and enchantment of seamless sensing and morphological actuation. However, the novelty of such designs was a key factor to the impressed and intrigued response of most people, deeming such designs still not entirely suitable for everyday use such as within domestic environments. Although numerous implementation techniques where explored with various materials, reaching a level of durability, reliability and robustness was still difficult due to technical reasons. Therefore, a long-term study to explore how people might live with OUI artefacts or within OUI interiors, is still sought after. Nevertheless, the deployed case studies herein provide helpful insight towards how people perceive and interact with OUI interactive spaces and interior elements.

Through several exhibitions and publications (see Appendices D to G), I believe my work provides inspiring case-studies supporting others who might wish to design and develop OUI Interiors for different contexts. This work will help advance and continue the research commenced (Gaver et al., 2006; Gronvall et al., 2014; Khoo and Salim, 2013; Yu et al., 2016; Buechley et al., 2010; Meese et al., 2013; Mennicken et al., 2014b; Taylor and Robertson, 2014) around interactive spaces, furniture and everyday objects. The beauty of interactive decorative artefacts (unlike novel gadgets) is that whether they interact (accurately or entirely) or not, the object still has value. Its failure to interact at any time will not lead to a crisis of affordance (Gaver et al., 2006), as it remains part of the interior design and a decorative aesthetic artefact in its own right. This work points to the future potential of new materialities, merging interaction design with interior design.

Bibliography

Eric Akaoka, Tim Ginn, and Roel Vertegaal. DisplayObjects: Prototyping Functional Physical Interfaces on 3D Styrofoam, Paper or Cardboard Models. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction - TEI '10*, page 49, Cambridge, Massachusetts, USA, 2010. ISBN 9781605588414. doi: 10.1145/1709886.1709897. URL http://doi.acm.org/10.1145/1709886.1709897.

Hamed Alavi, Elizabeth Churchill, David Kirk, Julien Nembrini, and Denis Lalanne. Deconstructing Human-Building Interaction. *Interactions*, pages 60–62, 2016. ISSN 10725520. doi: 10.1145/2991897. URL http://dl.acm.org/citation.cfm?id=2991897.

Jason Alexander, Viljakaisa Aaltonen, Johan Kildal, Andrees Lucero, Kasper Hornbæk, and Sriram Subramanian. Interaction with Deformable Displays. In *MobileHCI*, San Francisco, CA, USA, 2012. ISBN 9781450314435. doi: 10.1145/2371664.2371723.

Leonardo Angelini, Maurizio Caon, Denis Lalanne, and Elena Mugellini. Towards an Anthropomorphic Lamp for Affective Interaction. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI'15)*, pages 661–666, 2015. ISBN 9781450333054 (ISBN). doi: 10.1145/2677199.2687914. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-84924077942{&}partnerID=40{&}md5=2680de40b34a5b608f0667a60b682ac4.

Bare Conductive. How to Make a Dimmer Lamp with Your Electric Paint Lamp Kit - Bare Conductive, 2018. URL https://www.bareconductive.com/make/how-to-make-the-dimmer-lamp/.

Hrvoje Benko, Ad Wilson, and Ravin Balakrishnan. Sphere: Multi-touch Interactions on a Spherical Display. *UIST '08*, 2008. doi: 10.1145/1449715.1449729. URL http://dl.acm.org/citation.cfm?id=1449729.

James M Bern, Kai-Hung Chang, and Stelian Coros. Interactive Design of Animated Plushies. *ACM Transactions on Graphics (TOG)*, 36(4):80–91, 2017. doi: 10.1145/3072959.3073700. URL http://doi.acm.org/10.1145/3072959.3073700.

Joanna Berzowska. Memory Rich Clothing: Second Skins That Communicate Physical Memory. In *Proceedings of the 5th conference on Creativity and Cognition*, pages 32–40, 2005. ISBN 1595930256. doi: 10.1145/1056224.1056231. URL http://portal.acm.org/citation.cfm?doid=1056224.1056231.

Joanna Berzowska and Marguerite Bromley. Soft Computation through Conductive Textiles. In *Proceedings of the International Foundation of Fashion Technology Institutes Conference*, number 3, pages 1–12, 2007.

Joanna Berzowska and Marcelo Coelho. Kukkia and Vilkas: Kinetic Electronic Garments. In *IEEE International Symposium on Wearable Computers (ISWC2005)*, volume 3, Osaka, Japan, 2005. ISBN 0769524192. doi: 10.1109/ISWC.2005.29.

Gilbert Beyer, Florian Alt, Jörg Müller, Albrecht Schmidt, Karsten Isakovic, Stefan Klose, Manuel Schiewe, and Ivo Haulsen. Audience Behavior Around Large Interactive Cylindrical Screens. In *SIGCHI Conference on Human Factors in Computing Systems ACM CHI*, number 1, pages 1021–1030, Vancouver, BC, Canada, 2011. ISBN 9781450302289. doi: 10.1145/1978942.1979095. URL http://portal.acm.org/citation.cfm?id=1979095{%}5Cnhttp://portal.acm.org/citation.cfm?doid=1978942.1979095.

Mark Blythe. Research Through Design Fiction: Narrative in Real and Imaginary Abstracts. In *Proc. CHI'14*, Toronto, ON, Canada, 2014. ISBN 9781450324731.

Mark Blythe. Research Fiction: Storytelling, Plot and Design. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*, pages 5400–5411, Denver, CO, USA, 2017. ACM. ISBN 9781450346559. doi: 10.1145/3025453.3026023. URL http://doi.acm.org/10.1145/3025453.3026023.

Alice Bodanzky. Exploring the Expressiveness of Shape-Changing Surfaces. In *Proceedings of the Sixth International Conference on Tangible, Embedded, and Embodied Interaction Design*, pages 403–404, Kingston, ON, Canada, 2012. ISBN 9781450311748. doi: 10.1145/2148131.2148235. URL http://dl.acm.org/citation.cfm?id=2148235.

Jay David Bolter and Diane Gromala. *Windows and Mirrors: Interaction Design, Digital Art, and the Myth of Transparency*. MIT Press, Cambridge, Massachusetts, USA, 2003.

John Bowers. The Logic of Annotated Portfolios: Communicating the Value of 'Research Through Design'. In *Proceedings of the Designing Interactive Systems Conference (DIS '12)*, pages 68–77. ACM, 2012. ISBN 9781450312103. doi: https://doi.org/10.1145/2317956.2317968.

Alan Branzel, Christian Holz, Daniel Hoffmann, Dominik Schmidt, Marius Knaust, Patrick Luhne, Rene Meusel, Stephan Richter, and Patrick Baudisch. GravitySpace: Tracking users and their poses in a smart room using a pressure-sensing floor. In *SIGCHI Conference on Human Factors in Computing Systems*, Paris, France, 2013. ISBN 9781450319522. doi: 10.1145/2470654.2470757.

Virginia Braun and Victoria Clarke. Using Thematic Analysis in Psychology. *Qualitative Research in Psychology*, 3(2):77–101, 2006. doi: 10.1191/1478088706qp063oa. URL http://www.tandfonline.com/doi/abs/10.1191/1478088706qp063oa.

Leah Buechley and Kanjun Qiu. *Sew Electric*. HLT Press, 2014. ISBN 9780989795609.

Leah Buechley, David Mellis, Hannah Perner-Wilson, Emily Lovell, and Bonifaz Kaufmann. Living Wall: Programmable Wallpaper for Interactive Spaces. In *Proceedings of the international conference on Multimedia*, pages 1401–1402, Firenze, Italy, 2010. ISBN 9781605589336. doi: 10.1145/1873951.1874226. URL http://doi.acm.org/10.1145/1873951.1874226.

Eva Burneleit and Fabian Hemmert. Living Interfaces: The Impatient Toaster. *Proceedings of TEI'09*, pages 21–22, 2009. doi: 10.1145/1517664.1517673.

Carlos Calderon. *Interactive Architecture Design*. Number December. Harvard Graduate School of Design, Cambridge, Massachusetts, USA, 2009. ISBN 9781934510094.

Matthew Chalmers and Ian MacColl. Seamful and Seamless Design in Ubiquitous Computing. In *Proc. Ubicomp 2003 Workshop At The Crossroads: The Interacton of HCI and Systems Issues in Ubicomp.*, number January, page 8, Seattle, WA, USA, 2003. doi: 10.1.1.104.9538. URL http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.104.9538{&}rep=rep1{&}type=pdf.

Bernard Cheng, Antonio Gomes, Paul Strohmeier, and Roel Vertegaal. Mood Fern: Exploring Shape Transformations in Reactive Environments. In *ACE'14*, Funchal, Portugal, 2014. doi: 10.1145/2663806.2663818.

Marcelo Coelho and Pattie Maes. Sprout I/O: A Texturally Rich Interface. *Proceedings of the 2Nd International Conference on Tangible and Embedded Interaction*, pages 221–222, 2008. doi: 10.1145/1347390.1347440. URL http://doi.acm.org/10.1145/1347390.1347440.

Marcelo Coelho and Pattie Maes. Shutters: A Permeable Surface for Environmental Control and Communication. In *Proceedings of the Third International Conference on Tangible and Embedded Interaction (TEI'09)*, pages 13–18, Cambridge, UK, 2009. ACM. ISBN 9781605584935. doi: 10.1145/1517664.1517671. URL http://doi.acm.org/10.1145/1517664.1517671.

Marcelo Coelho and Jamie Zigelbaum. Shape-changing Interfaces. *Personal and Ubiquitous Computing*, 15(2):161–173, 2011. ISSN 16174909. doi: 10.1007/s00779-010-0311-y.

Marcelo Coelho, Hiroshi Ishii, and Pattie Maes. Surflex: A Programmable Surface for the Design of Tangible Interfaces. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '08, pages 3429–3434, New York, NY, USA, 2008. ACM. ISBN 978-1-60558-012-8. doi: 10.1145/1358628.1358869. URL http://doi.acm.org/10.1145/1358628.1358869.

Marcelo Coelho, Ivan Poupyrev, Sajid Sadi, Roel Vertegaal, Joanna Berzowska, Leah Buechley, Pattie Maes, and Neri Oxman. Programming Reality: From Transitive Materials to Organic User Interfaces. In *CHI 2009 Workshops*, Boston, MA, USA, 2009. doi: 10.1145/1520340.1520734.

Sandra Coelho. Art Evolves through Technology: Haptic after the Hegemony of Visual Art. In *LNICST*, volume 101, pages 171–176, 2011. doi: 10.1007/978-3-642-33329-3_21.

Peter Dalsgaard. Experimental Systems in Research through Design. In *Proc. of CHI2016*, pages 4991–4996, San Jose, CA, USA, 2016. ISBN 9781450333627. doi: 10.1145/2858036.2858310.

Nicholas S Dalton, Holger Schnadelbach, Mikael Wiberg, and Tasos Varoudis. *Architecture and Interaction*. Springer, 2016. ISBN 9783319300269.

Dalziel & Pow. Engaging Space, 2015. URL http://www.dalziel-pow.com/projects/interactive-animations/.

Felecia Davis. The Textility of Emotion: A Study Relating Computational Textile Textural Expression to Emotion. In *C&C'15*, volume 2, pages 1977–1982, Glasgow, United Kingdom, 2015. ISBN 9781450335980. doi: 10.1145/2702613.2732739. URL http://dx.doi.org/10.1145/2702613.2732739.

Felecia Davis, Asta Roseway, Erin Carroll, and Mary Czerwinski. Actuating Mood: Design of the Textile Mirror. In *TEI '13 (ACM) - Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, pages 99–106, Barcelona, Spain, 2013. ISBN 9781450318983. doi: 10.1145/2460625.2460640. URL http://dl.acm.org/citation.cfm?id=2460640.

Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-wei Gong, M Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, Kimiko Ryokai, and U C Berkeley. "I don't want to wear a screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 6028–6039, San Jose, CA, USA, 2016. ISBN 9781450333627. doi: 10.1145/2858036.2858192. URL http://doi.acm.org/10.1145/2858036.2858192.

Christine Dierk, Sarah Sterman, Molly Jane, Pearce Nicholas, and Eric Paulos. HairIO: Human Hair as Interactive Material. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '18).*, pages 148–157, New York, NY, USA, 2018. ACM. ISBN 9781450355681. URL https://doi.org/10.1145/3173225.3173232.

Simon Dodsworth. *The Fundamentals of Interior Design*. 2009. ISBN 2940373922. URL https://books.google.co.za/books/about/The{_}Fundamentals{_}of{_}Interior{_}Design.html?id=mjLeHozmCaYC{&}pgis=1.

Delia Dumitrescu, Marjan Kooroshnia, and Hanna Landin. Silent colours: Designing for wellbeing using smart colours. In *Proceedings of AIC 2018 Colour & Human Comfort*, Lisbon, Portugal, 2018. URL http://urn.kb.se/resolve?urn=urn:nbn:se:hb:diva-15304.

Anthone Dunne and Fiona Raby. *Design Noir: The secret life of Electronic Devices*. Birkhauser, 2001.

Abigail C Durrant, John Vines, Jayne Wallace, and Joyce S R Yee. Research Through Design: Twenty-First Century Makers and Materialities. *Design Issues*, 33(3):3–10, 2017. doi: 10.1162/DESI_a_00447. URL https://doi.org/10.1162/DESI{_}a{_}00447.

W.K. Edwards and R.E. Grinter. At Home with Ubiquitous Computing: Seven Challenges. In *Proceedings of the 3rd international conference on Ubiquitous Computing*, pages 256–272, 2001. ISBN 3540426140. doi: 10.1007/3-540-45427-6. URL http://www.springerlink.com/index/H4NW9N0WFTF3RP02.pdf.

Chris Elsden, Bettina Nissen, Andrew Garbett, David Chatting, David Kirk, and John Vines. Metadating: Exploring the Romance and Future of Personal Data. In *Proc. of CHI2016*, San Jose, CA, USA, 2016. ISBN 9781450333627.

Chris Elsden, David Chatting, Abigail C Durrant, Andrew Garbett, Bettina Nissen, John Vines, David S Kirk, and Newcastle Tyne. On Speculative Enactments. In *Proc. of CHI2017*, Denver, CO, USA, 2017. ISBN 9781450346559.

Aluna Everitt and Jason Alexander. PolySurface: A Design Approach for Rapid Prototyping of Shape-Changing Displays Using Semi-Solid Surfaces. In *In Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17)*, pages 1283–1294. ACM, 2017. ISBN 9781450349222. URL https://doi.org/10.1145/3064663.3064677.

Nicholas Farrow, Naren Sivagnanadasan, and Nikolaus Correll. Gesture Based Distributed User Interaction System for a Reconfigurable Self-Organizing Smart Wall. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction - TEI '14*, pages 245–246, Munich, Germany, 2014. ISBN 9781450326353. doi: 10.1145/2540930.2540967. URL http://dl.acm.org/citation.cfm?doid=2540930.2540967.

Marinella Ferrara and Murat Bengisu. *Materials that Change Color: Smart Materials, Intelligent Design*. 2013. ISBN 9783319002897.

Anna Flagg, Diane Tam, Karon MacLean, and Robert Flagg. Conductive Fur Sensing For a Gesture-Aware Furry Robot. In *Haptics Symposium 2012, HAPTICS 2012 - Proceedings*, pages 99–104, Vancouver, BC, Canada, 2012. ISBN 9781467308090. doi: 10.1109/HAPTIC.2012.6183776.

Sean Follmer, Daniel Leithinger, Alex Olwal, Nadia Cheng, and Hiroshi Ishii. Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-Changing Devices. In *Proceedings of UIST'12*, page 519, Cambridge, Massachusetts, USA, 2012. ISBN 9781450315807. doi: 10.1145/2380116.2380181. URL http://dl.acm.org/citation.cfm?id=2380116.2380181.

Sean Follmer, Daniel Leithinger, Alex Olwal, and Akimitsu Hogge. inFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'13)*, pages 417–426, St. Andrews, UK, 2013. ISBN 9781450322683. doi: 10.1145/2501988.2502032.

Markus Funk, Stefan Schneegaß, Michael Behringer, Niels Henze, and Albrecht Schmidt. An Interactive Curtain for Media Usage in the Shower. *Proceedings of PerDis'15*, 2015. doi: 10.1145/2757710.2757713.

William Gaver. Making Spaces: How Design Workbooks Work. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*, pages 1551–1560, Vancouver, BC, Canada, 2011. ISBN 9781450302678. doi: https://doi.org/10.1145/1978942.1979169.

William Gaver. What Should We Expect From Research Through Design? In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'12)*, pages 937–946, Austin, Texas, USA, 2012. ACM. ISBN 9781450310154. doi: 10.1145/2207676.2208538.

William Gaver, John Bowers, Andy Boucher, Andy Law, Sarah Pennington, and Nicholas Villar. The History Tablecloth: Illuminating Domestic Activity. In *In Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '06)*, pages 199–208. ACM, 2006. ISBN 1595933417. doi: 10.1145/1142405.1142437.

Elisa Giaccardi and Elvin Karana. Foundations of Materials Experience: An Approach for HCI. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 2447–2456, Seoul, Korea, 2015. ACM. ISBN 9781450331456. doi: 10.1145/2702123.2702337. URL http://doi.acm.org/10.1145/2702123.2702337.

Scott M. Gilliland, Nicholas Komor, Thad Starner, and Clint Zeagler. The Textile Interface Swatchbook: Creating graphical user interface-like widgets with conductive embroidery. In *International Symposium on Wearable Computers (ISWC) 2010*, pages 1–8, 2010. doi: 10.1109/iswc.2010.5665876.

Audrey Girouard, Roel Vertegaal, and Ivan Poupyrev. Second International Workshop on Organic User Interfaces. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction - TEI '11*, page 381, Funchal, Portugal, 2011. ISBN 9781450304788. doi: 10.1145/1935701.1935791. URL http://portal.acm.org/citation.cfm?doid=1935701.1935791.

Audrey Girouard, Roel Vertegaal, and Ivan Poupyrev. Special Issue: Organic User Interfaces. *Interacting with Computers*, 25(2):115–116, 2013. doi: 10.1093/iwc/iws001. URL http://iwc.oxfordjournals.org/.

Mark Goulthorpe. Aegis Hyposurface, 2000. URL http://www.hyposurface.org/.

Daniel Groeger and Elena Chong Loo. HotFlex: Post-print Customization of 3D Prints Using Embedded State Change. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'16)*, pages 420–432, San Jose, CA, USA, 2016. ISBN 9781450333627. URL http://dx.doi.org/10.1145/2858036.2858191.

Erik Gronvall, Sofie Kinch, Marianne Graves Petersen, and Majken K. Rasmussen. Causing Commotion with a Shape-Changing Bench. In *Proceedings of CHI'14*, Toronto, ON, Canada, 2014. ISBN 9781450324731. doi: 10.1145/2556288.2557360. URL http://dl.acm.org/citation.cfm?id=2611205.2557360.

Anton Gustafsson and Magnus Gyllenswärd. The Power-Aware Cord: Energy Awareness Through Ambient Information Display. *CHI EA'05*, page 1423, 2005. doi: 10.1145/1056808.1056932. URL http://portal.acm.org/citation.cfm?id=1056808.1056932{%}5Cnhttp://portal.acm.org/citation.cfm?doid=1056808.1056932.

Nur Al-huda Hamdan, Simon Voelker, and Jan Borchers. Sketch & Stitch: Interactive Embroidery for E-Textiles. In *Proc. of CHI'18*, pages 1–13, Montréal, QC, Canada, 2018. ISBN 9781450356206. doi: 10.1145/3173574.3173656. URL https://doi.org/10.1145/3173574.3173656.

John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'15)*, pages 19–28, Seoul, Republic of Korea, 2015. ISBN 9781450331456. doi: 10.1145/2702123.2702599.

Chris Harrison and Scott E. Hudson. Providing dynamically changeable physical buttons on a visual display. In *Conference on Human Factors in Computing Systems - Proceedings*, pages 299–308, 2009. ISBN 9781605582474. doi: 10.1145/1518701.1518749.

Steve Harrison, Deborah Tatar, and Phoebe Sengers. The Three Paradigms of HCI. In *Alt. Chi. Session at the SIGCHI Conference on human factors in computing systems*, pages 1–18, San Jose, CA, USA, 2007.

Felix Heibeck, Basheer Tome, Clark Della Silva, and Hiroshi Ishii. uniMorph - Fabricating Thin-Film Composites for Shape-Changing Interfaces. In *Proceedings of UIST'15*, Charlotte, NC, USA, 2015. ISBN 9781450337793. doi: 10.1145/2807442.2807472.

David Holman and Roel Vertegaal. Organic User Interfaces: Designing Computers in Any Way, Shape or Form. *Communications of the ACM*, 51(6):48, 2008. ISSN 00010782. doi: 10.1145/1349026.1349037. URL http://doi.acm.org/10.1145/1349026.1349037.

David Holman, Jonathan Diehl, Thorsten Karrer, and Jan Borchers. Organic User Interfaces - Media Computing Group - Aachen University, 2006. URL https://hci.rwth-aachen.de/organic.

David Holman, Audrey Girouard, Hrvoje Benko, and Roel Vertegaal. The Design of Organic User Interfaces: Shape, Sketching and Hypercontext. *Interacting with Computers*, 25(2), 2013. ISSN 09535438. doi: 10.1093/iwc/iws018.

Tim Ingold. *Making: Anthropology, Archaeology, Art and Architecture*. Routledge, London, UK, 2013.

Hiroshi Ishii. The Tangible User Interface and its Evolution. *Communications of the ACM*, 51 (6), 2008a. doi: 10.1145/1349026.1349034.

Hiroshi Ishii. Tangible Bits : Beyond Pixels. In *TEI'08 Proceedings of the 2nd International Conference on Tangible and Embedded Interaction*, 2008b. ISBN 9781605580043. doi: 10.1145/1347390.1347392.

Hiroshi Ishii, David Lakatos, Leonardo Bonanni, and Jean-Baptiste Jb Labrune. Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials. *Interactions*, XIX(February):38–51, 2012. ISSN 10725520. doi: 10.1145/2065327.2065337. URL http://dl.acm.org/citation.cfm?id=2065337.

Hiroshi Ishii, Daniel Leithinger, and Sean Follmer. TRANSFORM: Embodiment of "Radical Atoms" at Milano Design Week. In *CHI'15 Extended Abstracts*, Seoul, Republic of Korea, 2015. ISBN 9781450331463. doi: 10.1145/2702613.2702969.

Heekyoung Jung, Youngsuk L Altieri, and Jeffrey Bardzell. SKIN: Designing Aesthetic Interactive Surfaces. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 85–92, Cambridge, Massachusetts, USA, 2010. ISBN 9781605588414. doi: 10.1145/1709886.1709903.

Tatsuya Kaihou and Akira Wakita. Electronic origami with the color-changing function. In *Proceedings of the second international workshop on Smart material interfaces: another step to a material future*, pages 7–12. ACM, 2013.

Hsin-liu Cindy Kao, Deborah Ajilo, Oksana Anilionyte, Artem Dementyev, Inrak Choi, Sean Follmer, and Chris Schmandt. Exploring Interactions and Perceptions of Kinetic Wearables. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS'17)*, pages 391—-396, Edinburgh, UK, 2017. ACM. ISBN 9781450349222. doi: 10.1145/3064663.3064686. URL http://doi.acm.org/10.1145/3064663.3064686.

Hsin-Liu Cindy Kao, Abdelkareem Bedri, and Kent Lyons. SkinWire: Fabricating a Self-Contained On-Skin PCB for the Hand. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 2(3):116:1—-116:23, sep 2018. ISSN 2474-9567. doi: 10.1145/3264926. URL http://doi.acm.org/10.1145/3264926.

Yoshihiro Kawahara, Steve Hodges, Nan Wei Gong, Simon Olberding, and Jurgen Steimle. Building Functional Prototypes Using Conductive Inkjet Printing. *IEEE Pervasive Computing*, 13(3):30–38, 2014. ISSN 15361268. doi: 10.1109/MPRV.2014.41.

Barbara Keating. Bees Banquet! - Tyneside Beekeepers Association, 2018. URL https://tynesidebeekeepers.wordpress.com/2018/04/19/bees-banquet/.

Sarah Kettley. *Designing with smart textiles.* Bloomsbury Publishing, 2016. ISBN 978-1-4725-6915-8.

Sarah Kettley, Katherine Townsend, Sarah Walker, and Martha Glazzard. Electric Corset: an approach to wearables innovation. In *Proceedings of the 3rd Biennial Research Through Design Conference (RtD'17)*, pages 486–500, 2017. doi: 10.6084/m9.figshare.4747027.Image.

Chin Koi Khoo and Flora D. Salim. Lumina: A Soft Kinetic Material for Morphing Architectural Skins and Organic User Interfaces. In *Proceedings of UbiComp'13*, page 53, Zurich, Switzerland, 2013. ISBN 9781450317702. doi: 10.1145/2493432.2494263. URL http://dl.acm.org/citation.cfm?id=2493432.2494263.

Tomomi Kono and Keita Watanabe. Filum: A Sewing Technique to Alter Textile Shapes. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology*, pages 39–41, Quebec City, QC, Canada, 2017. ISBN 9781450354196. doi: 10.1145/3131785.3131797. URL http://doi.acm.org/10.1145/3131785.3131797.

I. Koskinen, J. Zimmerman, T. Binder, J. Redstrom, and S. Wensveen. *Design Research Through Practice: From the Lab, Field, and Showroom.* Elsevier, 2011.

Kristi Kuusk. Crafting Butterfly Lace: Conductive Multi-Color Sensor-Actuator Structure. *UBICOMP/ISWC '15 ADJUNCT*, pages 595–600, 2015. doi: 10.1145/2800835.2801669. URL http://dx.doi.org/10.1145/2800835.2801669.

Stacey Kuznetsov, Piyum Fernando, Emily Ritter, Cassandra Barrett, Jennifer Weiler, and Marissa Rohr. Screenprinting and TEI : Supporting Engagement with STEAM through DIY Fabrication of Smart Materials. In *TEI'18*, pages 211–220, Stockholm, Sweeden, 2018. ACM. ISBN 9781450355681. doi: 10.1145/3173225.3173253.

Julian Lepinski and Roel Vertegaal. Cloth displays: interacting with drapable textile screens. *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*, 2011. doi: 10.1145/1935701.1935765. URL http://doi.acm.org/10.1145/1935701.1935765.

Jessica Lo and Audrey Girouard. Fabricating Bendy: Design and Development of Deformable Prototypes. *IEEE Pervasive Computing*, 13(3):40–46, 2014.

Clara Mancini, Yvonne Rogers, Arosha K Bandara, Tony Coe, Lukasz Jedrzejczyk, Adam N Joinson, Blaine A Price, Keerthi Thomas, and Bashar Nuseibeh. ContraVision: Exploring Users' Reactions to Futuristic Technology. In *Proc. of CHI2010*, Atlanta, Georgia, USA, 2010. ISBN 9781605589299.

Rupert Meese, Shakir Ali, Emily-Clare Thorne, Steve D Benford, Anthony Quinn, Richard Mortier, Boriana N Koleva, Tony Pridmore, and Sharon L Baurley. From Codes to Patterns: Designing Interactive Decoration for Tableware. In *Proceedings of CHI'13*, pages 931–940, Paris, France, 2013. ISBN 978-1-4503-1899-0. doi: 10.1145/2470654.2466119.

Achim Menges and Steffen Reichert. Material Capacity: Embedded Responsiveness. *Architectural Design*, 82(2):52–59, 2012. ISSN 00038504. doi: 10.1002/ad.1379.

Sarah Mennicken, A. J. Bernheim Brush, Asta Roseway, and James Scott. Exploring interactive furniture with EmotoCouch. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication*, 2014a. ISBN 9781450330473. doi: 10.1145/2638728.2638846. URL http://dl.acm.org/citation.cfm?id=2638846.

Sarah Mennicken, A.J. Bernheim Brush, Asta Roseway, and James Scott. Finding Roles for Interactive Furniture in Homes with EmotoCouch. In *Ubicomp'14*, Seattle, WA, USA, 2014b. ISBN 9781450330473. doi: 10.1145/2638728.2641547.

Stephen A Morin, Robert F Shepherd, Sen Wai Kwok, Adam A Stokes, Alex Nemiroski, and George M Whitesides. Camouflage and Display for Soft Machines. *Science*, 337(6096): 828–832, 2012.

Nadia Mounajjed and Imran A Zualkernan. From Simple Pleasure to Pleasurable Skin: An Interactive Architectural Screen. In *DPPI '11*, Milano, IT, 2011. doi: 10.1145/2347504.2347537.

Sara Nabil and Atef Ghalwash. Organic Interactive Displays: A Bridge from History. *The 5th International Symposium on Frontiers in Ambient and Mobile Systems (FAMS 2015) - Procedia Computer Science*, 52, 2015. ISSN 1877-0509. doi: 10.1016/j.procs.2015.05.109. URL http://dx.doi.org/10.1016/j.procs.2015.05.109.

Sara Nabil and David S. Kirk. Interactive Interior Design and Personal Data. In Holger Schnädelbach and David Kirk, editors, *People, Personal Data and the Built Environment*, chapter 5. Springer International Publishing, 1 edition, 2019. ISBN 978-3-319-70874-4. doi: 10.1007/978-3-319-70875-1. URL https://www.springer.com/gp/book/9783319708744.

Sara Nabil, David S. Kirk, Thomas Plötz, Julie Trueman, David Chatting, Dmitry Dereshev, and Patrick Olivier. Interioractive: Smart Materials in the Hands of Designers and Architects for Designing Interactive Interiors. In *Proceedings of the 2017 Conference on Designing Interactive Systems - DIS'17*, pages 379–390, Edinburgh, UK, 2017a. ISBN 9781450349222. doi: 10.1145/3064663.3064745. URL http://dl.acm.org/citation.cfm?doid=3064663.3064745.

Sara Nabil, Thomas Ploetz, and David S Kirk. Interactive Architecture: Exploring and Unwrapping the Potentials of Organic User Interfaces. In *Proc. of TEI'17*, pages 89–100, Yokohama, Japan, 2017b. ISBN 9781450346764. doi: 10.1145/3024969.3024981. URL http://dx.doi.org/10.1145/3024969.3024981.

Sara Nabil, Aluna Everitt, Miriam Sturdee, Jason Alexander, Simon Bowen, Peter Wright, and David Kirk. ActuEating: Designing, Studying and Exploring Actuating Decorative Artefacts. In *Proceedings of DIS'18*, pages 327–339, Hong Kong, 2018a. ISBN 9781450351980. doi: https://doi.org/10.1145/3196709.3196761.

Sara Nabil, Reem Talhouk, Julie Trueman, David S Kirk, Simon Bowen, and Pete Wright. Decorating Public and Private Spaces: Identity and Pride in a Refugee Camp. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–6, 2018b. ISBN 9781450356213. doi: 10.1145/3170427.3188550. URL https://doi.org/10.1145/3170427.3188550.

Sara Nabil, Jan Kučera, Nikoletta Karastathi, David Kirk, and Peter Wright. Seamless Seams: Crafting Techniques for Embedding Fabrics with Interactive Actuation. In *Proceedings of DIS'19*, San Diego, CA, USA, 2019. ACM. doi: 10.1145/3322276.3322369. URL https://doi.org/10.1145/3322276.3322369.

Kosuke Nakajima, Yuichi Itoh, Takayuki Tsukitani, Kazuyuki Fujita, Kazuki Takashima, Yoshifumi Kitamura, and Fumio Kishino. FuSA2 Touch Display: A Furry and Scalable Multi-touch Display. In *Proceedings of ITS'11*, Kobe, Japan, 2011. ISBN 9781467312462. doi: 10.1109/VR.2012.6180852.

Ned Kahn Studios. Ned Kahn, 2016. URL http://nedkahn.com/.

William Odom, Richard Banks, Abigail Durrant, David Kirk, and James Pierce. Slow Technology: Critical Reflection and Future Directions. In *Proceedings of the Designing Interactive Systems Conference on - DIS '12*, number October 2015, pages 816–817, Newcastle, UK, 2012. ISBN 9781450312103. doi: 10.1145/2317956.2318088. URL http://dl.acm.org/citation.cfm?id=2317956.2318088.

William Odom, Abigail J. Sellen, Richard Banks, David S. Kirk, Tim Regan, Mark Selby, Jodi L. Forlizzi, and John Zimmerman. Designing for Slowness, Anticipation and Re-visitation: A Long Term Field Study of the Photobox. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*, pages 1961–1970, Toronto, ON, Canada, 2014. ISBN 9781450324731. doi: 10.1145/2556288.2557178. URL http://dl.acm.org/citation.cfm?id=2611528.2557178.

Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. Foldio: Digital fabrication of interactive and shape-changing objects with foldable printed electronics. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology (UIST 2015)*, pages 223–232, 2015. ISBN 9781450337793. doi: 10.1145/2807442.2807494.

Yoshiharu Ooide, Hiroki Kawaguchi, and Takuya Nojima. An Assembly of Soft Actuators for an Organic User Interface. In *Proceedings of the adjunct publication of the 26th annual ACM symposium on User interface software and technology - UIST '13 Adjunct*, St. Andrews, UK, 2013. ISBN 9781450324069. doi: 10.1145/2508468.2514723. URL http://dl.acm.org/citation.cfm?doid=2508468.2514723.

Kas Oosterhuis and Nimish Biloria. Interactions with Proactive Architectural Spaces. *Communications of the ACM*, 51(6), 2008. ISSN 00010782. doi: 10.1145/1349026.1349041.

Takeshi Oozu, Aki Yamada, Yuki Enzaki, and Hiroo Iwata. Escaping Chair: Furniture-Shaped Device Art. In *TEI 2017*, pages 403–407, Yokohama, Japan, 2017. ISBN 978-1-4503-4371-8. doi: 10.1145/2945078.2945086. URL http://doi.acm.org/10.1145/2945078.2945086.

Maggie Orth. 100 Electronic Art Years, 2009. URL http://www.maggieorth.com.

Jifei Ou, Lining Yao, Daniel Tauber, Jürgen Steimle, Ryuma Niiyama, and Hiroshi Ishii. jamSheets: Thin Interfaces with Tunable Stiffness Enabled by Layer Jamming. In *Proceedings of TEI'14*, pages 65–72, Munich, Germany, 2014. ISBN 9781450326353. doi: 10.1145/2540930.2540971. URL http://dl.acm.org/citation.cfm?doid=2540930.2540971.

Patrick Parzer, Kathrin Probst, Teo Babic, Christian Rendl, Anita Vogl, Alex Olwal, and Michael Haller. FlexTiles: A Flexible, Stretchable, Formable, Pressure Sensitive, Tactile Input Sensor. In *Prof. of CHI EA '16*, San Jose, CA, USA, 2016. ISBN 9781450340823. doi: 10.1145/2851581.2890253. URL http://doi.acm.org/10.1145/2851581.2890253.

Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, and Michael Haller. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, pages 745–756, New York, NY, USA, 2018. ACM. ISBN 978-1-4503-5948-1. doi: 10.1145/3242587.3242664. URL http://doi.acm.org/10.1145/3242587.3242664.

Roshan Lalintha Peiris, Jeffrey Tzu Kwan Valino Koh, Mili John Tharakan, Owen Noel Newton Fernando, and Adrian David Cheok. Ambi Kraf Byobu: Merging Technology with Traditional Craft. *Interacting with Computers*, 25(2):173–182, 2013. ISSN 09535438. doi: 10.1093/iwc/iws013.

Hannah Perner-Wilson and Leah Buechley. Handcrafting Textile Mice. In *DIS '10 Proceedings of the 8th ACM Conference on Designing Interactive Systems*, pages 434–435, 2010a. ISBN 9781450301039. doi: 10.1145/1858171.1858257.

Hannah Perner-Wilson and Leah Buechley. Making textile sensors from scratch. In *TEI '10 Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*, pages 349–352, Cambridge, Massachusetts, USA, 2010b. ACM. ISBN 9781605588414. doi: 10.1145/1709886.1709972.

Hannah Perner-Wilson and Leah Buechley. Handcrafting Textile Interfaces from A Kit-of-No-Parts. In *TEI '11 Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*, pages 61–67, 2011. ISBN 9781450304788. doi: 10.1145/1935701.1935715.

Anna Persson. Exploring textiles as materials for interaction design. Number 4. University of Borås, 2013. ISBN 978-91-85659-88-3. URL http://urn.kb.se/resolve?urn=urn:nbn:se:hb:diva-3652{%}0A.

Marianne Graves Petersen. Squeeze: Designing for playful experiences among co-located people in homes. In *Proceedings of the ACM 2007 Conference on Human Factors in Computing Systems*, pages 2609–2614, San Jose, CA, USA, 2007. ISBN 9781595936424. doi: 10.1145/1240866.1241050.

Philips Lighting. Philips Luminous Patterns, 2016. URL http://www.lighting.philips.com/main/systems/packaged-offerings/retail-and-hospitality/luminous-patterns.html.

Sarah Pink, Elisenda Ardèvol, and Débora Lanzeni. *Digital Materialities: Design and Anthropology*. Bloomsbury Academic, 2016.

Irene Posch and Ebru Kurbak. CRAFTED LOGIC: Towards Hand-Crafting a Computer. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pages 3881–3884, San Jose, CA, USA, 2016. ACM. ISBN 9781450340823. doi: 10.1145/2851581.2891101. URL http://doi.acm.org/10.1145/2851581.2891101.

Ernest Post, M Orth, P R Russo, and N Gershenfeld. E-broidery: Design and fabrication of textile-based computing. *IBM Systems Journal*, 39:840–860, 2000. doi: 10.1147/sj.393.0840.

Ivan Poupyrev, Philipp Schoessler, Jonas Loh, and Munehiko Sato. Botanicus Interacticus: interactive plants technology. In *ACM SIGGRAPH 2012 Emerging Technologies (SIGGRAPH '12)*, pages 1–1, 2012. ISBN 9781450314350. doi: 10.1145/2343456.2343460.

Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E Robinson. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 4216–4227, New York, NY, USA, 2016. ACM. ISBN 978-1-4503-3362-7. doi: 10.1145/2858036.2858176. URL http://doi.acm.org/10.1145/2858036.2858176.

Larissa Pschetz and Richard Banks. Long Living Chair. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*, pages 13–14, Paris, France, 2013. ACM. ISBN 9781450319522. doi: 10.1145/2468356.2479590.

Jie Qi and Leah Buechley. Animating Paper using Shape Memory Alloys. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 749–752, Austin, Texas, USA, 2012. ACM. ISBN 9781450310154. doi: 10.1145/2207676.2207783. URL http://doi.acm.org/10.1145/2207676.2207783.

Jie Qi and Leah Buechley. Sketching in Circuits: Designing and Building Electronics on Paper. In *Proc. of Human Factors in Computing Systems*, pages 1713–1721, Toronto, ON, Canada, 2014. ACM. ISBN 9781450324731. doi: 10.1145/2556288.2557391.

Majken K Rasmussen, Esben W Pedersen, Marianne G Petersen, and Kasper Hornbæk. Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems (CHI'12)*, pages 735–744. ACM, 2012. ISBN 9781450310154. doi: 10.1145/2207676.2207781. URL http://dl.acm.org/citation.cfm?id=2207676.2207781.

Matt Ratto. Critical Making: Conceptual and Material Studies in Technology and Social Life. *The Information Society*, 27(4):252–260, 2011. doi: 10.1080/01972243.2011.583819. URL https://doi.org/10.1080/01972243.2011.583819.

Redfern Electronics. The Crumble Controller, 2018. URL https://redfernelectronics.co.uk/crumble/.

Johan Redström. Towards user design? on the shift from object to user as the subject of design. *Design Studies*, 27(2):123–139, 2005. ISSN 0142694X. doi: 10.1016/j.destud.2005.06.001.

Jun Rekimoto. Organic Interaction Technologies: From Stone to Skin. *Communications of the ACM*, pages 38–44, 2008. ISSN 00010782. doi: 10.1177/1464700109355214.

Hans-Jörg Rheinberger. *An epistemology of the concrete: Twentieth-century histories of life*. Duke University Press, 2010.

Axel Ritter. *Smart Materials in Architecture, Interior Architecture and Design*, volume 1. Birkhauser, 2015. ISBN 9788578110796. doi: 10.1017/CBO9781107415324.004.

Francesca Rogers and Daniele Gualeni Design Studio. Light-Form, 2010. URL https://www.gualenidesign.it/.

Daniel Saakes, Masahiko Inami, Takeo Igarashi, Naoya Koizumi, and Ramesh Raskar. Shader printer. In *ACM SIGGRAPH 2012 Emerging Technologies on - SIGGRAPH '12*, pages 1–1, Los Angeles, CA, USA, 2012. ISBN 9781450316804. doi: 10.1145/2343456.2343474. URL http://dl.acm.org/citation.cfm?doid=2343456.2343474.

Munehiko Sato, Ivan Poupyrev, and Chris Harrison. Touché: Enhancing touch interaction on humans, screens, liquids, and everyday objects. In *Conference on Human Factors in Computing Systems - Proceedings*, pages 483–492, 2012. ISBN 9781450310154. doi: 10.1145/2207676.2207743.

Mika Satomi and Hannah Perner-Wilson. How To Get What You Want, 2019. URL https://www.kobakant.at/DIY/.

Holger Schnadelbach, Ainojie Irune, David Kirk, Kevin Glover, and Patrick Brundell. ExoBuilding: Physiologically Driven Adaptive Architecture. *ACM Transactions on Computer-Human Interaction*, 19(4), 2012. ISSN 10730516. doi: 10.1145/2395131.2395132.

Nicolas Schöffer. Spatiodynamic, Luminodynamic & Chronodynamic. In *Nicolas Schöffer's Précurseur de l'Art Cybernétique Exhibition*, Paris, France, 2005.

Donald A. Schön. *The Reflective Practitioner: How professionals think in action.* Routledge, 1983. ISBN 0465068782.

Michael Schwab. *Experimental Systems: Future Knowledge in Artistic Research*. Leuven University Press, 2013. ISBN 978 90 5867 973 4.

Mark Selby and David Kirk. Experiential Manufacturing: The Earthquake Shelf. In *RTD2015*, number March, pages 25–27, Cambridge, UK, 2015. doi: 10.6084/m9.figshare.1327994.

Manlin Song, Chenyu Jia, and Katia Vega. Eunoia: Dynamically Control Thermochromic Displays for Animating Patterns on Fabrics. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers*, UbiComp '18, pages 255–258, New York, NY, USA, 2018. ACM. ISBN 978-1-4503-5966-5. doi: 10.1145/3267305.3267557. URL http://doi.acm.org/10.1145/3267305.3267557.

P J Stappers and E Giaccardi. *Research Through Design*, volume 2nd Ed. The Interaction Design Foundation, 2017.

Paul Strohmeier, K.V. Swensen, Cameron Lapp, Audrey Girouard, and Roel Vertegaal. A Flock of Birds: Bringing Paper to Life. In *Proceedings of the 6th International Conference on Tangible, Embedded and Embodied Interaction, TEI 2012*, pages 333–334, Kingston, ON, Canada, 2012. ISBN 9781450311748. doi: 10.1145/2148131.2148208.

Miriam Sturdee. *Sketching as a Support Mechanism for the Design and Development of Shape-Changing Interfaces*. PhD thesis, 2018.

Miriam Sturdee, Jason Alexander, Paul Coulton, and Sheelagh Carpendale. Sketch & The Lizard King: Supporting Image Inclusion in HCI Publishing. In *CHI EA '18 Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, New York, USA, 2018. ACM.

Yuta Sugiura, Gota Kakehi, Anusha Withana, Calista Lee, Daisuke Sakamoto, Maki Sugimoto, Masahiko Inami, and Takeo Igarashi. Detecting shape deformation of soft objects using directional photoreflectivity measurement. In *Proceedings of UIST '11*, page 509, Santa Barbara, CA, USA, 2011. ISBN 9781450307161. doi: 10.1145/2047196.2047263. URL http://dl.acm.org/citation.cfm?doid=2047196.2047263.

L Sun, W M Huang, Z Ding, Y Zhao, C C Wang, H Purnawali, and C Tang. Stimulus-responsive shape memory materials: A review. *Materials and Design*, 33:577–640, 2012. ISSN 0261-3069. doi: 10.1016/j.matdes.2011.04.065. URL http://dx.doi.org/10.1016/j.matdes.2011.04.065.

Tomomi Takashina, Kotaro Aoki, Akiya Maekawa, Chihiro Tsukamoto, Hitoshi Kawai, Yoshiyuki Yamariku, Kaori Tsuruta, Marie Shimokawa, Yuji Kokumai, and Hideki Koike. Smart Curtain as Interactive Display in Living Space. In *SIGGRAPH Asia 2015 Posters*, Kobe, Japan, 2015. ISBN 978-1-4503-3926-1. doi: 10.1145/2820926.2820971. URL http://doi.acm.org/10.1145/2820926.2820971.

Joshua Tanenbaum, Karen Tanenbaum, and Ron Wakkary. Design Fictions. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, pages 347—-350, Kingston, ON, Canada, 2012. ACM. doi: 10.1145/2148131.2148214. URL http://doi.acm.org/10.1145/2148131.2148214.

Sarah Taylor and Sara Robertson. Digital Lace: A Collision of Responsive Technologies. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers (ISWC'14 Adjunct)*, pages 93–97. New York: ACM, 2014. ISBN 9781450330480. doi: 10.1145/2641248.2641280. URL http://dl.acm.org/citation.cfm?id=2641280.

The Northern Echo. Help create a buzz around bees at Newcastle University's Great North Museum: Hancock, 2018. URL https://www.thenorthernecho.co.uk/news/local/northdurham/tyneandwear/regional/16080873.

Jonas Togler, Fabian Hemmert, and Reto Wettach. Living interfaces: the thrifty faucet. *Communications of the ACM*, pages 43–44, 2009. doi: 10.1145/1517664.1517680. URL http://portal.acm.org/citation.cfm?id=1517664.1517680.

Todd Treece. Metal Inlay Capacitive Touch Buttons, 2015. URL https://learn.adafruit.com/metal-inlay-capacitive-touch-buttons/overview.

Giovanni Maria Troiano, John Tiab, and Youn-kyung Lim. SCI-FI: Shape-Changing Interfaces, Future Interactions. In *NordiCHI'16*, Gothenburg, Sweden, 2016. ISBN 9781450347631. doi: 10.1145/2971485.2971489. URL http://dx.doi.org/10.1145/2971485.2971489.

Kohei Tsuji and Akira Wakita. Anabiosis: An Interactive Pictorial Art Based on Polychrome Paper Computing. In *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology*, pages 80:1–80:2, Lisbon, Portugal, 2011. ISBN 978-1-4503-0827-4. doi: 10.1145/2071423.2071521. URL http://doi.acm.org/10.1145/2071423.2071521.

Kentaro Ueda, Tsutomu Terada, and Masahiko Tsukamoto. Input Interface Using Wrinkles on Clothes. In *ISWC'16*, pages 56–57, Heidelberg, Germany, 2016. ISBN 9781450344609. doi: 10.1145/2971763.2971782.

V2_Lab. Why technology inspires us, 2018. URL http://v2.nl/lab/blog/why-wearable-technology-inspires-us.

Roel Vertegaal and Ivan Poupyrev. Organic User Interfaces. *Communications of the ACM*, 51 (6):26, 2008. ISSN 00010782. doi: 10.1145/1349026.1349033. URL http://portal.acm.org/citation.cfm?doid=1349026.1349033.

Yvonne Y F Chan Vili. Investigating Smart Textiles Based on Shape Memory Materials. *Textile Research Journal*, 77(0):290–300, 2007. doi: 10.1177/0040517507078794.

Luke Vink, Viirj Kan, Ken Nakagaki, Daniel Leithinger, Sean Follmer, Philipp Schoessler, Amit Zoran, and Hiroshi Ishii. TRANSFORM as Adaptive and Dynamic Furniture. *Proceedings of CHI EA '15*, pages 183–183, 2015. doi: 10.1145/2702613.2732494. URL http://dl.acm.org/citation.cfm?id=2702613.2732494.

Anita Vogl, Patrick Parzer, Teo Babic, Joanne Leong, Alex Olwal, and Michael Haller. StretchEBand: Enabling Fabric-Based Interactions through Rapid Fabrication of Textile Stretch Sensors. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 2617—-2627, Denver, CO, USA, 2017. ISBN 9781450346559. doi: 10.1145/3025453.3025938. URL http://doi.acm.org/10.1145/3025453.3025938.

Luisa von Radziewsky, Antonio Krüger, and Markus Löchtefeld. Scarfy: Augmenting Human Fashion Behaviour with Self-Actuated Clothes. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '15, pages 313–316, New York, NY, USA, 2015. ACM. ISBN 978-1-4503-3305-4. doi: 10.1145/2677199.2680568. URL http://doi.acm.org/10.1145/2677199.2680568.

Akira Wakita and Midori Shibutani. Mosaic Textile: wearable ambient display with non-emissive color-changing modules. In *Proceedings of the 2006 ACM SIGCHI international conference on Advances in computer entertainment technology (ACE '06)*, New York, NY, USA, 2006. ACM. URL https://doi.org/10.1145/1178823.1178880.

Mark Weiser. The Computer for the 21st Century. *Scientific American*, 265(September 1991): 94–104, 1991. ISSN 15591662. doi: 10.1145/329124.329126.

Mark Weiser and John Seely Brown. The Coming Age of Calm Technology. In *Beyond Calculation*. Springer, New York, NY, USA, 1996. doi: 10.1.1.129.2275.

XSLabs. Nitinol, 2018. URL http://www.xslabs.net/skorpions/tech.html.

Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology - UIST '13*, pages 13–22, St. Andrews, UK, 2013. ISBN 9781450322683. doi: 10.1145/2501988.2502037. URL http://dl.acm.org/citation.cfm?doid=2501988.2502037.

Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*, pages 1–10, 2015. ISBN 9781139855952. doi: 10.1017/CBO9781139855952.100.

Bin Yu, Nienke Bongers, Alissa van Asseldonk, Jun Hu, Mathias Funk, and Loe Feijs. Living-Surface: Biofeedback through Shape-changing Display. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 168–175, Eindhoven, Netherlands, 2016. ISBN 9781450335829. doi: 10.1145/2839462.2839469. URL http://dl.acm.org/citation.cfm?doid=2839462.2839469.

Michelle Yuen, Arun Cherian, Jennifer C Case, Justin Seipel, and Rebecca K Kramer. Conformable Actuation and Sensing with Robotic Fabric. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 581–586, Chicago, IL, USA, 2014. ISBN 9781479969333.

Clint Zeagler, Scott Gilliland, Halley Profita, and Thad Starner. Textile Interfaces: Embroidered Jog-Wheel, Beaded Tilt Sensor, Twisted Pair Ribbon, and Sound Sequins. In *Proceedings of the 2012 16th Annual International Symposium on Wearable Computers (ISWC)*, ISWC '12, pages 60–63, Washington, DC, USA, 2012. IEEE Computer Society. ISBN 978-0-7695-4697-1. doi: 10.1109/ISWC.2012.29. URL https://doi.org/10.1109/ISWC.2012.29.

Kening Zhu and Shengdong Zhao. AutoGami: A Low-cost Rapid Prototyping Toolkit for Automated Movable Paper Craft. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 661–670, New York, NY, USA, 2013. ACM. ISBN 978-1-4503-1899-0. doi: 10.1145/2470654.2470748. URL http://doi.acm.org/10.1145/2470654.2470748.

John Zimmerman, Jodi Forlizzi, and Shelley Evenson. Research Through Design as a Method for Interaction Design Research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'07)*. ACM, 2007. doi: 10.1145/1240624.1240704.

John Zimmerman, Erik Stolterman, and Jodi Forlizzi. An Analysis and Critique of Research through Design : towards a formalization of a research approach. In *Proc. of DIS2010*, pages 310–319, Aarhus, Denmark, 2010. ISBN 9781450301039. doi: 10.1145/1858171.1858228.

Appendix A. Decoraction SwatchBook

My DECORACTION Swatch Book

SARA NABIL

1. 2D PAPER

My first and simplest form of shape-change was using SMA wire (Shape-Memory Alloy i.e. shape-changing material) on a planner piece of paper to experiment its behaviour upon applying different electric currents.
Because the SMA is attached to its back, the paper bends outwards not inwards as was expected.

Material:	Copy Paper
Shape:	10.5x3.5 cm strip
Shape-changing material	Flexinol (0.010" HT) 20 cm (3.6 Ω)
Fitted by:	Glue Gun
Connected to:	Clipped Wires
Power:	7V, 1Amp
Effect:	Bend (outwards)
Drama Rating:	★☆☆☆☆
Application:	Pillow/ Cushion bending edges


sec 0


sec 0.5

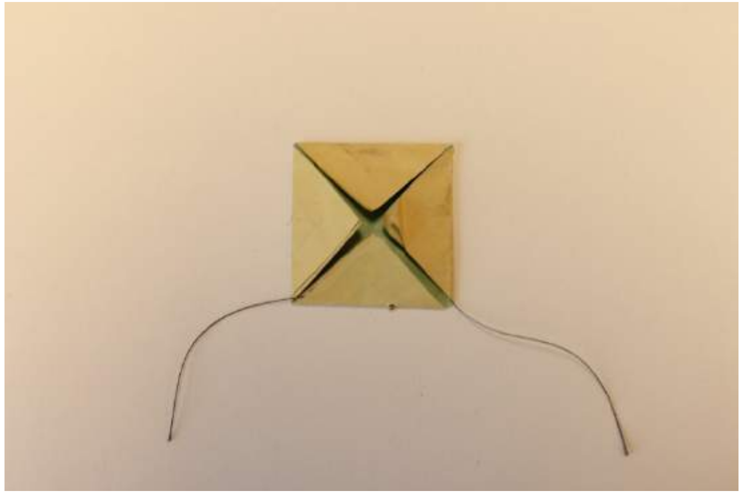

sec 1


sec 1.5

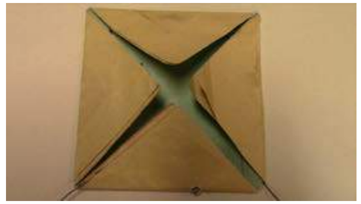

sec 2

2. 3D PAPER

As a 3D folding form of shape-change, this origami self-folding shape uses SMA between two pieces of paper to experiment its behaviour upon applying different electric currents.



Material:	Copy Paper
Shape:	3D Origami 5x5 cm
Shape-changing material	15 cm Nitinol muscle wire (0.006")
Fitted by:	Stitched
Connected to:	Conductive Thread
Power:	6-12V, 1Amp
Effect:	unfold
Drama Rating:	★★☆☆☆
Application:	Self-unfolding placemat or tablecloth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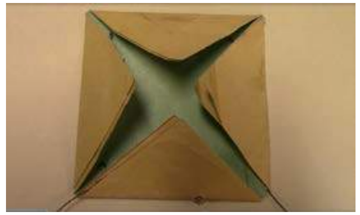
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sec 1


sec 1.5


sec 2

3. LEATHER

As the first example, but using leather as an interesting interior design material to form a unit (physical pixel) of a shape-changing interior artefact using SMA on the leather strip to experiment its behaviour upon applying different electric currents.

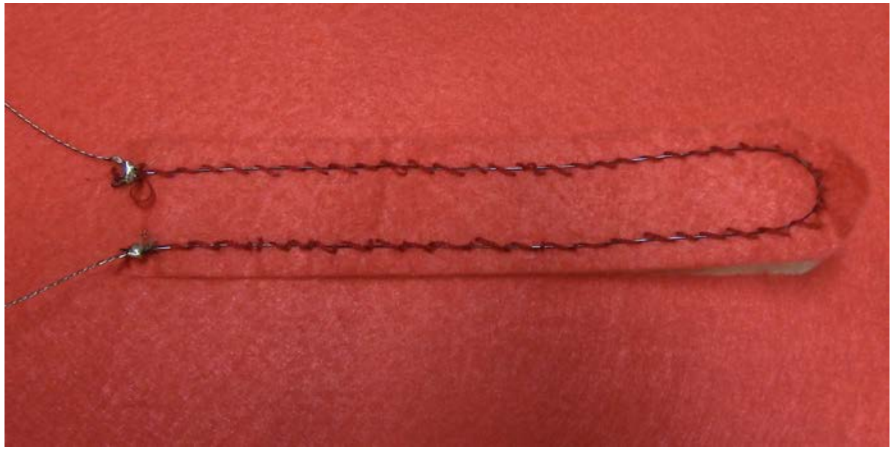
Material:	leather (1 mm)
Shape:	planner 10x3 cm strip
Shape-changing material	Flexinol (0.010" HT) 20 cm (3.6 Ω)
Fitted by:	Careful tilted stitching
Connected to:	Soldered wires
Power:	7V, 1Amp
Effect:	Bend
Drama Rating:	★★★★☆
Application:	Shaggy Rug or Interactive Curtain

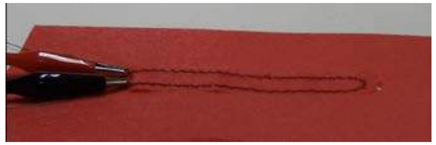
This can be used in groups as pixels to form a module of texture-changing leather interfaces/ artefacts.

4. FELT FINGER

Although quite simple, a planner felt strip has proven to be one of the most effective bending shape and material combination that give a quick, visible and robust output. Careful tight stitching in a tilted pattern gives best results and allow SMA to both shrink and relax at the same time. At both ends the SMA was connected to conductive thread using soldered crump-beads to allow flexible movement and firm contact, however the conductive thread having high resistance prevented the SMA from getting enough current to heat and thus actuate effectively.

Material:	Hard Felt (0.3 mm)
Shape:	Planer Strip cut-out 10x2 cm
Shape-changing material	Flexinol wire (0.010") 20 cm (3.6 Ω)
Fitted by:	Careful tilted Stitching
Connected to:	Conductive Thread
Power:	5V-7V, 1Amp
Effect:	bend
Drama Rating:	★★☆☆☆
Application:	Shape-changing textile

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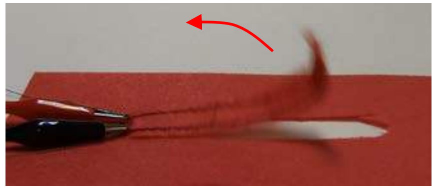
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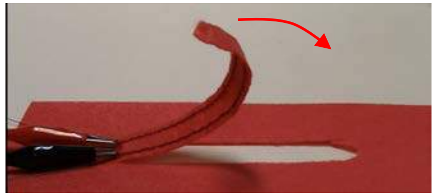
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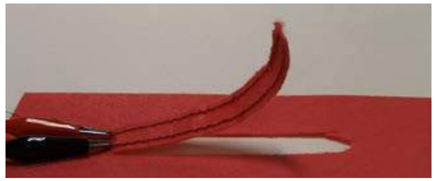
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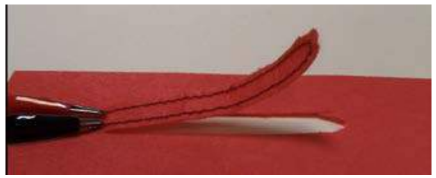
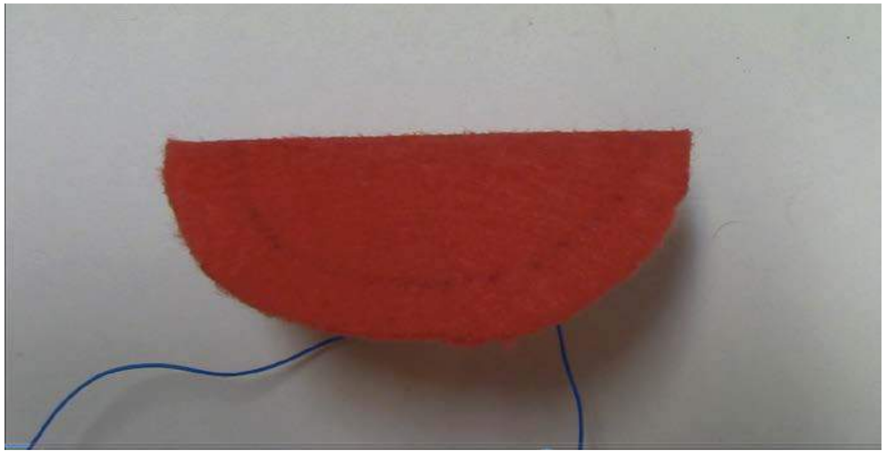
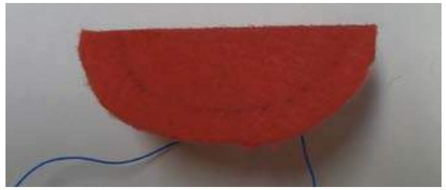

sec 2

5. FELT PUPPET

As an alternative to the strip, when trying a circular-shaped piece of felt, it didn't work as effectively, it was rather weaker in actuation even when connecting it through electric wires (instead of conductive thread) and even after applying much higher current (9v instead of 5v). It is clear how the pointy shape that is used to stitch/fix the SMA wire has significant influence to the actuation as opposed to a circular shape.

Material:	Hard Felt (0.3 mm)
Shape:	Circle 8 cm diameter
Shape-changing material:	Flexinol wire (0.006") 16 cm (3 Ω)
Fitted by:	Stitched
Connected to:	Soldered Wires
Power:	9v, 1Amp
Effect:	unbend
Drama Rating:	★★☆☆☆
Application:	Self-unfolding placemat or tablecloth





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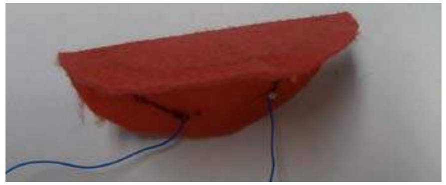

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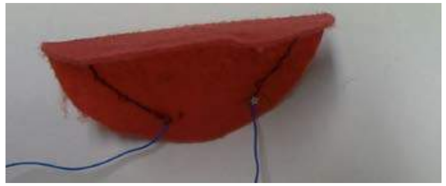

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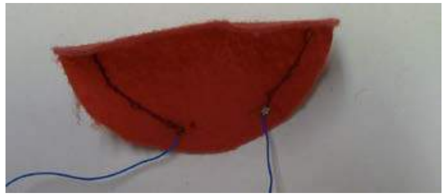

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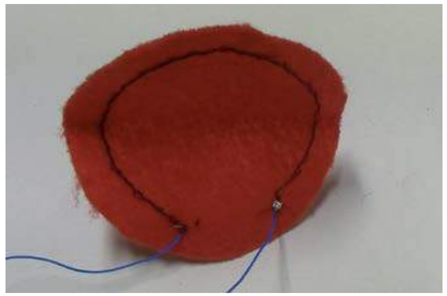
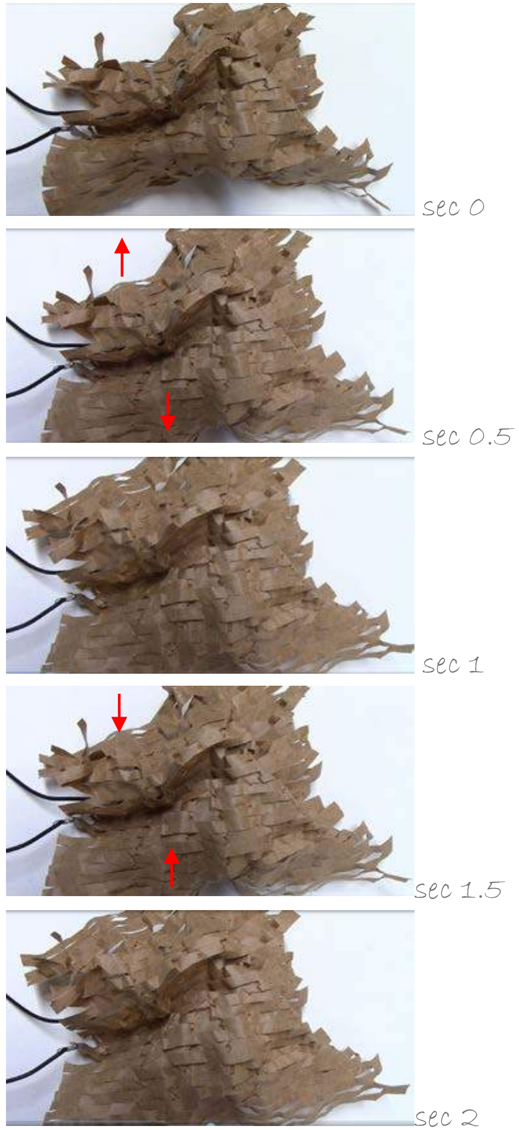


sec 1

6. BREATHING WRAP

As more complicated structure, this wrapping paper with its longitudinal cut-outs as expected gave a more complicated actuation effect. To make things more effective the SMA has been stitched to its back in a flower-shape to pull different corners inwards and outwards together forming an inhaling/ exhaling effect as if it is alive!

Material:	Wrapping Paper
Shape:	square 10x10 cm
Shape-changing material:	Nitinol wire (0.006") 40 cm (7 Ω)
Fitted by:	Stitched
Connected to:	Conductive Thread
Power:	6-12V, 1Amp
Effect:	Inhale/contract
Drama Rating:	★★★★☆
Application:	

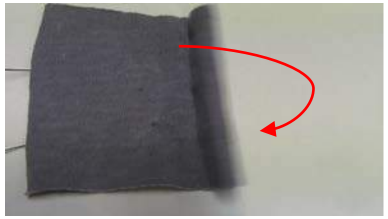


7. ROLLING FABRIC

When trying the SMA wire with thermochromic fabric, the result was great i.e. shape-change and colour-change intertwined together, where the heat of the electric current passing through conductive thread heats up the SMA wire and causes it to shrink therefore pulling the fabric outwards that unrolls it in this case, plus changing the colour of the fabric at the same time.

Material:	Thermochromic Fabric
Shape:	rectangular 12x7 cm
Shape-changing material:	15 cm Nitinol wire (0.006")
Fitted by:	Stitched
Connected to:	Conductive Thread
Power:	6-12V, 1Amp
Effect:	roll
Drama Rating:	★★★★☆
Application:	Self-unfolding placemat or table-runner


sec 0


sec 0.5


sec 0.75


sec 1

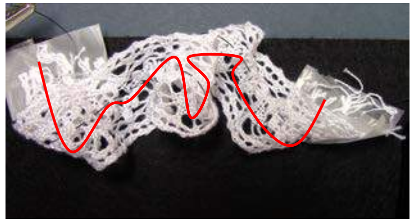

sec 1.5

8. SWIRLING LACE

As an interesting experiment this lace was embedded with SMA wire (without any stitching or gluing) and fixed on a felt surface. Although thought to be loose and lame, it turned out to be very unusual and unique as it swirled and swayed in a snake-like continuous motion in random non-uniform behaviour which appeared to alive!

Material:	Lace (0.5 mm)
Shape:	Snaky 18x2 cm
Shape-changing material:	Flexinol HT (0.010") 20 cm (3.6 Ω)
Fitted by:	embedded
Connected to:	Clipped wires
Power:	6-12V, 1Amp
Effect:	swirl
Drama Rating:	★★★★☆
Application:	Actuated Lace decorations and tassels


sec 0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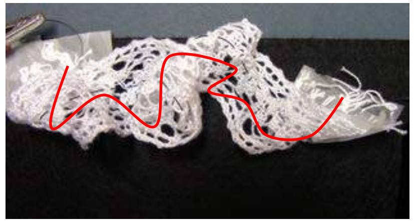
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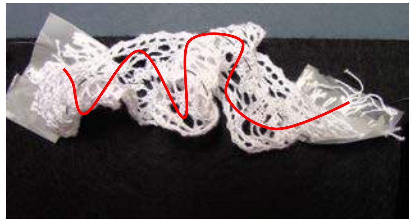
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sec

9. SHIVERING ACRYLIC

Although not textile (or paper) this semi-flexible 3D printed mesh pattern is inspiring to examine with muscle wire on the back and see how it behaves/ actuates. As it clearly wouldn't allow any stitching or embroidery, an idea of fixing the SMA using a glue gun on several spots was tested. The result was not necessarily impressive, but it did shiver forward and backward utilizing its flexible yet coherent structure.
This can be used to achieve a vibration effect with no need for any vibration motors and therefore avoiding their noisy sound.

Material:	Acrylic (3 mm)
Shape:	3D-Printed Flexible Mesh 15x(3-4) cm
SMA:	Nitinol wire (0.006")
	15 cm
Fitted by:	Glued
Connected to:	Conductive Thread
Power:	9V, 1Amp
Effect:	vibrate
Drama Rating:	★☆☆☆☆
Application:	

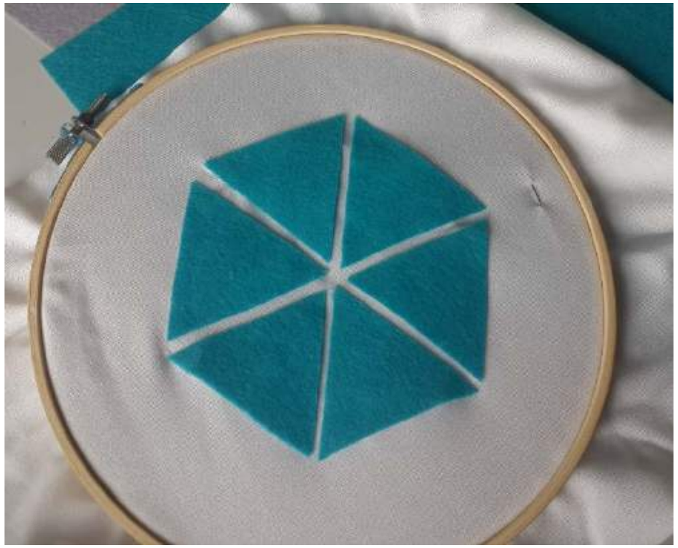
sec 0

sec 0.5

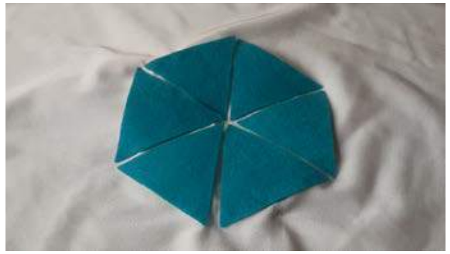
sec 1

10. PEAKING TEXTILE

As a shape-changing textile this swatch pops-out using 2 seamlessly embedded nitinol muscle spring underneath that are attached together each in a semi-circle shape controlling three triangles. Because of the semi-rigidity of the hard felt and the extreme flexibility of the stretchable Spandex fabric, this peaking module pops out in a second.



Material:	Stretchable Spandex and hard felt
Shape:	Triangular flexible pattern
SMA:	2 Nitinol Spring (0.010") 45°C
	(2-10 cm) each
Fitted by:	Selective Stitching
Connected to:	Conductive Thread
Power:	7V, 1Amp
Effect:	Rising peak (pop out)
Drama Rating:	★★★★☆
Application:	Actuated table runner



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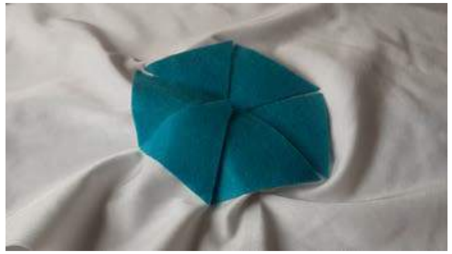

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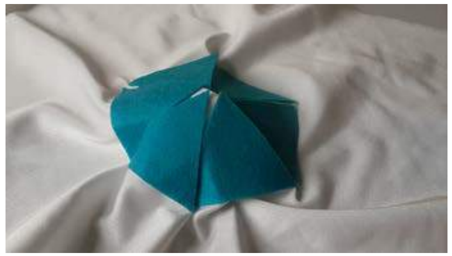
sec 0.70



sec 1

11. FLIPPING TEXTURE 1

A technique I learnt from Irene Posch is electromagnetic actuation using 0.10 mm Enamelled Copper Wire forming a coil that flips a magnetic spherical bead with switching the polarity of electric current back and forth.
What I have done is to extend the capabilities of this by attaching a `wing' double-faced piece of fabric to the top of the bead, so that it would flip.
Although simple, if multiplied, this technique can be used to create safe, silent and delicate texture-changing or pattern-changing textiles that are motor-free, SMA-free and pneumatic-free.

Material:	Thermochromic Fabric
Shape:	Triangular bi-faced wing
Shape-changing Material:	Magnetic spherical bead
Fitted by:	Embroidery
Connected to:	Enamelled Copper Wire
Power:	9v battery
Effect:	Flapping
Drama Rating:	★★★☆☆
Application:	Texture-changing or Pattern-changing Textile


sec 0


sec 0.25


sec 0.5

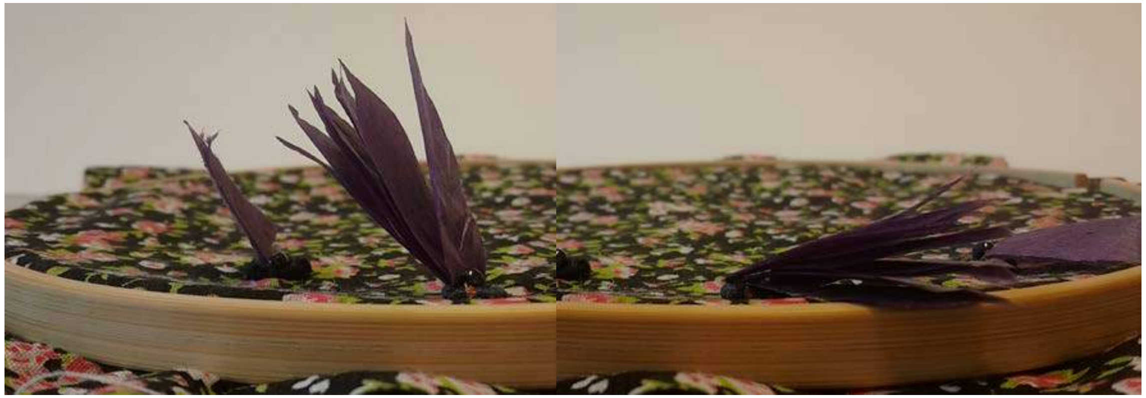

sec 0.75


sec 1

12. FLIPPING TEXTURE 2

To extend the previous example of the single bead (inspired by the work of Irene Posch), this one multiplied the flipping texture by using 3 beads resulting in the swatch being actuated by on/off bi-state texture-change i.e. either spiky or flat.
If this module is multiplied, we can have an entire texture-changing piece of fabric that actively or autonomously spikes its fur or tassels at the edge of a rug.

Material:	Cotton Fabric Swatch
Shape:	Pointy petal-like wing
Shape-changing Material:	Magnetic spherical bead
Fitted by:	Embroidery
Connected to:	Enamelled Copper Wire
Power:	9v battery
Effect:	Flapping
Drama Rating:	★★★★☆
Application:	Texture-changing or Pattern-changing Textile



sec 0

sec 1

sec 0.25

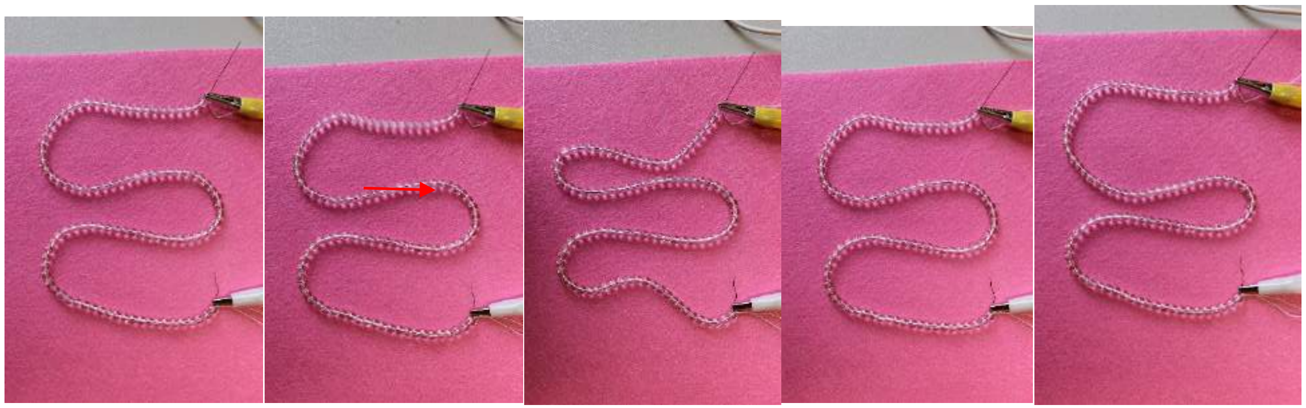
sec 0.5

sec 0.75

13. THE BEADS

By threading the Flexinol wire into beads, then fixing the thread on a soft surface, the bead thread started swirling back and forth as if it's an alive snack moving closer and further from each other in random curved paths and an organic behaviour.

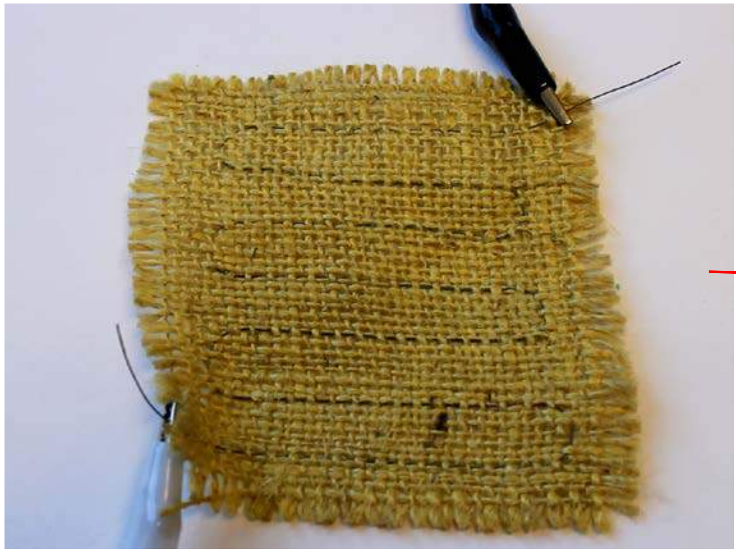
Material:	Plastic Beads
Shape:	Clear Spherical beads
Shape-changing Material:	Flexinol HT (0.010") 20 cm (3.6 Ω)
Fitted by:	Beaded
Connected to:	Clipped wires
Effect:	Shape-change
Drama Rating:	★★★★☆
Application:	Actuating bead decorations and trimmings

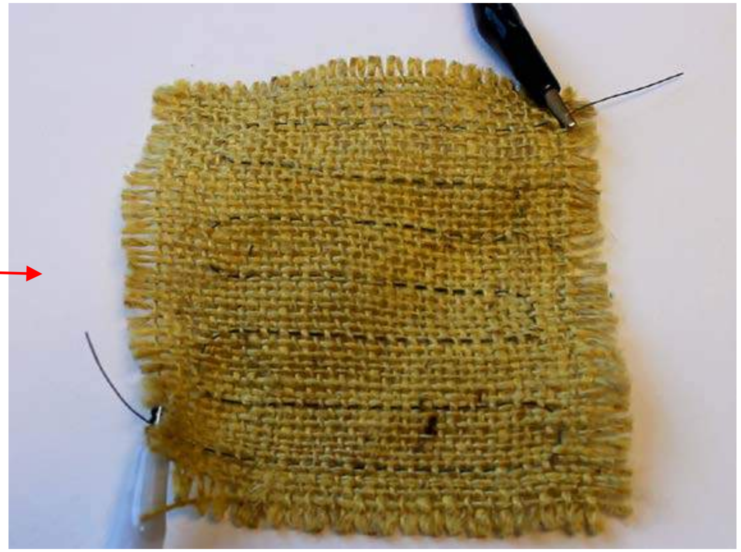


14. Weaved Linen

Experimenting with firm and sturdy fabrics such as linen is interesting yet challenging. We tried different pattern of threading the wire within the linen swatch but most of which did not work/ actuate due to relatively loose bends and ends, which prevents the wire of giving a sensible actuation effect.
Finally this pattern (systematic snack shaped) achieved a subtle wrinkling effect within the fabric itself which is not significant yet could be useful and desired in some cases.

Material:	Course Linen Cloth
Shape:	10x10 cm square swatch
Shape-changing Material:	Flexinol HT (0.010") 20 cm (3.6 Ω)
Fitted by:	weaved
Connected to:	Clipped wires
	6-12v, 1Amp
Effect:	wrinkle
Drama Rating:	★☆☆☆☆
Application:	Wrinkling upholstery or interactive rug



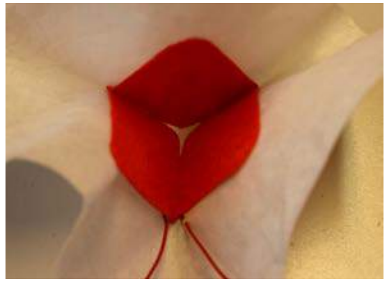


*This work has been done through collaboration with Architect/Researcher Yomna El-ghazi

15. Trio 1

Trio is a triangular-based tessellation module of 3 symmetrical petals designed to experiment the effect of different wire patterns/forms on the actuation effect. In the different versions of Trio a blossom actuation effect was the result. In this version we applied the wire in a Y-shape going through the middle of each petal. The 3 pieces of felt Petals are completely separated from each other but are glues on top of an interfacing fabric layer to hold the pattern together.

Material:	Soft Felt
Shape:	Triangular Petals Tessellation
Shape-changing Material:	Flexinol HT (0.010") 40 cm (7.2 Ω)
Fitted by:	Tightly stitched
Connected to:	Soldered wires
	7V, 1Amp
Effect:	blossom
Drama Rating:	★★★☆☆
Application:	Modular SC soft pattern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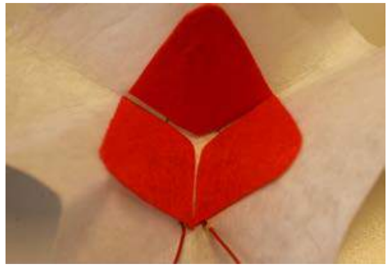
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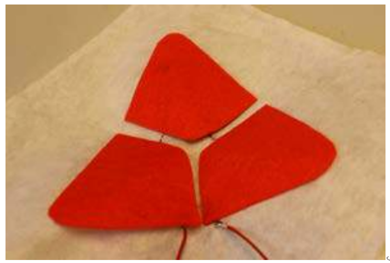
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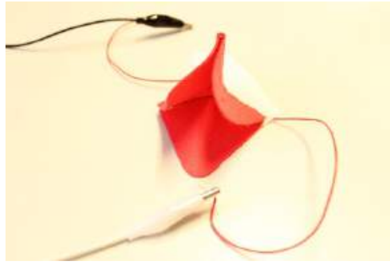
*This work has been done through collaboration with Architect/Researcher Yomna El-ghazi

16. Trio 2

Trio is a triangular-based tessellation module of 3 symmetrical petals designed to experiment the effect of different wire patterns/forms on the actuation effect. In the different versions of Trio a blossom actuation effect was the result. In this version we applied the wire in a Y-shape on the tangent lines between the 3 petals.

Material:	Soft Felt
Shape:	Triangular Petals Tessellation
Shape-changing Material:	Flexinol HT (0.010") 20 cm (3.6 Ω)
Fitted by:	Y-shaped tight stitches
Connected to:	Soldered wires
	6V, 1Amp
Effect:	blossom
Drama Rating:	★☆☆☆☆
Application:	Modular SC soft pattern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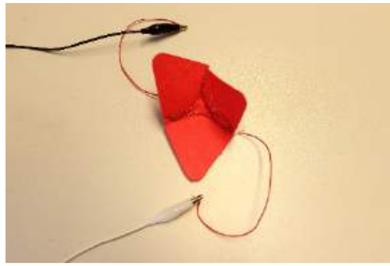
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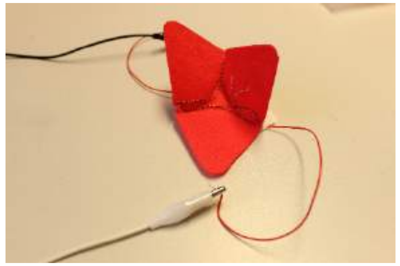
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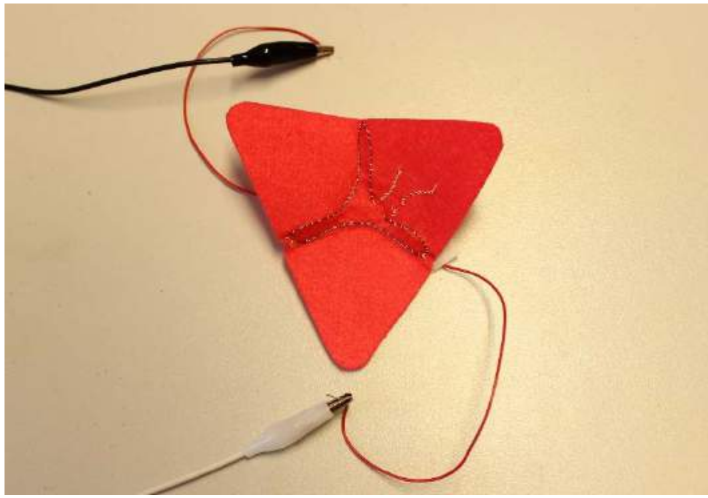
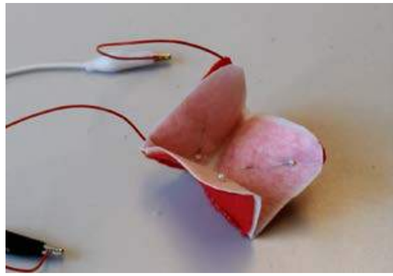


*This work has been done through collaboration with Architect/Researcher Yomna El-ghazi

17. Trio 3

Trio is a triangular-based tessellation module of 3 symmetrical petals designed to experiment the effect of different wire patterns/forms on the actuation effect. In the different versions of Trio a blossom actuation effect was the result. In this version we tried to enhance trio v1 by cutting the extra interfacing fabric layer (to the exact triangular shape) allowing it to move freely through eliminating any possible strain force preventing it from full actuation.

Material:	Soft Felt
Shape:	Triangular Petals Tessellation
Shape-changing Material:	Flexinol HT (0.010") 20 cm (3.6 Ω)
Fitted by:	Y-shaped tight stitches
Connected to:	Soldered wires
	6V, 1Amp
Effect:	Blossom
Drama Rating:	★☆☆☆☆
Application:	Modular SC soft pattern



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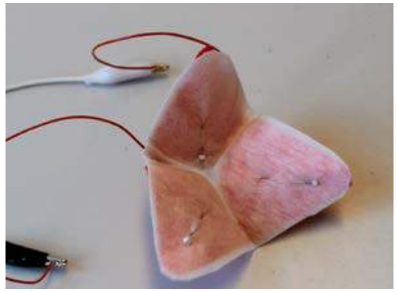

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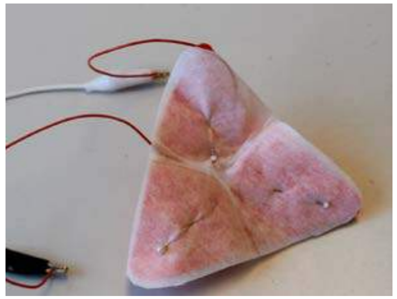

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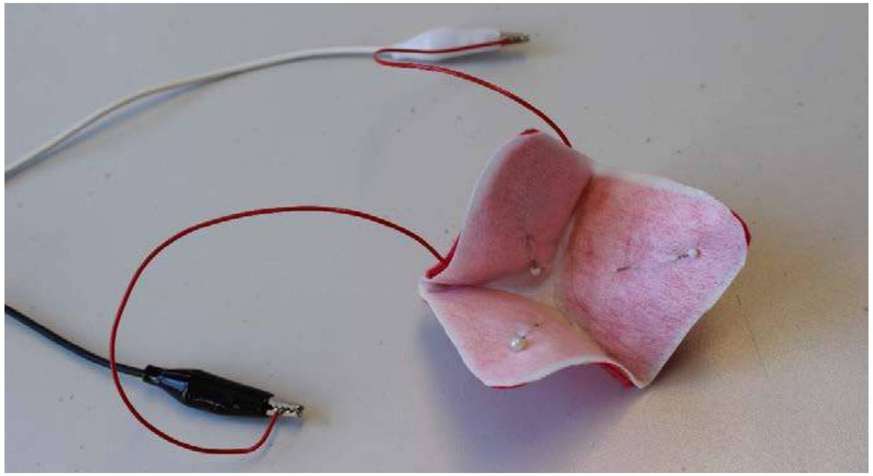
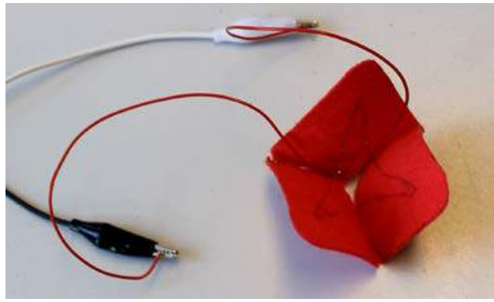


*This work has been done through collaboration with Architect/Researcher Yomna El-ghazi

18. Trio 4.1

Trio is a triangular-based tessellation module of 3 symmetrical petals designed to experiment the effect of different wire patterns/forms on the actuation effect. In the different versions of Trio a blossom actuation effect was the result. In this version we did not split the three petals entirely from each other, but applied a cut out of the core Y-shape in the center of the triangular pattern.

Material:	Soft Felt
Shape:	Triangular Petals Tessellation
Shape-changing Material:	Flexinol HT (0.010") 20 cm (3.6 Ω)
Fitted by:	Y-shaped tight stitches
Connected to:	Soldered wires
Effect:	6V, 1Amp
Drama Rating:	★★☆☆☆
Application:	Modular SC soft pattern



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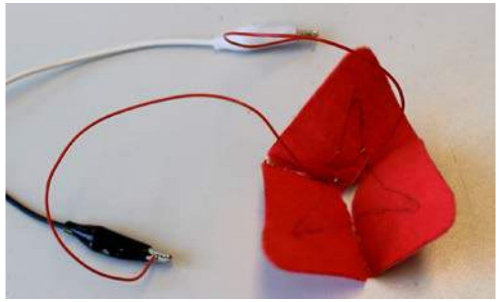

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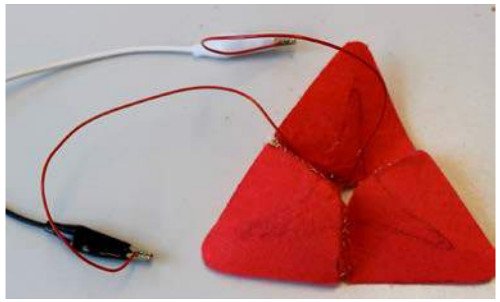

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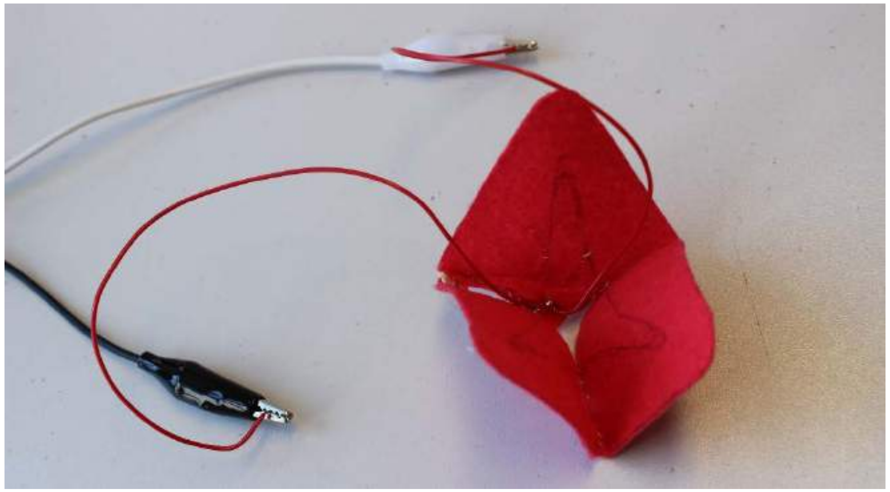
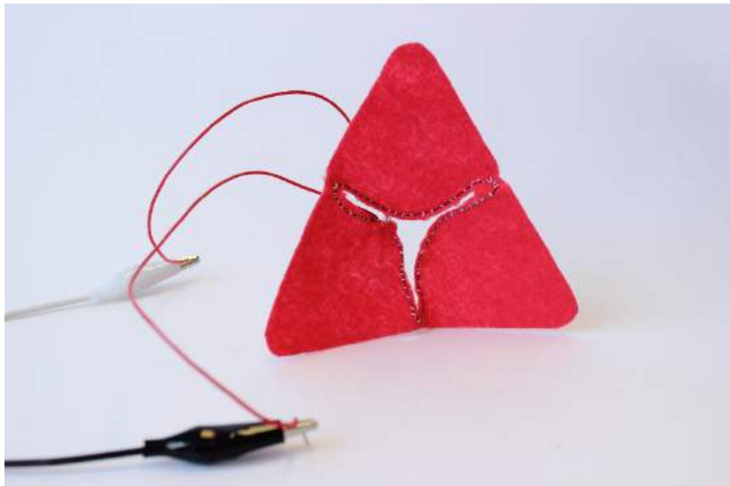


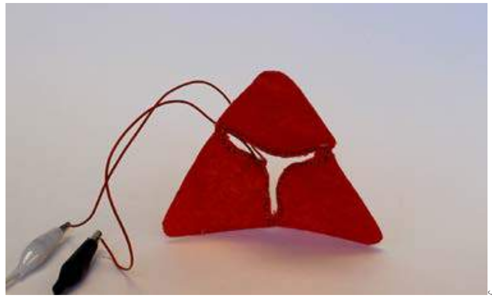
*This work has been done through collaboration with Architect/Researcher Yomna El-ghazi

19. Trio 4.2

Trio is a triangular-based tessellation module of 3 symmetrical petals designed to experiment the effect of different wire patterns/forms on the actuation effect. In the different versions of Trio a blossom actuation effect was the result. In this version we did not split the three petals entirely from each other, but applied a cut out of the core Y-shape in the center of the triangular pattern. When allowing it to stand vertically, the pattern hesitated in which direction would it bend inwards!

Material:	Soft Felt
Shape:	Triangular Petals Tessellation
Shape-changing Material:	Flexinol HT (0.010") 20 cm (3.6 Ω)
Fitted by:	Y-shaped tight stitches
Connected to:	Soldered wires
	6-12V, 1Amp
Effect:	Partial closure
Drama Rating:	★★☆☆☆
Application:	Modular SC soft pattern





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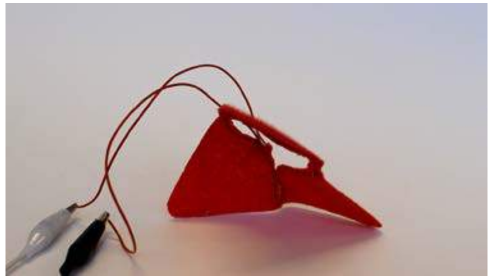

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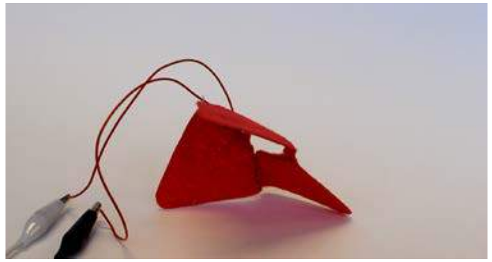


Sec 2

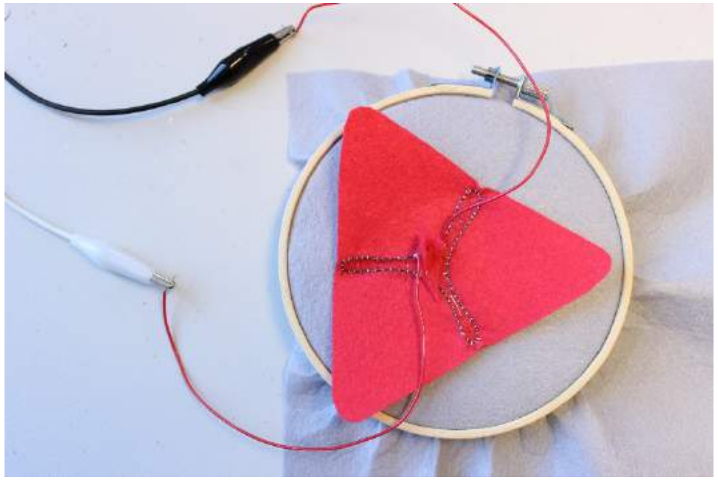
Sec 3

*This work has been done through collaboration with Architect/Researcher Yomna El-ghazi

20. Trio 5

Trio is a triangular-based tessellation module of 3 symmetrical petals designed to experiment the effect of different wire patterns/forms on the actuation effect. In the different versions of Trio a blossom actuation effect was the result. In this version we fixed Trio v2 on a firm felt layer to hold it downwards and assumed it would allow it to bend the petals freely to close inwards, but this did not allow them to move at all.

Material:	Soft Felt
Shape:	Triangular Petals Tessellation
Shape-changing Material:	Flexinol HT (0.010") 20 cm (3.6 Ω)
Fitted by:	Y-shaped tight stitches
Connected to:	Soldered wires
	6-12V, 1Amp
Effect:	Did Not Work
Drama Rating:	★★★☆☆
Application:	Did Not Work

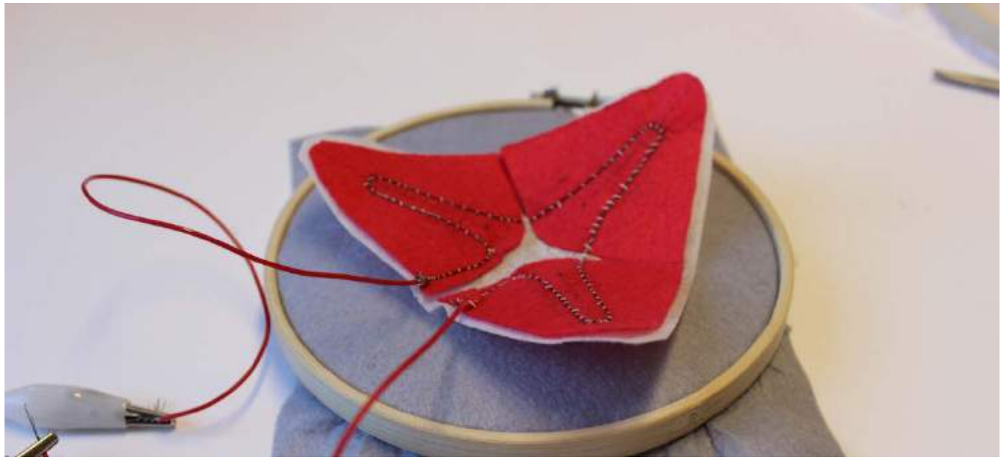


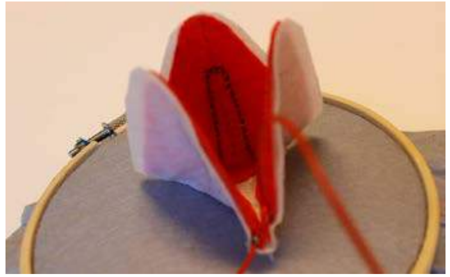
*This work has been done through collaboration with Architect/Researcher Yomna El-ghazi

21. Trio 6

Trio is a triangular-based tessellation module of 3 symmetrical petals designed to experiment the effect of different wire patterns/forms on the actuation effect. In the different versions of Trio a blossom actuation effect was the result. In this version we learnt from all previous versions, and chose to re-use Trio v3, but fix/stitch the core Y-shape in the center of the triangular pattern onto another felt layer fixed downwards, which allowed the petals to open freely and blossom as whole.

Material:	Soft Felt
Shape:	Triangular Petals Tessellation
Shape-changing Material:	Flexinol HT (0.010") 40 cm (7.2 Ω)
Fitted by:	Y-shaped tight stitches
Connected to:	Soldered wires
	7V, 1Amp
Effect:	Blossom
Drama Rating:	★★★☆☆
Application:	Modular SC soft pattern





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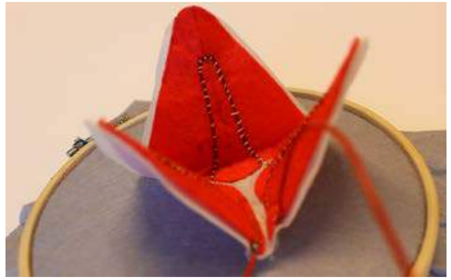

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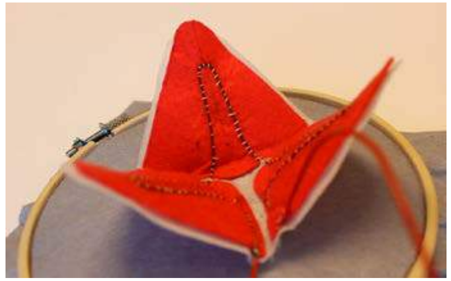

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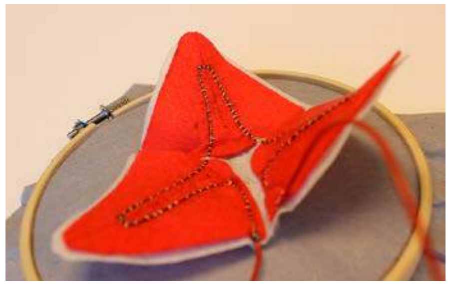


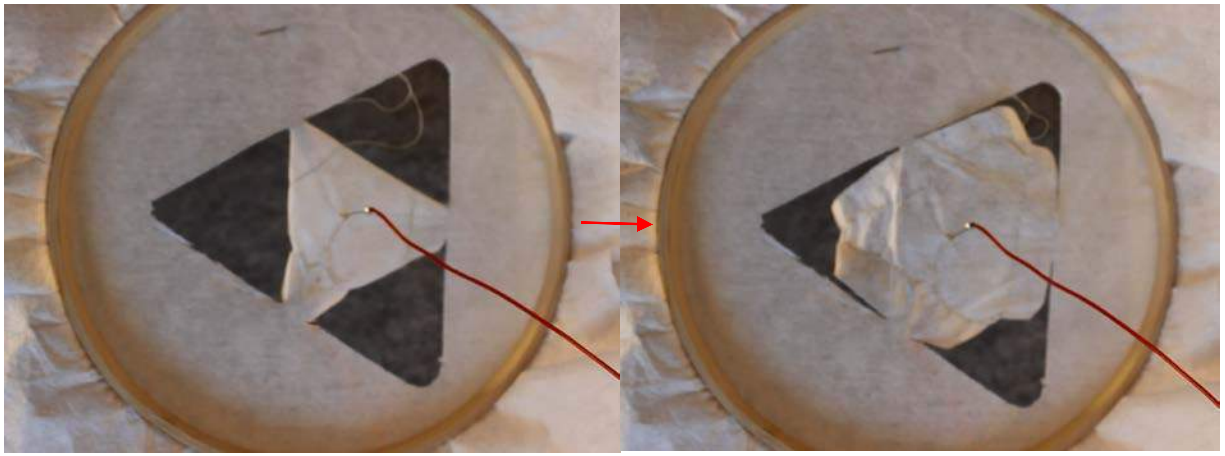
Sec 5

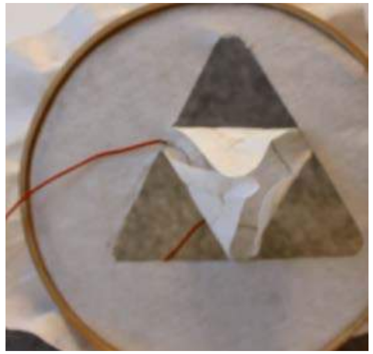
*This work has been done through collaboration with Architect/Researcher Yomna El-ghazi

22. Trio 7

Trio is a triangular-based tessellation module of 3 symmetrical petals designed to experiment the effect of different wire patterns/forms on the actuation effect. In the different versions of Trio a blossom actuation effect was the result. In this version we performed cut-outs on thin light-weight interfacing fabric, which allowed the wire to actuate the petals by moving freely opening outwards.

Material:	Interfacing Thin fabric
Shape:	Triangular Petals cutouts Tessellation
Shape-changing Material:	Flexinol HT (0.010") 40 cm (7.2 Ω)
Fitted by:	tight stitches
Connected to:	Soldered wires
	7v, 1Amp
Effect:	blossom
Drama Rating:	★★★☆☆
Application:	Modular SC soft pattern





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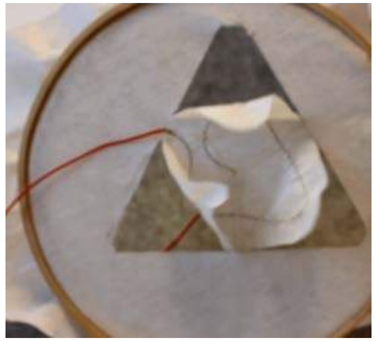

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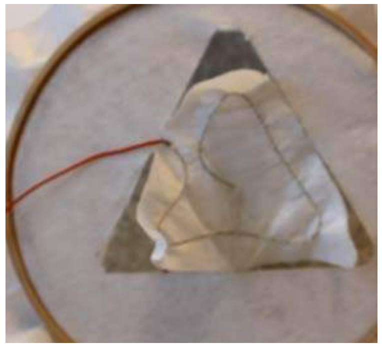


Sec 2

*This work has been done through collaboration with Architect/Researcher Yomna El-ghazi

23. Paper Displays

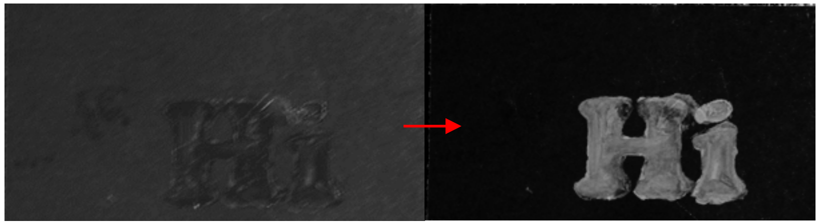
Thermochromic paints can be used to `reveal' a hidden message, content or notification, or can be used to `hide' or `transform' content as well.
Here are three examples where change in colour transforms, reveals and conceals!

Material:	Cardboard Paper
Shape:	Rectangular Display
Color-changing Material:	Thermochromic paints
Fitted by:	Painted
Connected to:	DC Heating Pad
Effect:	Colour-change
Drama Rating:	★★★★☆
Application:	Colour-changing or Pattern-changing Soft Furnishing

Min 0

Min 2

Min4

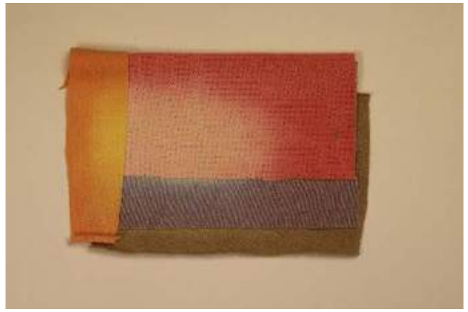


24. THE CAMELEON

Thermochromic dyed fabrics can be mixed together to form appearance-changing interior artefacts and pattern-changing soft furnishing from curtains, cushion and rugs to sofas, chairs and tablecloths.

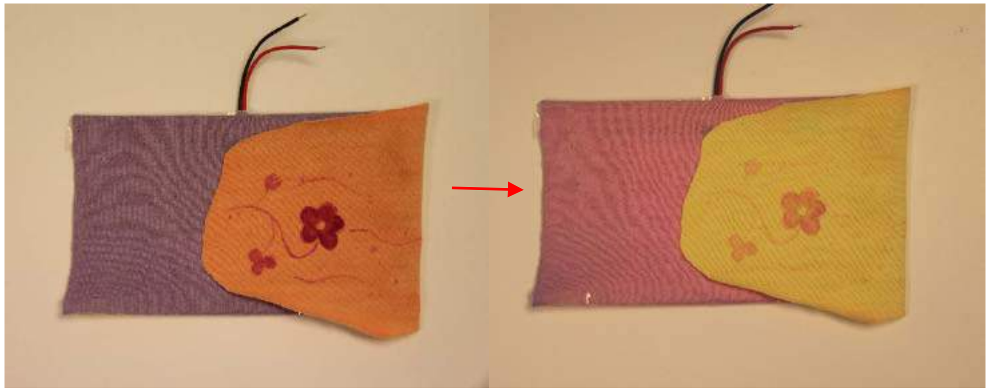
Material:	Cotton Fabric
Shape:	Rectangular Swatch
Color-changing Material:	Thermochromic Fabric
Fitted by:	Dyed
Connected to:	DC Heating Pad
Effect:	Colour-change
Drama Rating:	★★★★☆
Application:	Colour-changing or Pattern-changing Soft Furnishing

Min 0



Min 2

Min 4



25. Thermo-Acrylic Tan

Mixing Acrylic painting colours with black 35°C thermochromic pigment creates a palette of tanned colours that immediately transforms to lighter shades responding to heat from a hair dryer or an iron!

Material:	Paper
Shape:	Painted stokes
Shape-changing Material:	Thermochromic pigment mixed with acrylic paint
Fitted by:	Paint brush
Connected to:	Medium hot Iron
Effect:	Colour-change
Drama Rating:	★★★★☆
Application:	Colour-changing Painting and wall art

Sec -1

Sec 0

Sec 1

26. Pattern-ing Fabrics (1 of 3)

Creating Pattern-changing swatches by dying patterned fabrics with a thermochromic pigment that makes it transition from plain to patterned, in response to heat (~35°C).

Material:	Cotton Fabric Swatches
Shape:	Dyed patterns
Shape-changing Material:	Thermochromic pigment mixed with acrylic paint
Fitted by:	Paint brush
Connected to:	Medium hot Iron
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing

Sec 0

Sec 1

Sec 0

Sec 1

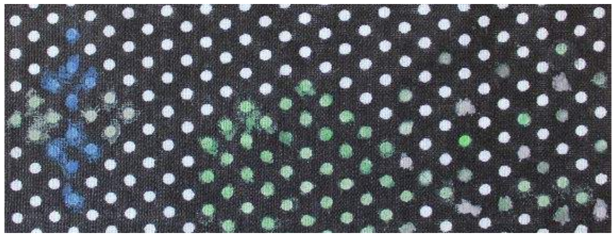
27. Pattern-ing Fabrics (2 of 3)

Creating Pattern-changing swatches by dying patterned fabrics with a thermochromic pigment that makes it transition from plain to patterned in response to heat (~35°C)

Material:	Cotton Fabric Swatches
Shape:	Dyed patterns
Shape-changing Material:	Thermochromic pigment mixed with acrylic paint
Fitted by:	Paint brush
Connected to:	Medium hot Iron
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing

Sec 0

Sec 1

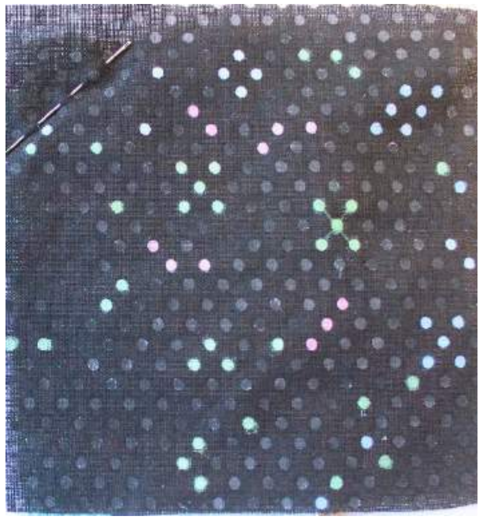


28. Pattern-ing Fabrics (3 of 3)

Creating Pattern-changing swatches by dying patterned fabrics with a thermochromic pigment that makes it transition from plain to patterned in response to heat (~35°C)

Material:	Cotton Fabric Swatches
Shape:	Dyed patterns
Shape-changing Material:	Thermochromic pigment mixed with acrylic paint
Fitted by:	Paint brush
Connected to:	Conductive Thread
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing

Sec 0



Sec 1

29. WaterDrop Cushion

These decoractive artefacts are a pair of colour-changing matching painting and cushion that are made using thermochromic paint on conventional materials (acrylic painting canvas and cotton fabric) featuring 'water'. These dynamic artefacts change the amount of visible water painted in response to the water consumption rate in the household. By accessing smart-meter online readings or uploading meter reading into an app, people can realize how much water is being consumed over time, through multi-faceted aesthetics that is part of their interior decoration, see Figure 8. These multi-faceted decoractives rely on an impressionistic approach that is better suited to interior aesthetic experiences.

Material:	Cotton White Fabric
Shape:	Dyed patterns
Shape-changing Material:	Thermochromic pigment mixed with acrylic paint
Fitted by:	Paint brush
Connected to:	USB Heating Pad
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing


Sec 0


Sec 10

30. BacterioChromic Placemat

As a colour-changing placemat that supposedly responds to harmful bacteria with instant colour-change in bacteria-inspired organic patterns that are digitally designed and laser-cut on thermochromic fabric revealing potential contamination from hands or tableware/ utensils. Colour-change appears to grow gradually from one part of the placemat to another using multi-threads of embedded copper enamelled wire that are separately controlled.

Material:	Cotton Fabric
Shape:	Organic/bacteria patterns
Shape-changing Material:	Laser-cut thermochromic Fabric on top of felt fabric
Fitted by:	Sewing
Connected to:	Cu 0.1 mm enamelled wire
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing

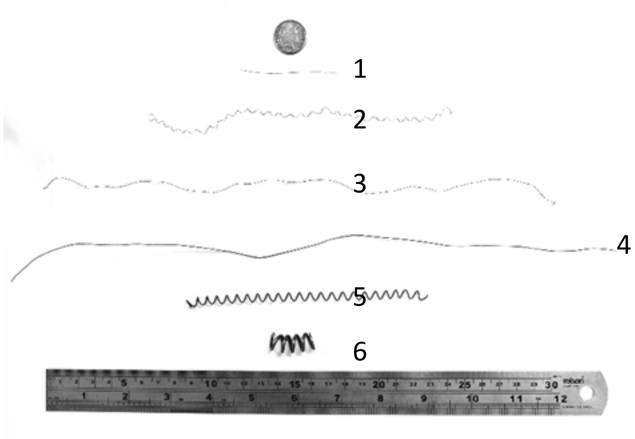
Sec 0

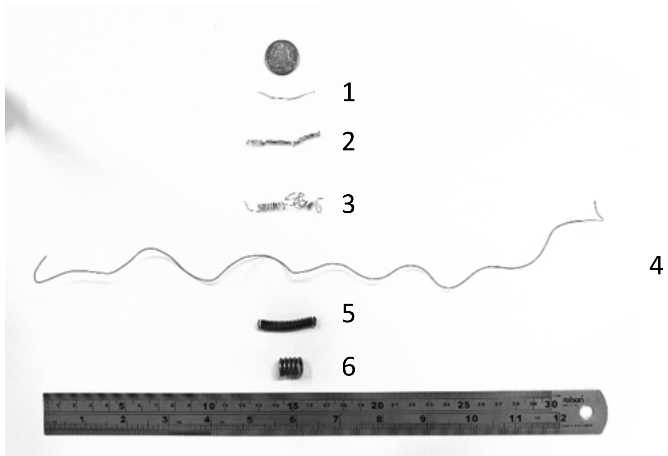
sec 2

sec 4

31. Comparing Muscle Springs

	Supplier	Product	Training	Diameter (mm)	Length before (Martensite)	Length After (Austenite)	Shrink by %	Tested with	Resistance (Ω/m)	Recommended Current (mA)	Pull Force (g)	Activation Temp.	Price per pack	Price/m	Price/ Spring
1	TOKI BMX	BMX750	Pre-T	0.075	6	3	50	3v,0.1A	1600	100	5	70	£22	-	£ 22.00
2	Kelloggs Labs KRL	Nitinol Micro-Spring	Pre-T	0.25	25	5	**80**	**3v,0.7A**				45	£6.97	-	£ 6.97
3	Muscle Wires	Flexinol Wire 0.010" HT	Y	0.25	30	3	**90**	**5v,1A**	18.5	1050	891	90	£25.58/5m	£ 5.12	£ 1.67
4	Smart Wires	Nitinol Wire	Y	0.5	40	30	25	5v,1.6				70	7.66 €/1.5m	£ 4.46	£ 1.49
5	Rapid Education	Smart Niti Spring	Pre-T	0.75	14	3	79	5v,3A	2	3000	500	70	£5.30	-	£ 5.30
6	MindsetsOnline	Two-Way Memory Spring	Pre-T	1.5	1	2.5	-150	–		_	_	90	£3.30	-	£ 3.30
7	Muscle Wires	Flexinol Wire 0.006" LT	Y	0.15	30				55	410	321	70	£25.58/5m	£ 5.12	£ 1.67
8	Light Stitches	Muscle Wire w Ring Terminals 0.006"	Y	0.15	15	14.25	5	**3v**	55	410	320	70/90	£10.56/5 wires	-	£ 2.11
9	Kelloggs Labs KRL	Nitinol Wire 0.010" ST	Y	0.25	30							45	$5/5f	£ 3.30	£ 1.10

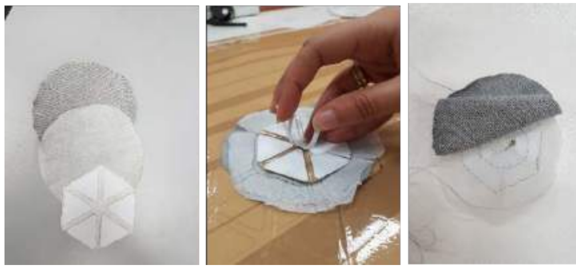


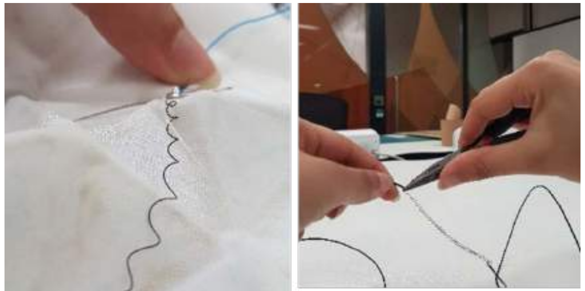


32. ActuEater 2

This engaging experience started by designing interactive set of a dining table-runner (ActuEater) and tableware (ActuSet) that complements a dining space interior style. ActuEater changes its shape by crumbling (through SMA thin springs stitched to the inner fabric) and changes its colour (of thermochromic fabric parts) in response to hand-touch and physical interaction with tableware, using thin capacitive sensing fabric sewn inside the runner.

Material:	Cotton Fabric Swatches
Shape:	Dyed patterns
Shape-changing Material:	Thermochromic pigment mixed with acrylic paint
Fitted by:	Paint brush
Connected to:	Medium hot Iron
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing

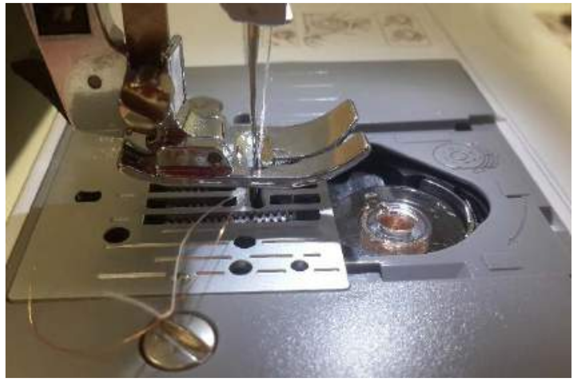




33. Machine Sewing Copper Wire (1 of 3)

By winding enamelled 0.1 mm copper wire in the bobbin of a sewing machine, careful stitching can create Cu-wire stitches that acts as heating agent to actuate thermochromic colour-change. This could be sewn using a straight running stitch directly onto normal fabrics then dyed or screen-printed with a thermochromic layer on top.

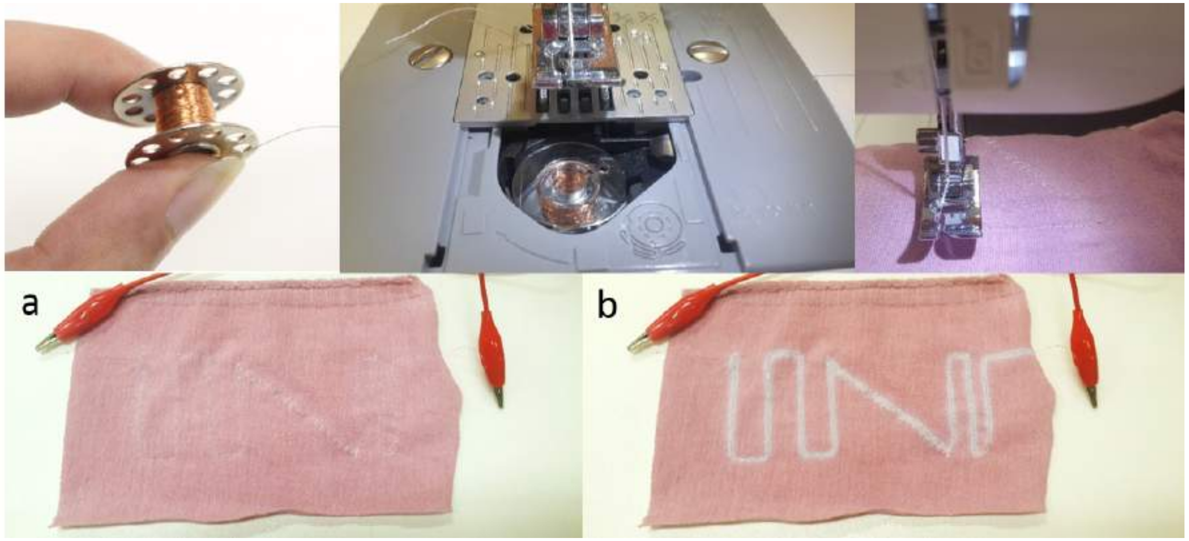
Material:	Cotton Fabric Swatches
Shape:	Machine-sewn Cu wire
Shape-changing Material:	Thermochromic Ink
Fitted by:	Sewing Machine
Connected to:	3V, 1Amp
Effect:	Colour-change
Drama Rating:	★☆☆☆☆
Application:	Pattern-changing Soft furnishing



34. Machine Sewing Copper Wire (2 of 3)

By winding enamelled 0.1 mm copper wire in the bobbin of a sewing machine, careful stitching can create Cu-wire stitches that acts as heating agent to actuate thermochromic colour-change. This could be sewn directly onto thermochromic fabrics causing seamless stitches to 'glow' when current passes through.

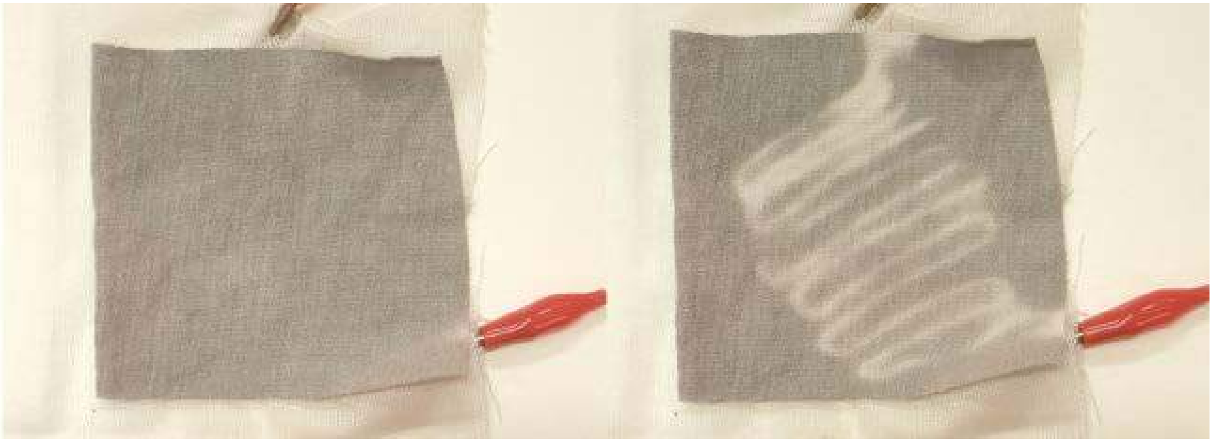
Material:	Cotton Fabric Swatches
Shape:	Machine-sewn Cu wire
Shape-changing Material:	Thermochromic Fabric
Fitted by:	Sewing Machine
Connected to:	3V, 1Amp
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing as a 'display'



35. Machine Sewing Copper Wire (3 of 3)

By winding enamelled 0.1 mm copper wire in the bobbin of a sewing machine, careful stitching can create Cu-wire stitches that acts as heating agent to actuate thermochromic colour-change. This could be sewn directly onto any fabric (e.g. an interfacing or interlining thin fabric layer) with a thermochromic layer on top.

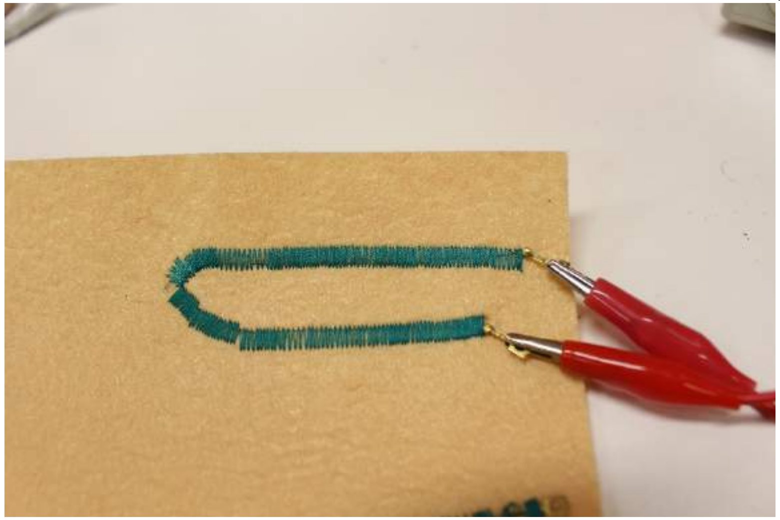
Material:	Cotton Fabric Swatches
Shape:	Machine-sewn Cu wire
Shape-changing Material:	Thermochromic Fabric
Fitted by:	Sewing Machine
Connected to:	3V, 1Amp
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing



36. Muscle Wire Sewing 1

When stitching muscle wire to fabric in almost any pattern that is not close to the edge of the fabric, it does not succeed to cause any deformation when connected to a power source. This is due to the weight and tension of most normal fabrics that causes a challenging barrier towards the relatively-weak pulling force of such muscle wire.
However, when a cut-out is applied around the stitched pattern, the wire is able to contract and therefore cause actuation by bending the cut-out fabric towards it (i.e. upwards). Still, this actuation is merely considered as visible or noticeable in unity.

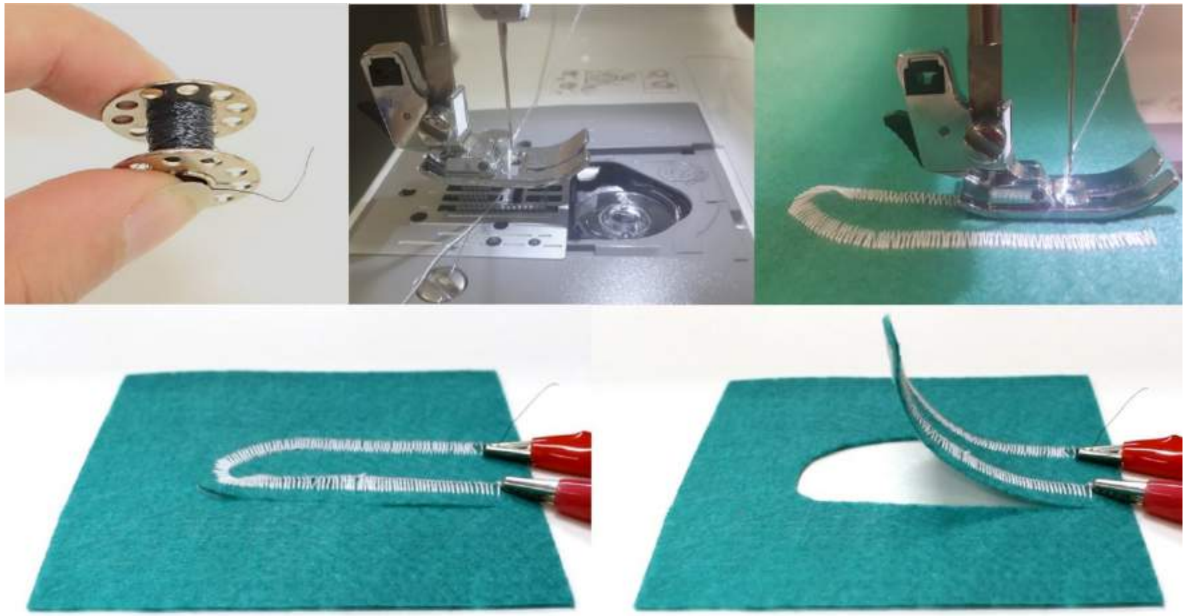
Material:	Felt Fabric
Shape:	15 cm Finger-shape
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm stitched muscle wire
Fitted by:	Sewing Machine
Connected to:	3.6V, 450 mA (3.6Ω)
Effect:	Shape-change (arouse)
Drama Rating:	★☆☆☆☆
Application:	Shape-changing Fabrics




37. SMA Sewing 1

Although SMA wire is much harder to control as it physically tends to loosen and wobble due to its unique alloy, and cannot be firmly bent or tightened, we can machine-sew it by using thin wire, firmly griping the ends in one's fingers to avoid its unrolling, working quickly and accepting that the wire will somewhat loosen, it is applicable to achieve neat seams using SMA wire in the bobbin and normal cotton spools. A cut-out was formed around the pattern and the stitched pattern could move freely by bending upwards when connected.

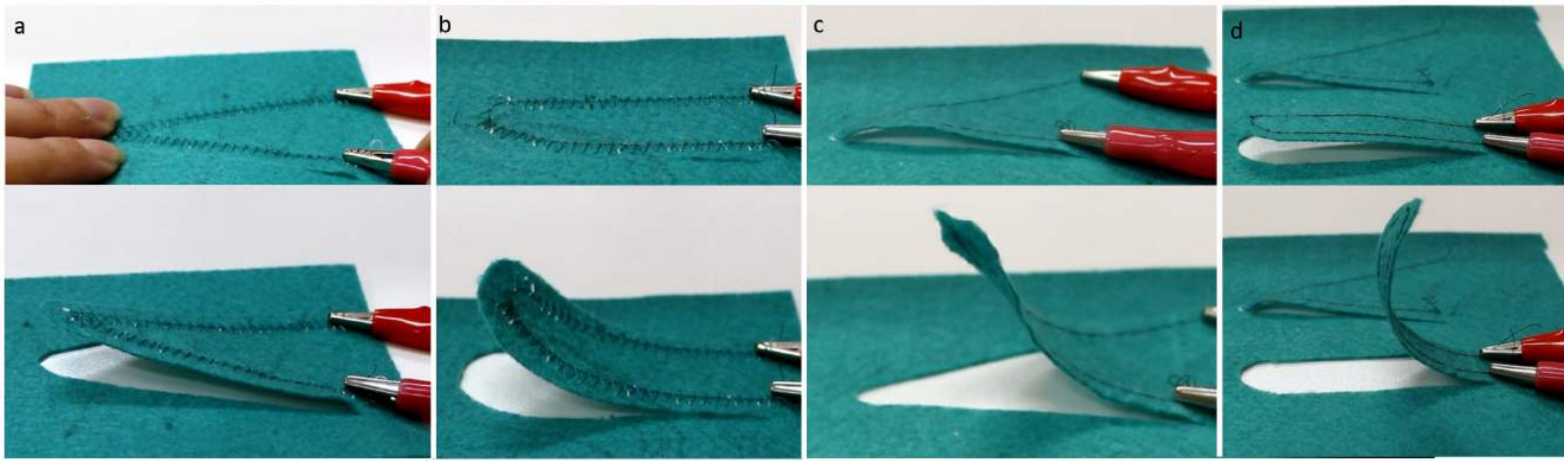
Material:	Felt Fabric
Shape:	12 cm Finger-shape
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.006" Flexinol
Fitted by:	Sewing Machine
Connected to:	3.6V, 450 mA (3.6Ω)
Effect:	Shape-change (arouse)
Drama Rating:	★☆☆☆☆
Application:	Shape-changing Fabrics



38. SMA Sewing 2

Several parameters impacting the deformation (Type of fabric, type of thread, type of stitch & its tightness, the pattern of stitching, type of wire, the austenite form, the martensite form, length of wire, and the distance between the SMA wire/seam and the edge of the fabric), I chose two variables (the type of stitch, and the pattern of stitching) and fixed other parameters to get insights on how to optimize the SMA machine-sewing technique. By experimenting different stitches, I found both the running stitch and the zigzag stitch to be efficient, with the tighter the stitch, the more dramatic the deformation is. Through testing different patterns, we found that the more curved the pulling end is, the more the pulling-force of the wire is maximized. Below figure compares the four combinations of two patterns (triangular pointy peak, round curved peak) and two stitches (wide zigzag and tight running stitch).

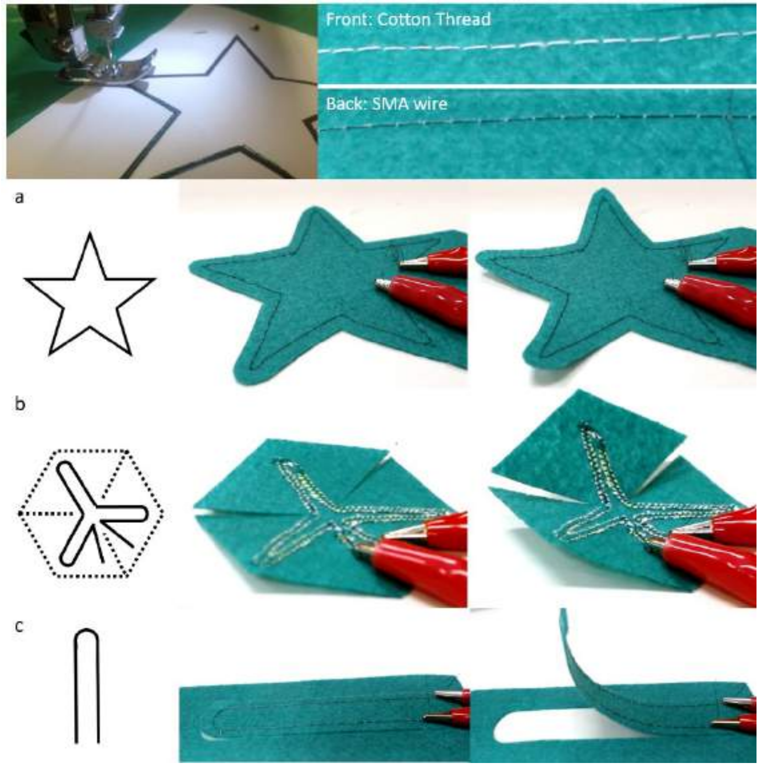
Material:	Felt Fabric
Shape:	14 cm Triangle & Finger-shape
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.006" Flexinol
Fitted by:	Sewing Machine a,b: wide zigzag stitch -braided c,d: straight stitch -sewn
Connected to:	3.6V, 450 mA (3.6Ω)
Effect:	Shape-change (arouse)
Drama Rating:	★☆☆☆☆
Application:	Shape-changing Fabrics



39. SMA Sewing 3

The great benefit of using a sewing machine rather than hand-stitching SMA wire is the opportunity of enabling rapid prototyping of different shape-changing effects. We can now machine-sew actuation directly into fabric and rapidly and systematically compare different patterns and shapes. Using paper patterns is an old traditional sewing method to cut fabric to desired sizes and a natural step to learn when sewing garments, and soft artefacts. Consequently, we utilized and re-purposed this same technique of using a paper pattern to enable creating complex shape-changing patterns. This technique enabled us to simply follow the lines while machine-sew SMA wires into various curves easily. Figure 8 shows some of the paper patterns we stitched with SMA wire using the sewing machine, including a star shape, a hexagonal inner shape and again a finger-outline shape. Comparing the resultant actuations of different stitched patterns yielded a conclusion of which ensured how that later pattern is effective in terms of visibility of deformation.

Material:	Felt Fabric
Shape:	Patterned shapes (35cm star, 17cm pentagon and 22cm finger shapes)
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol
Fitted by:	Sewing Machine straight-stitch
Connected to:	5V
Effect:	Shape-change (arouse)
Drama Rating:	★☆☆☆☆
Application:	Shape-changing Fabrics

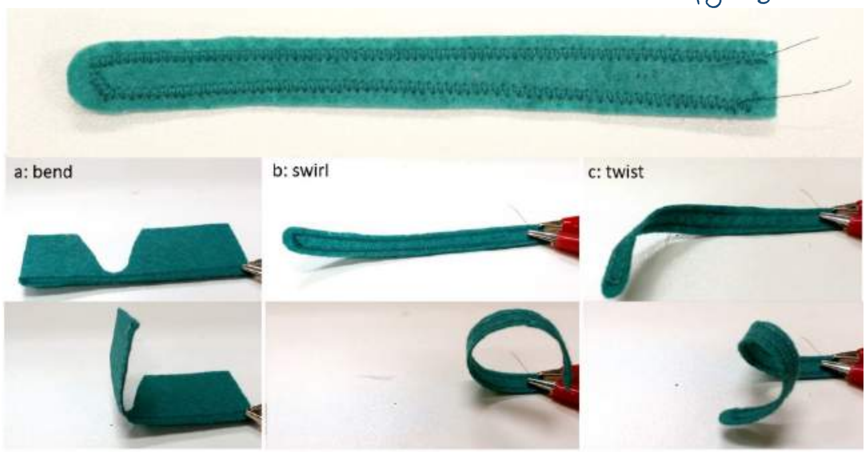


40. SMA Sewing 4

Learning from Experiment 3 how the finger-outline pattern worked nicely, we went on to try different versions of this pattern. We learned that by changing the size of the pattern to a narrower width and longer length, we can achieve more visible variations of shape deformation. Learning through making (as research through design) helps us understand things in often better ways than other scientific approaches. For example, we learned by coincidence, that a bend can be controlled at a particular desired part of the fabric through less weight at this part. Figure 9a shows a scrap that actuates in a right angle bend at the point where less fabric strain is found. Below figure shows how the pull-force is maximized (compared to previous experiment) when the pattern gets narrower, allowing more grip. By changing the parameter of the martensite state (i.e. twisting and untwisting Figure 9b by hand), the same piece deforms in a different way by twisting itself -instead of swirling. In this experiment, the fabric relaxes back and obeys gravity once no electric current flows through them.

Material:	Felt Fabric
Shape:	22 cm narrow finger
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol
Fitted by:	Sewing Machine - braiding Tight zigzag stitch Martensite shape: c) twisted
Connected to:	5V
Effect:	Shape-change (bend, swirl, twist)
Drama Rating:	★★★★☆
Application:	Shape-changing Fabrics

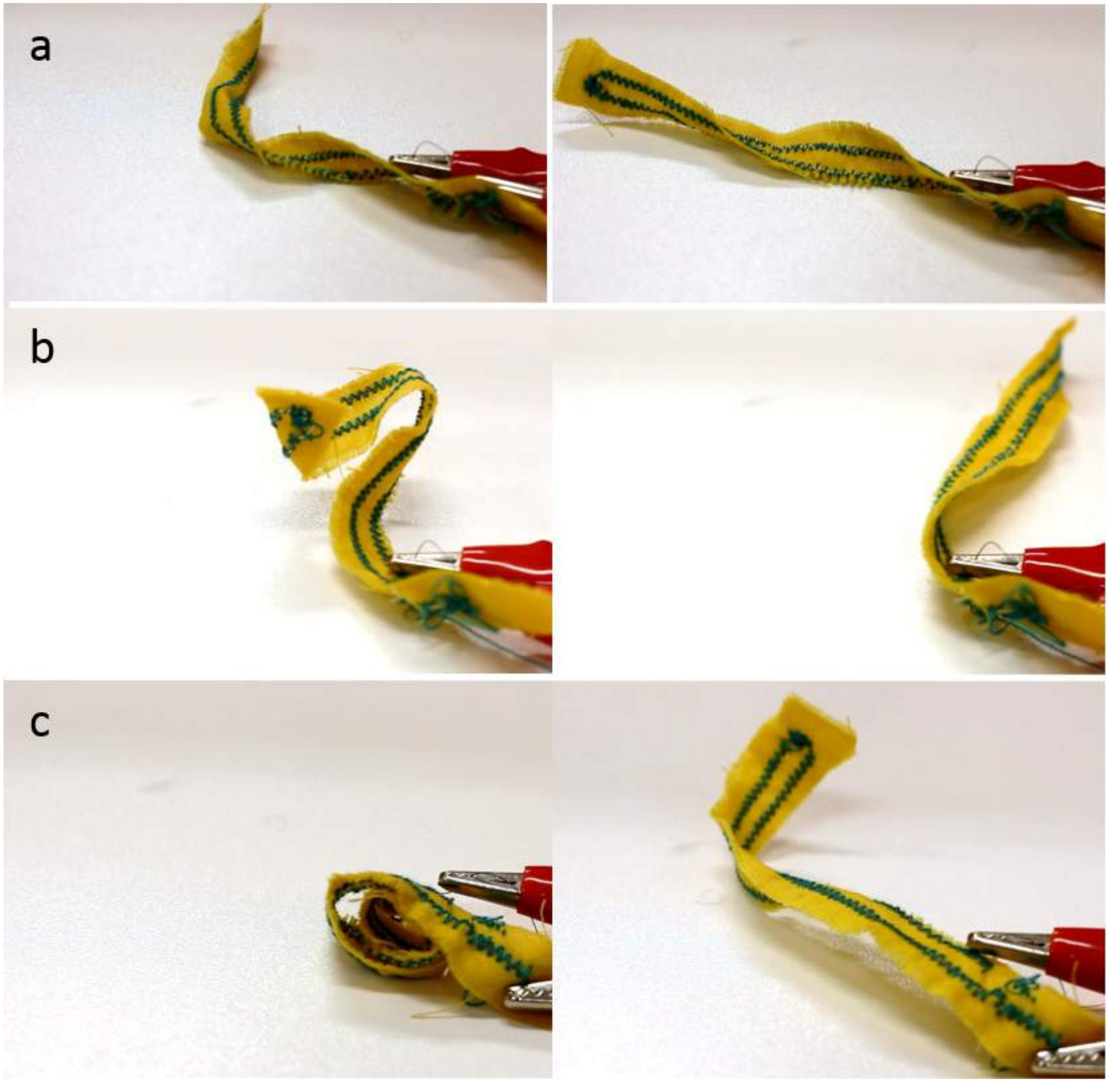
Potential applications for such repetitive consistent deformation or displaying a specific message are: e.g. a cushion's corner can bend twice notifying one that something has happened.



41. SMA Sewing 5

Rather than controlled actuation, we were interested in the unexpected ways SMA wire deforms the fabric in a non-computerized but more organic behaviour. To allow such freestyle actuation we can manipulate parameters of the martensite state (i.e. hand manipulation input before actuation) and utilize light-weight fabric to avoid rigid repetitive deformation. In this experiment, we fixed other parameters (such as the stitch, pattern and wire) to the most effective ones we have found so far.

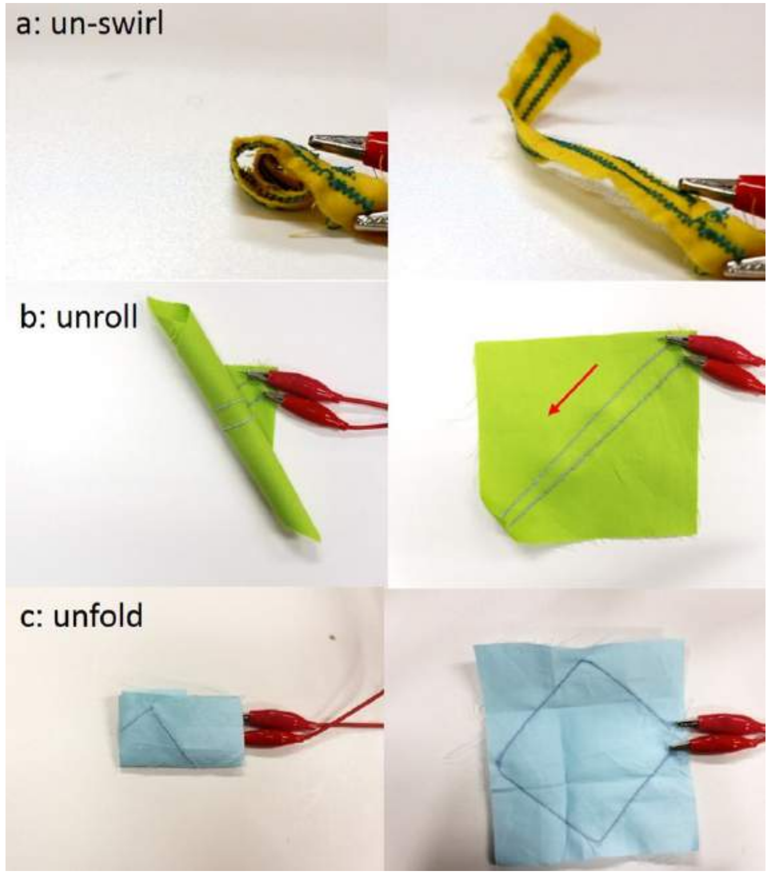
Material:	Cotton Fabric
Shape:	18 cm Narrow finger
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol
Fitted by:	Sewing Machine - braiding
Connected to:	5V
Effect:	Shape-change (unswirl, uncurl) Martensite freestyle
Drama Rating:	★★★☆☆
Application:	Shape-changing Fabrics



42. SMA Sewing 6

Deformations resulting from a) swirling, b) rolling, and c) folding hand manipulations of the fabric can result from changing the martensite state of the fabric prior to actuation. Results informed how autonomous behaviour of SMA actuated fabrics can often yield more interesting original forms and organic shape-changes depending on user direct manipulation as opposed to programmed consistent outputs. This technique can suit applications around wearables wear people deform their garments in different (free-style) and unique ways.

Material:	Felt Fabric
Shape:	18 cm narrow fingers and rhombus
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol
Fitted by:	Sewing Machine – Tight zigzag stitch- braiding
Connected to:	5V
Effect:	Shape-change (un-swirl, unroll, unfold) Martensite: curled, rolled and folded
Drama Rating:	★★★★☆
Application:	Shape-changing Fabrics



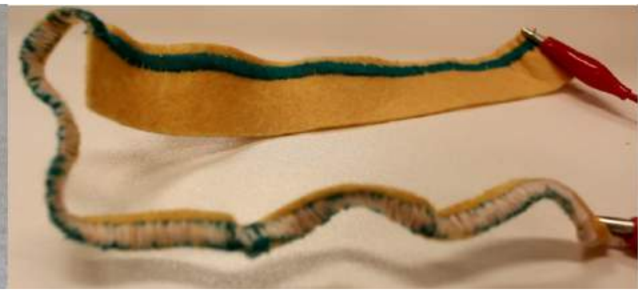
43. SMA Sewing 7

To achieve a crumbling fabric deformation, the wire needs to significantly contract (not just bend, swirl or twist). Relevant previous work in material science has looked into training SMA wire to remember a certain austenite shape. Therefore, SMA wire can also be customized into remembering a specific desired shape by training the wire in a mould fixing it to that shape and applying 400C hot air for a few minutes [35], or a naked flame for a few seconds. For this experiment, we rapped the wire around a screw (to achieve a spring coil shape) and heated the wire using a hot air gun for 5 minutes on highest temperature, while taking health and safety measures such as mearing fire-resistant gloves and goggles. It is required to throw the wire immediately in cold water in a process called 'quenching' for the training to take effect. Some have recommended repeating this process numerous times to train the wire, but we found that it does remember from the first time.

Once the wire is physically-programmed to remember this spring shape, we can stitch it to the fabric. However, it is difficult now to roll the wire around the bobbin as it has bends of a different diameter (from the screw). To machine-sew this wire, we used the conventional machine-sewing technique called 'braiding'. Similar to adding decorative embellishments to fabric such as ribbons and thin braids, we used the spring-trained wire on top of the fabric to be fixed using the sewing machine's tight zigzag stitch. Although using a braiding or a couching foot would be suitable for this, we used the basic pressing foot that worked fine. We stitched the wire to the edge of firm felt fabric using an embroidery tight zigzag stitch.

However, the wire could not deform the fabric at all, as fabric swatch was too heavy and firm to be deformed. Then, we cut the fabric from around the wire, leaving some fabric attached to half of the wire length to compare the results. Figure 11 shows how the fabric transformed into a soft spring once connected to electricity, and the part with fabric still attached became wavy.

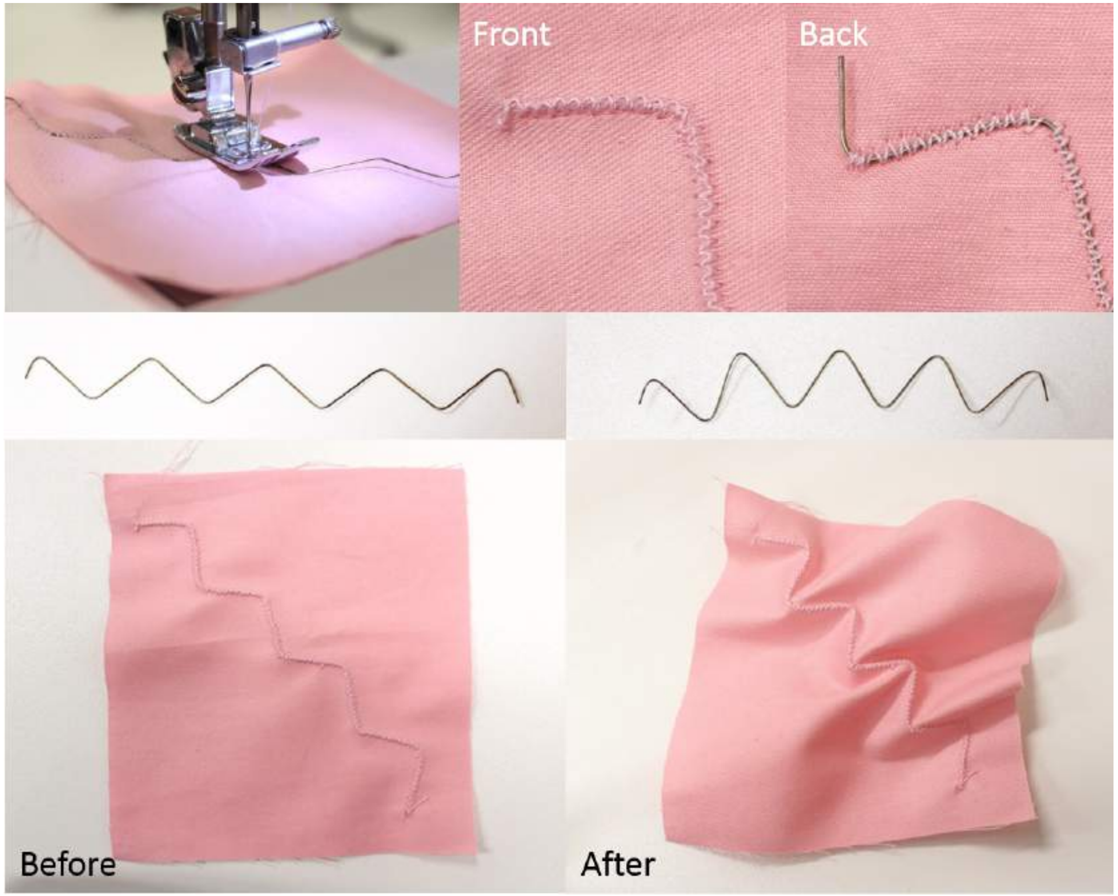
Material:	Felt Fabric
Shape:	37 cm L-shape
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.5 mm Nitinol
Fitted by:	Sewing Machine – embroidery stitch- top braided
Connected to:	9v, 1 Amp
Effect:	Shape-change (coil and wave)
Drama Rating:	★★★☆☆
Application:	Shape-changing Fabrics



44. SMA Sewing 8

As an alternative austenite memory-shape to train SMA wire (than a spring coil), I used a zigzag-trained muscle wire that is 16 cm long to investigate the shape-change pattern that will result. On the swatch in Figure 12 we machine-braided the zigzag-trained SMA wire on top of the cotton fabric swatch. When connected to the electric current, the fabric swatch deformed in a wavy form creating a different shape-change deformation that all the previous experiments.

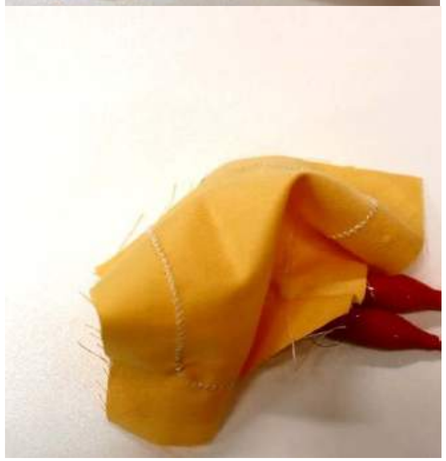
Material:	Cotton Fabric
Shape:	16 cm zigzag
Shape-changing Material:	0.25 mm "Smart Wires" zigzag
Fitted by:	Sewing Machine – tight stitch - braided
Connected to:	9v
Effect:	Shape-change (wrinkle/ crease)
Drama Rating:	★★★★☆
Application:	Shape-changing Fabrics



45. SMA Sewing 9

Learning from the previous 2 experiments, I thought of training the SMA wire while rolled on the bobbin, using the bobbin as its mould, then placing the bobbin (with the spring-trained wire) directly inside the sewing machine. This technique was much easier than braiding the wire on top of the fabric and resulted in new kinds of deformations. To hold the SMA wire from jumping out of the bobbin, we carefully closed the two ends with an adjustable wrench tool, then used the hot air gun over the bobbin for 5 minutes, quickly quenched it in tab water, and the bobbin was ready for sewing. Figure 13 shows how a tight zigzag-stitched square pattern crumbled the fabric swatch in less than 1 second.

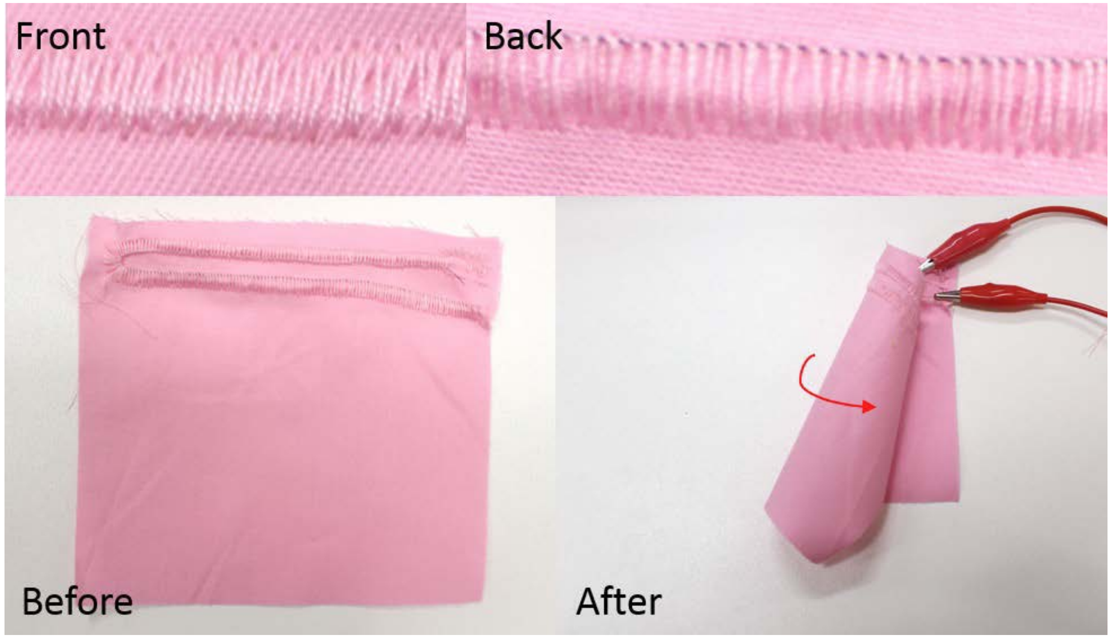
Material:	Cotton Fabric
Shape:	25 cm square
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol
Fitted by:	Sewing Machine – tight zigzag stitch - braided
Connected to:	9v, 0.5 Amp
Effect:	Shape-change (crumble)
Drama Rating:	★★★☆☆
Application:	Shape-changing Fabrics



46. SMA Sewing 10

Similar to the previous experiment, bobbin-trained SMA can be used for machine-sewing a rolling fabric using an embroidery stitch the goes back and forth through the fabric in a tight u-shape seam stretching the fabric to roll around itself when actuated.

Material:	Cotton Fabric
Shape:	19 cm narrow finger
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol
Fitted by:	Sewing Machine – embroidery stitch, sewn
Connected to:	5V, 450 Amp
Effect:	Shape-change (roll)
Drama Rating:	★★★★☆
Application:	Shape-changing Fabrics



47. SMA Sewing 11

Similar to the previous experiment, bobbin-trained SMA that was not trained properly (i.e. for a few minutes from all sides) ended up to be only wavy at one side of the wire. Thus, when the wire was sewn through the sewing-machine bobbin to the fabric using an embroidery stitch, it curved it slightly less than expected.

Material:	Cotton Fabric
Shape:	19 cm narrow finger
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol
Fitted by:	Sewing Machine – embroidery stitch, sewn Martensite: wavey
Connected to:	5V, 450 Amp
Effect:	Shape-change (re/un-wave)
Drama Rating:	★★☆☆☆
Application:	Shape-changing Fabrics

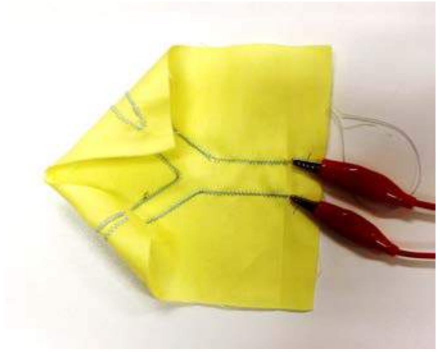
sec 0

sec 1

48. SMA Sewing 12

To experiment other patterns for machine-sewing SMA wire using the braiding technique, this swatch had SMA stitched in a Y-shaped narrow finger pattern that is meant to pull the two edges of the squared fabric swatch together. However, it didn't work as expected and it didn't deform when connected to a power supply. By changing the martensite shape from flat to folded, the fabric swatch unfolded itself immediately once the SMA stitched wire was connected to a power source.

Material:	Cotton Fabric
Shape:	19 cm narrow Y-fork finger
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol
Fitted by:	Sewing Machine – Tight zigzag stitch, braided Martensite: corner folded
Connected to:	5V, 450 Amp
Effect:	Shape-change (unfold)
Drama Rating:	★★☆☆☆
Application:	Shape-changing Fabrics



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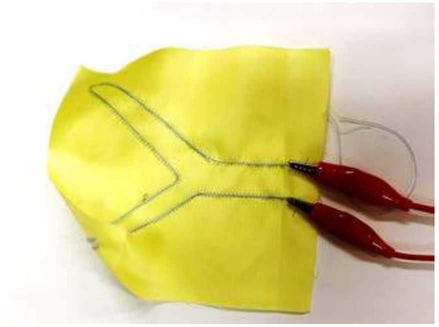
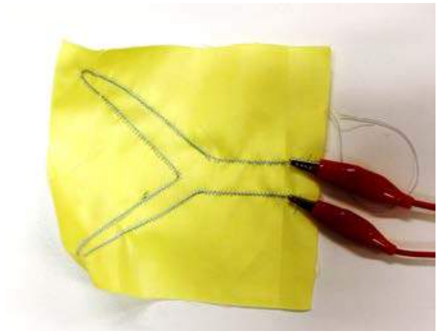


sec 0.5



sec 1

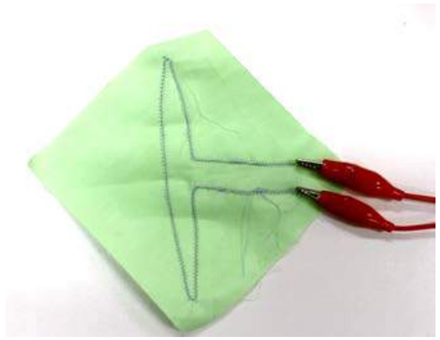
49. SMA Sewing 13

As another pattern experimentation, SMA wire is machine-sewn on this fabric swatch using a T-shaped narrow finger pattern placed on the diagonal of the squared swatch, hoping this would pull the corners inwards once actuated. However, it didn't work as expected and didn't deform the fabric's shape when SMA was connected to power. By changing the martensite shape from flat to folded, the fabric swatch unfolded itself immediately once the SMA stitched wire was connected to a power source.

Material:	Cotton Fabric
Shape:	19 cm narrow T-shape finger
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol
Fitted by:	Sewing Machine – Tight zigzag stitch, braided Martensite: corner folded
Connected to:	5V, 450 Amp
Effect:	Shape-change (unfold)
Drama Rating:	★★☆☆☆
Application:	Shape-changing Fabrics

sec 0

sec 0.5



sec 1

50. SMA Sewing 14

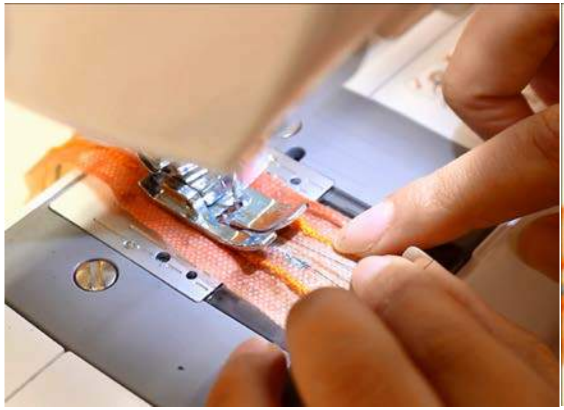
Many experiments attempted to test different patterns but failed to create actuating samples due to different factors, either because:

1) it depended on a straight line stitched wire rather than a u-curved finger-shaped stitched wire, which didn't allow any noticeable griping ability for the SMA wire's pulling force to deform the fabric;
2) or because the wire needed a more sophisticated pattern, austenite (trained-shape), or martensite (pre-actuation) shape to deform in a noticeable way.

51. SMA Sewing 15

By fixing two SMA wires, one on each side of the fabric, the front can be spring-trained to deform the fabric while the (thicker) wire on the back being flat pre-annealed wire to unfold it back. This leads to a counter-effect actuation that reverses the crumbling deformation into a de-crumbling awakening effect. In this case, both wires can be controlled consecutively to create an 'alive' piece of fabric.

Material:	Light Fabric
Shape:	50 cm narrow finger
Shape-changing Material:	SMA (Shape-Memory Alloy) 0.15 mm Flexinol – front 0.25 mm Flexinol - back
Fitted by:	Sewing Machine – Tight zigzag stitch, braided
Connected to:	9V, 1 Amp
Effect:	Shape-change (organic swirl)
Drama Rating:	★★★★☆
Application:	Shape-changing Fabrics




sec 0


sec 0.5


sec 1

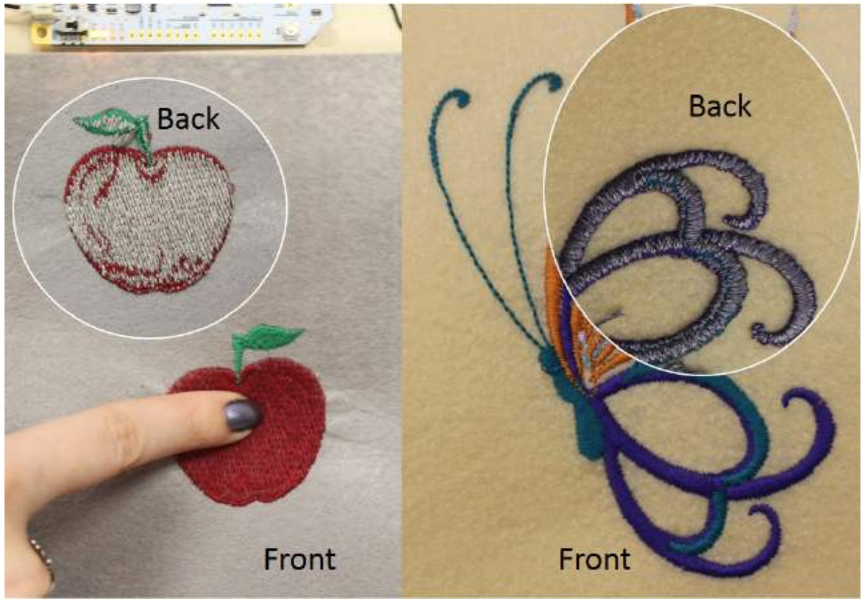

sec 1.5


sec 2

52. Touch-Embroidering

By winding conductive stainless steel thread in the bobbin of a digital embroidery machine, careful tension can create capacitive proximity and touch-sensitive embroidery designs. This could be embroidered directly onto any fabric (e.g. soft furnishing or upholstery) with normal thread on top of the fabric concealing the touch/proximity sensing conductive thread to the back of the fabric.

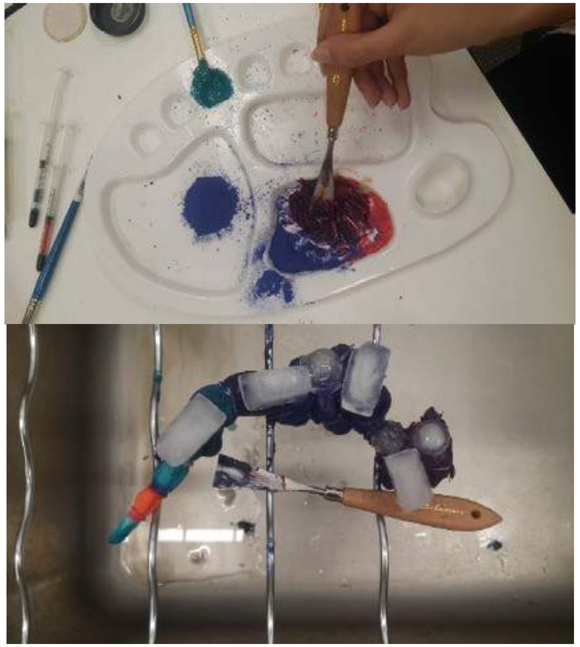
Material:	Felt Fabric
Sensing Material:	Machine-Embroidered conductive thread
Fitted by:	Embroidery Machine
Connected to:	Touch board micro-controller
Effect:	Capacitive touch-sensing
Drama Rating:	★★★★☆
Application:	Proximity & touch-sensitive Soft furnishing



53. -Tie-Thermo-Dye

By Tie-dying fabric with thermochromic-based inks mixed with fabric dyes, we can make unusual pattern-changing textiles with irregular organic patterns and colour formation with interesting textures resulting from the over-night dye in rubber bands/strings.

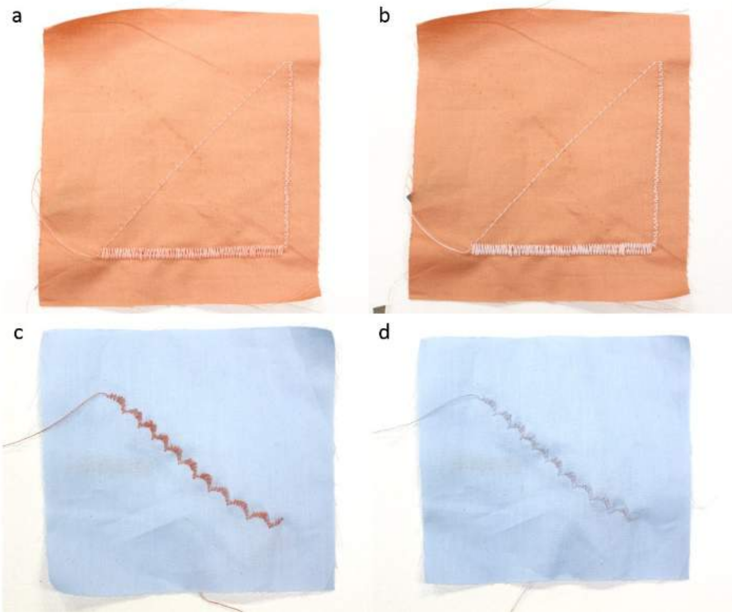
Material:	White Cotton Fabric
Shape:	Tie-dying
Shape-changing Material:	Thermochromic Pigments
Fitted by:	Rubber Bands/ Strings
Connected to:	5v heating pad
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing



54. ThermoThreads

By dying light-colour sewing yarn threads in different thermochromic pigments, we can have a palette of colour-changing yarns or bobbins that we can use directly into a sewing machine or an embroidery machine to stitch colour-changing seams onto any fabric. This tech. can be used with the previous technique of machine-sewing copper wire in the internal bobbin so that the actuating thermochromic threads and the Cu wire (as a heating agent) are simultaneously sewn together.

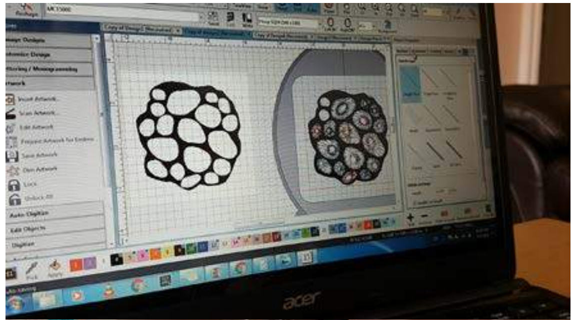
Material:	Cotton Thread yarns
Shape:	Dyed thread bobbins
Shape-changing Material:	Thermochromic Inks
Fitted by:	Dying
Connected to:	Heat >35°C
Effect:	Colour-change
Drama Rating:	★★★★☆
Application:	Actuating Seams on soft furnishing



55. BacterioChromic 1

Using digital embroidery can help design custom embroidery designs on the digitizer Software then the digital embroidery machine transforms these designs onto fabric. Using thermochromic fabric in this case creates a colour-changing medium where the embroidery is stitched towards. With heating pads attached to the back of the fabric, colour-change can be controlled to different parts of the embroidered design.

Material:	Cotton Fabric
Shape:	Machine-embroidered
Shape-changing Material:	Thermochromic Fabric
Fitted by:	Embroidery Machine
Connected to:	4.5V Heating pads
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing



56. BacterioChromic 2

Using a combination of previous techniques, we can make different colour and pattern-changing designs of fabrics that has tactile embroidered threads dyed with thermochromic inks, changing their colours in an organic behaviour when touched.

Material:	Cotton Fabric
Shape:	Machine-embroidered
Shape-changing Material:	Thermochromic threads
Fitted by:	Embroidery Machine
Connected to:	4.5V Heating pads
Effect:	Pattern-change
Drama Rating:	★★★★☆
Application:	Pattern-changing Soft furnishing

BacterioChromic is designed as an actuating wall-art that changes its patterns in response to bacteria in the surrounding space as means of ubiquitous interaction with the environment. This prototype speculates how future interior spaces can be dynamic and adaptive, not necessarily for structural/ functional purposes, but for revealing the hidden and visualizing the unseen. Accordingly, BacterioChromic reacts to, not only people, but the microscopic members of our ecology. The motivation behind it is the fact that bacteria do adapt themselves to the environment by developing antimicrobial resistance to our treatment drugs as their means to survive. Yet, we still lack the awareness, knowledge and actions required to such rise in antimicrobial resistance. Designing adaptive and `living' architecture that responds to such environmental stimuli is key to help raising people's awareness in both public and private spaces. Using Thermochromic pigments and fabrics, BacterioChromic changes its computational data-driven patterns (inspired from the bacterial growth patterns and dissemination paths on a surface) designed on the wall-art showing the changes in amount and risk of growing resistant bacteria in the environment. BacterioChromic visualizes real-time data of antimicrobial resistance in different areas across the UK, in an aesthetic form as an ambient display i.e. part of the interior space.

57. Thermo Knit

By dyeing coral cotton yarn with blue thermochromic pigment, we can use it to craft colour-changing knitted artefacts. This piece on the right-hand side shows two different knitting stitches: a tight purl stitch (left) and a wide garter stitch (right) to test their different effect. The wide one shifted colour faster with the hot air, while the tight one was more efficient with a heating pad.

Material:	Cotton Yarn
Shape:	Hand-Knitted
Shape-changing Material:	Thermochromic pigment
Fitted by:	Dyeing
Connected to:	Hot Air
Effect:	Knit Colour-change
Drama Rating:	★★★★★
Application:	Colour-changing Knitted objects (e.g. cushion, throw blanket, etc)


0 sec


0.5 sec


1 sec

58. Thermo Knitted Bugs

By weaving conductive thread within thermochromically-dyed white & yellow wool yarn with blue thermochromic pigment, I was able to craft colour-changing knitted soft artefacts. These pieces were knitted using the stocking stitch. The conductive thread acted as the heating material connected to my MuscleMuffin Arduino, actuating the colour-change for 60 seconds in response to the capacitive touch sensing of an inner layer of conductive fabric..

Material:	White & Yellow Wool Yarn
Shape:	Hand-Knitted
Shape-changing Material:	Blue Thermochromic pigment
Fitted by:	Dyeing + Weaving
Connected to:	Conductive Thread 3-Ply
Effect:	Knit Colour-change
Drama Rating:	★★★★☆
Application:	Colour-changing Knitted plushy soft decorative artefacts.

0 sec

30 sec

60 sec

59. Soft Sensor 1: Stroke Frill

The first straight-forward technique to explore soft-sensing was to machine-sew touch-sensing fabric. Conductive fabrics can be used for adding seamless sensing into interior elements and furniture (in the form of upholstery lining) such as backs of bed headboards, or bottoms and arms of chairs and sofas.
For example, I have made these two overlapping sensors by machine-sewing a double frill (out of black silk and pink cotton-based conductive fabrics) that can detect touch, stroke, stretch, flip, etc.

Material:	Conductive silk and cotton fabrics
Shape:	Machine-Sewing
Effect:	Soft tactile sensing
Drama Rating:	★★★★★
Application:	Soft switches for tactile input (stroke, poke, squeeze, stretch)


60. Soft Sensor 2: Squeeze Knit

Using conductive yarn on a knitting machine or tool can help crafting soft sensors. The tool I had in hand was a knitting mill, which helps create tubular knit of 10-15 mm diameter with its four needles. The end result is a soft stretch-sensor that can be pulled away as it lowers its resistance across the two ends as it gets stretched. This soft sensor that I have knitted using both conductive yarn (80% polyester and 20% stainless steel) and a bright sparkly green non-conductive yarn. This created a squeeze sensor that can be used as a soft-pressure sensor.

Material:	Conductive grey yarns and non-conductive green yarn
Shape:	Knitted using a 4-needle Knitting Mill
Effect:	Soft tactile sensing
Drama Rating:	★★★★★
Application:	Soft switch for tactile input (squeeze, pressure) can be used for embellishment in curtains, cushions, etc.

61. Soft Sensor 3: Stretch Knit

This is the second version of the Knitted sensor in the previous example, but because it is made using conductive yarn only, it is stretchable.

I have knitted this stretch sensor using cotton conductive yarn (80% polyester and 20% stainless steel) of which the resistance falls from 120KΩ to 800Ω when fully stretched.

Material:	Conductive yarn
Shape:	Knitted using a 4-needle Knitting Mill
Effect:	Soft tactile sensing
Drama Rating:	★★★★★
Application:	Soft switch for tactile input (stretch) can be used for embellishment in curtains, cushions, etc.

62. Soft Sensor 4: Embroidery

Thread yarns that have stainless steel can be used for add interactive embellishment and decorative details such as embroideries to soft furnishing. We can then make aesthetically-looking soft switches to control any desired program.

I hand-embroidered this soft switch designed in a floral pattern using teal-coloured conductive thread (mixed with 31% stainless steel,). In this example, I used three basic embroidery stitches: the chain stitch, the daisy chain and the French knot.

Material:	Conductive threads
Shape:	Hand-Embroidered
Effect:	Soft tactile sensing
Drama Rating:	★★★★★
Application:	Soft switches for tactile input as embroidered motifs on linens, curtains and soft furnishing.

63. Soft Sensor 5: Poke Felt

Using the dry felting technique, I've created soft sensors by needle felting, using conductive wool (80% wool, 20% stainless steel) felted onto base synthetic felt of a colourful material (50:50).
Any felted shape can be achieved with such a mixture and result in aesthetic shapes that can be soft sensors detecting either pressuring or squeezing of the conductive wool.
I have felted, this 'flower sensor' using a mixture of Bekaert conductive wool with red synthetic fibre using a felting needle.

Material:	Conductive fibre
Shape:	Dry-Felted
Effect:	Soft tactile sensing
Drama Rating:	★★★★★
Application:	Soft switches for tactile input (poke, squeeze)

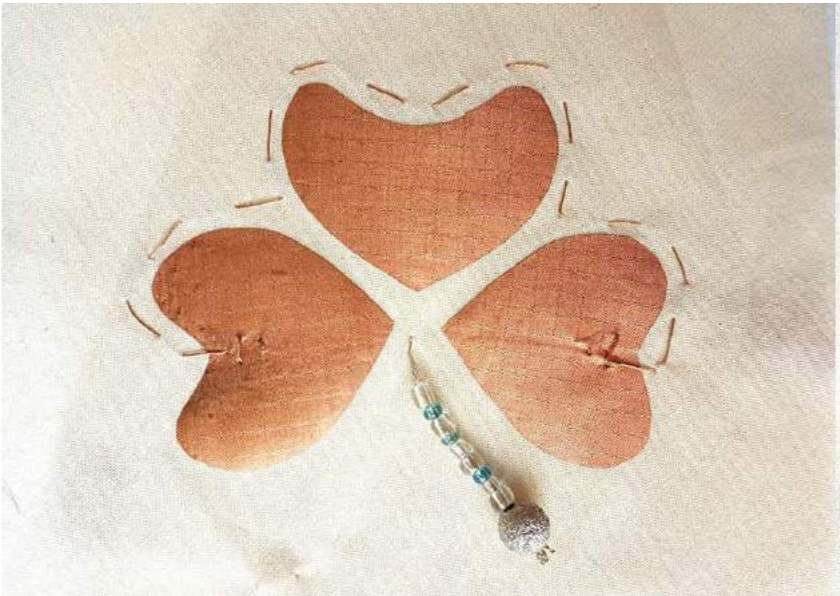
64. Soft Sensor 6: Tilting Bead

Metal and glass beads are commonly used in decoration and adornment of soft artefacts. I found a way to incorporate beads in wearables sensing (Kobakant) and I thought of re-appropriating this crafting technique for interior furnishing as well. The technique basically resembles the basic contact switch that detects if two contact points are touching or not. By extending one of the contact points with conductive thread and a metal bead as a dangling weight,

I can create a sensor that detects the tilting direction. The (conductive) thread can be embellished with colourful glass/plastic beads appropriate for the design aesthetics. The metal bead swings with gravity and touches different pieces of conductive fabric with open contact as it gets tilted.

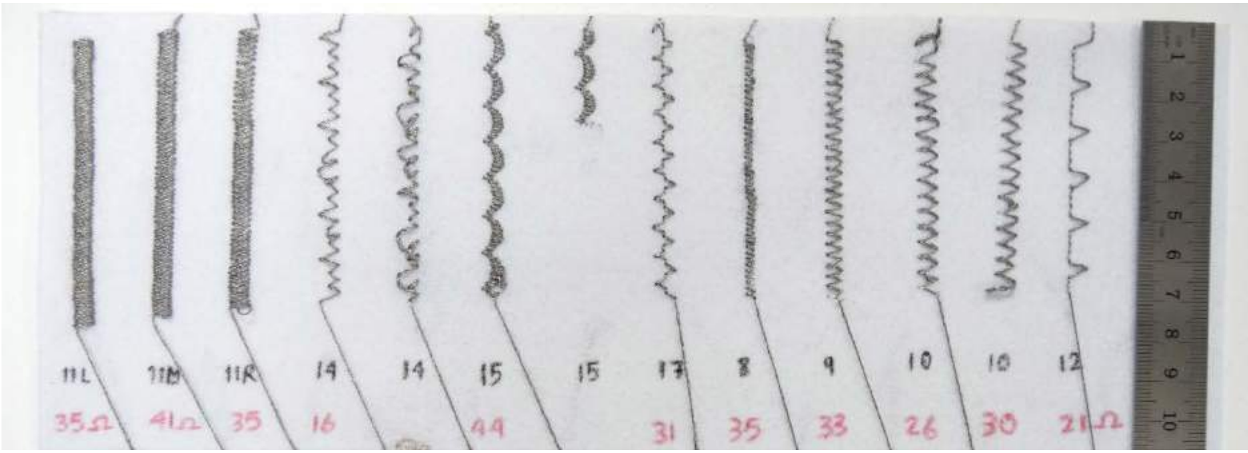
I designed this tilt sensor in a floral pattern using copper conductive thread and copper conductive fabric.

Material:	Conductive threads
Shape:	Hand-Embroidered
Effect:	Soft tactile sensing
Drama Rating:	★★★★★
Application:	Soft switches for tactile input as embroidered motifs on linens, curtains and soft furnishing.



65. Soft Resistors

Resistors come in different shapes and sizes but most of them might negatively affect the material experience and affordance to which it has added undesirable rigidity.
To solve this dilemma, I created a way to make small 'soft resistors', by machine-sewing conductive thread to fabric patches and stitch them directly to the interactive soft object. Different machine stitches give different resistance due to their varying amount of thread used and the pattern they are stitched into, in addition to the type/resistance of conductive thread.
These are some of the 'soft resistors' that I have created using this machine-sewing technique to complement the resistance in the circuit to the desired value. I have experimented with over 40 samples of 10 different sewing machine stitches sewn in varying lengths.

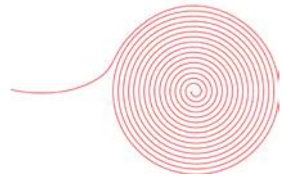


66. Soft Speakers

Inspired by Kobakant's hand-embroidered fabric speakers, I wanted to experiment this crafting method as yet another means of interactivity that can be embedded seamlessly in soft artefacts. The drawback of this technique is that it is both time consuming and needs exquisite precision to hand-stitch the conductive thread neatly in a circular path close together but without touching each other. The tighter the conductive thread is embroidered together, the more turns can fit in a smaller area, the louder the sound.

Taking this technique further, soft fabric speakers can be also crafted using a digital sewing machine. By designing the coil shape on a digitizer illustration software, and uploading the machine's bobbin case with conductive thread, we can obtain precise stitches that create better quality soft speakers custom-made to the size and sound volume we need in a more efficient and easier technique.

An accurate arithmetic spiral shape can be designed on illustrator (www.youtube.com/watch?v=nHkZ79llrc0) then the exported png can be imported as Artwork Auto-Digitize.



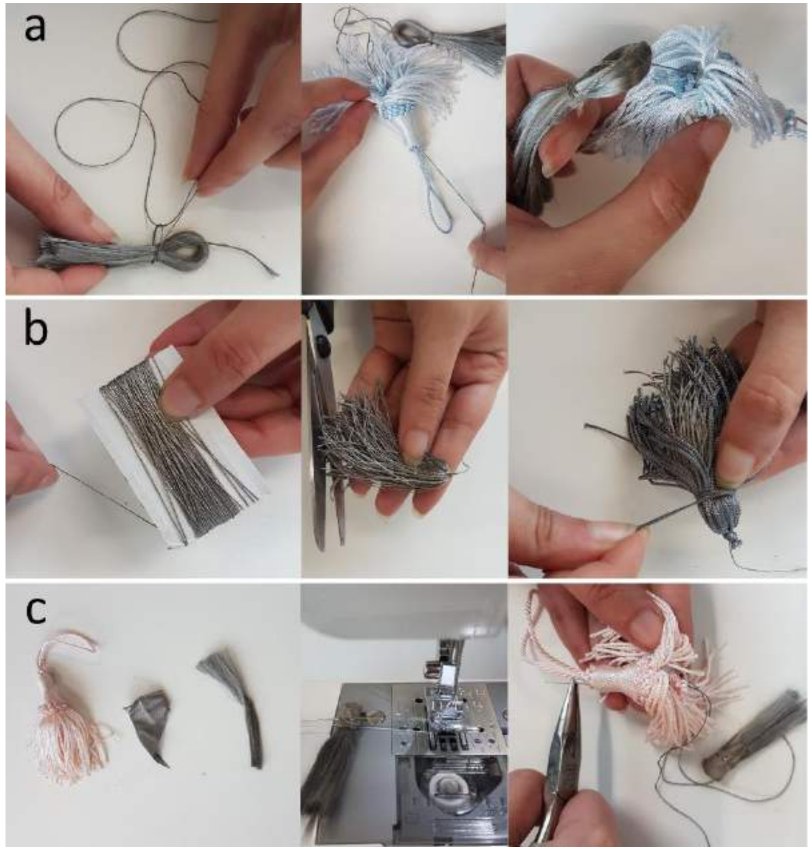
67. Tassel Sensors

For seamless interior sensing, I wanted to make sensors out of decorative elements such as tassels. Looking into different techniques to make tasselled-sensors I used sewing tools and conductive e-textiles to make a few.

Technique a:
Using Conductive Fibre (AdaFruit), bent together using conductive thread (SparkFun) then threaded within a ready-made fabric tassel (with plastic core) to be sensitive. As the fibre is bendy, it is not entirely seamless within the tassel.

Technique b:
I spun Conductive Thread (SparkFun) around a small piece of cardboard as if I was making a pompom, to create an inner-tassel-body within a fully-fabric tassel that became soft sensing.

Technique c:
Using Conductive Fibre (AdaFruit), I machine sew a small piece of conductive fabric to the fibre's edge to form a soft head, using conductive thread, then pulled the thread from the machine to get a length before cutting it off and used that extra thread (sewn to both the fibre and fabric) to weave through a ready-made tassel using a sewing needle to connect it via the hanging thread.




SARA NABIL
DÉ
COR
ACT
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Appendix B. Decoraction Catalogue


DÉCORACTION
The new collection of actuating decorative objects that bring interior furnishing to an unpreceded aesthetic level of visceral and conceptual values. From a throw that waves to you in a shivering breath effect, and a pattern revealing-hiding lamp, to a matching cushion and wall-art that change their colours when touched or squeezed.
2020
DECORACTION
Bringing Action to Decor
1 WATERFALL Colour-Changing Wall Art
£24.90
NEW
2 WATERDROP Colour-Changing Cushion
£19/ea
3 DESPOT Thermo-Chromic Lamp
£32
4 TIKALIQ Shape Changing Throw
£28
And Bringing Decor into Action


£83
CONVX
Shape
Changing
6 Pouffe
£179
LITHER
5 Shape-Changing Rug


ACTUEATER
The Shape-Changing Table Runner deforms its shape and reveals hidden patterns within its fabric in response to physical interaction with people and the matching 'interactive' tableware, such as plates, mugs, shakers, cutlery and more.
£74
7 ACTUEATER Shape-Changing Table Runner
£9.90
8 ACTUSET Interactive Matching Tableware


SOFT SENSING MATERIALS
1- Flex-sensors (Left to right: shake, tilt, pressure and touch sensors)
2- Conductive Fabrics (top to bottom: knit jersey, woven and knit touch-sensing fabrics)
3- Conductive Threads (Stainless steel, golden beige and teal)
4- Zebra Stretch-sensing Fabric
5- Conductive Fabric adhesive tape
6- Conductive Ribbon
7- Conductive Soft Fibres
8- Conductive Paper: Velostat, Copper Tape and Foil Sheets
9- Conductive Paints
10- Conductive Metal Powders (Silver, Gold and Copper)
1
2
3
4
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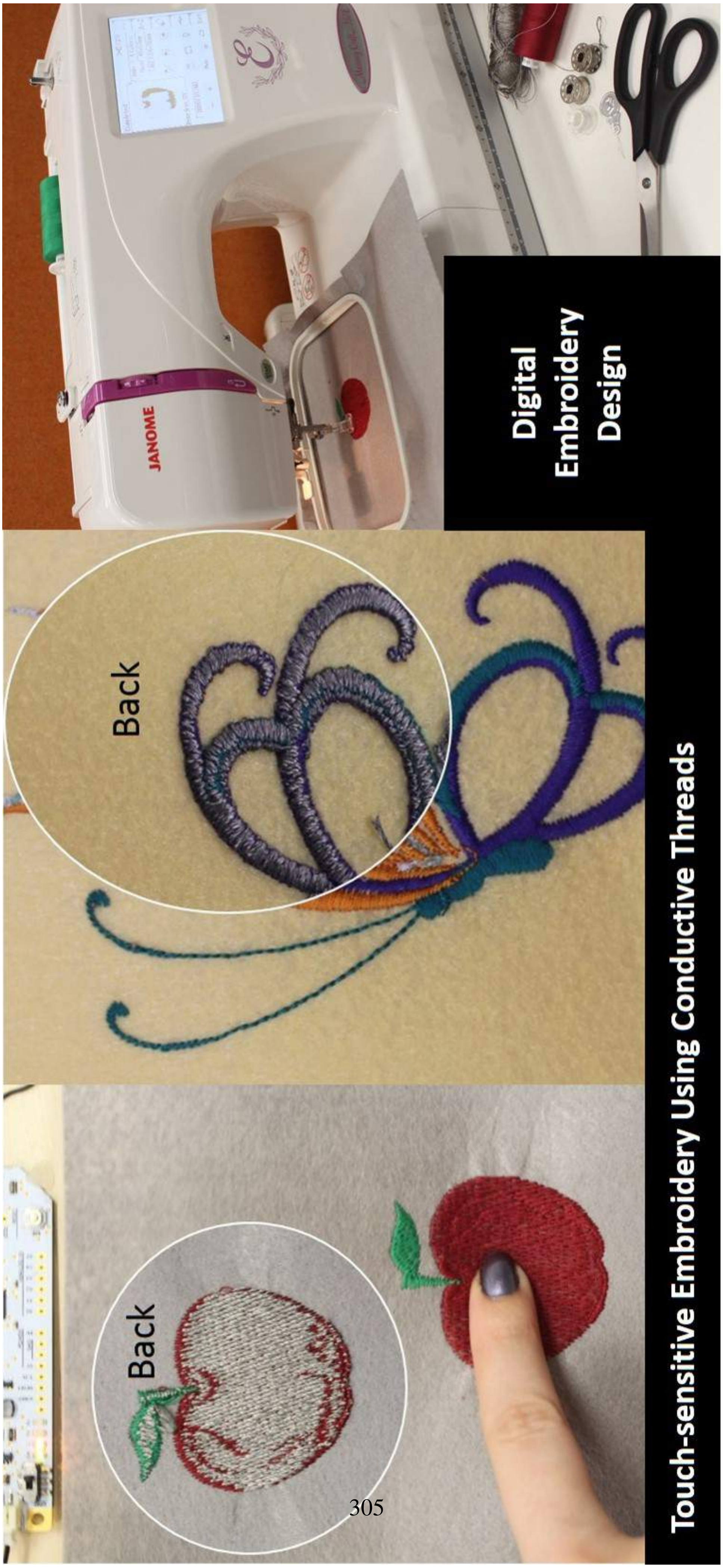
9
10


DÉCORACTION
Touch-sensitive engravings in hard materials such as wood, acrylic and other coatings are an unconventional means of turning anything on and off. Metal powders that come in gold, silver and copper colours can be used to fill-in these engravings to add touch-sensitivity to any design.
Engravings can be designed in any way that matches the style and concept of the interior space. Designs can be laser-cut and/or hand-engraved.

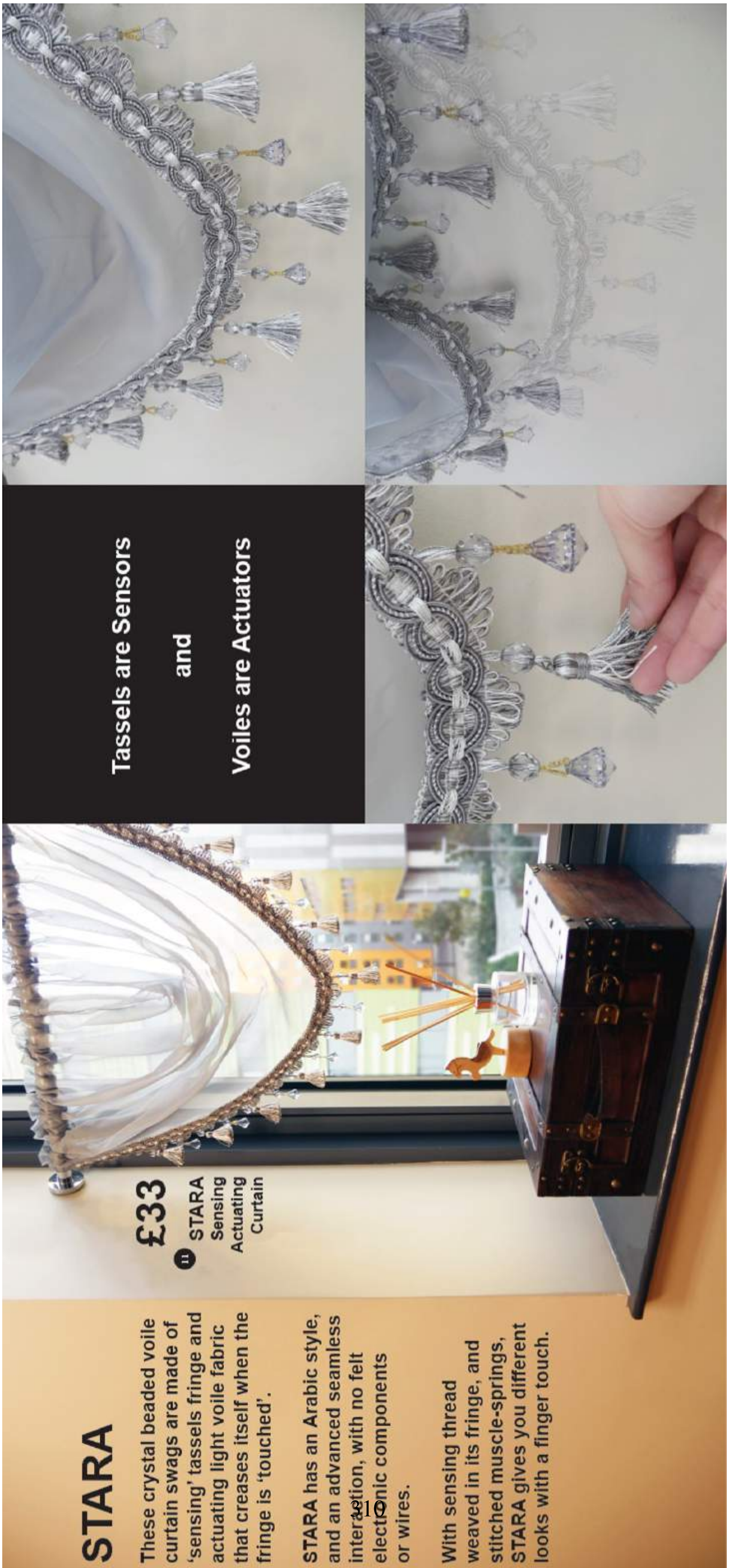

Digital Embroidery Design
JANOME
Back
Back
Touch-sensitive Embroidery Using Conductive Threads


Sensational
Touch-sensing honey wax
Conductive Threaded Pollen
Tactile Interaction + Audio Feedback
IMMERSIVE HIVE
Bees! Exhibition 2018, Great North Museum, Newcastle, UK
Engaging, Tactile, Playful and Educative


ActuEater
Domestic Interactive Interior Space
The Living with Adaptive Architecture Exhibition 2018
Lakeside Arts Gallery, Nottingham, UK
BacterioChromic


TacTile
Heat-responsive tiles that changes colour with
ambient heat from smokey monochromic dark
blue to Ottoman floral geometric patterns.
TacTiles are also touch-sensitive!
9
TacTile
Pattern-changing Tile
(30x30 cm)
£56/ea


MORVAZ
The Morphing vase that changes its shape in response to interaction with it via touch, proximity or placing flowers.
MORVASE is different than traditional vases that are static in shape and behaviour, in that one can perceive it as if it feels what is happening around/ it and bends itself in an origami-like structure reflecting context-awareness and autonomy.
MORVAZ
Morphing Vase
10
£74.90


STARA
These crystal beaded voile curtain swags are made of 'sensing' tassels fringe and actuating light voile fabric that creases itself when the fringe is 'touched'.
STARA has an Arabic style, and an advanced seamless interaction, with no felt electronic components or wires.
With sensing thread weaved in its fringe, and stitched muscle-springs, STARA gives you different looks with a finger touch.
£33
11 STARA Sensing Actuating Curtain
Tassels are Sensors
and
Voiles are Actuators

Appendix C. Decoraction Dystopian-Fiction Stories

Figure C.1 Nina in bed occasionally noticing the blossoming and closing flowers on her shape-changing LifeWall connected to her granddaughter's laptop. This drawing has been hand-sketched, then scanned and rendered in Photoshop.

C.1 Story 1: The LifeWall

It is 2029, Emma lies in her bed, an urgent beeping draws her to glance across to the orange hued alarm, telling her it is 7:00AM. Yawning, she looks up at the LifeWall in front of her. The interactive LifeWall has 3D butterflies on top that are fluttering their wings in a subtle and joyful way every few seconds. Emma smiles as she sees the butterflies bouncing and gets out of bed, comfortably knowing that her grandmother Nina is safe and well. Later that day, after finishing her last video-conference, Emma finishes her daily work-from-home tasks, takes another look at the LifeWall and decides to go visit Nina. In her bed, Nina lies comfortably reading a book, occasionally noticing on her LifeWall the flowers that bloom and close as Emma types away at her keyboard, at home. After a while Nina notices that her LifeWall has completely stopped. She puts the book down and stares at it for a few minutes. "Hi Nina!" announces Emma as she walks briskly in to the room. “Well, hello my dear. I was wondering if you were on your way over, the flowers had stopped moving” said Nina. “Sure, I promised we’d have dinner together tonight, remember?” Back at home, later that night, Emma awakes with a start. Her alarms glows with a 04:17AM. Peering through the dark she notices that the butterflies are not moving at all. Panicking Emma calls the care home, but no one is answering. Emma keeps calling again and again, as she stares up at the now ‘DeadWall’. Terrified about her grandmother, she jumps in her car to drive to the care home. As she races through the doors she bumps in to a night porter and tries to explain “No, her heart beat has stopped, my LifeWall has stopped. The butterflies are dead! Something must have happened! We have to get in to her room”. Meanwhile, at her door is Nina saying good bye to an elderly gentleman, just leaving her room, “good job I took this heart-rate monitor off, or they’d know all about what we’ve been getting up to” she says with a wink.

C.2 Story 2: SmartSofa

It is 2031, and it has been four months since Sarah last redecorated her living room. Bored, her friend Tina encourages Sarah to search online for a new pattern for her pattern-changing SmartSofa. There are several platforms available online that provide hundreds of amazing themes to change, at a finger-touch, the SmartSofa's fabric pattern, with its compatible SmartCushions and SmartCurtains, but always at a price. But Sarah wants to do it on a budget this time, and in spite of Tina's warnings, Sarah opts for a free pattern. "I like this floral one, it suits the spring spirit better, don't you agree?" Sara asks. "Well, it's not bad, but are you sure you want to agree to their terms and conditions? Why are they asking you for access to all this personal data?" Not noticing the clause in the terms and conditions Sarah downloads the free pattern, not understanding that her sofa now has ad-space attached. As she sits down with Tina to have a cup of tea she looks on, horrified, as the floral pattern on the sofa arm next to Tina dissolves to reveal a message. "Dear Sarah, we see you've been sitting uncomfortably… Try our new Recto-Cream..."

C.3 Story 3: A Cardbox

It is 2025, and an eventful year as Bob has proposed to Mary, and they are to be wed. In the week before the wedding Bob has gone to stay with his parents. Back at home their Cardbox is regularly printing out touching postcards from family and friends on social media, who create friendly digital designs online and click ‘Card-it’ to have physical cards printed out at Bob and Mary’s house. When Mary comes back from a dress-fitting, the antique Cardbox she shares with Bob is glowing, telling her she has a few more cards sent from friends, congratulating the happy couple on their upcoming big day and wishing them the best. The next day, Mary and Bob have an appointment to visit the cake-maker in town for final checks. Kelly, Bob’s ex-wife, sees the happy couple together going in to the cake shop. She had seen from shared friends on social media that they were getting married and is green with envy, for she had not forgotten about Bob, the one-who-got-away. Immediately she is determined to find a way of ruining their big day. Remembering some old intimate photos she took with Bob, Kelly wonders about whether Bob ever changed his login and password for his Cardbox. She tries to log on to it, and finds that Bob hasn’t changed his settings in years! As the sun peaks through the curtains on the day of the wedding Mary wakes up to the buzzing of the printer in the antique Cardbox in the corner of her bedroom. “How sweet” she thinks to herself, knowing that her friends must have sent her some lovely messages…

Figure C.2 Adam trying to take control over his online account history of art preference on his eyeFrame smart TV, to avoid being identified and targeted. This drawing has been hand-sketched, then scanned and rendered in Photoshop.

C.4 Story 4: The eyeFrame

It is 2038, in the drought-ridden and troubled country Palaleica, which is on the verge of a civil war. A military coup takes over and starts rounding up members of the political opposition. The only obstacle for the new authorities is how to identify the targeted ‘green people’ if they don’t look different nor live separately to other Palaleicans. Understanding how many people have new eyeFrame TVs installed, they begin to wonder if they might be able to detect political sympathies from art choices. The government secretly compels the eyeFrame Corporation to sell Palaleicans’ personal profile data. Although concerned by the potential public response, eyeFrame Corporation finalizes the profitable deal quickly on the basis of its right to “share data with other third-party applications or bodies” from its End User License Agreement (a deal no longer possible in other legal jurisdictions) and also cites the interests of ‘national security’. The new Government uses its data scientists to write algorithms to look for patterns in the art preferences of the people it has already arrested. And the conspiracy news spreads. Fearing for his life, Adam quickly starts a quiet campaign of raising awareness amongst his fellow green friends to change their eyeFrame art selection into any other artwork that would not be identified as representing a ‘green’ affiliation. Poor Adam thinks his family is now safe, not knowing the Government has purchased his entire logged history of art choices, and that the algorithms are quietly comparing his data to that of known dissidents. They come after all of them eventually... one after the other.

Appendix D. Thematic Analysis Sample

Code	Line	Quote
Theorize the cause and meaning	[24-25] [425] [44,113]	P4: We were trying to contemplate like what was causing the various movements and whether, you know discuss and theorize the reasons" P4: we were theorizing at some points but, we moved and tested.. P6: Yeah, they're controlling it. You do forget that they actually see us. P6: You were remotely controlling it. Also because I saw you touching the keyboard
Theorizing it has an intention	[153] [115-122]	P2: Or maybe it's just trying to bring us all together? P2: Was it to do with how engaged you are in the conversation? P1: Or is it kinda.. I don't know, you know stop eating, talk to people, that kinda thing. P6: It did try to nudge me because I was so focused while eating.
a resource for social engagement	[135-157]	P4: Maybe certain people that were quieter in the conversation then it would interact. P4: Well, just anyone who was quite at that given time. like when everyone's talking and everyone's engaged then it ,like, rested and then when one person would say anything, at that moment it just gets up, and if people are not talking it gets interactive at their end P1: Is sort of a voice activated thing. If it's quiet at one end it might just go wing wing wing P5: (interrupting) or might just suddenly all go up. P4: Or maybe when no one's talking? P4: It doesn't necessarily need to be all quiet P2: Or maybe it's just trying to bring us all together? P5: Yeah. P2: Yeah.

Table D.1 (1 of 4) Sample of thematic analysis coding of anonymized quotes for "Sense-Making" theme from transcribed qualitative data of the ActuEater situated study.

Code	Line	Quote
Tensions around implicit sensing	[159-171]	P4: I don't like to ... if I'm being impeded because I'm being quiet in a conversation. I think ok maybe I would find it entertaining if I'm bored, maybe, but if it.. but that's ... intension to me you know.. I might not like that.. I might be trying to listen to people P5: There might be an aspect to reversing it.. if someone's speaking it actually points to who's talking rather than whose not talking, so if it did that that might be interesting. P4: I guess my argument is that if someone's talking then the attention is already on them, whereas by bringing attention to someone who isn't talking it balances it out a bit more. P5: mmm.. yeah!
	[218-219]	P1: You know when you touch it, it might slow down, I don't know.
Sound as potential input	[37]	P1: It seems that with music, it just moves.
	[39]	P4: I think it maybe noise-related.
	[41]	P6: No otherwise it would be able to make a move (while he knocks once then twice on the table just beside it)
	[175]	P5: Or with keywords! Like in large conversations when someone says something it goes up.
	[425-445]	P4: we were theorizing at some points but, we moved and tested.. there was nothing really P5: the major thing we came to is.. sound! P4: Yeah P5: Yeah, there was no specific pattern, It wasn't obvious when it went 'P6: Yeah but the problem with sound is that there is so much noise, so it must be really really sensitive P6: Yeah, I mean with all the cutlery and all the stuff we use on the table P5: And the music as well P6: Music, voices and the whole environment noise, to make sensitive just to voices would be quite hard, especially for just a decoration, so I don't think it would be noise sensitive or sound sensitive in any way.

Table D.2 (2 of 4) Sample of thematic analysis coding of anonymized quotes for "Sense-Making" theme from transcribed qualitative data of the ActuEater situated study.

Code	Line	Quote
Sound as potential input	[707-714]	P4: maybe conversation, where the conversation would be I suppose it would redden in that area (unclear) it gets on more 'red' if someone keeps on talking (unclear) kind of realize they've dominated the conversation too much P3: Maybe even noise, so if you're getting a little bit too loud, It goes red, say if I start talking much a bit too loudly it goes red, when I get a little bit more quiet it goes blue and then maybe if I'm talking quietly it goes green, just maybe to give someone (unclear)
	[747]	P2: Was it to do with how engaged you are in the conversation? P2: yeah like physicalizing it (sound)
Illigibility is Confusing	[48]	P5: (laughing) It's hard to answer that when we don't really know what it is.
	[102]	P2: Why was it nudging, eh, or was it a random thing? Was it random nudging?
	[133]	P5: Wasn't it popping and poking anyway?!
	[173]	P1: So it can be random!
	[300-302]	P4: I guess there is something with the randomness of it. Sometimes it. . . .. feels nice to think you're quite sure, I don't know. Like you can run in a wave if you .. (interrupted)
	[425]	'P4: we were theorizing at some points but, we moved and tested.. there was nothing really
	[432]	P5: Yeah, there was no specific pattern, It wasn't obvious when it went
Legibility is easier to relate to	[394-398]	P2: I wanna (unclear) like that and then it bounces back. P2: You do something, and it repeats it/ does something.. I don't know what.
	[603-606]	P4: I think when it's completely random it obviously wear off quite quickly, not necessarily having to know what controls it but just knowing the fact that something going on in the environment is causing the movements makes it more meaningful interactions.
	[727]	P4: I don't know.. a more explicit social cue!

Table D.3 (3 of 4) Sample of thematic analysis coding of anonymized quotes for "Sense-Making" theme from transcribed qualitative data of the ActuEater situated study.

Code	Line	Quote
Having Control is Preferable	[304-305]	P5: (interrupting) yeah if you could set the forms of the patterns, like when it went along up and down the table..
	[307]	P2: (interrupting) (unclear) to figure out .. (unclear)
	[309-310]	P4: (interrupting) yeah exactly, like try to spot or figure out the patterns it would be very nice
	[574-588]	P6: I wish to have a level of control P6: well, I wouldn't see the point of full control because I think our imagination can get this just that far, probably having some pre-set patterns and the possibility to control the select of patterns for example from an app. P5: yeah. P6: Yeah. Also to be exact one would be able to turn it off (laughing).. remotely P5: yes a set program.
Nothing underneath can be magical	[494-496]	P2: I did pick it up, but actually I didn't lift it far enough, it was further than I expected, I was trying to see where the cut went in the table, but it is way further in, it's much further than I expected
	[508-512]	P6: yeah, What made me look was because I started wondering if you actually had something moving from below or if those squares were actually motorized (unclear) so I was just trying to figure out if there was a hole in the table or the table was actually normal and the whole sheet was able to move itself.. which would make it even an easier thing.
	[550-552]	P6: but that was actually what I was curious about in the beginning, the reason why I looked at it is that it would be much easier to use and to move and would not have to put a , first of all put a hole in the table and second having all these things..
	[558]	P4: And keep all the mystery alive because you look under the table and oh no, it must be in the table!
	[520-522]	P6: what kind of sorcery is this! P5: yeah exactly! (laughing together)
	[548]	P2: I'd like that!
	[536]	P2: Exactly, but the illusion of it was it did just look like a surface just like that (pointing to the wall behind her).

Table D.4 (4 of 4) Sample of thematic analysis coding of anonymized quotes for "Sense-Making" theme from transcribed qualitative data of the ActuEater situated study.

Appendix E. Paper 1: Seamless Seams and BacterioChromic

Seamless Seams: Crafting Techniques for Embedding Fabrics with Interactive Actuation

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ABSTRACT
Traditional crafting methods such as stitching, embroidering, dyeing and machine sewing can be enhanced to create novel techniques for embedding shape-changing and colour-changing actuation into soft fabrics. In this paper, we show how embedding Shape-Memory Alloy (SMA) wire, copper wire and thermochromic thread into needles and bobbins, we were able to successfully machine sew interactive morphological capabilities into textiles. We describe the results of extensive design experiments, which detail how differing actuations can be achieved through a matrix of parameters that directly influence a fabric's deformational behaviours. To demonstrate the usefulness of our 10 techniques, we then introduce and discuss an interactive artefact we produced, using a subset of these techniques. We contribute such new techniques for creating soft-interfaces, imbued with actuation through tactile and self-morphing capabilities without motors or LEDs. We draw insights from this on the potential of the proposed techniques for crafting interactive artefacts.

Author Keywords
Shape-change; colour-change; actuation; soft-sensing; sew; fabric; dye; bacteria; research-through-design.

INTRODUCTION
Embedding sensing and actuation in everyday materials has inspired recent research in areas such as tangible, organic and soft user interfaces [18, 49, 44]. Some take the approach of innovating new materials that have computational properties [24, 16, 30, 55], while others fix electronic sensors, pneumatic or motor actuators into existing materials, such as paper, fabrics, wood, etc [56, 43, 19, 26]. In this paper, we explore an alternative approach to creating soft interfaces, which is to incorporate smart materials directly into the crafting and making stages of the sewn fabrics. Smart materials that have morphological (shape and colour-changing) capabilities such as thermochromic inks and shape-memory wires can be literally stitched, knitted and weaved into different textiles. Our research aims to explore the different emergent materialities [35] of fabrics crafted from such smart materials. To achieve this, we have adopted a 'Research through Design' [13] approach, which we refer to as 'co-designing with our materials'. We draw on the insights of Gaver [15], who frames the production of annotated portfolios as a rigorous theory and a developing form of research-through-design, to underpin our presentation of a series of laboratory experiments. This portfolio of design explorations, from our own creative practice, offers novel insight into the interactive potentials of the techniques we have exploited.

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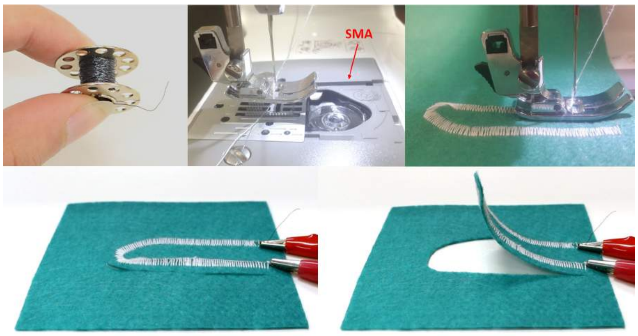

Figure 1. Technique 3: Machine-sewing SMA wire to fabric.

In this paper, we bring material science innovation of actuating *wires* to a new context and appropriated practices, as *threads*. This bridging between technology and crafting enables 'smart' materials to have new encounters with other materials (such as fabrics and textiles), other tools (such as needles and bobbins) and other machines (such as sewing machines or embroidery machines), see Figure 1. This approach broadens the accessibility of technology prototyping and has the potential to enable new previously unrealizable possibilities. For example, it allows any person to sew for themselves a shape-changing garment or make a colour-changing cushion gift without much of the common paraphernalia of digital technology development. Recent research in interactive e-textiles using servomotors and LEDs [22, 25] sits in opposition to notions of 'ubiquitous', 'seamless' and 'everyday use'. However, stitching threads, that alter their appearance and/or interactively deform constituent fabric, making the *seams* hide and reveal new aesthetics might also be thought of as a productive play on the idea of seamless and seamful interaction [6].

The objective of our exploratory experimentation is to find novel and user-friendly ways to embed subtle and silent organic movements and actuations that do not disturb people or require constant attention as with other interfaces such as light emitting displays [27]. We present our learning through making in several techniques that explore machine-sewing copper wire, nitinol shape-memory wire and thermochromic thread. Moreover, we introduce the novel technique of re-training shape-memory wire on the bobbin of the sewing machine to create self-crumpling fabrics. Finally, we present our BacterioChromic artefact, crafted using our developed techniques that embed it with morphological actuation as a case study with some insights on how people perceived its materiality and interactivity. Our work contributes a set of appropriations and exploits that can be adopted by others to support the making and crafting of soft-interfaces with morphological capabilities.

In summary, this paper makes the following contributions: 1) Introduces several novel techniques for embedding morphological actuation into fabrics i.e. machine-sewing shape-changing materials such as SMA wires and copper wire with thermochromic-dyed threads; 2) Presents a new SMA austenite shape-training method i.e. coiling the wire directly on the sewing machine's metal bobbin as the memory shape; 3) Identifies the 10 parameters that directly affect the intensity of fabric deformation when sewing SMA is used for embedding actuation; and 4) Showcases and evaluates an interactive artefact crafted using these techniques.

RELATED WORK

The most recent work on e-textiles [17] defined it as fabrics of stitched circuitry with electronic components. The majority of previous e-textile research focused on activating LEDs or motors [19, 22, 5], creating *robotic* fabrics [57]. Although some have explored crafting sensors [34, 37, 58], investigating actuating fabrics has been limited and difficult to replicate. Taking this work further into realising self-morphing fabrics using replicable methods has not been investigated before, aside from online tutorials and blogs stating that machine-sewing shape-changing wire (i.e. SMA) cannot be done [54] and therefore such e-textile applications are not yet ready for mass production and consumption [14].

Actuating fabrics as *computational materials* [48] have been motivating research in the fields of both wearable technology [3, 53] and interactive interior spaces [28, 33]. Motivations of such research come from the opportunity to create multi-aesthetic artefacts [10] using colour-changing and shape-changing materials that embody dynamics and playfulness, reflecting more subtle and poetic [2] aspects of the identity of both people and places.

Embedding colour-changing actuation within fabric can be achieved using thermochromic [11, 29], photochromic [46], hydrochromic [2] and electrochromic inks [52], leveraging digital technology beyond the *neon* era. Thermochromics, in particular, can be electronically controlled used a heating agent (e.g. conductive thread, copper wire, nichrome, etc). In this sense, some used thermochromics for designing fabric animations using conductive thread [41, 29], while others dyed the conductive thread with thermochromic pigments to achieve sensing-actuating textiles [23, 11]. However, the drawbacks of conductive threads include its high resistance, fraying and being uninsulated, potentially causing short circuits.

Unlike servo-motors and stepper-motors that create a disturbing sound, weight and rigidity for everyday materiality, other shape-changing techniques can create morphological effects that are calm, quiet and appropriate for everyday use. Shape changing materials such as thermal-responsive SMA wire can be an alternative solution for creating interesting deformations [12, 59], not only because of its subtle shape-changing effects, but also due to its light weight, experiential transparency, silent operation and organic expression [4]. Examples of previous work that explored the use of SMA wire with fabrics include the Kukkia and Vilkas actuating dresses [3], wrinkling trousers [47], the Textile Mirror [10] and the Shutters curtain [9], which all used hand-stitching to fix SMA wire to their fabrics. Alternatively, Vili [50] proposed 'yarn-spinning' for creating actuating textiles by *incorporating* SMA strands within fabric yarns to enhance both the functionality and aesthetics of interior textiles such as curtains and room dividers.

Machine-sewing techniques have been used for textile actuation in very limited work. For instance, Bern [1] envisioned the design of actuating plushy toys, but only *simulated* them and stated that "this actuation complexity is clearly well beyond current fabrication capabilities". Animating Paper [38] vaguely used "sewing" SMA –mentioning no machines– and Kono [22] proposed using strings and "sewing methods" to make shape-changing fabrics, but still actuated the fabric deformation using rotating servo-motors to pull the strings.

Other crafting methods used include hand-embroidering copper wire [36], hand-sewing soft sensors [51, 32] and crocheting conductive thread using chain stitches [21]. Recently, research has looked into machine-sewing sensing yarns [31], machine-embroidering conductive thread for e-textile connections [17] and machine-sewing copper wire as a safe on-skin electric connections [20], all excluding the potentials of shape-change. Sprout I/O [8] has briefly introduced SMA to textile techniques not only by hand-stitching SMA wire to felt fabric but also intertwining SMA spun yarn with Teflon to curl a fur strand down taking advantage of its soft properties and textural changes. Other previous work that explored SMA wires, or springs, fixed both ends only to the soldered connections of the circuit without any sewing to the fabric [7, 47].

TECHNIQUES FOR CRAFTING FABRIC-MORPHOLOGY

In this research, we focus on machine sewing: 1) copper thread, 2) thermochromic-dyed threads, and 3) SMA muscle wire, as these materials are *thread-like* and can be both physically and electronically *i)* actuated, *ii)* used for sensing (using their capacitance as conductive materials), and *iii)* sewn directly onto or woven within textiles. We used a standard brother AE17000 sewing machine for sewing, and a Janome MemoryCraft 350e digital embroidery machine, with its CAD software for embroidery. SMA Flexinol wire was supplied

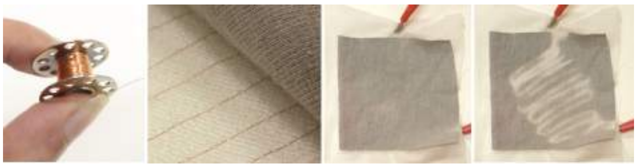

Figure 2. Technique 1: Machine-sewing copper thread to light mesh fabric with a thermochromic fabric layer on top.

from RobotShop.com, the 0.1 mm copper enamelled reel was supplied by Sourcingmap (Amazon), and the thermochromic pigment from Rapidonline.com. Such materials thereby create unprecedented seamless and seamful interaction [6] with fabrics and everyday soft objects. In this sense, we adopt a 'Research through Design' [42] methodology to explore creative ways of embedding organic actuation and deformation in fabrics aiming towards novel opportunities of future uses, expressions and design possibilities not previously associated with textiles [40]. We describe in a condensed format, the results of almost 100 experiments, summarized in 10 techniques, which were reproduced and observed for a repetitive behaviour.

Technique 1: Machine-Sewing Copper Wire

Copper enamelled wire with 0.1 mm diameter is as thin as thread and can be used for embedding actuation in e-textiles in various ways. For example, Posch et al. [36] used copper enamelled wire to embroider coils creating a few logic gates as 1-bit displays using electro-magnetic shape-change. Their approach was delicate and interesting, yet unique and difficult to replicate. We wanted to develop a simple technique to help anyone sew their own actuation. After realizing how hand-stitching copper wire can have its complications in terms of time and breakage, we believed using a sewing machine could be a simpler idea. Copper enamelled 0.1 mm wire can be easily used for loading the bobbin case of a sewing machine and can be threaded smoothly through the sewing machine's needle. Any normal thread spool can then be used to stitch the copper. We tested different stitches and found the basic straight stitch to be perfect for thin feeds, while the tight satin stitch (resembling embroidery) was ideal for thick covering. One method is to stitch it directly onto thermochromic fabric, but the copper seam will be visible. Another is to use a thin mesh fabric underneath thermochromic fabric to reveal its hidden pattern and achieved different results, see Figure 2. Once connected to power, the thermochromic fabric glows around the stitched seams revealing another colour. Once disconnected, the fabric slowly returns back to its monochromic colour. Machine-sew copper wire can be also used to activate colour-change in normal fabric (not thermochromic) in the same way. After stitching through, the fabric can be screen-printed or hand-painted along the seams with thermochromic paint, allowed to dry, then activated. We found that angular flat brushes achieve better results in painting fabric with thermochromic pigments than pointed round brushed, due to its thickness. The fabric seams immediately change colour around the printed or painted pattern along the copper seams, revealing the fabric's original colour or pattern underneath. Alternatively, we explored other fabrication methods with this technique such as *tie-dyeing* fabric with thermochromic pigments and ice cubes (the latter being commonly used in tie-dyeing to allow gradual colour absorption). The results were not as expected, as thermochromic pigments are not inherently fabric dyes, but it still made creative and interesting colour-changing patterns. Fabric painting allowed us to explore the interplay between the pattern-changing print and the fabric's original pattern.

Figure 3. Technique 2: a) Dyeing light-coloured threads with dark thermochromic pigments, b) drying, c) bobbins in room temperature, d) bobbins when heated (changing back to their original colours).

Technique 2: Machine-Sewing Thermochromic Thread

Given that neither conventional fabrics are thermochromic, nor painting fabric is easy, we developed a much simpler solution that achieves the same previous results: machine-sewing thermochromic thread. Similar to any normal yarns, thermochromic thread can be machine-sewn. We dyed some light-coloured cotton threads with darker thermochromic pigments, see Figure 3. We followed the standard usage of thermochromic pigments (described in the user manual of most suppliers) where all inks are accompanied by a binder, mixed 50/50 with the ink, to produce the desired amount of useable ink/dye. Light-coloured cotton thread and dark-coloured thermochromic pigments together achieve the best results. The dyeing process starts by soaking thread for at least 30 minutes in a shallow bath of thermochromic dye (Figure 3.a). Then, the thread is taken out and dried overnight on layers of tissue paper (Figure 3.b). Afterwards, the thread is subjected to bobbin winding for use with the sewing machine (Figure 3.c). Any hard crumbles or dry pieces should be removed before or during this step. Finally, thermochromic-dyed threads on bobbins can be tested using heat, changing back to their original colours (Figure 3.d).

This technique can be used independently (reacting to ambient heat) or concurrently with Technique 1, where thermochromic threads are the main thread spool of the sewing machine, and copper thread fills the bobbin case. In this technique, the sewing machine stitches *controlled* colour-change directly into any kind of fabric. Once connected to a battery, the fabric seams transition from one colour to another. Similarly, an embroidery machine can be used to stitch colour-changing embroideries using thermochromic-dyed thread. We used a digital embroidery machine to produce numerous colour-changing embroideries designed on the illustrating software. Apart from colour-change, and to demonstrate further effects, two approaches were tested: *hiding* and *revealing*. When using dyed thread with a matching colour to the fabric, seams seem seamless, but reveal once actuated. Alternatively, stitching fabric with thread that has a matching 'original' colour causes

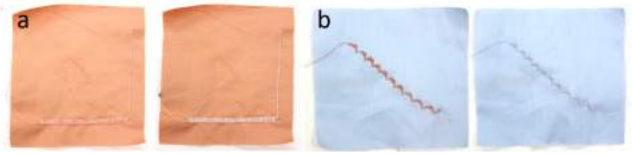

Figure 4. Machine-sewing thermochromic-dyed threads (in the spool) with copper enamelled 0.1 mm thread (in the bobbin) where the stitched pattern (a) reveals and (b) hides.

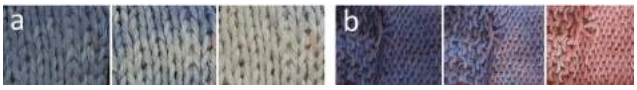

Figure 5. Gradual colour-change of (a) white and (b) pink knitted yarns dyed in blue thermochromic pigments.

the seams to be contrasting/visible, then hidden once activated, see Figure 4. Another fabrication method that can be used in the same sense is knitting with yarn that is thermochromically-dyed, either using a knitting machine or knitting needles. Copper enamelled wire can be either knitted with the dyed yarn or weaved through the knit after finishing (see Figure 5).

Technique 3: Machine-Sewing SMA Wire

In the same way of filling the sewing machine's bobbin case with copper wire, we explored machine-sewing SMA wire. We mostly used Flexinol HT 0.006" and 0.010" muscle wire as our Shape-Memory alloy actuators. Such SMA wire is pre-trained to shrink by around 4% of its total length and flatten when adequate current flows through and heats it up (around 0.4A and 1A respectively). This causes the wire to usually erect (lift and bend outwards) along with the material it is fixed on. Alternatively, SMA springs retract significantly (up to 80%) causing compression or creasing deformation of the material to which they are affixed depending on its affordance. SMA wire can also be re-trained to actuate in any desired form by heating it on a fixed mould of that required shape up to 400-500°C for a few minutes then immediately quenching it in cold water to *remember* that shape. Once the electric current flows through the SMA wire, it begins to reveal the deformation effect it is trained upon and this essentially causes the fabric to undergo physical movement according to the applied stitching form and sewn stitches. We used and tested different stitches and stitch forms until we obtained the best results through zigzag short and tight stitches fixing the SMA wire in a U-shaped pattern.

In general, SMA wire is much harder to control as it physically tends to loosen and wobble due to its unique alloy, so it cannot be firmly bent or tightened. However, by using thin 0.006" Flexinol wire, firmly gripping the ends in one's fingers to avoid its unrolling, working quickly and accepting that the wire will somewhat loosen, it is applicable to achieve neat seams using SMA wire. Once stitching is done, both the wire and thread should be cut, leaving 1-2cm of the wire to allow electronic connection. Figure 1 shows how SMA wire was rolled around the bobbin and loaded into the bobbin case of the sewing machine underneath the presser foot. Then the bobbin wire stitched the spool thread neatly on a tight zigzag stitch through a U-shape pattern. In this example, we consumed 20cm of this wire that has 55Ω/m leaving us with 11Ω for this piece. When applying 410mA (the recommended current for this wire) using 4.5V, the wire couldn't move as the fabric around our pattern forced too much weight, pressure and stiffness beyond the pull force of the wire (321 grams). In such cases, the pattern needs to be free, so a cut-out should be formed around the pattern allowing the stitched pattern to move freely by bending when connected.

Technique 4: Parametric Machine-Sewing SMA Wire

To investigate the relationship between different stitches and the shape-changing actuation effect, we held systematic experimentations of over 60 swatches with different combinations of the different factors that impact the deformation to understand their effect. Various parameters played a role in the equation of fabric actuation resulting in different deformation effects. These 10 SMA deformation parameters are:

1. **Type of fabric**: The more malleable it is, the easier it is for the wire to deform the fabric. However, the type of fabric (determining its stiffness, rigidity/elasticity and weight) is correlated with the type of desired actuation e.g. firm fabrics can bend, while lighter ones can twist, (un)roll and crumple. Rigid fabric should be chosen for controlled actuation, while light-weight fabrics can support organic deformation. Flammable fabric should be avoided when sewing SMA.

2. **Type of thread**: Certain types of threads may have different impacts on the tension of the wire fitted on the fabric and therefore the deformation effect when connected. We found that loose thread minimizes deformation while tight-able thread maximizes wire pull-force and thus amplifies fabric deformation. For precaution, the thread type used should not be flammable to avoid catching fire if the wire gets unexpectedly heated too much.

3. **Type of stitch & its tightness**: the shape and tightness of the stitch that fits the SMA wire to the fabric is of significant importance. In general, the wire needs to be held tight to deform the fabric when actuated. However, if it is too tight it will not allow any deformation to take place. On the other hand, loosely fitted SMA wire will deform between stitches without causing visible deformation in the fabric.

4. **The pattern of stitching**: The most significant parameter that affects resultant deformation is the shape of the wire traces when stitched onto fabric. It has been agreed between practitioners that one of the most successful patterns that causes visible shape-change is a U-shape pattern. This pattern maximizes the pull-force of the wire causing the material to bend upwards when the wire actuates, acting like an arm muscle that can lift objects upwards by contracting. Other patterns can cause the wire's pull-force to be distributed in uneven loads minimizing its actuation capability.

5. **Type of wire**: SMA wires are commercially available as Nitinol, Flexinol, muscle wire or smart wire, and can be as malleable and thin as normal thread (e.g. 0.15 or 0.25 mm) with pulling force ranging between 320 and 900 grams at 410mA and 1050mA respectively (see Table 1). If high current (more than the recommended by the manufacturer)

SMA Product (Supplier)	*Diameter (mm)*	*Resistance (Ω/m)*	*Current (mA)*	*Pull-force (g)*
BMX750 (TOKI BMX)	0.075	1000	100	5
Flexinol 0.006" LT (Muscle Wires)	0.15	55	410	321
Flexinol 0.010" HT (Muscle Wires)	0.25	18.5	1050	891
Nitinol Wire (Smart Wires)	0.5	4	4000	3500
Smart Niti Spring (Rapid Education)	0.75	2	3000	500

Table 1. Examples of SMA wires commercially available.

is applied for more than 10 seconds, the wire may burn. Thicker SMA wire usually has a much higher pull-force which can deform fabric more intensely, even when it's heavier. However, thicker SMA wire requires significantly higher power. Accordingly, thicker wire increases the deformation boundaries but simultaneously adds rigidity and stiffness to the fabric that might affect its malleability, affordance or texture.

6. **The austenite form** (trained shape): The *memory* shape that the SMA wire has been trained (i.e. heated up to 400-500°C) to remember when activated by 40-90°C is called the austenite form/state. The austenite default shape of off-the-shelf SMA wire is a straight-line; that is, it flattens unfolding itself and often slightly shrink by 4% of its length when connected to electric current. This shape can be changed as required if the wire is re-trained to remember a new shape. Most SMA actuates repetitively for millions of cycles, but if high stress or strain is imposed, the actuation only lasts for a few hundred cycles. This parameter can dramatically change the SMA wire actuation behaviour resulting in different deformation effects for each different austenite form, i.e. trained shape (see Figure 6).

7. **The martensite form**: SMA wire is very malleable and hand-deformable in room temperature (when no electric power or heat is applied). This malleable state is called the martensite state. In this idle state, the wire accepts any physical deformation applied to it. Once the wire is connected or heated, it returns back to its memorized austenite shape. However, the deformation is not always consistent and is often affected by the martensite form. That is, the shape-change is affected by the manipulation applied to it earlier. In other words, if the wire is bent, rolled or twisted by force, then actuated, it will unbend, unroll or re-twist itself back. This allows a variety of repertoires between people and actuating soft artefacts in the form of a conversation where physical input affects output.

8. **The fabric orientation**: As the pull-force of thin SMA wires are relatively not high enough, the fabric deformation is significantly affected by the seam orientation. The fabric might not be able to actuate vertically, but could on a horizontal surface, where it's not working against the gravity.

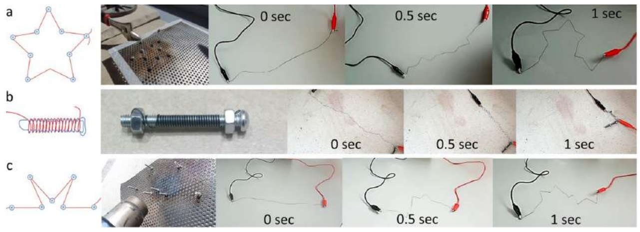

Figure 6. Training SMA wire to remember different shapes.

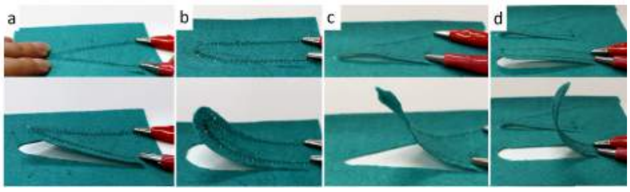

Figure 7. Technique 4: Parametric machine-sewing SMA wire to fabric over a U-shape pattern using a loose zigzag stitch (a: pointy, b: curved) and a tight straight stitch (c: pointy, d: curved).

Also, non-spring SMA can only deform the fabric towards the side it's stitched on, not the other way. Gravity can also be used to work with the design (rather than against it) if utilized as the reverse mechanism, pulling the contracted SMA back down while cooling achieving a two-way actuation.

9. **Length of wire**: Although used as thread, the length of consumed wire determines its resistance, thus the amount of electric current it draws according to Ohm's Law ($V = I \times R$), consequently affecting the deformation effect that occurs. For example, a 20cm pattern of a 55Ω/m wire forms 11Ω requiring 4.5V for its recommended 410mA. However, a 50cm long pattern stitched with the same wire forms 27.5Ω requires 11V to be able to draw its recommended current. The deformation of SMA of length between 15 and 50cm was observed to be the highest.

10. **The distance between the seam (SMA wire) and the edge of the fabric**: The same combination of all previous parameters may work if the pattern is stitched by the edge of the fabric, but may not work if placed in the middle of the fabric, as more weight will be applied on the wire beyond its pulling-force. This is the reason why, in most cases, a cut-out around the pattern is essential to allow the deformation to take place.

For instance, by altering two variables (the type of stitch, and the pattern of stitching) and fixing other parameters, insights can be drawn on how to optimize the SMA machine-sewing technique. By experimenting with different stitches, we found the straight stitch, the satin stitch and the zigzag stitch to be efficient, with tighter stitches causing more dramatic deformations. Through testing different patterns, we found that the more curved the pulling end is, the more the pulling-force of the wire is maximized. Figure 7 compares the four combinations of two patterns (triangular pointy peak, round curved peak) and two stitches (wide zigzag and tight running stitch).

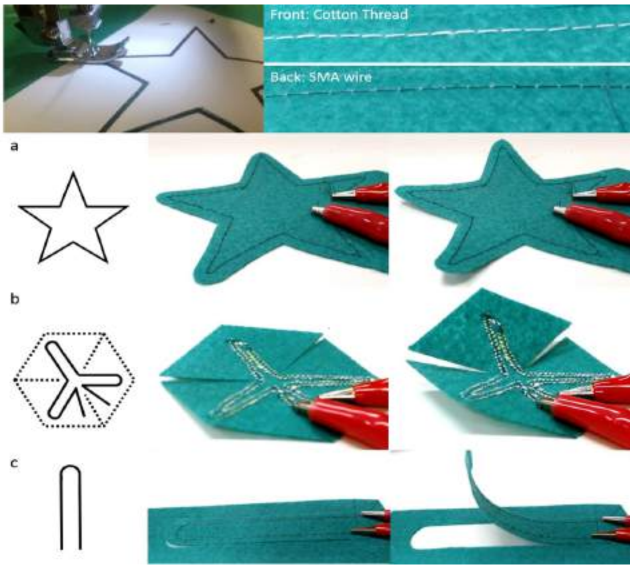

Figure 8. Technique 5: Using Sewing patterns in machine-sewing SMA wire to create complex shapes.

Technique 5: Sewing-Patterns for Machine-Sewing SMA

The great benefit of using a sewing machine rather than hand-stitching SMA wire is the ability to rapidly design and prototype different shape-changing effects. We can now machine-sew actuation directly into fabric and rapidly and systematically compare different patterns and shapes. 'Marking' is a standard practice in sewing and can be used to trace a shape-changing template or transfer an SMA pattern to the fabric using tailor's chalk or fabric pencils. Using *paper patterns* is also an old traditional sewing method for cutting fabric to desired sizes and is a natural step to learn when sewing garments, and soft artefacts. Consequently, we utilized and re-purposed these same methods to enable the creation of complex shape-changing patterns. This technique enabled us to simply follow the lines while machine-sewing SMA wires into various curves easily. Figure 8 shows some paper patterns we have machine-sewn using SMA wire, including a star shape, a hexagonal inner shape and again a U-shape. Comparing the resultant actuations of different stitched patterns yielded a conclusion that the latter pattern is most effective in terms of visibility of deformation.

Technique 6: Controlling Fabric Deformation

Learning from Technique 3 how the U-shape pattern worked nicely, we went on to try different versions of this pattern. We learned that by changing the size of the pattern to a narrower width and longer length, more visible variations of shape deformation can be achieved. Learning through making helps us develop understanding often in better ways than other scientific approaches. For example, we learned by coincidence, that a bend can be controlled at a particular desired part of the fabric through less weight at this part. Figure 9.a shows a scrap that actuates in a right angle bend at the point where less fabric strain is found. Figure 9.b shows how the pull-force is maximized (compared to Figure 8.c) when the pattern gets narrower, allowing more grip, causing swirling. By changing the parameter of the martensite state (i.e. twisting and untwisting Figure 9.b by hand), the same piece deforms in a different way by twisting itself instead of swirling. In this technique, the fabric relaxes back and obeys gravity once no electric current flows through the wire. However, the deformation is repetitive and the resultant actuation is the same every time. Such techniques can be used when the actuation output needs to be designed and performing in a specific constant way to achieve a certain task or display a specific message to a user e.g. a cushion's corner can bend twice notifying one that something has happened. Such actuation needs to be consistent and can thus be achieved in one of these controlled deformations.

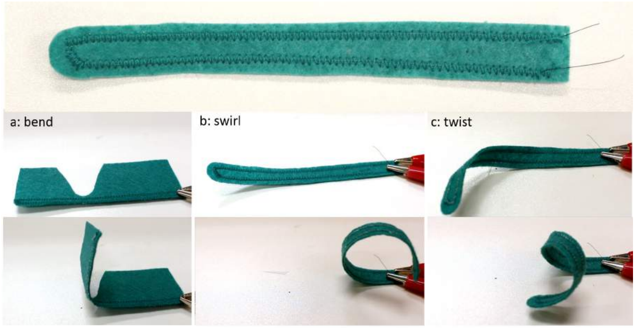

Figure 9. Technique 6: Machine-sewing SMA wire over a U-shape pattern using a tight zigzag stitch (a: bend, b: swirl, c: twist).

Technique 7: Manipulated Fabric Deformation

Rather than controlled actuation, we were interested in the unexpected ways SMA wire deforms the fabric in a non-computerized but more organic behaviour. To allow such free-style actuation, the martensite state parameter (i.e. hand manipulation input before actuation) can be manipulated and light-weight fabrics can be used to avoid rigid repetitive deformation. In this technique, other parameters (such as the stitch, pattern and wire) are fixed to the most effective ones we have found so far. Figure 10 shows deformations resulting from a) swirling, b) rolling, and c) folding hand manipulations of the fabric. Results informed how autonomous behaviour of SMA actuated fabrics can often yield more interesting forms and organic shape-changes depending on user direct manipulation as opposed to programmed consistent outputs. This technique can suit applications around wearables where people deform their garments in different (free-style) and unique ways.

Technique 8: Machine-Braiding Trained SMA Wire

To achieve a crumpling fabric deformation, the wire needs to significantly contract (not just bend, swirl or twist). Relevant previous work in material science has looked into training SMA wire to remember a certain austenite shape [45]. Therefore, SMA wire can also be customized into remembering a specific desired shape by training the wire in a mould, fixing it to that shape and applying 500°C of hot air for a few minutes [45], or a naked flame for a few seconds. For this technique, we re-train the wire to remember different austenite shapes then machine-braid it on top of the fabric. For example, a wire actuating into a spring shape can be achieved by rolling

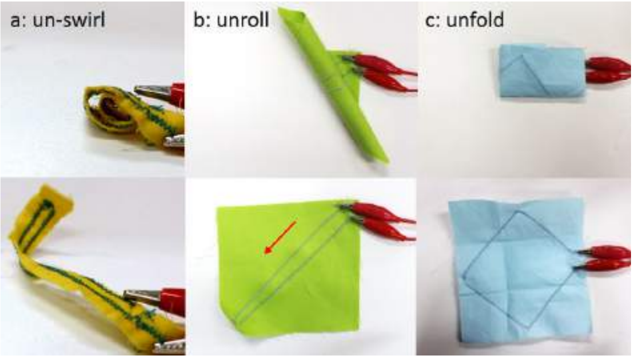

Figure 10. Technique 7: Machine-sewing SMA wire then hand-manipulating the martensite state (left), and after actuation (right).

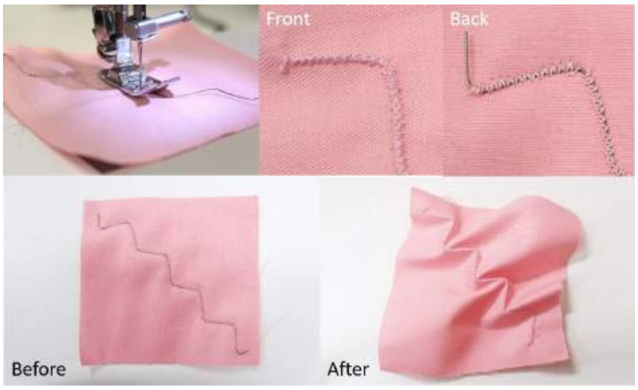

Figure 11. Technique 8: Machine-sewing zigzag-trained SMA wire (top), before and after actuation creases the fabric (bottom).

the wire around a screw (to achieve a spring coil shape) then heating the wire using a hot air gun for 5 min in direct contact, or a candle flame for 2 min. It is required to throw the wire immediately afterwards in cold water in a process called 'quenching' for the training to take effect. Some have recommended repeating this process numerous times to train the wire, but we found that it does remember from the first time.

Once the wire is physically-programmed to remember this spring shape, we can stitch it to the fabric. However, it is difficult now to roll the wire around the bobbin as it has bends of a different diameter (from the screw). To machine-sew this wire, we use the conventional machine-sewing technique called 'braiding'. Similar to adding decorative embellishments to fabric such as ribbons and thin braids, we use the spring-trained wire on top of the fabric to be fixed using the sewing machine's tight satin stitch. Although using a braiding or a couching foot would be suitable for this, we used the basic presser foot which worked fine. If the wire could not deform the fabric at all, it is likely that the fabric is too heavy and firm to be deformed. A cut-out close to the seam will solve this problem. Another austenite memory-shape to train SMA wire (than a spring coil), is a zigzag shape. Figure 11 shows a 16cm long zigzag-trained SMA wire machine-braided on top of a cotton fabric swatch. When activated, the fabric deforms in a wavy form creating a different shape-change deformation than all the previous techniques.

Technique 9: Machine-Sewing Bobbin-Trained SMA Wire

Based on previous techniques, the idea can be developed to investigate a new possibility: why aren't SMA wires pre-programmed directly on the machine's bobbin? In other words, training the SMA wire while rolled on the bobbin, using the bobbin as its mould, then placing the bobbin (with the spring-trained wire) directly inside the sewing machine. This technique is much easier than braiding the wire on top of the fabric and results in new kinds of deformations. To hold the SMA wire from jumping out of the bobbin, the two ends can be carefully closed with an adjustable wrench tool, then the bobbin SMA can be trained, and be ready for sewing. When using this bobbin then to machine-sew a tight zigzag-stitched square pattern, the SMA -once actuated- crumples the fabric (Figure 12). However, when machine-sewing the bobbin-trained

Figure 12. Technique 9: Heat Training SMA wire in the bobbin to a spring shape. After actuation, the fabric crumples itself inwards.

SMA wire in a narrow U-shape pattern using a satin stitch, the fabric rolled around itself once connected (Figure 13). In all these techniques, the SMA wire is intertwined with the normal thread, causing the fabric deformation at the *seam*, only visible from the back, and is entirely *seamless* from the front of the fabric.

Technique 10: Machine-Sewing Shape-Colour-Change

By combining Technique 2 with Technique 9, colour-change and shape-change can both be achieved simultaneously. In this technique, thermochromic-dyed thread is used on the top spool pin, all the way through the thread guide, the take-up lever and the needle. On the other hand, the bobbin is filled with SMA wire that can be re-trained in a spring austenite shape for a contracting actuation. With a tight zigzag stitch, to hold both threads in place, and prevent excessive thread consumption (as with the satin stitch), we experimented this technique on different fabrics and threads. As with Technique 2, using matching colours of fabric and thread, will hide and reveal

Figure 13. Technique 9: Machine-sewing bobbin-trained SMA wire with thread. After actuation, the fabric rolls around itself.

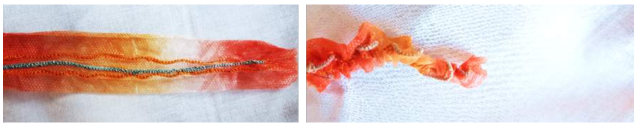

Figure 14. Technique 10: Machine-sewing bobbin-trained SMA wire with thermochromic thread. After actuation, the fabric seam changes both its shape and colour.

a contrasting seam that swirls, bends, rolls or crumples once actuated, according to the SMA trained shape, as in Technique 9. Figure 14 shows one of the samples in a vibrant coral colour fabric and teal thermochromic dyed thread, that changes both shape and colour simultaneously once connected.

CASE STUDY: TECHNIQUES IN USE

To demonstrate the use of the techniques presented, a case study was carried in which we crafted a meaningful and usable artefact utilizing morphological fabrics. Herein, we describe the design process and evaluation of 'BacterioChromic', which was a piece of interactive wall-art designed with morphological capabilities, changing its patterns, colours and shape (see Figure 15). Beyond responding to a specific brief (see below), the discussed crafting techniques allowed us to explore a future of interior spaces that can be artfully dynamic and adaptive. We used the mentioned techniques of fabric painting with thermochromic paints (Technique 1), machine-embroidering thermochromic-dyed threads (Technique 2), bobbin-training SMA wire (Technique 9) and machine-sewing SMA wire (Techniques 3, 4, 7, 8 and 10).

Design Concept

Inspired by the patterns of bacterial growth in petri-dishes, BacterioChromic was designed as a wall-art piece, as part of the 'Living with Adaptive Architecture (LWAA) Exhibition 2018'. The concept behind this crafted artwork was to simulate the interaction with bacteria in the surrounding space, to help stimulate awareness and discussion around Anti-Microbial Resistance (AMR). Designing tactile and living artefacts that respond to environmental stimuli is potentially valuable for raising people's awareness in both public and private spaces. We saw an opportunity to realise this, in an aesthetic form as an ambient display i.e. part of the interior space, rather than the more expected charts and graphs encountered in health communication. This artefact had a dual purpose of allowing us to concurrently speculate on how future interior spaces might be dynamic and adaptive, and not purely for structural or functional purposes, but for visualizing the unseen.

Crafting & Implementation

Shape-change was embedded in loose strands of thin fabric resembling a type of resistive bacteria, by machine-sewing Shape-Memory Alloy (SMA) wire to the fabric. Learning from our experiments, we utilized the parameter values that were recorded in SMA parametric design to achieve the best results in terms of deformation intensity (Technique 4). That is, thin light-weight fabric was used to help reduce any additional weight hindering the pulling-force of the SMA wire. Then tight zigzag stitches were used for machine-sewing the SMA to the fabric using thermochromic-dyed thread that

Figure 15. BacterioChromic wall-art exhibited at the LWAA 2018 Exhibition responding to touch by changing its patterns, colours and shape.

changed colour simultaneously as the SMA actuated and heated to change-shape (Technique 10). Organic actuations were achieved by manipulating the martensite (Technique 7) and austenite forms (Technique 8) using machine-braiding the SMA wire directly on top of the fabric. The U-shape sewing pattern was used to realize the desired form and deformation of the bacteria-like fabric strand. To achieve two-way shape change, SMA wire that is pre-trained as *straight* was machine-sewn to one side of the fabric, while bobbin-trained SMA (Technique 9) as a *spring* was machine-sewn to the other side. The choice of the wire was also carefully made, as thin 0.006" SMA was used for bobbin-trained retracting spring side, a thicker 0.010" SMA was used in its default straight austenite, to have a stronger pulling-force (891 grams) enough to unfold the strand again from the other side. As a result, when each side is controlled in sequence -in response to user touch input- the fabric strand appears to be living, blossoming and unfolding and then rolling itself back, crumpling in organic imprecise patterns and forms.

Colour-change was embedded through thermochromic-dyed threads and machine-embroidering them to the fabric (Technique 2) in bacteria-driven patterns that react to user input. A digital embroidery machine was used to embed different morphochromic shapes on plain white cotton fabric, see Figure 16. The *digitizer* software of the digital embroidery machine allowed illustrating the design then automating the embroidery onto any fabric. Both thermochromic fabric and normal fabric (painted with thermochromic colours) were also used (Technique 1) to achieve colour-changing digitally-designed microbial patterns on the fabric itself rather than on the embroidered patterns. To compensate for any skipped stitches by the machine due to any errors in its program, hand-stitching filled these minor gaps to obtain a neat finish. Sensing was achieved using conductive fabric sewn and layered underneath the top fabric layer, utilizing capacitive-sensing in close proximity in

Figure 16. Machine-sewn and embroidered colour-changing bacteria-driven patterns with thermochromic-dyed threads.

seamless interaction, with no visible electronic components. Crumble microcontrollers [39] were used to control each *petri dish* individually due to their thin and small size and motor outputs which we programmed to control the thermal-responsive actuation of shape-changing and colour-changing materials in response to capacitive-sensing. High-current MOSFETs were used to allow enough power to be drawn from the back-mounted batteries to the SMA and heating wire. With most of the circuit being threads on top of the fabric wall-art, the rest (the microcontroller, transistors and battery) was less than 9 mm thick, and was *stitched* to the back of each hoop and hung on the wall with no external cables or power source needed. This enabled visitors to perceive it as a crafted wall-art, but also appreciate its interactivity once approached.

Exhibition & Audience Interaction

Over 6 weeks, BacterioChromic was installed as part of the LWAA 2018 Exhibition at the Lakeside Arts gallery in Nottingham, UK. Around 1285 members of the public were reported to have visited the exhibition during this period. The lead author was present for some of these days and took field notes, made video recordings, observed visitors' interactions, and spoke to visitors about their experiences. Through their questions, comments and reflections, visitors gave us insights into designing similar artefacts. This engagement gave us a better understanding of the potentials and limitations of the crafting techniques we had deployed. Further, we audio recorded informal interviews with 6 visitors who were happy to discuss our research further. The exhibition was visited by a diverse audience (age, gender, background, family groups, individuals) which provided a wider perspective on the engagement with our artefact than inviting participants to a lab setting. Inside the gallery, BacterioChromic was placed beside other actuating interior artefacts, but those which rely on mechanical actuation i.e. using rotating servo- motors. This gave visitors useful context on differing forms of actuated interior spaces.

Many visitors expressed curiosity about what was causing the shape-change, how the fabric was shifting its colour and where the batteries were (if any). Also, video recordings showed unexpected proxemic user behaviour, ranging from gently touching, pointing, poking, stroking, pulling strands, warming up with hand palms and even blowing at it. Blowing, in particular, is an unusual interaction with a wall-art piece, yet at least 5 visitors were observed using it as a playful and unusual interactive experience, happily enjoying the colour-change their breath caused and the gradual fading back of that colour-change in the embroidery afterwards, see Figure 17. We also noticed that interestingly, small-sized circular shapes in the pattern received a lot of pointing/clicking as if they were mentally associated with *buttons* that afford pressing. Pulling the shape-changing free fabric strands was particularly unique in the fact that every interaction manipulated its martensite state, therefore, changing the resultant deformation. These interactions caused the output actuations to vary in form and intensity, depending on the exerted input. While some visitors were amazed by unexpected organic deformations in the fabric itself, others were disinterested and impatient to wait for a few seconds to perceive a visible output.

Post-Exhibition Reflection

Based on our observations, field notes, video recording of public engagement and audio-recorded informal interviews, we were able to gather data and insights into the potential value and impact of using these techniques to produce morphological actuation in interactive artefacts.

Aesthetic vs. Hectic

Participants acknowledged and thoroughly discussed the design concept presented, but mostly valued the fact that no 'demanding' technology was used to convey it. Encountering BacterioChromic and its gentle patterns of revealing and hiding colours and moving fabric, participants felt that it was communicating a message about AMR, and generating an experience that was pointedly different from normal health communication. People appreciated the interactivity of an aesthetic object, that does not appear to have any 'offensive' technology, as a means of communicating a serious medical problem of public concern. For example, one visitor stated that *" as an aesthetic object, you can live with it without having to live with lots of offensive looking warning signs."* (V1) which points to how we should potentially design technology that avoids the appearance of digital devices, if we need and/or want people to enjoy 'living' with them. Another visitor highlighted how this seamless interaction of a non-device-looking object gives it its value: *"you could get carried away putting more and more technology into it, it doesn't have sensors and wires, it's got simple interaction"* (V3).

Organic vs. Mechanic

The *organic* and *slow* morphological transitions of patterns and movements were also described by many visitors as being more *natural* versus the *mechanical* actuating objects placed beside BacterioChromic. Although the silent and slow actuation of BacterioChromic made it look as if it was *"alive"*, it also caused it to be, at times, unnoticeable and gallery visitors passed it by whilst it actuated and failed to grab their attention. Several people were observed advising their friends or family members to *"wait and see"* as it slowly morphed, after a user's interaction. Whilst some walked away perceiving this actuation as too slow, others described it more poetically, articulating its morphological actuation as *"the breeze of the air"*, suggesting that it might *"remind us of sea waves"* (V5),

Figure 17. Interactions with the BacterioChromic wall-art through different tactile manipulations e.g. touch, stretch, and blow.

or that it *"looks like a sea creature"* and reminds one of *"sitting in the woods, where everything is moving around you"* (V6). Most likely, these *organic* interpretations would not be drawn from motor driven actuators or LED e-textiles, not only because of their sound and flashing light, but also due to their rigidity and lack of naturalness.

Crafted vs. Mass Produced

The *crafted nature* and *making* of the BacterioChromic was a conversation topic among some visitors. Most were surprised by how the fabric itself changed its shape or colour. Yet the behaviour of different elements of the piece presented new possibilities to them, away from mainstream product design. A designer who visited the gallery reflected on how she realized that the actuation was stitched into the fabric itself, and that this made it -unlike any other interactive object- *"move naturally, depending on where and how you touch it."* (V5). This reflects the quality of crafting methods as techniques for embedding actuation in soft artefacts as opposed to the previous work on shape-changing interfaces. Other visitors suggested other soft artefacts that could be weaved with actuation like BacterioChromic, including garments, cushions and gorilla knitting in public spaces. Some compared it verbally to IKEA products to point out the apparent differences between its crafted individualised and bespoke quality versus *"mass production and mass design"* (V6). All these examples emphasize the value of craftness when designing interactive actuating artefacts.

DISCUSSION AND CONCLUSION

This paper is an exploration of machine-sewing actuation seamlessly and the impacts of doing this. We have introduced a range of novel techniques of machine sewing and physically programming actuating threads/wires into fabrics. Our techniques enabled both the colour change of seams and soft shape-changes such as bend/unbend, swirl, twist, roll/unroll, curl, crumple and crease. From observations of experiments sewing SMA to fabrics, 10 parameters were realized as the impacting factors that control the deformation intensity: fabric type, thread type, stitch type, sewing pattern, wire type, wire austenite, wire martensite, fabric orientation, wire length and its distance to the fabric edge. In developing 10 techniques for machine sewing actuation, we have productively built upon the work of Hamdan [17] and other previous work on e-textiles that generally focused on LEDs and motor-based actuation by sewing conductive threads. Thus, our techniques for sewing shape-changing and colour-changing threads represent an evolutionary step towards the ultimate goal of providing a high-fidelity experience to users, designers and researchers. This paper also extends previous work on SMA shape-change by examining deformational parameters affecting the fabric's morphological effect. Finally, we designed and exhibited a case study evaluated by members of the public, which shows the potentials of creating aesthetic artefacts with colour-changing and shape-changing capabilities, crafted in seamless ways, moving beyond intrusive technology and mass produced devices.

These findings evoke design opportunities that pave the way for a vast amount of future work on actuating *everyday* soft objects, contrasting previous notions that argued for a need to create novel computational composites and peculiar materialities. Applications include shape-changing, colour-changing and haptic soft interfaces ranging from wearables and garments to interactive soft furnishing. Machine-sewing actuating threads will change the topology of how such interfaces are designed, crafted and manufactured, on a scalable level. Designers and researchers can now use such techniques to create predictable, replicable and scalable rapid prototypes and designs. In addition, this should also inspire crafters and tech-makers to develop "sewing books" of different *seamless seams* that can change their colours or shapes using various sewing patterns in an array of real-world artefacts. Once non-technical designers learn and understand how smart threads can be sewn into their designs (not just wearables, but also soft furnishings such as a chair arm or a pillow case), this might bring us to a brave new world of interactive possibilities.

REFERENCES

[1] James M Bern, Kai-Hung Chang, and Stelian Coros. 2017. Interactive Design of Animated Plushies. *ACM Transactions on Graphics (TOG)* 36, 4 (2017), 80–91. DOI:http://dx.doi.org/10.1145/3072959.3073700

[2] Joanna Berzowska. 2005. Memory Rich Clothing: Second Skins That Communicate Physical Memory. In *Proceedings of the 5th conference on Creativity and Cognition*. 32–40. DOI: http://dx.doi.org/10.1145/1056224.1056231

[3] Joanna Berzowska and Marcelo Coelho. 2005. Kukkia and Vilkas: Kinetic Electronic Garments. In *IEEE International Symposium on Wearable Computers (ISWC2005)*, Vol. 3. Osaka, Japan. DOI: http://dx.doi.org/10.1109/ISWC.2005.29

[4] Alice Bodanzky. 2012. Exploring the Expressiveness of Shape-Changing Surfaces. In *Proceedings of the Sixth International Conference on Tangible, Embedded, and Embodied Interaction Design*. Kingston, ON, Canada, 403–404. DOI: http://dx.doi.org/10.1145/2148131.2148235

[5] Leah Buechley and Kanjun Qiu. 2014. *Sew Electric*. HLT Press.

[6] Matthew Chalmers and Ian MacColl. 2003. Seamful and Seamless Design in Ubiquitous Computing. In *Proc. Ubicomp 2003 Workshop At The Crossroads: The Interacton of HCI and Systems Issues in Ubicomp*. Seattle, WA, USA, 8. DOI: http://dx.doi.org/10.1.1.104.9538

[7] Marcelo Coelho, Hiroshi Ishii, and Pattie Maes. 2008. Surflex: A Programmable Surface for the Design of Tangible Interfaces. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems (CHI EA '08)*. ACM, New York, NY, USA, 3429–3434. DOI: http://dx.doi.org/10.1145/1358628.1358869

[8] Marcelo Coelho and Pattie Maes. 2008. Sprout I/O: A Texturally Rich Interface. *Proceedings of the 2Nd International Conference on Tangible and Embedded Interaction* (2008), 221–222. DOI: http://dx.doi.org/10.1145/1347390.1347440

[9] Marcelo Coelho and Pattie Maes. 2009. Shutters: A Permeable Surface for Environmental Control and Communication. In *Proceedings of the Third International Conference on Tangible and Embedded Interaction (TEI'09)*. ACM, Cambridge, UK, 13–18. DOI:http://dx.doi.org/10.1145/1517664.1517671

[10] Felecia Davis, Asta Roseway, Erin Carroll, and Mary Czerwinski. 2013. Actuating Mood: Design of the Textile Mirror. In *TEI '13 (ACM) - Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. Barcelona, Spain, 99–106. DOI:http://dx.doi.org/10.1145/2460625.2460640

[11] Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-wei Gong, M Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, Kimiko Ryokai, and U C Berkeley. 2016. "I don't want to wear a screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. San Jose, CA, USA. DOI: http://dx.doi.org/10.1145/2858036.2858192

[12] Christine Dierk, Sarah Sterman, Molly Jane, Pearce Nicholas, and Eric Paulos. 2018. HairIO: Human Hair as Interactive Material. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '18)*. ACM, New York, NY, USA, 148–157. https://doi.org/10.1145/3173225.3173232

[13] Abigail C Durrant, John Vines, Jayne Wallace, and Joyce S R Yee. 2017. Research Through Design: Twenty-First Century Makers and Materialities. *Design Issues* 33, 3 (2017), 3–10. DOI: http://dx.doi.org/10.1162/DESI_a_00447

[14] V2_Lab For the unstable media. 2018. Why technology inspires us. (2018). http://v2.nl/lab/blog/why-wearable-technology-inspires-us

[15] William Gaver. 2012. What Should We Expect From Research Through Design?. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'12)*. ACM, Austin, Texas, USA, 937–946. DOI:http://dx.doi.org/10.1145/2207676.2208538

[16] Daniel Groeger and Elena Chong Loo. 2016. HotFlex: Post-print Customization of 3D Prints Using Embedded State Change. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'16)*. San Jose, CA, USA, 420–432. http://dx.doi.org/10.1145/2858036.2858191

[17] Nur Al-huda Hamdan, Simon Voelker, and Jan Borchers. 2018. Sketch & Stitch: Interactive Embroidery for E-Textiles. In *Proc. of CHI'18*. Montréal, QC, Canada, 1–13. DOI:http://dx.doi.org/10.1145/3173574.3173656

[18] Hiroshi Ishii, David Lakatos, Leonardo Bonanni, and Jean-Baptiste Jb Labrune. 2012. Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials. *Interactions* XIX, February (2012), 38–51. DOI: http://dx.doi.org/10.1145/2065327.2065337

[19] Hsin-liu Cindy Kao, Deborah Ajilo, Oksana Anilionyte, Artem Dementyev, Inrak Choi, Sean Follmer, and Chris Schmandt. 2017. Exploring Interactions and Perceptions of Kinetic Wearables. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS'17)*. ACM, Edinburgh, UK, 391—-396. DOI: http://dx.doi.org/10.1145/3064663.3064686

[20] Hsin-Liu Cindy Kao, Abdelkareem Bedri, and Kent Lyons. 2018. SkinWire: Fabricating a Self-Contained On-Skin PCB for the Hand. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 3 (sep 2018), 116:1—-116:23. DOI: http://dx.doi.org/10.1145/3264926

[21] Sarah Kettley. 2016. *Designing with smart textiles*. Bloomsbury Publishing.

[22] Tomomi Kono and Keita Watanabe. 2017. Filum: A Sewing Technique to Alter Textile Shapes. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology*. Quebec City, QC, Canada, 39–41. DOI: http://dx.doi.org/10.1145/3131785.3131797

[23] Kristi Kuusk. 2015. Crafting Butterfly Lace: Conductive Multi-Color Sensor-Actuator Structure. *UBICOMP/ISWC '15 ADJUNCT* (2015), 595–600. DOI: http://dx.doi.org/10.1145/2800835.2801669

[24] Jessica Lo and Audrey Girouard. 2014. Fabricating Bendy: Design and Development of Deformable Prototypes. *IEEE Pervasive Computing* 13, 3 (2014), 40–46.

[25] Sarah Mennicken, A. J. Bernheim Brush, Asta Roseway, and James Scott. 2014. Exploring interactive furniture with EmotoCouch. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication*. DOI: http://dx.doi.org/10.1145/2638728.2638846

[26] Stephen A Morin, Robert F Shepherd, Sen Wai Kwok, Adam A Stokes, Alex Nemiroski, and George M Whitesides. 2012. Camouflage and Display for Soft Machines. *Science* 337, 6096 (2012), 828–832.

[27] Sara Nabil, Aluna Everitt, Miriam Sturdee, Jason Alexander, Simon Bowen, Peter Wright, and David Kirk. 2018. ActuEating: Designing, Studying and Exploring Actuating Decorative Artefacts. In *Proceedings of DIS'18*. Hong Kong, 327–339. DOI:http://dx.doi.org/https://doi.org/10.1145/3196709.3196761

[28] Sara Nabil, David S. Kirk, Thomas Plötz, Julie Trueman, David Chatting, Dmitry Dereshev, and Patrick Olivier. 2017. Interioractive: Smart Materials in the Hands of Designers and Architects for Designing Interactive Interiors. In *Proceedings of the 2017 Conference on Designing Interactive Systems - DIS'17*. Edinburgh, UK, 379–390. DOI: http://dx.doi.org/10.1145/3064663.3064745

[29] Maggie Orth. 2009. 100 Electronic Art Years. (2009). http://www.maggieorth.com

[30] Jifei Ou, Lining Yao, Daniel Tauber, Jürgen Steimle, Ryuma Niiyama, and Hiroshi Ishii. 2014. jamSheets: Thin Interfaces with Tunable Stiffness Enabled by Layer Jamming. In *Proceedings of TEI'14*. Munich, Germany, 65–72. DOI:http://dx.doi.org/10.1145/2540930.2540971

[31] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, and Michael Haller. 2018. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. ACM, New York, NY, USA, 745–756. DOI: http://dx.doi.org/10.1145/3242587.3242664

[32] Patrick Parzer, Kathrin Probst, Teo Babic, Christian Rendl, Anita Vogl, Alex Olwal, and Michael Haller. 2016. FlexTiles: A Flexible, Stretchable, Formable, Pressure Sensitive, Tactile Input Sensor. In *Prof. of CHI EA '16*. San Jose, CA, USA. DOI: http://dx.doi.org/10.1145/2851581.2890253

[33] Roshan Lalintha Peiris, Jeffrey Tzu Kwan Valino Koh, Mili John Tharakan, Owen Noel Newton Fernando, and Adrian David Cheok. 2013. Ambi Kraf Byobu: Merging Technology with Traditional Craft. *Interacting with Computers* 25, 2 (2013), 173–182. DOI: http://dx.doi.org/10.1093/iwc/iws013

[34] Hannah Perner-wilson, Leah Buechley, High-low Tech, Mass Ave, and Cambridge Ma. 2011. Handcrafting Textile Interfaces from A Kit-of-No-Parts. In *TEI '11 Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*. 61–67. DOI:http://dx.doi.org/10.1145/1935701.1935715

[35] Sarah Pink, Elisenda Ardèvol, and Débora Lanzeni. 2016. *Digital Materialities: Design and Anthropology*. Bloomsbury Academic.

[36] Irene Posch and Ebru Kurbak. 2016. CRAFTED LOGIC: Towards Hand-Crafting a Computer. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems.* ACM, San Jose, CA, USA, 3881–3884. DOI: http://dx.doi.org/10.1145/2851581.2891101

[37] Ernest Post, M Orth, P R Russo, and N Gershenfeld. 2000. E-broidery: Design and fabrication of textile-based computing. *IBM Systems Journal* 39 (2000), 840–860. DOI: http://dx.doi.org/10.1147/sj.393.0840

[38] Jie Qi and Leah Buechley. 2012. Animating Paper using Shape Memory Alloys. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, Austin, Texas, USA, 749–752. DOI: http://dx.doi.org/10.1145/2207676.2207783

[39] Redfern Electronics. 2018. The Crumble Controller. (2018). https://redfernelectronics.co.uk/crumble/

[40] M Redström, J Redström, and R Mazé. 2005. *IT+Textiles*. http://redstrom.se/johan/papers/IT+Textiles

[41] Manlin Song, Chenyu Jia, and Katia Vega. 2018. Eunoia: Dynamically Control Thermochromic Displays for Animating Patterns on Fabrics. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers (UbiComp '18)*. ACM, New York, NY, USA, 255–258. DOI: http://dx.doi.org/10.1145/3267305.3267557

[42] P J Stappers and E Giaccardi. 2017. *Research Through Design*. Vol. 2nd Ed. The Interaction Design Foundation. 1–94 pages.

[43] Paul Strohmeier, K.V. Swensen, Cameron Lapp, Audrey Girouard, and Roel Vertegaal. 2012. A Flock of Birds: Bringing Paper to Life. In *Proceedings of the 6th International Conference on Tangible, Embedded and Embodied Interaction, TEI 2012*. Kingston, ON, Canada, 333–334. DOI: http://dx.doi.org/10.1145/2148131.2148208

[44] Yuta Sugiura, Gota Kakehi, Anusha Withana, Calista Lee, Daisuke Sakamoto, Maki Sugimoto, Masahiko Inami, and Takeo Igarashi. 2011. Detecting shape deformation of soft objects using directional photoreflectivity measurement. In *Proceedings of UIST '11*. Santa Barbara, CA, USA, 509. DOI: http://dx.doi.org/10.1145/2047196.2047263

[45] L Sun, W M Huang, Z Ding, Y Zhao, C C Wang, H Purnawali, and C Tang. 2012. Stimulus-responsive shape memory materials: A review. *Materials and Design* 33 (2012), 577–640. DOI: http://dx.doi.org/10.1016/j.matdes.2011.04.065

[46] Sarah Taylor and Sara Robertson. 2014. Digital Lace: A Collision of Responsive Technologies. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers (ISWC'14 Adjunct)*. New York: ACM, 93–97. DOI:http://dx.doi.org/10.1145/2641248.2641280

[47] Kentaro Ueda, Tsutomu Terada, and Masahiko Tsukamoto. 2016. Input Interface Using Wrinkles on Clothes. In *ISWC'16*. Heidelberg, Germany, 56–57. DOI: http://dx.doi.org/10.1145/2971763.2971782

[48] Anna Vallgårda. 2009. *Computational Composites: Understanding the Materiality of Computational Technology (Unpublished doctoral dissertation)*. Ph.D. Dissertation. The IT University of Copenhagen.

[49] Roel Vertegaal and Ivan Poupyrev. 2008. Organic User Interfaces. *Commun. ACM* 51, 6 (2008), 26. DOI: http://dx.doi.org/10.1145/1349026.1349033

[50] Yvonne Y F Chan Vili. 2007. Investigating Smart Textiles Based on Shape Memory Materials. *Textile Research Journal* 77, 0 (2007), 290–300. DOI: http://dx.doi.org/10.1177/0040517507078794

[51] Anita Vogl, Patrick Parzer, Teo Babic, Joanne Leong, Alex Olwal, and Michael Haller. 2017. StretchEBand: Enabling Fabric-Based Interactions through Rapid Fabrication of Textile Stretch Sensors. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Denver, CO, USA, 2617—-2627. DOI:http://dx.doi.org/10.1145/3025453.3025938

[52] Akira Wakita and Midori Shibutani. 2006. Mosaic Textile: wearable ambient display with non-emissive color-changing modules. In *Proceedings of the 2006 ACM SIGCHI international conference on Advances in computer entertainment technology (ACE '06)*. ACM, New York, NY, USA. https://doi.org/10.1145/1178823.1178880

[53] Rachael C C Winchester and George K Stylios. 2003. Designing knitted apparel by engineering the attributes of shape memory alloy. *International Journal of Clothing Science and Technology* 15, 5 (2003), 359–366. DOI:http://dx.doi.org/10.1108/09556220310492624

[54] XSLabs. 2018. Nitinol. (2018). http://www.xslabs.net/skorpions/tech.html

[55] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology - UIST '13*. St. Andrews, UK, 13–22. DOI: http://dx.doi.org/10.1145/2501988.2502037

[56] Bin Yu, Nienke Bongers, Alissa van Asseldonk, Jun Hu, Mathias Funk, and Loe Feijs. 2016. LivingSurface: Biofeedback through Shape-changing Display. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. Eindhoven, Netherlands, 168–175. DOI: http://dx.doi.org/10.1145/2839462.2839469

[57] Michelle Yuen, Arun Cherian, Jennifer C Case, Justin Seipel, and Rebecca K Kramer. 2014. Conformable Actuation and Sensing with Robotic Fabric. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Chicago, IL, USA, 581–586.

[58] Clint Zeagler, Scott Gilliland, Halley Profita, and Thad Starner. 2012. Textile Interfaces: Embroidered Jog-Wheel, Beaded Tilt Sensor, Twisted Pair Ribbon, and Sound Sequins. In *Proceedings of the 2012 16th Annual International Symposium on Wearable Computers (ISWC) (ISWC '12)*. IEEE Computer Society, Washington, DC, USA, 60–63. DOI: http://dx.doi.org/10.1109/ISWC.2012.29

[59] Kening Zhu and Shengdong Zhao. 2013. AutoGami: A Low-cost Rapid Prototyping Toolkit for Automated Movable Paper Craft. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 661–670. DOI: http://dx.doi.org/10.1145/2470654.2470748

Appendix F. Paper 2: ActuEating

ActuEating: Designing, Studying and Exploring Actuating Decorative Artefacts

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ABSTRACT
Actuating, dynamic materials offer substantial potential to enhance interior designs but there are currently few examples of how they might be utilised or impact user experiences. As part of a design-led exploration, we have prototyped (Wizard-of-Oz) an actuating, dining table runner (ActuEater1), and then developed a fully-interactive fabric version that both changes shape and colour (ActuEater2). Four in-situ deployments of 'ActuEaters' in different dinner settings and subsequent 'design crits' showed insights into how people perceive, interpret and interact with such slow-technology in interesting (and often unexpected) ways. The results of our 'ActuEating' studies provide evidence for how an actuating artefact can be simultaneously a resource for social engagement and an interactive decorative. In response, we explore design opportunities for situating novel interactive materials in everyday settings, taking the leap into a new generation of interactive spaces, and critically considering new aesthetic possibilities.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous.

Author Keywords
Shape-changing Interfaces; Organic User Interfaces; Interioraction; Multi-aesthetics; Colour-changing.

INTRODUCTION
Shape-changing interfaces (SCI) are physically, electronically, magnetically, pneumatically or mechanically capable of changing their shape as means of either input or output interaction with the user depending on shape-shifting materials or kinetic components that respond to different stimuli [5]. When situated within the built environment, SCI technology has the potential for many radically new diverse applications, e.g., dynamic artwork, shape-changing decoratives, pattern-changing fabrics, or even entire interactive interior spaces [35, 28]. Such notions of shape-changing dynamics have recently risen to prominence in both design and architecture literature. However, the 'artistic' and experiential aspects of SCI technology are rarely discussed and are thus identified as one of its main limitations [33]. Whilst many SCI explorations have focused heavily on the *development* of shape-changing materials and the *capabilities* of their interfaces, far fewer studies have considered the aesthetic value of the designs, overlooking how this might significantly influence user perception, engagement and ultimately, interaction, with such interfaces.

Whilst interior decorative objects have significant potential to become dynamic, reactive and responsive, through the incorporation of Shape-Changing, Tangible and/or Organic User Interface [38] technologies [15, 23], there have, to-date, been relatively few examples of successful actuated decorative artefacts. One reason for this may be that such emerging technologies (although innovative) are struggling to find a place in our everyday environments (remaining mostly as curiosities within research labs). To help develop the conceptual design spaces from within which new and better technologies might emerge, a deeper grounded understanding needs to be developed of how people might perceive, interact with and otherwise experience such interfaces [33]. There are broad opportunities to

Figure 1. ActuEating: participants curiously exploring ActuEater2

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explore digital interfaces embedded within everyday artefacts, with the aim to make smart spaces more inhabitable, and interactive artefacts more adoptable. Such interactive artefacts should not be designed to appear ‘technology-like’ but could be designed and built to act like artefacts that people already admire, cherish and live with. This would extend the user experience in the built environment by adding a dynamic nature to interior design elements that match inhabitants’ cultural expectations rather than appearing alien or ill-fitting. Taking shape-changing interfaces into an aesthetic design space opens up an opportunity for them to be incorporated into decorative artefacts, blending into our environments and supporting seamless transitions between physical and digital interactions.

The motivation behind our work is to 1) design exemplar interactive decorative artefacts and explore their potential, affordances, and limitations, 2) study how people interact with, interpret and experience an actuating piece of decorative fabric such as a table runner, and how it might change their experience of space and activity (in this case dining), and 3) discuss, from a user-centred perspective, possibilities and areas of future development for interactive spaces/materials.

In this paper, we present ‘ActuEater1’ and ‘ActuEater2’ as decorative centre-pieces on the dining table (see Figure 1). Utilising ‘ambiguity’ as a virtue [13] and ‘slowness’ as a value [31], our designs were created and then situated in-the-wild on four dining tables and subjected to post-study ‘design crits’ to drive the research forward. Our in-situ studies show how people perceive and interact idiosyncratically with a conventional decorative object that is ‘actuating’, yet concur when interpreting its interactions and discussing its impacts their dining experience. Furthermore, we present our reflections and discuss our main findings with regards to the overall experience of ‘ActuEating’ (social engagement in an interactive dining space) and the insights of people’s sense-making of both ActuEaters. Furthermore, we present reflections on designing shape-changing interactive decorative artefacts.

The main contributions of this work are: 1) exploring the aesthetic design space of shape-changing interfaces in the form of decorative artefacts blending ubiquitously into our environments, rather than standing out as digital devices; 2) studying shape-change in a social event and how it affects people’s experience in the space, and with each other; 3) exploring a broader interaction repertoire that is useful to learn how an SCI would be perceived and interacted with; and 4) studying how people learn and develop (individually and together) potential interactive scenarios with actuating objects.

RELATED WORK

Below we introduce some key considerations to help ground this work. Firstly, we discuss current efforts to develop shape-changing interior objects, then we discuss some aesthetic considerations of shape-changing materials before finally addressing the role of technology in supporting ‘dining’ experiences.

Shape-changing Interior Artefacts

Although there is some previous research around shape-changing actuation in furniture and interior objects, the work in this area is still somewhat limited. Examples of shape-changing interior objects in HCI research include the Earthquake Shelf [34], the colour-changing DigitalLace [36] and the Byobu room-divider [32]. Examples of shape-changing furniture include the colour-changing EmotoCouch [24], the shape-changing table/board [16] and coMotion [17], a horizontal shape-changing bench that changes its height and angle using 8 embedded linear actuator ‘motors’. The study of coMotion gathered insights from 120 ‘unaware’ members of the public who interacted with it (each for around 2mins). Although coMotion was remotely controlled by researchers i.e. Wizard of Oz (WoO), it enabled researchers to explore the users’ interpretations, sense-making and experiences of its affordances and transitions. The pattern shape-changing (not form shape-changing), History Tablecloth [12] is a prominent example for a long-term study of situated interactive furniture. The 4-month study in a single 2-person household, provided a deeper insight into what it means to design artefacts in a real-world environment. Today still, as Gaver stated a decade ago, less purposeful, more exploratory and playful engagements that encourage people to explore, speculate and wonder, are poorly served by current technologies [12] and therefore still needs further research. Other examples of advanced shape-changing tabletops are Transform [22, 39], inForm [11] and PolySurface [9]. However, real-world applications that fit into our interior spaces are still quite limited.

Shape-changing Aesthetics

Visionary work on Radical Atoms [21] suggested that thoughtfully designed interfaces can and should be embodied in different materials and forms in our physical world. Inspired by this, some actuating interfaces were designed to explore people’s experience with them and the sensational and emotional effects of such multi-aesthetic and deformable interfaces. For example, Textile Mirror [8], an actuated wall curtain, shows how interfaces can actively mirror and transform our feelings through traditional materials in our environments i.e. texture-changing fabrics can modify one’s emotional state from stressed or angry to happy and calm. Similarly, Davis [7] explored a variety of different emotional expressions that can be communicated to users through texture-changing artefacts. Ueda [37] also explored actuated textiles through wrinkling shape-changing fabric as means of user interaction, and Bodanzky [2] has explored some of the potential expressive qualities of shape-changing surfaces and their actuating designs. Concepts such as Neuroaesthetics [7] and ‘Aesthetic Interaction’ [23] proposes how the aesthetics of visual and tactile interactivity can be used to activate not only visceral put perceptual senses, meanings and values and provoke self-reflective awareness through ubiquitous interaction with textural-changing interfaces. Proposed motivations for such interfaces include: being a conversation starter, material for storytelling, overcoming temporal blindness [6], entertainment and playfulness [26] and visualizing the unseen [28].

Interactive Eating Experiences

Previous HCI research has explored debatable ways in which digital technology should or could be used to change and/or enhance the eating experience [4, 20]. For example, in working with families, Ferdous [10] has attempted to transform the disruptive experience of mobile phone use during family meals into a positive social experience, by utilizing phones as a form of collective engagement at the table. However, Hiniker [19] has studied the challenges of using mobile phones during family mealtimes and their implications on family members' social experience. Other work [14, 29] has considered the ways in which digital technology can help connect and engage lone diners geographically dispersed. Barden [1] explored the challenge of connecting distributed diners in a Telematic-Dinner-Party using cameras and projectors exploring augmented reality that blends into the physical world. Alternatively, Mitchell [25] designed a kinetic dining table that can synchronize the eating pace of dining companions to augment their social experience with mutual alignment. This work shows that such domestic and ritual activities can be prime settings for technological explorations, and point to the entanglement of technology with the aesthetic experiences of dining.

DESIGNING ACTUEATER1

Building on previous work, most notably coMotion [17], we wanted to explore SCIs as decorative artefacts, but embedded within complex social settings. Extending typical duration of user interaction to over an hour (instead of an average of 2mins) allows people the time to observe, practice, learn and develop a variety of interaction scenarios. A richer interaction repertoire can be designed using a wider range of different shape-changing physical actuations (than controlling one parameter/dimension) by controlling the location, scale, height and speed of a fine-grained grid of embedded actuators. For our first case study, we chose ShapeClips [18] to create a rapid working prototype. ShapeClips are prototyping toolkits for creating interactive shape-changing displays using vertical actuators (stepper-motors) animated with photo-sensors using any monitor.

Making

Inspired by PolySurface [9], we re-purposed the ShapeClips to build a dynamic and customizable shape-changing prototype that fits on a dining table as a traditional table runner. As ShapeClips vary between 8 and 18 cm in height, we embedded them within the table itself to ensure an initially flat surface on our table. After the software was re-programmed and the hardware electronic components were re-structured in the desired arrangements, a full-length table runner was made as ActuEater1 (see Figure 2). Similar to PolySurface [9], we designed ActuEater1 from stretchable Spandex fabric and a uniform custom-designed pattern laser-cut on 0.8 mm thin polypropylene sheets to give it a controlled semi-flexible moving capability. After fixing it together, we lined the edges with a satin golden-beige ribbon as a finishing touch to give it an original look and an aesthetic value similar to contemporary table runners. The final runner was 93×35 cm consisting of 10 ShapeClips in a 2×5 grid to control its inner body.

Actuations

Driven using a remote WoO interface, ActuEater1 could change its shape on top of the dining table in an array of different actuations: 1) Default state (sleep mode); 2) Located actuation (using a single bit in front of a certain diner) that either moves upwards and stays for a while or vibrates up and down slowly or rapidly; 3) Two located actuations (two bits away from each other interacting with users on both sides of the table); 4) Sequential deformation from one end to the other; 5) An animated wave motion moving across the table runner; 6) All-up and all-down. Height and speed are both controlled variables that allow variation in the resulting actuation. During testing we realized that when ActuEater returns to default state, it does not become flat, but leaves 'history wrinkles' i.e. traces of previous actuations, in the form of fabric bends. Although these traces were not intentional, it was an unexpected yet interesting feature of ActuEater1, showing a 'history' of actuation which we saw as an interaction richness rather than irregular performance.

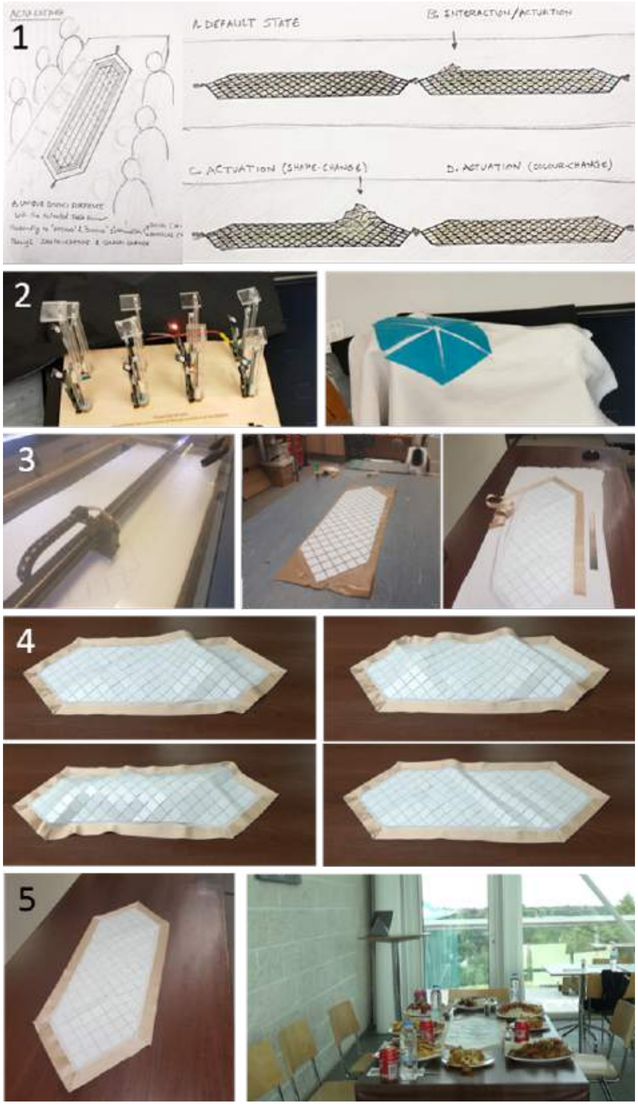

Figure 2. Designing and Making of Actuating1. 1) Ideation and Sketching. 2) Prototyping the Software and Hardware.3) Designing the Pattern. 4) Creating the Actuations. 5) ActuEater is ready and 'dinner is served'.

Interaction Repertoire

The eventual actuations performed by ActuEater1 were prototyped, live, in a WoO study (detailed below). The experimenter (first author) responded to emerging interactions and developed the following pattern of responses to users: when one participant was engaged with ActuEater1 or touched it, it vibrated (low actuation) the part in front of her/him by moving up and down in a small scale with limited height. When two participants were both engaged with it (talking about it with each other), it would vibrate in front of both of them. If two people touched it with their hands or used an object, it rose all up. Then if they tapped it, it went all down. If two or more people kept touching it, it animated in an organic wave motion going up and down from one end to the other. We were able to improvise actuations at some points to initiate interactions with one (or more) of the participants to explore the effects of this on their reactions to ActuEater1 and interactions with each other. For instance, a sequential low actuation can train from one end to the other if ActuEater1 'got bored of people ignoring it'. To allow for discoverability, we controlled the height of actuations to increase over time and usage, to see whether people will relate their interaction with the increase of deformation.

STUDYING ACTUEATER1

An initial evaluation study (A) took place in a terraced-rooftop restaurant with a group of 6 friends (P1-P6), with mixed genders (2F / 4M), age-groups and backgrounds (Media, Design, Economics, Computing, Chemistry and Psychology) who signed-up to participate in the study. Participants were not briefed as to what to expect beyond their voluntary participation in a study over a dinner meal. The meal was audio-video recorded from two different angles to capture as many of the users' expressions, interactions and conversations as possible. The dinner lasted about an hour, then we joined participants for a post-study 'design crit', a group discussion, lasting 30 mins where participants had the opportunity to express their reflections on their experience and provide us with critical feedback on our design and further design opportunities.

EVOLUTION OF THE ACTUEATER

Study A suggested a number of user-desired potential developments to ActuEater1: 1) Control: not be remotely-controlled and be legible (they assumed it was randomly actuating because human control (WoO) was not always immediate and consistent to all 6 participants); 2) Interaction: be responsive to their physical interactions (e.g. touch and physical objects); 3) Hardware: not to have such a bulky structure, loud noise or create a hole in the table; 4) Aesthetics: blend with the surrounding space and be more colourful; 5) Capabilities: colour-change was suggested to complement and enrich the shape-change; 6) Experience: be entertaining/ dancing, autonomous (have agency of its own), and interact with the surrounding space (music, objects); and 7) Meaning/ value: reveal/support further values (believing ActuEater1 had a hidden agenda of some good intention and meaningful purpose).

Therefore, we designed ActuEater2 to be a silent stand-alone fabric runner (with no motors required beneath the table) that is touch-sensitive and still has some agency designed to be more colourful with colour-changing capabilities (as well as shape-changing). Then further studies should then inform our research about how these changes affected the experience to show what meanings and values would people draw from their experience with ActuEater2. These further studies should give more insights on other findings i.e. social engagement, interaction repertoire, physical manipulations, and seamful/seamless sensing beyond interaction boundaries.

DESIGNING ACTUEATER2

In response to the suggested evolutions of ActuEater1, we developed ActuEater2 to have more organic actuations (rather than mechanical ones), direct physical interactions (rather than WoO), and richer capabilities (colour-change as well as shape-change). The redesign also shifted us away from demanding, bulky and noisy hardware (requiring a big hole in the table). Broadly speaking, ActuEater2 was intended to not be a radical departure from the design of ActuEater1, but build upon what we had learnt in terms of both design and user experience. ActuEater2 presented an organically-actuating soft decorative object which we could use to further study how multi-aesthetic interactions from a shape-changing decorative could impact people's experience of a given interior space/activity over time.

Making

ActuEater2 (see Figure 3) is a 60×40 cm cotton fabric envelope, with a stretchable spandex top holding the deformable pattern, both sandwiching a silicon rubber layer in between, holding a set of SMA (Shape Memory Alloy) wires. This layering technique was inspired by the HotFlex [15] technique for making interactive printed objects, which proved to achieve better results allowing ActuEater2 to be malleable enough to deform yet firm enough to relax again. Moreover, the layering acted as an insulating cover for the SMAs (a useful safety feature). The 9 SMAs used were each 1-inch pre-trained shape-changing 'nitinol' shape-memory springs from Kelloggs Research Labs that actuate at 'standard temperature' (45°C) or equivalent 5V and 0.7A drawn from a MOSFET transistor, pulling it back to its 1-inch spring shape from any malleable form. ActuEater2 also had capacitive sensing parts (green flowers) using 10×10 cm concealed knit conductive fabric to enable soft touch and proximity sensing through $1M\Omega$ resistors. We used an Arduino microcontroller to program ActuEater2 and control the behaviour of its interactions.

As nitinol SMA springs are not solderable, we used a crimping technique where we carefully attached to both ends of each spring a conductive (silver) crimp bead to form a connection with an insulated copper wire. Through this crimping, we were able to connect and control SMA springs through the Arduino, which was sleaved and concealed out of user sight. We found that stitching the ends of SMA carefully to the fabric gives it better grip force to 'pull' it upwards without moving freely elsewhere. As SMA 'one-way' springs work by shrinking with heat or current, it crumbles the fabric in between both ends it is stitched to creating deformations. The weight of the runner and force of gravity then brings it back slowly to the table. Working out a perfect material weight that could be light-enough to deform with SMA, but still be heavy-enough to return to flat, was key to achieving a 'two-way' actuation. Moreover, this meant that the most perceivable deformations were the ones stitched to the edges of the runner, not in the centre, where the weight is maximum, preventing visible deformation. Finally, to entirely conceal 'technology' from visibility, ActuEater2 was carefully finished using a sewing machine where we enclosed all its core components with nothing visible other than a power cable (that is replaceable with a Lipo battery).

Similar to ActuEater1, we designed ActuEater2 with a uniform custom-designed pattern laser-cut on 0.8 mm thin polypropylene sheets to give it a controlled semi-flexible moving capability. This time we optimized the pattern into triangular tessellation (instead of squares) to allow more organic deformations in different orientations. ActuEater2 was also designed to be more colourful. Thermochromic 'grey' fabric was used in some parts to add the capability of colour-change. By embedding a heating wire underneath, the thermochromic fabric was controlled to reveal a hidden pattern as an ambient display and means of richer interactivity.

Actuations

ActuEater2 changes shape more subtly, slowly and silently than ActuEater1, making it appear far more organic and less mechanical. Different parts of ActuEater2 behaved in different ways according to the affordance, stiffness and weight of the material at differing points i.e. edges deformed more freely than the centre. Touch-sensitive 'green' parts acted as ubiquitous sensing that triggered actuation of parts beside it. Agency was also enabled in the algorithm of ActuEater2 to display autonomous actuations if ignored for some time. Similar to ActuEater1, during the testing phase we realized that when ActuEater2 goes back to the default state, it also does not return entirely flat, again leaving unintentional traces showing a potentially interesting/useful 'history' of interaction.

STUDYING ACTUEATER2

We studied ActuEater2 in-situ, using methods and settings consistent with Study A (ActuEater1). We successfully ran 3 sessions with a total of 13 participants. We varied location for the meals to enhance the ecological validity of our exploration. The first (Study B) took place in a Lebanese restaurant (evening meal) with a group of 4 Middle-Eastern friends (1F, 3M) with backgrounds in Psychiatry, Health-care, Business and Biotechnology (P7-P10). The second (Study C) took place in a University cafe (lunch followed by tea and cake) with a South-Eastern Asian group of 5 female friends with backgrounds in Business, Computing, Architecture (2) and Dentistry (P11-P15). Finally, the third (Study D) was a dinner party at home (evening meal), where a group of 4 mixed international friends (2F, 2M) with backgrounds in Education, Social Work, Business and Civil Engineering (P16-P19) met at P18's home.

In all three studies, participants were not briefed about the ActuEater, or that is was an interactive artefact to give them the chance of having their meal as usual and discovering the ActuEater themselves. Although we purposely had participants from different cultures, backgrounds and age groups, we observed clear consistencies in most people's behaviour around ActuEater2 across groups. In both study B and C, the 'waiter' and 'waitress' were unexpected participants, where

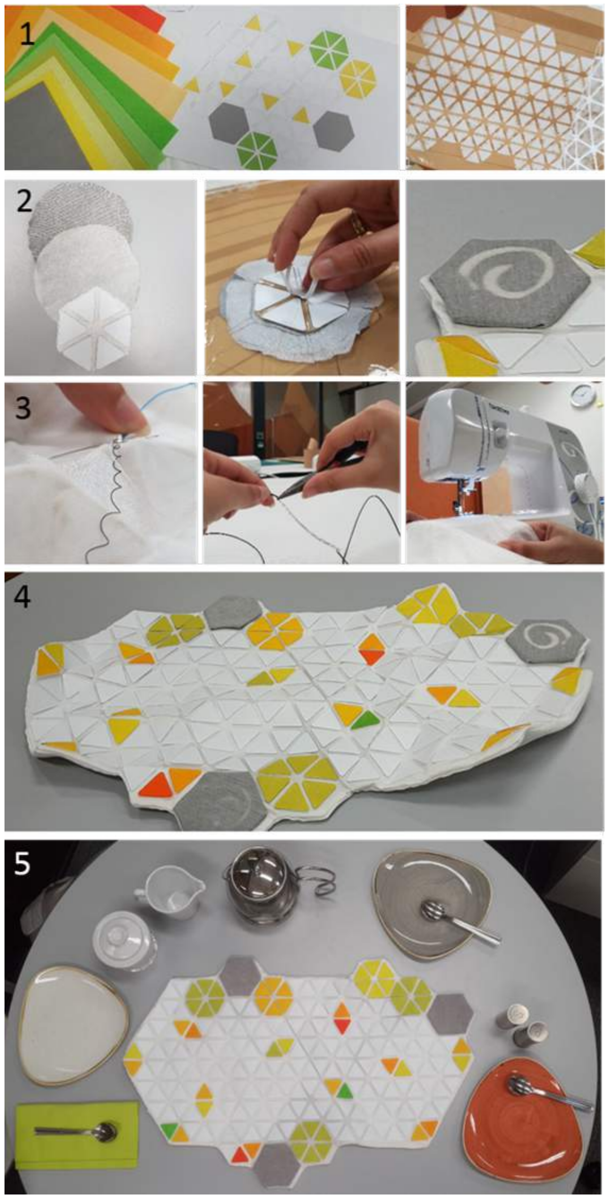

Figure 3. Designing and Making of Actuater2. 1) Designing the Pattern. 2) Making the Colour-changing parts. 3) Stitching, Crimping and Sewing. 4) Creating the Actuations. 5) ActuEater2 is ready.

the ActuEater responded to them whilst placing appetizers in the centre of the table (on top of ActuEater2). In study C, we hacked the sugar pot, plates, cinnamon and chocolate powder shakers, and the teapot, to be all capacitive, using stainless steel frames or aluminium foil bottom layer, and therefore interacting with ActuEater2. In study D, the home owner i.e. host dealt confidently with ActuEater2 in which she replaced objects and plates on top of it as she pleased, and lifted the ActuEater and re-positioned it on her dining table.

As in study A, meals were audio-video recorded from multiple angles to capture users' expressions, interactions and conversations. After each meal a design crit group discussion was held to critically evaluate the design of our ActuEaters in terms of: 1) Sense-making and interpretation (how did

ActuEater make them think? Does ActuEater look, feel and sound right?); 2) Interaction and emotional engagement they had with ActuEater, and with each other in relation to it; 3) Complex scenarios and interactions beyond expected legible interactivity; 4) Proposing possible enhancements (in terms of design, interaction, purpose, meaning/value and/or context) in light of: constructive feedback about the design itself; materiality (evaluating the material quality and finish), and pros and cons (what is bad and what is good about the design). Data from the meals and the post-meal design crits was transcribed and then subjected to Thematic Analysis [3].

UNDERSTANDING THE ACTUEATING EXPERIENCE

In this section, we discuss the results of our thematic analysis drawing on the data from all four of our in-situ studies (A-D incorporating both ActuEater 1 and 2). Our orientation to use a 'situated design crit' as an evaluatory mechanism means that the emphasis of our results is less on the 'dining experience' and more on a critical reflection on the design of the ActuEater. Accordingly, the themes we discuss unpack the ActuEating experience, exploring how users made sense of both ActuEaters, and how they imagine they could be better designed, used or employed.

Experience Sense-Making

Describing the Experience

People made sense of our actuating decoratives in various ways. While ActuEater1 was described as *"an attention seeker, not distracting in a bad way, it's more of an interesting distraction."* (P4), ActuEater2 was more *"subtle, it can take the attention, but not all the attention."* (P7) described: *"like a cherry on top, just a nice part of our conversation, but not focus demanding"* (P10). Variously, the ActuEaters were seen as conversation-starters, e.g. *"an ice-breaker* (P13) and *"an interesting talking piece"* (P5). But some focused more on its enigmatic qualities framing it as *"very creative and interesting"* (P8), *"revolutionary"* (P7), *"mysterious, quite alive"* (P19), *"unbelievable"* (P17) and *"an object of curiosity"* (P16). However, we understand how this was largely driven by its novelty effect. Nevertheless, some saw immediately entertaining qualities in the ActuEater suggesting it was playful like a *"treasure box"* (P12), a board game and generally *"fun and entertaining"* (P11). Whilst others saw it as something more meditative *"like a water fountain"* (P1) and *"calming like ocean waves"* (P8), and *"great to meditate or gaze at, like a fireplace"* (P7). When describing some of the deformations and interactions of ActuEater1, participants used more mechanical terms like *paused, rested, nudging, popping and poking, all go up, moving across and slow down*. Whilst, ActuEater2 was defined in perhaps more fluid terms as *changing, moving, crumbling, dancing* and *"it's almost like breathing!"* (P18).

Understanding the WHY

Understanding interactions with the ActuEater had clearly occupied a great portion of the conversation among participants over their meal. Some discussed how it might be proximity/motion sensing, and not any touch, but the way they touch it *"that's why when I touch it, it goes brighter than when you touch it, you have to calm down P12, see, if you're gentle to it, it responds"* (P13). Also, sound-sensing was frequently suggested and tested with its different versions: *voice*, *volume* or *conversation engagement*, *restaurant music*, *cutlery sound*, *noise in the environment*, or even *keywords*, all assuming it is *"physicalizing it (sound)"* (P2). Although it responded to their touch and physical interactions, some suggested further para-sensing beyond that, wondering if it picked up their *"heat, or energy"* (P19), *"mood"* (P12), *"stress"* (P13), *"brain waves or heartbeat"* (P16). To validate their theories, participants tested their ideas in different ways: group D gathered around it covering it up to warm it with their hands in a spiritual manner, group B and C 'clicked' it together on different parts simultaneously, while group A patted it together like a pet.

Perceiving the Meaning & Value

Besides its entertaining aspects, participants were keen to give ActuEater further values believing it had a hidden agenda of some good intention and meaningful purpose. Group A questioned *"Was it to do with how engaged you are in the conversation?"* (P2), *"or is it kinda 'stop eating' and 'talk to people'?"* (P1), *"It did try to nudge me because I was so focused while eating."* (P6), *"or maybe it's just trying to bring us all together"* (P2). Likewise, group B suggested how it could be a good conversation starter if people are not quite friends, group C also expressed it is a way to help people interact with each other, and group D argued that: *"it could be interactive with people who speak the most or speak the least, because I finished my food, that's why it is reacting more on my side"* (P19). Through conversations, participants were building assumptions that ActuEater was a resource for social engagement. Participants' responses implied how they thought ActuEater 'wanted' them to engage with each other and sought to develop a deeper social interaction amongst them.

Envisioning the Concept

The overall experience of ActuEating helped us better understand how decorative artefacts, or 'decoractives', can uplift the state-of-the-art to a new level. Envisioning decoractives in general can be drawn from participants' comments about the ActuEaters in the design crits as an abstract concept for interactive decorative artefacts in general, not specifically a table runner. For instance, participants' thinking about the broader relevance and use of decoractives was describing in study C as *"the fun part of the boring life"* (P11) elaborating on how such aesthetic interaction allows people to have fun with objects that they might not actually take notice of on a daily basis. In study B, P7 also ensured that the ActuEating experience changed his perspective about decorative objects, furniture and aesthetics in general. Moreover, in study D, P16 highlighted how *"the best value is the merge of technology where everyday objects can do more things and react to our presence and actions"*. In this sense, we need to start exploring other decorative objects and investigate ways they can be of further purposes, meanings and values to people beyond their static aesthetics.

Evolution of Interaction

Users' Roles

Participants' desire to interact with the ActuEater ranged from reluctant to frequent. During the 4 studies, participants created similar scenarios, engaging with ActuEaters through three different roles: 1) the 'explorer' role who was actively engaging and frequently interacting (9/19 participants); 2) the 'observer' closely watching in a spectator role and occasionally interacting with ActuEaters (6/19 participants), and 3) the 'bystander' role of those who rarely touched it and were reluctant to take part in 'physically' exploring it (4/19 participants). Particularly one in each group was a bystander/reluctant to touch it or look at it, yet still reflecting on it and analyzing its behaviour. Observers analyzed every interaction and assumed meanings and interpreted its actuations. Despite their different roles and positions, all participants at some point during the 4 studies attempted to explore ActuEaters either physically, by finger touching, poking, hand patting, lifting up the fabric off the table, or looking down under the table to realize what is causing the shape-change.

Social Engagement

The way participants responded to and interacted with the ActuEater varied over time and for different situations, bringing opportunities for rich social engagement. They frequently exchanged eye-contact when it moved, especially those adjacent to the moving part, expressing it felt as a personal message for them, while exchanging smiles, laughs and jokes about it, acknowledging their amusement, surprise and enjoyment of its unexpected behaviour. Four female participants were observed taking photos of their ActuEating experience using their smart phones to share on social media. Three or more participants often physically explored the ActuEater together, which made them establish social engagement around it. For example, both P2 and P5 kept their hands on ActuEater1, together, while smiling for a while, as it was actuating, enjoying the feeling of it going up and down. With ActuEater2, several participants touched 'similar' parts simultaneously to explore it together imitating each other's interactions from gentle touches to firm pressing strokes. As actuations varied, participants were developing interactions together in a self-learning exploratory process, learning from each other in playful ways, collaborating and exchanging techniques. E.g. *"wait, if we touch one by one together, what will happen?"* (P13), *"let's press it together at the same time"* (P10 to P7). On a few occasions, some would interact on behalf of others when they felt that the ActuEater needed to be responded to but was being ignored.

Physical Manipulations

Once ActuEater1 had gained users attention it attracted their touch interactions (first fingertip touch, then hand and palm touch), initially passive (responding to) then active (initiating) interaction. Then interactions went beyond touch into more physical 3D manipulations according to the shape, material and its affordance (such as grasp, pat, squeeze, bend, etc), see Figure 4. After thoroughly exploring direct physical interactions, participants became more creative. For instance, P1, P3 and P5 used water bottles, salt shakers and mobile phones to place onto ActuEater1 to explore its response. Further exploration with ActuEater2 brought richer physical manipulations to the table. For example, many participants frequently touched the coloured 'felt' parts with a brushing stroke on its soft texture, although these elements weren't sensitive. 'Hover' hand in-air gestures above sensitive parts were used by all groups when proximity-sensing was realized. Some covered up thermochromic parts with both hands to 'feel the heat'. Some lent forward or backwards in their seats to test proximity. Some repositioned physical objects (that were initially placed randomly) precisely on particular parts of ActuEater2 to test them. Many were observed 'tracing' the colour-changing pattern with one finger in a continuous satisfying way.

Figure 4. Interactions with ActuEater1 (left) and ActuEater2 (right)

Physical interactions were quite directly proportional with actuations in terms of scale. That is, we noticed that they responded to located (small) low actuations of ActuEater1 by one fingertip, higher ones with their three middle fingers, and when it was all up, they used their whole palms. ActuEater2 was definitely manipulated more intensely, it was flipped over or pulled off the table, bent, felt and squeezed, and perceived more like a 'fabric' runner than as a shape-changing device like ActuEater1. This reflects how people develop their own interactions based on their own perceptions, interpretations, backgrounds and instincts. Yet, people learn together and from each other, developing their ideas, perceptions and engagements with a certain artefact.

A Complex Behavioural Repertoire

Beyond the Boundaries

Several participants had an irresistible urge to 'tidy up' both ActuEaters after actuations by flattening the 'history wrinkles' that were created by its actuation. This physical interaction (maybe due to neatness or maybe expecting a default state of being totally flat) triggered more actuations thereafter. Observing how participants took extra effort to interact with it (e.g. stretch out their arms to reach it, put down cutlery, etc) shows their 'willingness' to physically engage with it. Interacting blindly with it (without even looking at it) shows 'expertise' and confidence. Participants not only interacted with the actuating parts of ActuEaters, but they tended to explore the boundaries of sensitivity to discover the edges of 'seamless and seamful' interaction, evident by manipulating even the satin ribbon edge of ActuEater1 and the plain senseless petals of ActuEater2.

'Interaction Boundaries' were even crossed to explore other potential means of engagement. For example, ActuEater2 received several 'voice commands' to test speech as possible input interaction: *"Hi" (P12, P13), "Move" (P13), "By the power in me, rise!" (P8).* At the end of study B, P10 held its edge with a firm grip and shook hands with ActuEater2 saying *"nice to meet you"*. Participants often felt an urge to initiate interaction with ActuEaters deliberately, when they were not actuating, driven by an inner desire to have fun through playing and to find out more about how it works. This creates space for contradicting scenarios where they want to stop it when it's up/active, and yet they wanted it active when it sleeps. Such complicated behaviour resembles typical interactions with pets or children: when quiet, we want to play with them, but when they are manic, we wish them calm. It can also explain participants' tender 'pat' interaction, as their way to calm it down, revealing a zoomorphic interpretation of the actuations. *"stroke it carefully, it's like your pet!"* (P13). Others showed further 'empathy' towards it: *"you should just touch it, not squeeze it like that"* (P7 to P10).

Curiosity and Mystery

Curiosity was evident in all four studies, where participants explored and talked about how it works, and sneaked a peek underneath. Every participant at some point picked the table runner up from the table, pressed it to feel its inner body, or bent downwards to look underneath the table. ActuEater1 obviously had the shape-changing mechanism under the table and participants commented on how it would be more practical not to have a hole in the table *"and keep all the mystery alive, because you look under the table and oh no, it must be in the runner!"* (P4), *"what kind of sorcery would this be!"* (P6).

Accordingly, we designed ActuEater2 to be self-actuating using SMA wires which caused participants to flip it, bend it and pull it off the table to ensure there is nothing underneath, then squeeze it and press it to feel what is inside. P10 put his hand underneath the table below ActuEater2 testing if the capacitive sensing would work through the glass downwards. P17 'rolled' it firmly to realize its affordance and materiality when others wondered whether there was something inside it. Participants expressed a mysterious aspect not just in the movement but also in the colour-change: *"notice those colouring spirals again, it doesn't look like an electrical light"* (P18), *"It is totally unexpected, it would never cross my mind that a table fabric can actuate like this. I wonder how it changes? what causes the colour-change? and how does this pattern reveal?"* (P7). This shows us how people think about inter-weaving technology into everyday objects in a hidden way and how it is more 'magical' from a user perspective.

Discoverability and Illegibility

Designing for discoverability by 'hiding the interaction' creates a variable and playful repertoire of behaviours, while designing for illegibility (non-obvious and inconsistent) by 'hiding the logic' creates a sense of autonomy and a spatio-temporal aspect of 'Interioraction' [27]. In our research we wanted to explore these design directions where discoverable and illegible systems could be perceived as mysterious and magical. During the initial study, participants criticized ActuEater1 for not having an immediate consistent response to their actions. Although there was a specific pattern mapping inputs to outputs, participants expressed how they still require an explicit cue to fully understand. Apparently, ActuEater1 made participants of study A feel unconfident about its illegible and discoverable interactions, when some autonomous interactions were perceived as random. Participants not only expressed how legibility is easier to relate to, but also how a level of control over ActuEater1 was desirable.

As a result, we designed ActuEater2 to be both sensing (and reacting) and autonomous at the same time, which was appreciated in the design crits: *"It's nice to have some control of it and it is also nice that it does its own thing by itself as well"* (P18). In addition to direct and immediate input-output relationships, we explored participants' view of the artefact's behaviour that evolves with their interactions over time and usage, instrumenting discoverable interaction as an adventure: *"was it moving that much from the beginning?"* (P10), *"as we talk about it more, it moves more"* (P9), *"we'll keep playing with it and at the end we'll find out it's a Jumanji!"* (P13), *"or find the treasure"* (P12). *"it could evolve more over our dinner party and break out a dance at the end to celebrate!"* (P16). This shows how people were readily orienting to a world where objects known to be static cannot only change over time, but can change unexpectedly and in an adventurous manner with different paces, taking various forms, that could be ultimately rewarding.

Design Explorations

During their group discussion in the design crits, participants suggested many enrichments to both ActuEaters and proposed other functional and aesthetic possibilities. They also proposed different artefacts that could be similarly interactive and suggested other types of spaces where they believed it might be interesting to interact, adopt and utilize such technology.

Proposed Functions

Participants focused their suggestions of potential functions on three main themes: 1) extending, 2) engaging, and 3) entertaining. 1) 'Extending' decorative objects by augmenting them with further capabilities was suggested as an alternative to smart devices and gadgets, e.g. *"now we're getting into an era where we expect objects to be that smart and you can just talk to them and tell them what to do"*, *"so Alexa should be part of my decor and have more interactive capabilities than activating heating or obeying commands"* (P16); 2) 'Engagement' was frequently mentioned for i) bringing people together and provoking social engagement, or ii) occupying people waiting for something or feeling lonely, iii) engaging children in different situations such as doctors' waiting rooms, and iv) creating an ice-breaking object for those meeting for the first time; and 3) 'Entertainment' and stimulating was also discussed as a useful purpose for such an object as: *"it is great for an absent mind to meditate or gaze at"* (P10), *"gives a sense of calmness.. I can keep looking at it for hours"* (P7), *"it reduces stress, like a fidget-spinner"* (P12) and *"stimulating curiosity of children, how is it moving and changing colour?"* (P7). P13 expressed a similar functional quality of keeping children entertained without a digital screen i.e. a display-less display, and P18 suggested a changing wall-art that entertains, but unlike a TV set, is not focus demanding. All these functions represent the value of non-demanding and non-disrupting technology (people aspire for) that keeps the essence of social quality time and adds a bonus dessert to it.

Proposed Artefacts

As they perceived it as a gaze-drawing object, some participants suggested other artefacts that could be similarly (or more) interesting. Some suggested other flat surfaces such as *"colour-changing coasters or placemats that entertain me until the next course, or warms my plate"* (P10), *"a mat or a rug on the floor that we sit on and crumbles when one moves away"* (P11), *"a seat that changes colour the more you stay sitting down too long then moves urging you to get up"* (P15) and *"a mirror or a painting"* (P4). P7 imagined wall-art that gives different shadows or shapes responding to proximity and an entire wall that autonomously reveals and moves parts such as butterfly wings decorating the wall to actuate his home decor. Moreover, others suggested 3D objects such as *"a playful sculpture"* (P16), *"a moving vase"* (P9), *"a pillow to help my neck problems"* (P11), *"a lampshade that starts dancing like this when I'm in a 'dancey' mood"* (P7), *"a coffee table itself"* (P18, P5), *"a blanket that crumbles around you would be great to give you warmth"* (P7).

Proposed Interactive Aesthetics

A crucial aspect of decorative artefacts is their need to blend-in to complement an interior style and are usually matching other objects in the same space. Therefore, we were keen to choose settings where the ActuEaters could fit-in and complement those spaces with matching objects, such as matching tableware, interior colour-scheme and style (as much as possible): *"I didn't notice anything weird at first as it had the same colours of the restaurant chairs and napkins, and petals shape are the same as the table glass engravings."* (P7). However, more tailored design for all details has to be carried out for each individual space, e.g. *"It looks elegant and the colours are matching but the shape has to be round because the table is round"* (P13), while some saw it as a *"futuristic design"* (P10, P17) preferring more traditional aesthetics.

Although we carefully eliminated any LEDs from ActuEater1 to keep it as normal and traditional as possible, 4 of our 6 participants expressed how they expected/wanted ActuEater1 to have 'lights'. This indicates how they do not entirely perceive it as a (normal) table-runner, but as a 'digital' object. When they were asked about colour-changing capabilities instead of lights (e.g. using thermochromic inks), they showed excitement and suggested that colour-change could complement and enrich the shape-change, adding *"a more interesting layer"* (P3). When we enabled thermochromic colour-change in some parts of ActuEater2, they suggested that all petals should change colour and recommended hydrochromics as well *"if it responds to water or spilt liquids, it would turn an embarrassing bad situation into an interesting conversation re-starter"* (P9). Other richer multi-aesthetic interactions suggested that petals could move freely and blossom in 3D, or it plays music and amplifies itself with the volume to *"hit as many senses as possible"* (P16).

Proposed Environments

In terms of spaces, participants proposed different environments in which they envisioned such technology. Restaurants and silent spaces such as libraries, museums, clinics, waiting rooms and specifically waiting areas at the doctors' surgeries to entertain people while waiting, were proposed by several participants across the 4 studies. Other proposed environments, included classrooms as a board that *"attracts focus of students"* (P12), toilets *"instead of reading the shampoo ingredients if you forget your smart phone"* (P6) and office spaces *"to distract from work, to refresh, take a breath and de-stress"* (P12), but *"not in a formal setting as meeting rooms, it becomes distracting"* (P11). Alternatively, having them in homes was debatable. Some expressed their worry about the finite number of actuations that wear its novelty out too quickly for home occupants, but still found it exquisite and delightful for their guests. So careful design should create actuating capabilities that makes it 'sustainably interesting'. Others saw it *"as a creative or a special object that you'd like to display"* (P8) and saw opportunities in which a domestic artefact can change colour based on ambient temperature or display household data such as water or energy consumption.

DESIGN OPPORTUNITIES

Our exploration of critical responses to the ActuEater has suggested a number of key learnings which we highlight below in the form of a set of design opportunities to consider when designing interactive decoratives. We should *design for*:

- Meaningfulness: Although people acknowledge that decorative objects are for aesthetic purposes, not necessarily functional, they still give them purpose in terms of *meanings* and *values*. This applies to 'decoractives' as well where people interpret their *overall experience* in deeper meanings and give a purposeful value to the actuations often beyond what was designed for (in either positive or negative ways), which is a design feature to be exploited.

- Spatiality: When technology blends into our daily environment, people perceive it as part of their overall *spatial experience* and expect it to interact with the space, relating shape-changes to factors beyond their direct input such as music, conversation topics, space occupancy, weather, etc. This does not apply to digital devices that do not blend in, but stand out, requiring full attention of users.

- Sociability: *Social engagement* around an actuating artefact is rich in terms of the noticeable exploratory, collaborative and playful nature of how people interact with such technology together. This should inspire designers investigating this design space, shaping how interactive interior elements might be dealt with to utilize and support sociability.

- Tactility: Evident by how ActuEaters attracted touch, hand manipulations and *physical interaction* through other objects, designers should seize this opportunity to design for tactility utilizing the intuitive affordance of different material textures and physical objects already in the space.

- Seamlessness: People anticipate shape-changing interfaces that are portable, weavable and seamlessly hidden (instead of bulky, cabled and demanding machines), stimulating their sense of *curiosity and mystery*, believing it would be magical and more efficient in terms of everyday use in their normal environments. There is a great opportunity to augment existing artefacts with shape-changing materials instead of embedding mechanical solutions within them.

- Beyondness: Actuating decoratives are explored *beyond the boundaries* of designed interactions, where people navigate away from observed sensors and cruise through new possibilities, from voice and gestures to shaking hands. Unlike robotic SCIs, when designing organic actuations (smooth and malleable), people will tend to develop a notion of empathy and tenderness in their interactions with it, even with no designed zoomorphic shape, texture or sound, people still believe it has a body, mood and intentions.

- Discoverability: Systems that are not consistent and obvious, but enable actuations to evolve over time or usage can be misleading, incomprehensible, or perceived as random. However, careful iterative design and the use of situated studies (beyond minutes) can create opportunities for designers to explore novel possibilities and *mysterious designs* that promote discoverability in actuating interiors, to increase *adventurous exploration* of artefacts.
- Significance: Designing decorative objects that are useful through *potential functions*, creates a greater value to them. Through slow interaction and calm technology, we can (and should) make decoractives with 'extended' functionalities, beyond their aesthetics, 'engaging' people together through artefacts and 'entertaining' them with their multi-aesthetics in diverse and novel ways.
- Match-making: As decorative objects usually have other matching items in the same interior space (to blend and complement the space aesthetics and style), people relate these relationships intuitively. Therefore, when designing 'decoractives', we can utilize such relationships in developing spatial interactions (with different elements in the space) such as our *proposed artefacts* creating a rather richer experience, e.g. a matching cushion and throw, or a curtain with a rug, can interact together or through each other.
- Colourfulness: People expect shape-changing interfaces, especially decorative ones, to be colour-changing as one of their main *proposed aesthetics*, even through lights. A good design practice to create *display-less displays* is to embed colour-changing properties in the material itself instead of using lights (e.g. thermochromic or photochromic inks) as means of both sustainable actuation and spatial interaction.
- Blending-in: Shape-changing interfaces can enhance the social experience of a group of people in different *potential environments*. In a given context, when designed to blend into their environment (instead of standing out as a separate device), people can choose when to ignore it and when to use it together as a social probe, to talk about, interact with, and engage together through it.

DISCUSSION & CONCLUSION

In this paper, we presented a series of design explorations, critically examining the potential use of shape-changing materials in the design of interactive decorative artefacts. We believe our work provides an inspiring case-study supporting others who might wish to design and develop actuating decorative artefacts for different contexts and cultures. The ActuEating study offered an open-ended set of observations in terms of user behaviour, interpretation, reactions and expectations. The intention wasn't studying the dining experience in itself, but to explore the design of interactive artefacts and how people may perceive, interact with and experience such technologies in relevant settings and to gain deeper knowledge and insight into designing interactive everyday objects as decorative artefacts.

As with both coMotion [17] and the History-Tablecloth [12], the improvised interactivity and often confusing behaviours, added value and richness to the ActuEating experience in ways that had not been anticipated, allowing for complex interpretations. While controlling ActuEater1 from behind the scenes, we learnt how participants collaborated to realize how to control it themselves, not just theorizing what triggers it, but by testing different input interactions beyond our expectations. We then designed ActuEater2 to be both physically-interactive and autonomous. From voice commands, knocking on the table and observing music patterns, to stroking, patting and using other objects (e.g. teapots, salt, sugar and phones) on top of it, participants developed interactions themselves through social engagement to explore its potentials, interaction boundaries and limitations. Despite the 'engaging' and 'entertaining' benefits realized by the ActuEating studies, we understand the limitations in terms of the effect of 'novelty' on user experience, and are planning to address this in our future work.

The challenges we faced to conceal technology within an everyday fabric artefact ubiquitously, were aimed at experimenting how hidden interactivity in objects (that blend into the space design) could be of value, meaning and significance to space occupants over an in-situ social event (in a restaurant or at home). We emphasize on how weaving technology into real-world objects, specifically decorative ones, can deliver a rather richer 'spatial experience' in a given contextual setting. By taking previous work further, we were able to explore new territories of this design space. However, the design constraints we set included studying only actuating table runners in dining settings. Further research should explore other artefacts, in other contexts, to realize the latent and intrinsic potentials of extending their capabilities, seamlessly. Although ActuEaters were designed as non-functional artefacts, their aesthetic qualities as decorative objects are rather useful as they don't need constant attention, which aligns well with slow and calm technology concepts [30].

This work will help advance and continue the research commenced by the HistoryTableCloth [12] and coMotion [17] around shape-changing interfaces and interactive spaces, furniture and everyday objects. The beauty of interactive decorative objects (unlike novel gadgets) is that whether they interact (accurately or entirely) or not, the object still has value. Its failure to interact at any time will not lead to a crisis of affordance [12], as it remains a decorative aesthetic artefact in its own right. Our work points to the future potential of new materialities, merging interaction design with interior design.

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REFERENCES

1. Pollie Barden, Rob Comber, David Green, Daniel Jackson, Cassim Ladha, Tom Bartindale, Nick Bryan-kinns, Tony Stockman, and Patrick Olivier. 2012. Telematic Dinner Party: Designing for Togetherness through Play and Performance. In *Proceedings of the 2012 Conference on Designing Interactive Systems (DIS'12)*. Newcastle, UK, 38–47. https://doi.org/10.1145/2317956.2317964
2. Alice Bodanzky. 2012. Exploring the Expressiveness of Shape-Changing Surfaces. In *Proceedings of the Sixth International Conference on Tangible, Embedded, and Embodied Interaction (TEI'12)*. Kingston, ON, Canada, 403–404. DOI: http://dx.doi.org/10.1145/2148131.2148235
3. Virginia Braun and Victoria Clarke. 2006. Using Thematic Analysis in Psychology. *Qualitative Research in Psychology* 3, 2 (2006), 77–101. DOI: http://dx.doi.org/10.1191/1478088706qp063oa
4. Jaz Hee-jeong Choi, Marcus Foth, and Greg Hearn. 2014. *Eat, Cook, Grow: Mixing Human-Computer Interactions with Human-Food Interactions*. https://mitpress.mit.edu/books/eat-cook-grow
5. Marcelo Coelho and Jamie Zigelbaum. 2011. Shape-changing Interfaces. *Personal and Ubiquitous Computing* 15, 2 (2011). DOI: http://dx.doi.org/10.1007/s00779-010-0311-y
6. Nicholas S Dalton, Emily Collins, and Paul Marshall. 2015. Display Blindness? Looking Again at the Visibility of Situated Displays using Eye Tracking. In *Proceedings of the 2015 CHI Conference on Human Factors in Computing Systems*. ACM, Seoul, Republic of Korea, 3889–3898. DOI: http://dx.doi.org/10.1145/2702123.2702150
7. Felecia Davis. 2015. The Textility of Emotion: A Study Relating Computational Textile Textural Expression to Emotion. In *C&C'15*, Vol. 2. Glasgow, United Kingdom, 1977–1982. DOI: http://dx.doi.org/10.1145/2702613.2732739
8. Felecia Davis, Asta Roseway, Erin Carroll, and Mary Czerwinski. 2013. Actuating Mood: Design of the Textile Mirror. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI'13)*. Barcelona, Spain, 99–106. DOI: http://dx.doi.org/10.1145/2460625.2460640
9. Aluna Everitt and Jason Alexander. 2017. PolySurface: A Design Approach for Rapid Prototyping of Shape-Changing Displays Using Semi-Solid Surfaces. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS'17)*. Edinburgh, UK, 1283–1294. http://dx.doi.org/10.1145/3064663.3064677
10. Hasan Shahid Ferdous, Frank Vetere, Hilary Davis, Bernd Ploderer, Kenton O Hara, Rob Comber, and Geremy Farr-wharton. 2017. Celebratory Technology to Orchestrate the Sharing of Devices and Stories during Family Mealtimes. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Denver, CO, USA, 6960–6972. https://doi.org/10.1145/3025453.3025492
11. Sean Follmer, Daniel Leithinger, Alex Olwal, and Akimitsu Hogge. 2013. inFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'13)*. St. Andrews, UK, 417–426. DOI: http://dx.doi.org/10.1145/2501988.2502032
12. William Gaver, John Bowers, Andy Boucher, Andy Law, Sarah Pennington, and Nicholas Villar. 2006. The History Tablecloth: Illuminating Domestic Activity. In *Proceedings of the 2006 Conference on Designing Interactive Systems (DIS'06)*. University Park, Pennsylvania, USA, 199–208. DOI: http://dx.doi.org/10.1145/1142405.1142437
13. William W Gaver. 2003. Ambiguity as a Resource for Design. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'03)*. Ft. Lauderdale, Florida, USA, 233–240. DOI: http://dx.doi.org/10.1145/642611.642653
14. Catherine Grevet, Anthony Tang, and Elizabeth Mynatt. 2012. Eating Alone, Together: New Forms of Commensality. In *Proceedings of the 17th ACM international conference on Supporting group work (GROUP '12)*. Sanibel Island, Florida, USA, 103–106. http://dx.doi.org/10.1145/2389176.2389192
15. Daniel Groeger and Elena Chong Loo. 2016. HotFlex: Post-print Customization of 3D Prints Using Embedded State Change. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'16)*. San Jose, CA, USA, 420–432. http://dx.doi.org/10.1145/2858036.2858191
16. Jens Emil Grønbæk, Henrik Korsgaard, Marianne Graves Petersen, Morten Henriksen Birk, and Peter Gall Krogh. 2017. Proxemic Transitions: Designing Shape-Changing Furniture for Informal Meetings. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'17)*. Denver, CO, USA, 7029–7041. http://dx.doi.org/10.1145/3025453.3025487
17. Erik Gronvall, Sofie Kinch, Marianne Graves Petersen, and Majken K. Rasmussen. 2014. Causing Commotion with a Shape-Changing Bench. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'14)*. Toronto, ON, Canada, 2559–2568. DOI:http://dx.doi.org/10.1145/2556288.2557360
18. John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'15)*. Seoul, Republic of Korea, 19–28. DOI: http://dx.doi.org/10.1145/2702123.2702599

19. Alexis Hiniker, Sarita Y Schoenebeck, Ann Arbor, and Julie A Kientz. 2016. Not at the Dinner Table: Parents' and Children's Perspectives on Family Technology Rules. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing (CSCW '16)*. San Francisco, CA, USA, 1376–1389. https://doi.org/10.1145/2818048.2819940

20. Annika Hupfeld and Tom Rodden. 2012. Laying the Table for HCI: Uncovering Ecologies of Domestic Food Consumption. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. Austin, Texas, 119–128. http://dx.doi.org/10.1145/2207676.2207694

21. Hiroshi Ishii, David Lakatos, Leonardo Bonanni, and Jean-Baptiste Jb Labrune. 2012. Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials. *Interactions* XIX, February (2012), 38–51. DOI: http://dx.doi.org/10.1145/2065327.2065337

22. Hiroshi Ishii, Daniel Leithinger, and Sean Follmer. 2015. TRANSFORM: Embodiment of "Radical Atoms" at Milano Design Week. In *CHI'15 Extended Abstracts*. Seoul, Republic of Korea. DOI: http://dx.doi.org/10.1145/2702613.2702969

23. Young Suk Lee. 2015. Spiky Starfish: Exploring 'Felt Technology' Through a Shape Changing Wearable Bag. In *Proceedings of the 9th International Conference on Tangible, Embedded, and Embodied Interaction (TEI'15)*. Stanford, CA, USA, 419–420. DOI: http://dx.doi.org/10.1145/2677199.2690878

24. Sarah Mennicken, A.J. Bernheim Brush, Asta Roseway, and James Scott. 2014. Finding Roles for Interactive Furniture in Homes with EmotoCouch. In *Proceedings of Ubicomp'14 Adjunct*. Seattle, WA, USA, 923–930. DOI: http://dx.doi.org/10.1145/2638728.2641547

25. Robb Mitchell, Alexandra Papadimitriou, Youran You, and Laurens Boer. 2015. Really Eating Together: A Kinetic Table To Synchronise Social Dining Experiences. In *Proceedings of the 6th ACM Augmented Human International Conference (AH'15)*. ACM, Singapore, Singapore, 173–174. http://dx.doi.org/10.1145/2735711.2735822

26. Nadia Mounajjed and Imran A Zualkernan. 2011. From Simple Pleasure to Pleasurable Skin: An Interactive Architectural Screen. In *DPPI '11*. Milano, IT, 30–37. DOI:http://dx.doi.org/10.1145/2347504.2347537

27. Sara Nabil, David Kirk, Thomas Ploetz, Julie Trueman, David Chatting, Dmitry Dereshev, and Patrick Olivier. 2017a. Interioractive: Smart Materials in the Hands of Designers and Architects for Designing Interactive Interiors. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS'17)*. Edinburgh, UK, 379–390. http://doi.acm.org/10.1145/3064663.3064745

28. Sara Nabil, Thomas Ploetz, and David S Kirk. 2017b. Interactive Architecture: Exploring and Unwrapping the Potentials of Organic User Interfaces. In *Proceedings of the 11th International Conference on Tangible, Embedded, and Embodied Interaction (TEI'17)*. Yokohama, Japan, 89–100. DOI: http://dx.doi.org/10.1145/3024969.3024981

29. Mamoun Nawahdah. 2013. Virtually Dining Together in Time-Shifted Environment: KIZUNA Design. In *Proceedings of the 2013 conference on Computer supported cooperative work (CSCW '13)*. San Antonio, TX, USA, 779–788. https://doi.org/10.1145/2441776.2441863

30. William Odom, Richard Banks, Abigail Durrant, David Kirk, and James Pierce. 2012. Slow Technology: Critical Reflection and Future Directions. In *Proceedings of the 2012 Conference on Designing Interactive Systems (DIS'12)*. Newcastle, UK, 816–817. DOI: http://dx.doi.org/10.1145/2317956.2318088

31. William T. Odom, Abigail J. Sellen, Richard Banks, David S. Kirk, Tim Regan, Mark Selby, Jodi L. Forlizzi, and John Zimmerman. 2014. Designing for Slowness, Anticipation and Re-visitation: A Long Term Field Study of the Photobox. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'14)*. Toronto, ON, Canada, 1961–1970. DOI: http://dx.doi.org/10.1145/2556288.2557178

32. Roshan Lalintha Peiris, Jeffrey Tzu Kwan Valino Koh, Mili John Tharakan, Owen Noel Newton Fernando, and Adrian David Cheok. 2013. Ambi kraf byobu: Merging technology with traditional craft. *Interacting with Computers* 25, 2 (2013), 173–182. DOI: http://dx.doi.org/10.1093/iwc/iws013

33. Majken K Rasmussen, Esben W Pedersen, Marianne G Petersen, and Kasper Hornbæk. 2012. Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions. In *Proceedings of the 2012 ACM Annual Conference on Human Factors in Computing Systems (CHI'12)*. Austin, Texas, 735–744. DOI: http://dx.doi.org/10.1145/2207676.2207781

34. Mark Selby and David Kirk. 2015. Experiential Manufacturing: The Earthquake Shelf. In *RTD2015*. Cambridge, UK, 25–27. DOI: http://dx.doi.org/10.6084/m9.figshare.1327994

35. Miriam Sturdee, John Hardy, Nick Dunn, and Jason Alexander. 2015. A Public Ideation of Shape-Changing Applications. In *Proceedings of the International Conference on Interactive Tabletops and Surfaces (ITS'15)*. Madeira, Portugal, 219–228. DOI: http://dx.doi.org/10.1145/2817721.2817734

36. Sarah Taylor and Sara Robertson. 2014. Digital Lace: A Collision of Responsive Technologies. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers (ISWC'14 Adjunct)*. New York: ACM, 93–97. DOI:http://dx.doi.org/10.1145/2641248.2641280

37. Kentaro Ueda, Tsutomu Terada, and Masahiko Tsukamoto. 2016. Input Interface Using Wrinkles on Clothes. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers (ISWC'16)*. Heidelberg, Germany, 56–57. DOI: http://dx.doi.org/10.1145/2971763.2971782

38. Roel Vertegaal and Ivan Poupyrev. 2008. Organic User Interfaces. *Commun. ACM* 51, 6 (2008), 26. DOI: http://dx.doi.org/10.1145/1349026.1349033

39. Luke Vink, Viirj Kan, Ken Nakagaki, Daniel Leithinger, Sean Follmer, Philipp Schoessler, Amit Zoran, and Hiroshi Ishii. 2015. TRANSFORM as Adaptive and Dynamic Furniture. In *Proceedings of CHI EA '15*. Seoul, Korea, 183–183. DOI: http://dx.doi.org/10.1145/2702613.2732494

Appendix G. Paper 3: Enchanted Architecture and Interactive Theatre

Interioractive: Smart Materials in the Hands of Designers and Architects for Designing Interactive Interiors

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ABSTRACT
The application of Organic User Interface (OUI) technologies will revolutionize interior design, through the development of interactive and actuated surfaces, furnishings and decorative artefacts. However, to adequately explore these new design landscapes we must support multidisciplinary collaboration between Architects, Interior Designers and Technologists. Herein, we present the results of two workshops, with a total of 45 participants from the disciplines of Architecture and Interior Design, supported by a group of HCI researchers. Our objective was to study how design disciplines can productively engage with smart materials as a design resource using an evolving set of techniques to prototype new interactive interior spaces. Our paper reports on our experiences across the two workshops and contributes an understanding of techniques for supporting multidisciplinary collaboration when designing interactive interior spaces.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous; J.5 Computer Applications: Arts & Humanities – Architecture

Author Keywords
Organic User Interfaces; smart materials; e-textiles; Interactive Architecture; Interior Design.

INTRODUCTION
Over several centuries the architectural movements that have impacted our built environments have adopted varying levels of reference to nature. It is not uncommon to see architectural forms that try to mimic the flowing lines and natural references of the living environment. This was evident (arguably) in the gothic, baroque, rococo and art nouveau periods [36] and then more recently and literally in 'Biophylic Design'. Since the art deco and modernist periods however, buildings have adopted increasingly abstract and metaphorically static shapes. That is not to say however that buildings are static and non-dynamic. As Brand [3] astutely illustrates buildings change over time. They have a patina, that develops through use and they age ostensibly, through weathering and other effects of time. It is also true to say that interiors, the artefacts and furnishings we have within our buildings, are moved, age and are replaced over time, shaping a dynamic environment within the buildings themselves [9]. However, these dynamic features of buildings often sit outside of the temporal flows that make them readily perceivable to the average occupant. We are aware of change over time, but the time-scales at play often mean we do not actively attend to it (beyond specific demarcated points of transition). Within environmental psychology there has long been a discussion around the restorative benefits of the natural environment, and concern for how this might be installed within the built environment [18]. One area of research Attention Restoration Theory (ART) [19] posits that dynamic, moving and possibly interactive elements of the built environment might support inhabitant well-being along a number of dimensions. From this we believe that our built environment should be designed to have the capacity for dynamic interactive change, at a time scale that is more perceptible to inhabitants. Not only could our homes morph as we grow old in them, and thus be more adaptable to our experiences and comforts over a lifespan, but also be more responsive to our daily needs and moods.

Research already exists in the area of Interactive Architecture [6, 22] but with limited understanding of Interactive interiors that does not really address matters of interior design in many kind of ways. However, deeper study and research for Interactive Interiors will help and support the vision of ubiquitous computing. In various ways researchers are beginning to think about more dynamic and adaptable living and working spaces [28, 14]. Organic User Interfaces (OUIs), including the use of smart materials offer a rich potential to 'retrofit' [22] interactivity in to domestic artefacts and surfaces. OUIs are defined as non-flat multi-touch interfaces that can exist in both rigid or flexible forms, can take any shape, and can -actively or passively- change this shape [35]. This kind of flexible and dynamic sensing and actuation is more feasible and affordable than ever. Smart materials such as shape-changing alloys (SMAs), colour-changing paints (thermochromic pigments), conductive materials (conductive fabrics, conductive

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Figure 1. Examples of Interactive Interiors: (Left) Light-Form [Daniele Gualeni Design Studio, 2010] [31], (Right) Engaging Retail Space [Dalziel & Pow, 2015] [7]. Images reproduced with permission.

paints, metal powders) and other flexible sensors all form an interesting medium for embedding both actuation and sensing capabilities into everyday objects and surfaces.

For the practical and aesthetic qualities of these materials to be fully exploited within interior architecture and design however, the materials must be brought to the attention and understanding of those who work most prevalently in the design of the built environment, namely architects and interior designers. To date however, there has been no significant exploration of how such communities can be supported in working with these new kinds of new materials in interior design projects. Evidently, there is a need to understand the processes through which designers can come to understand and work with such smart materials, in collaboration with technologists, if we wish to see visions of smart environments fully realised.

In this paper therefore, we discuss our study of interdisciplinarity between HCI and Interior Design. We explore the use of embedded smart materials to support new interactions in interior designs. In particular, we critically reflect upon our efforts to scaffold interior designers and architects, as two specific communities, learning to design with smart materials through hands-on exploration.

Below we first introduce some related work, which grounds some of our key understanding of interactive architectures and OUIs. We then unpack two case studies, as two workshops conducted with architects then interior designers respectively, which brought them in to collaboration with an HCI team who scaffolded their prototyping with new interactive materials, whilst designing novel interactive interior spaces. In each case we were utilising techniques for supporting their exploration (with smart materials) of 4D interaction. We conclude the paper with reflections on the process of supporting interior designers and architects to design with new materials and in doing so try to tackle some of the proposed challenges of Interactive Architecture [22], namely Radical Interdisciplinarity, Appropriation and Retrofitting, and Scalability.

RELATED WORK

Interactive Architecture that used shape-change as means of reflection and interactivity with users has been subject to a few HCI studies [6, 22] and prototypes, such as ExoBuilding [32] a physiologically driven Adaptive Architecture prototype, the MuscleTower [24] another prototype of an interactive/ proactive architectural structure and the Kinetic Interactive Architecture [27] that explores bodily interactions with different dynamic interior surfaces. But when we observe the design of any of these examples, we can't seem to picture them as architecture to live with. The interactivity, adaptivity, and proactivity researchers introduced in these previous examples were basically kinetic. Other research looked into the possibilities of designing entire building facades as digital displays [11, 33].

On the other hand, architects took kinetic and adaptive architecture to another level where scalability essentially triggers new forms of dynamic behaviours, capabilities and challenges. The most basic type would be the Kinetic sun-shade facades that take a variety of shapes and motion axes, from the very early examples such as the Institut du Monde Arabe in Paris (Jean Nouvel, 1987) [23] to the modern recent buildings such as the Kolding Building of SDU in Denmark (Henning Larsen Architects, 2014) [16], Al Bahr Towers in Abu Dhabi (Aedas Architects, 2012) [1], and the Kiefer Technic Showroom (Giselbrecht, 2010) [12]. Other kinetic architecture may transform the entire structure such as the shape-changing Hoberman's Arch (Hoberman, 2004) [17]. Current Interactive Architecture - other than being kinetic - often include colour-changing LED displays such as the Luminous Interactive Public Art Platform in Darling Quarter, Sydney [8].

A primary aspect of interior architecture is lighting and finding creative ways of manipulating lighting with other forms of kinetic actuations to realise user interaction. In interior design practice, interactive design firms are starting to create interactive spaces to engage and react to users or the ambient environment as well, using light and sound. Examples of interactive interior designs are the Engaging Retail Space (Dalziel & Pow, 2015) [7] that responds to touch using capacitive paint on wood wall panels and reacts through audible sounds and projected graphical animations, and the Aegis Hyposurface kinetic wall (Mark Goulthorpe, 2000) [13] that actuates its shape-changing mechanism either autonomously (pre-programmed) or responding to ambient sounds or noise. Other examples that involve LED interactivity are Light-Form (Francesca Rogers, 2010) [31] and the Philips Luminous Patterns [26]. More immersive experiences can be also found in some novelists' work such as Nicolas Schoffer's Spatiodynamic Luminodynamic & Chromodynamic Space [34]. All these examples were designed and built to extend the user experience in the space by pushing the boundaries and adding a dynamic nature to the interior design instead of being just static as traditional designs (see Figure 1).

OUI materials leverage these possibilities from being mechanical into organic in terms of the nature and effect of the actuation's interaction and materialism. Such smart materials have the physical changeable properties that are reversible and repeatable, responding by changing their shape (morphogenic), skin texture, opacity or colour (chromogenic) or other morphological forms [29] reacting to external stimuli such as heat (thermo-), light (photo-), electricity (electro-), pressure, water/humidity (hydro-/hygro-), magnetism or chemical reactions [30]. Other smart materials may have sensing qualities rather than actuating ones. For example: conductive fabrics, conductive paints and flexible sensors that allow a range of manipulative and tactile sensing (from light touch to pressure) onto other normal materials. Previous research has looked into how OUI materials in Interactive Architecture can be used to create prototypes for both skin-changing OUIs such as Morphing Lumina Architectural Skins [20], Morphogenic Adaptive Building Skins [2], and OUI Interiors such as the LivingSurface [37], LivingWall [4] and the playful home interior Squeeze [25].

Therefore, interactive interiors based on OUI smart materials have great potential to create immersive enriched user experiences within interior spaces in a range of contexts. Some may be designed as a conversation starter, for storytelling or to stand out from the crowd and/or overcome temporal blindness [5]; while others may be driven by the need to use technology in a way that redefines the identity of the space or the service being presented and practiced within. Other motivations for OUI interactive interiors includes visualizing the unseen [37], yielding pleasure [21] and uplifting emotions and feelings of people through adding new dimensions to the spatial context such as discoverability, revealing, playfulness and temporality.

EXPLORING INTERACTIVE INTERIORS

Our review of related work identified two barriers to the transfer of research into practice. First, previous HCI research does not emphasize the 'design' of the prototypes, in large part due to the computing approach that tends to frame the challenge as one of functional problem-solving nature that is primarily concerned with system performance. That is, an emphasis on functionality and operational aspects of their design rather than the visceral and aesthetic qualities and values it creates and imposes. The second issue is that interactive interior practitioners are rarely concerned with deeper and long-term examinations of how people will interact, perceive and live with such designs for lifetime. Consequently, if we want to explore the design space of different interactive spaces and unwrap the potentials of smart materials in designing interactive interiors and objects, HCI researchers need to engage professional interior designers and architects in a multi-disciplinary exploratory process.

In our study we held two workshops with a total of 45 participants from both disciplines: Architecture and Interior Design, together with a group of supporting HCI researchers to develop concepts and designs for interactive interior spaces. Our objective was to get design disciplines to engage with and explore smart materials using an evolving set of techniques.

INTERIORACTION: CASE STUDY 1

The first case study was a hands-on workshop for a group of architects to get them to experience interactive materials and explore together ways of utilizing and embedding them into building fabrics as a means for designing interactive interior spaces, or as we term 'interioractives'.

Method

The first case study was with the School of Architecture, Newcastle University, UK in which we had 9 participants (3 undergraduate students, and 6 postgraduates in different programs: MArch and MSc in Experimental Architecture) out of which there was 1 male and 8 females. The workshop was held over a full week and was located within our research lab, facilitated by three researchers, and participants signed up willingly as a part of a pre-teaching 'Design Week'. The objective was to collaborate together in groups to ideate and design a interactive interior spaces. Participants were first briefed about the concepts of OUI Architecture and interaction design, then introduced to an array of OUI materials (sensing and actuation) and controlling them using Arduino programming. Several group discussions and brainstorming sessions took place in between their learning sessions to allow them (and us) to evaluate, and critically reflect upon concepts of Interactive Interiors. The smart materials used included shape-memory muscle wires, thermochromic paints, conductive materials and flexible pressure and bend sensors. Participants had a goal to design an interactive interior space that could potentially make use of these novel technologies.

Activity 1: Material Exploration

Participants had the opportunity and time to not only examine the smart materials but to use them in the form of well prepared kits by themselves. We introduced the basics of Arduino electronics and programming to facilitate their hands-on prototyping of different interactive OUIs. They wired different capacitive materials (fabric, thread, fibre, paint, ink and metals) and flexible pressure, tilt, squeeze, bend and stretch sensors as input, and SMA (Shape-Memory Alloy) muscle wires and controllable heating pads for colour-changing thermochromic paints as actuations/output.

Activity 2: Ideation

After the exploring and playing with the materials, participants were asked to work in groups discussing different applications of sensing and actuating interior architectural spaces on four different categories: spaces, surfaces (walls, floors, ceilings, windows, etc), furniture, decoration and accessories. Eventually, few ideas were generated for both the 'spaces' (the whole) and 'accessories' (the detailed), but rather participants focused on 'structural surfaces' and 'furniture'. The ideation activity led to 39 different applications ranging from the simple obvious "window regulating indoor ventilation according to weather or pollution" to the creative and immersive "show warmest place in the house using thermochromic paint" or "lighting sculpture that glows more the more the WiFi-connected number of users in the building". We then analyzed

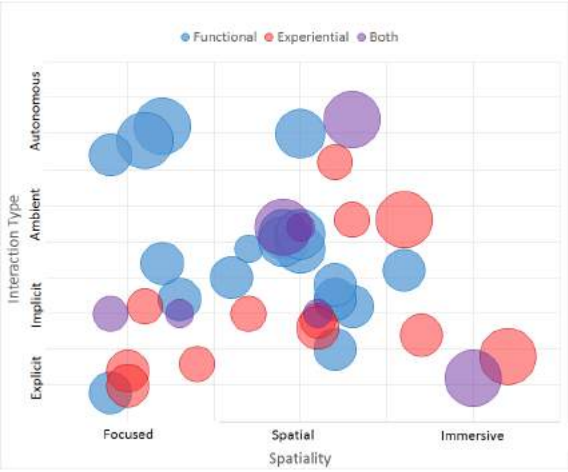

Figure 2. Visualization of data analysis of Case Study 1 Ideation Activity using different dimensions: (a) Spatiality (x-axis), (b) Interaction Type (y-axis), (c) Engagement (diameter), and (d) purpose (colour).

these ideas to unwrap the inherited features and attributes these applications incorporated. Their ideas were (unexpectedly) equally distributed among three types of interaction: (1) Explicit Deliberate Interaction (hand manipulation i.e. touch, press, in-air gestures, speech control); (2) Implicit Motion (motion: proximity/ moving around, posture: sitting down/ laying/ standing, displacement: moving/dropping objects); (3) Ambient and Autonomous: surrounding environment (weather: temperature/ humidity), ambient conditions (sound, light, time, heat) and based on external network feed.

We analyzed these ideas by coding key aspects of each idea/ application according to the type of interaction, spatiality, engagement dimensions, purpose, legibility and re-adaptability. We rated the level of spatiality (over a spectrum from focused to spatial to immersive) and the interaction type (from deliberate explicit control to implicit user actions to ambient conditions recognition and finally autonomous behaviour). We also considered the dimensions of user engagement as: 1D: linear, 2D: planar, 2.5D: planar with an object, 3D: spatial/bodily, 3.5D: building-scale, and 4D: adds the effect of temporality to the 3D engagement. Then we identified the purpose of each application to be either functional, experiential or aiming both function and experience. The result of this analysis is shown in Figure 2 as plotted data points on scales of spatiality and interaction, with the size indicating the dimensions of engagement, for functional (blue), experiential (red) and combined (purple) purposes. Through this approach we only intend to visualize data in a meaningful way that shows the spectrum on a qualitative scale with no emphasis on any particular numerical value so no quantitative rating is considered. As shown in Figure 2, we concluded these findings:

- The average dimension or level of engagement (size of circles) of applications or ideas increases with the increase of the spatiality and/or the interaction getting less intentional i.e. implicit and ambient.
- The average dimension or level of engagement (size of circles) of applications or ideas that has both experiential and functional purposes (purple) is larger than that of those introducing functions only or experience only.

Activity 3: Design Challenge

The whole group then moved from the lab to the wild, with the aim of designing an interactive interior space, in a gallery room around 6m x 4m. The resulting design concept was: creating a playful experience in the form of an 'enchanted' interior, a cave-like dark room with hidden maze-like qualities, themed as 'Alice in Wonderland', and augmented with interactive installations and clue(s) leading to the location of a treasure (a magical object). Based on the sensing and actuation techniques they had learnt about, they split themselves into smaller groups to design and build six interactive installations to augment their interior walls with interactivity:

1. A tactile wallpaper/poster that used conductive fibre and paint to display audio feedback for users playing with it.
2. A touch-sensitive wood wall-panel using capacitive paint manipulating LED lights that shows an arrow for the right way in the maze.
3. A 2D cardboard light switch based on conductive paint, that activated a far away lighting sign showing users what to do next.
4. A haunted/actuated curtain that moved flipping cut-outs using SMA reacting to proximity sensing.
5. A hidden clue painted with thermochromic paint on a wall that only revealed the invisible treasure code when a connected corresponding pressure-sensitive chair was sat on.
6. A treasure (i.e. actuated object) designed as a mushroom model that activated (bounced cap using SMA wire and lights up LEDs) when a user entered the right code by dipping a finger in capacitive connected tea cups.

All designs were then installed and the room was opened for public visitors as part of a bigger architecture gallery event.

Data Analysis

Our gathered data consisted of 8 hours of audio data, recorded during the workshops, to which we chose to perform selective audio transcription of 2.5 hours that formed the entire length of group discussions and presentations after each group activity. The collected data was also supplemented by participants' sketches, schematic architectural drawings, textual written descriptions of their ideas and designs, and most importantly our observational notes made throughout the sessions.

During this workshop, we not only empowered these designers with brief knowledge on new frontier possibilities of dynamic designs and embedded interactions, but we also had the opportunity to to; (1) investigate how they perceived OUI Architecture; (2) examine their views on appropriation and applicability; (3) unwrap new ideas and potentials of such OUIs; (4) discuss and raise new challenges and considerations; (5) design and implement six different interactive artefacts using OUI smart materials; (6) create an Interactive Interior space with an enchanted theme; (7) capture visitors' user experiences with the OUI interior developed, and (8) observe user reactions and interaction behaviours of novice users (i.e. exhibit visitors) with OUI artefacts.

Findings

The results of our data analysis can be articulated in three main themes, describing the unwrapped ideas, potentials and challenges of interioractives. For anonymity, we refer to participants as P1 to P9.

Spatio-Autonomy & Context-Awareness

Participants mainly ideated around different context-aware functional uses for interactive interiors, rather than their aesthetics. For example, P4: *"proximity activates lights leading the way to get somewhere"*, P4: *"curtains change opacity whether it was heated up or it was more brighter outside, the curtains' back would become more or less opaque so the space would be more comfortable inside"* and P5: *"if you walk by, chairs pop out so it reacts to you wanting to sit down."* Other functional purposes were also proposed for interioractive objects such as furniture with context-aware ergonomics such as P3: *"more comfortable furniture that shape your body"*, P6: *"reading chair checks and regulates the surrounding ambient lights"* and furniture responding to noise in the space or supporting space comfort: P5: *"chairs would heat up or become more comfortable and soft the colder you are and then also get rather sturdy and colder if you're too hot"*. Throughout the sessions, we observed how designers started thinking of and referring to interior objects as living things that have minds of their own e.g. P6: *"when bins feel full they can tell us they need to be put out at the night before"*, P6: *"plant pot that moves to stay in the sun"*.

Playfulness vs. Calmness

Temporarily Playful: participants expressed how they feel interioraction can be more appropriate for non-permanent installations (e.g. museum seasonal exhibits, shows, tourist sculptures/ attractions, retail stores, temporary entertainment). For instance, P2: *"a lot of this is about the novelty, it's great when you've never seen it before and it's the first time, fantastic, but if that's on your wall forever, it kinda loses its novelty."* and P6: *"it has to be things that are consistently useful rather than being sort of transiently entertaining"*. So for exciting engagement, sequential interaction was discussed. For example: P2: *"you would touch something then it would tell you something to do next and then that does something else, for example it lights up and when you touch it, it tells you to jump around then when you jump around something else happens."* On the other hand, architects suggested residences and permanent spaces should be designed with "calmness" in mind i.e. designing for permanent settings should be carefully considered to avoid boredom and/or frustration through creating hidden and/or calm interaction scenarios. Alternatively, participants pointed out how interior interaction can not only be pleasurable but provoking as means for promoting physiological wellbeing P1: *"what else could get people moving, for example, if you sat too long on a seat it would get really cold or really warm so that it would help you move like a little provocation somehow so not always pleasurable"*. Still, the design challenge showed how participants kept considering these two paths as an interaction 'double-edged sword' where designing a simple logic is too obvious, unimpressive and therefore not quite playful, while the complicated scenario is unintuitive and often incomprehensible to users. At the end, however, they succeeded in designing their enchanted exhibition in a way where visitors were observably enjoying the playful experience, commenting how it was a *"curious"*, *"surprising"* and a *"wow"* experience (see Figure 6). Although, unexpected user interaction behaviour for exhibit visitors was not uncommon, for example, some visitors were observed repeatedly touching everything as if playing a musical beat with interactive sounds and lights.

Design Constraints and Limitations

Scalability issues bring limitations to some designs; P5: *"probably anything that is out in the rain but needs to be controlled by an electric current would become way more difficult to construct it and also would break much easier*. Other aspects such as the expectations of users were also raised; P2: *"you don't want to make people lazy, you still want them to want to interact with things, but if everything is constantly being done for you, if you have sensors that tell you what the weather is like outside"*, P6: *"what if you want it to be brighter, what if you want to sit in the dark"*, P2: *"when you want the design to stop being intuitive and for you to then as the user to take over that"*. Designs were also constrained by the simple but delicate materials that are quite easy to use/prototype but lack the resilience required for a public installation, so careful considerations needed to be taken (e.g. transparent coating, tight fixing, soldering, etc.).

Critical Reflections

Collaborating with architects yielded a productive framework to design interactive spaces. Architect participants successfully: *(1)* understood how to use smart materials in their designs, *(2)* learnt basic programming and electronics essentials to connect/ build their own circuits with sensors and actuators, *(3)* were able to design and create a playful theme of an interactive interior space in a sequential interaction approach, and *(4)* build an interactive space from raw materials of conductive and electronic products we provided. Although not structurally dynamic or adaptive, the space they designed and constructed was context-aware with embedded interactions within the walls, furniture (sensitive seat) and interior objects (enchanted treasure: cups and center piece) using Arduino microcontrollers controlling motion sensors, tactile conductive, shape-changing and colour-changing materials. What slowed down the design process at the beginning was their need to visit and check the physical location, which wasn't ready from Day 1. We have learnt how the site visit is a crucial starting point for interior architects to be able to conceptualize any design. This should be considered by interaction designers wishing to collaborate with architects to create an interactive space i.e. having the physical space ready before hand and scheduling the site visit at the very beginning. Another lesson we have learned from this case study regards the visitors' reaction and behaviour within the exhibit: not all people should be expected to act in the same normal way. For instance, some visitors were overly cautious while gently touching the touch-sensitive walls, while others were too intense and rough (consumption of wine was involved!). A good interaction design should therefore take such different kinds of users into account.

INTERIORACTION: CASE STUDY 2

Method

The second case study was in the School of Interior Design where 36 students (7 male and 29 female) in their final year of three-year undergraduate program, participated in a full day workshop in their own studio space, together with 3 HCI researchers to facilitate the planned activities. Our research goal was to explore with them the potentials of OUI materials in Interior Design as a means of designing interactive interior spaces in different contexts and using different traditional finishing materials such as Wood, Metal, Paint, Acrylic, Glass, Ceramics, etc. Participants were briefed as part of a module they were attending to develop an interior space for a theatre set for a production of 'Pan's Labyrinth', which we incorporated into our workshop plan to investigate what interesting interaction designs might be employed in such an unusual exciting interior.

Activity 1: Material Exploration

For demonstrating interactive materials to interior design students who are accustomed to material samples from different suppliers, we prepared four sample models that would show tactile and flexible input and colour-change and shape-change output each embedded in standard interior design materials that students may be more familiar with. For example, we designed a tactile palette to demonstrate to designers a variety of possible embedded capacitive-sensing in the form of wood sheet, wood engraving, fabric, leather, fibre, thread, paint, glass, acrylic and ceramic tile, using flexible conductive materials underneath such as capacitive paints, fabrics and metal powders (see Figure 3). These ready made models we prepared helped in rapid learning, exploration of physical interaction and how such materials can be weaved into their normal interior designs.

Activity 2: Ideation

This group activity was designed in a way that is closer to how interior designers work. Their methodology is mainly about how a design concept would be developed based on a series of fixed constraints such as space or building typology, in addition to a set of parameters which allow for creative exploration. As we wanted to explore designing different interactive spaces, we had a set of space contexts (educational, clinical, entertaining, retail, residential and an eatery). We also wanted to explore the possibilities of embedding a variety of the normal interior finishing materials (wood, metal, paint, acrylic, glass and fabrics) with sensing and actuation capabilities. Data sensing may include Explicit hand manipulations or air-gestures, Implicit motion or pressure, Bio-sensing, Environmental conditions, and Ambient sounds or lights, while actuation may include change in physical shape, colour, skin or style, pattern or texture, and activating feedback such as sound, light/shadow or motion. Consequently, we designed six 3 by 3 jigsaw puzzles each containing four pieces (from the set of space contexts, finishing materials, data sensing and

Figure 3. Tactile Palette: a design tool created for Case Study 2 for introducing capacitive-sensing embedded within different interior finishing materials (e.g. wood, fabrics, leather, glass, acrylic, ceramic).

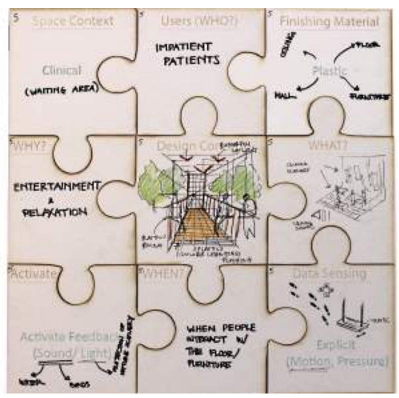

Figure 4. Ideation Jigsaw: a design tool created for Case Study 2 for supporting the development of design concepts to interactive interiors.

actuation effects) that are pre-defined as means of constraining the design with some boundaries, and four other pieces left as variables they can decide (who are the users, what is the interactive surface or object, when will it transform or trigger reaction, and why will it do that). With four constraints and four variables, plus a main middle piece for the design concept, each group would have random nine pieces to help define their interactive interior idea (see Figure 4). This method resulted in a variety of ideas with different combinations of interaction attributes (users, inputs, outputs, context, usability and user experience).

The result was impressive as using this technique proved to be a rapid ideation allowing creativity yet bounded to some constraints. After a few minutes, each of the six groups developed a creative idea of an interactive interior design as following:

1- Shopping in Space: glowing footprints of retail customers would appear on the pressure-sensitive wood floor near key areas (entrance, stairs/lifts, changing rooms) visualizing their flow as they step-in and wander in the shop, could direct them also to area they want, then fading over time. Hangers could also glow to direct customers to their size reacting to speech, all for creating a memorable experience in shopping.

2- 4D Cinema: hall that changes colours/ patterns of soundproofing fabric covering walls, floors based on ambient sounds/ light of movie scenes creating immersive story moods for enhancing people's movie experience, or even seats that could have glowing seat numbers for late audience.

3- Campus Navigator: a wayfinding/ outdoors map navigation system embedded across a university campus that stores and shows students and visitors different routes and paths on opacity-changing glass panels that are touch-sensitive to allow users to point to where they want to go and it shows the path on the interactive glass panel in front of the map background board offering information for lost visitors or students on open days directing them to classes, refreshments, toilets, etc.

4- Sensory Assisted Living: texture-changing (uplifting) and colour-changing (associated to emotions) residential object (water cube sculpture/ wall covering/ floor/ toy tunnel) responding to bio-sensing and facial expressions of special needs (impaired/ blind/ child patients) when different moods detected (through heart rate, etc) by kinetic changing patterns and textures to turn their bad days into good ones, motivate, encourage positivity, optimism, inclusion, normality and playfulness.

5- Healthy Smoothies Bar: an eatery for children designed with organic installations (trees) that moves branches, glows LEDs and transforms colour when heated based on busy rate and day and night temperature for educating kids (healthy nutrition awareness, sustainability) and an interesting feature that when moves unleashes a story.

6- Butterfly Clinic: a clinical waiting area designed as a butterfly garden for impatient patients where pressure-sensitive floor panels (hanging bridge), walls or furniture could produce nature sound effects (birds, grass stepping, waterfall) and display calming nature sceneries, responding to user interactions such as moving around and sitting on motion-sensitive swings and passing underneath ceiling butterflies will move their wings, for relaxation and entertainment while waiting for their turn or stressful waiting for their relatives.

Activity 3: Design Challenge

During the design challenge, participants were split into five groups where they worked on theatre set designs that use smart materials and interaction technology to achieve two main goals: 1) immerse the audience within different scenes and 2) create changing scenery through dynamic shape-changing SMA and colour-changing materials. See Figure 5.

Group1: (War Scene) Use conductive fabric integrated in a sand bag to trigger different effects within the scene such as explosions and light effects, creating an integrated way of performing. Using light and photochromic fabric to change atmosphere of the scene from colourful to dark dingy scene or descending mist on stage activating hydrochromic fabric changing colour of the uniforms from crisp clean to military style gear which is important within that scene. Trees in the scene actuated using muscle wire instead of being a static object. Use photochromic foot prints illuminating way-

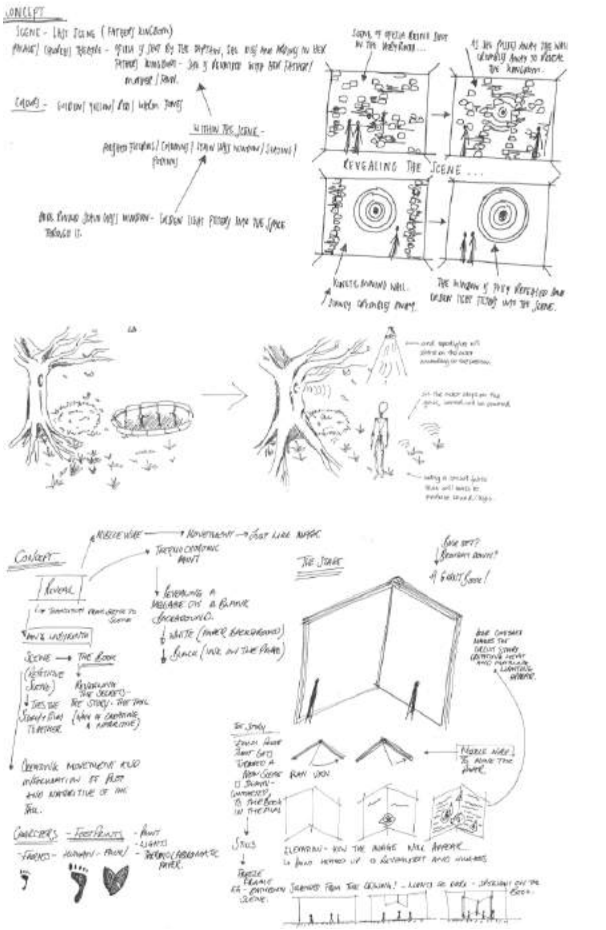

Figure 5. Some sketches from Case Study 2 drawn by participants during the Design Challenge.

finding within the dark theatre. Back-seat panels to produce special effects like smells and gust-air to simulate different senses.Group2: (Last Scene: Death) Use revealing concept to create a scene of stages where the prominent circular back window that lets a lot of light in would react to her death by turning dark once she's shot, colours would be dark, gloomy and dingy. The back wall will use SMA to crumble like rocks break away piece by piece then the wall would reveal another appearance for the next scene, then colours would convert to reveal the golden heaven kingdom. Ink that appears when she opens the book with narrative aspect could be a giant book that reveals the story using thermochromics when pages flip, and footprints of different characters (fairies, etc) would appear to make it magical.

Group3: (Start Scene) When she enters and steps on the grass, it will react to produce sound and spot light to shine on her and follow her as she walks in through the stage, and hidden pressure-sensitive buttons activates the curtain rolling down. The scene where she draws a doorway with a chalk will reveal the perspective view through thermochromics. Similarly, when she reads the book, it reacts by revealing pictures of her future when she touches it.

Group 4: (Labyrinth Pit Scene) when she enters and moves across the stage it will look like she's descending into the pit without actually moving down, using two interlocked circular slanted structures starts off both inline then create focus transition effect between two spaces. SMA hanging from the ceiling creating moving leaves of the forest, and changes the shadows behind it as it moves, as if the sunlight is coming through. Pressure-sensors on stage spark the noise of the forest at night.

Group 5: (Crawling under Tree Scene) getting the audience to make assumptions on what will happen in advance. Create a tree that had dead leaves and flowers that would come to life and open up using SMA to open and close thermochromic fabric flowers and leaves so that when it opens it starts slowly changing colour as well. As she crawls on the sensitive floor will glow beneath her in the dark stage, reflecting the frog scene, creating that sense of mystery. Mapping what is on the stage sets off another response in the cafe or box office, such as glowing footprints of actress, frog, fairies, etc.

Data Analysis

Our gathered data consisted of 6 hours of audio data, recorded during the workshop, to which we chose to perform selective audio transcription of 1.5 hours that form the entire length of group discussions and presenting back after each group activity. The collected data is also supplemented by participants' sketches, schematic architectural drawings and textual written descriptions of their ideas and designs. Again, the notes of our observations of activities constituted a significant part of the gathered data.

This data was then subjected to a process of thematic analysis. Initial codes were generated and refined through iterative analysis to produce coherent themes that were then refined to establish meaningful findings that contribute to the future research of interactive interior architecture and design. Thematic analysis was chosen to reflect the complexity of the research initiative and the desire to retain the generative possibilities of data analysis to support future interactive interior designs. As we had five groups in the Design Challenge activity, we will be referring to them as G1, G2, to G5 from hereafter. The result of thematic analysis process was four main themes described in detail below:

Findings

Special Effects: Light/Shadow, Sounds and Smell

One of the main themes that was clear throughout the data gathered was how designers focused on embedding special effects when asked to design for interactivity. Four out of the five groups used sound and light as means of output feedback/ interaction. Other effects such as smoke and smell (odour) were also used for a more immersive experience. Light was used in the form of both spot-lights and illuminating objects and floors as means of grabbing attention and/ or changing focus from one area or action to another. Personal light was also created to follow the user by G3: *"to shine on her and follow her as she walks"*. Sound effects were often triggered by implicit actions such as walking, stepping and approaching something or somewhere as means of immersive experience engaging different senses. Controlling both sound and light together was a clear theme across different designs with response to motion and other implicit user input, and were considered a bold mix of actuation effects that instantly captures user attention. Shadow was also manipulated with light to create a sense as per G4: *"as if the sunlight is coming through with a dappled shadow-lighting effect"*. Sound and light were also used separately as inputs to trigger other actions; G2:*"once she's shot, .."*, not just an output interaction. In this sense, one interaction can open the way to another, allowing the interior space to conceal and reveal interactions, unfolding as the user digs up embedded sensation/ interactivity and get exposed to hidden discoverability within the space.

Exploring Materiality through Tactile Sensations

All six groups were clearly enthusiastic about embedding sensation within the fabric of their interior design, using both capacitive materials and pressure sensors. Pressure-sensitive floor tiles seamed popular as four groups designed them in different ways considering them a form of G3: *"hidden buttons"* that can control/ activate some features. Apparently they all wanted their interior to have motion detection as means of implicit input that is either deliberate or not, such as walking, approaching or entering somewhere; G3: *"when she enters and steps on the grass"*, G4: *"when she gets to the center"*, G3: *"As she crawls on the sensitive floor"*. Others embedded pressure-sensing as weaved into the fabrics of soft decorative objects; G1: *"conductive fabric integrated in sand bags can trigger explosions and light effects of the war when stood on creating an integrated way of performing"*. Other designs of embedded sensing included manipulating interior objects such as: G3: *"when she holds it"*, G3: *"when she touches it"*. An interesting code was found as: G2: *"would react to her death by turning dark"* meaning that death can be sensed and can trigger the aesthetic death of the interior space of its owner for a mourning time.

Communicating Through Colour-Change

Realizing their disparate properties, participants used a variety of colour-changing materials in their designs to be triggered at different conditions/inputs. Photochromic footprints (triggered by light in the dark) on the floor was repeatedly thought of as means of immersiveness leaving a glowing mark behind to be faded over time, even that of imaginary or distant characters/users who do not necessarily exist within the same space; G5: *"creating that sense of mystery"*, G2: *"would appear to be magical"*. Hydrochromic dyed fabric was used to respond to mist, and thermochromic paints and dyes were used on walls, fabrics and decorative artefacts. Two main reasons were behind using colour-changing interaction in the six designs: 'revealing' and 'reversing'. 'Revealing' a hidden story, text, picture or view was a noticeable objective behind embedding colour-change in different interior elements and composed an essential part in designing discoverability within the space; G2: *"ink that appears to give a narrative aspect to the hanging book that reveals the story using thermochromics when pages flip"*, G3: *"it will reveal the perspective view through thermochromics"*, G3: *"it reacts by revealing pictures of her future when she touches it"*. On the other hand, 'reversing' was the aim of integrating colour-changing materials to change the atmosphere, the feeling and appearance of the space between three states normal/default, cheerful/colourful, and dark/gloomy on both the background (walls) and the foreground (objects) accounting on the psychological effects and social-norm interpretations of different hues of colour schemes; G1: *"to change the atmosphere of the scene from colourful to a dark dingy scene"*, G2: *"once she's shot, colours would be dark, gloomy and dingy.. then colours would convert to reveal the golden heaven kingdom"*. Although not designed, but during the discussions, colour-changing materials were considered appropriate to show the unseen such as mapping distant unseen actions or conditions.

Shifting Focus Through Shape-Change

SMA was mainly used to add dynamics to decorative objects that already exist in their designs and was explicitly justified by adding automated vibrance to the interior; G1: *"trees in the scene are actuated using muscle wire instead of being static"*, G2: *"The back wall will use SMA to crumble away like rocks break away piece by piece without anyone moving anything"*. Kinetic actuation in general was also used to allow a focus-shifting effect between two spaces, scenery transition, revealing a hidden appearance. Another usage of kinetic actuation was to create an illusion of spatial movement; G4: *"it would look like descending into the pit without actually moving down"*. SMA muscle wire was not just used for shape-change but to activate ambient subtle motions that could manipulate light shadows underneath; G4: *"as it (SMA) moves it would change the shadows behind it, as if sunlight is coming through with a dappled shadow/lighting effect"*. However, SMA was mostly considered for an organic actuation effect due to its linear lift and bend nature that resembles a subtle breath motion, so most groups embedded SMA within artificial flowers and tree leaves for ambiance. When integrated within thermochromic fabric the combined effect of shape-change with colour-change attributed to creating a living scenery; G5: *"dead leaves and flowers would come to life and open up using SMA to open and close thermochromic flowers and leaves so that when it opens it starts slowly changing colour as well"*. This technique actually utilized the same energy source/ wiring that heats up the SMA to implicitly heat up the thermochromic fabric triggering colour-change as well, so a flower would blossom and brighten at the same time, as if alive.

Critical Reflections

As much as they succeeded in designing with the concept of 'Revealing', other findings included difficulty of designing for 'Reflection, Speculation, Legibility (Indirectness) & Para-Engagement (Extra-involvement)'. For example, G5 mentioned that during their brainstorm: *"we thought getting the audience to make assumptions on what will happen next in advance"*, then they tried to frame it in other ways *"like mapping, so what is on the stage sets off another response in the cafe or box office"* and even *"get the audience to be part of the play, so what they do reflects on the stage or what actors perform can be projected around the audience, reflecting what happens in the scene"*. These 'para-engagement' types of designs create a deeper meaning of involving the users within a public space and takes engagement and interactivity to a level

Figure 6. Capturing visitors response with the interactive wall-paper at Workshop 1 Exhibition: 'Enchanted Architecture'.

that is beyond the traditional direct interaction that is obvious, discoverable and legible. However, they did not actually design much of these insightful preliminary ideas. Perhaps due to their complexity, deepness and unconventional nature.

While designers in Case 1 expressed more elaboration and interest on the 'structural' scale of surfaces (walls, floors, ceilings) and furniture, designers in Case 2 had a perspective of the 'ambient' scale joined both ends of the holistic view of the 'space' and the decorative details/ accessories that essentially contribute to their conceptual design identity and experience. This is mostly the result of the 'theme' at which each particular case study was framed upon. Therefore, we recommend clear and careful consideration of the setting and subject of collaboration with interior architects and designers to yield both 'functional' and 'experiential' applications and domains to enable the emerge of a new level of 'interioractive' designs.

DISCUSSION

From the observations in both workshops and our architects' and interior designers' efforts to understand and work with the smart materials, in addition to the visitors' feedback during the exhibit (see Figure 6), we have developed three considerations for the design of interactive interior elements. We explicate these below, before turning to discuss how our work is contributing to the developing challenges of 'Interioraction'.

Discoverability and Legibility

The discoverability of an interactive interior space ranges from fully discoverable and understandable to being hidden. By discoverability we mean the property or an interface that describes the extent to which a space is designed to express or hide its interactivity. That is; how quickly can people uncover interactive elements within a space and how an interior can unfold as users start interacting with it, either through implicit or explicit interactions. On the other hand, legibility defines how easily users can make a connection between the cause and effect i.e. input and output of interactions. Some spaces can be deliberately designed in a way that appears disconnected to urge users to systematically act within the space in order to reason what is happening. While we may not need or want to be reasoning about the legibility of some spaces, others should be designed in a way to reveal cause and effect relationships in dynamic environments.

	Fully Discoverable	Undiscoverable *(Hidden Interaction)*
Fully Legible	Obvious and Consistent	Hidden and Playful
Not Legible *(Hidden Logic)*	Spatio-Temporal and Autonomous	Mysterious and Magical

Table 1. Combinations between ranges of discoverability and legibility of an interactive interior space

In this sense, there is a clear relationship between discoverability (clarity of how to interact) and legibility (clarity of why it reacts). Table 1 shows how combining different ranges of discoverability and legibility can result in different space interactivity features and qualities. For example, a fully discoverable (flat) space that is fully legible (intuitive) with simple logic is understandable, obvious and consistent such as a regular light switch. An undiscoverable (unfolding) space that is also fully legible will be more playful (as it unfolds hidden interactions) depending on its learning curve as it still holds a 1-to-1 legible constant reaction, such as the Engaging Space [7] and the History Tablecloth [10]. On the contrary, a fully discoverable illegible interactive space is one that reacts to complicated logic/ scenarios that often use more variables in the interaction equation such as number of users/tangibles, their position/ roles within the space as well as variable time, distance/proximity or a composition of more variables creating spatio-temporal responses, sequential or accumulative interactions over time. This combination results in an autonomously-perceived space or object with no clear idea of why it is changing or behaving in a certain way, e.g. shape-changing bench [15]. Finally, a space that doesn't immediately show how to interact with it or why it is changing creates a mysterious atmosphere and can in the right circumstances then be perceived as a magical object or an enchanted space.

Revelation and Coherent Dynamics

How the interior space can conceal hidden appearances, and hidden personality of its own and be able to slowly reveal them through user interaction is an interesting aspect of an interactive interior. Although it is not necessarily always the case, a space that entirely transforms its interior elements together playing one symphony creates an immersive experience with its coherent dynamics. For example, colour-change and/or texture-change of an interior's wall paint, curtain, sofa cushion, flower vase, rug and wall art can create an impression of a whole new space or reveal a different feeling or mood. This can be achieved by wirelessly networking each of these soft decorative interfaces and playing with the options of appearance-changing in a coherent theme that can unfold together showing the veiled mystery beneath, designing for both the playfulness and aesthetics of interaction [25].

Spatio-Temporality and Spatio-Autonomy

An actual immersive experience is the one that takes interaction into 4-dimensions (rather than just 3D) by adding temporality as a key player in the user spatial interaction. An interior element can change its appearance as a result of interactions done over a week, capturing all the dynamics of the space within that period of time rather than instantaneous reactions developed in previous work [20, 37, 4] that relied on a direct and prompt action-reaction approach. Once we design interactive spaces that can change over time or possess some autonomy of their own, our environment can start communicating 'self-expression' through their unfolding interaction.

INTERIORACTION CHALLENGES

Through this exploratory study we aimed at tackling some of the key challenges of Interactive Architecture [22]. Primarily, 'Radical Interdisciplinarity' through engaging relevant design communities i.e. architects and interior designers. Our engagement -as interaction designers- with interior architecture designers has taken a shape that is beyond the traditional researcher-participant relationship. But was rather a co-designer and co-author interrelationship where we all worked together in collaborative ideation, exploration and design group activities and discussions. This yielded a unique and productive experience that should specifically be applied to research around interactive spaces which is inherently multi or interdisciplinary. Other challenges we tried to exploit included 'Appropriation and Retrofitting', where we succeeded in embedding interactivity into standard finishing materials and decorative objects with simple, affordable and available materials that are paintable, printable and programmable. Whilst a delicate and tricky task, the new techniques we have introduced (e.g. the jigsaw, tactile palette, etc), helped simplify the ideas and forms of retrofitting such normal materials and real-world objects in a way that keeps -and extends- the aesthetics of the interior space and does not jeopardize the social and emotional associations people have with daily physical objects and surfaces. However, with regards to 'Scalability', we faced numerous obstacles related to embedding them in room-sized scale, but found iterative design methods and special material considerations to be helpful.

CONCLUSION

Not only did we *i)* engage architects and interior designers in 'interaction design' for creating interactive spaces, but also, through this collaboration, we have *ii)* explored the design space of interioraction, usages and limitations, *iii)* explored the potentials of affordable interactive materials in designing and prototyping interioractives, *iv)* developed new design techniques to do so, *v)* designed six different interactive spaces with a holistic experience, and built an actual interactive interior space (with reactive walls, furniture and decorative objects), *vi)* addressed some of the challenges identified for interactive architecture, and finally *vii)* tested and captured user responses to interactive spaces of novice users (in the wild) who were visiting our 'enchanted' exhibition. As we intend to continue such engaging and inclusive studies, we encourage the community to carry on similar collaborations and investigate new possibilities and potentials of 'Interioraction'.

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REFERENCES

1. Aedas Architects. 2012. Al Bahr Towers. Abu Dhabi, UAE.
2. Nimish Biloria and Valentina Sumini. 2007. Performative Building Skin Systems: A Morphogenomic Approach Towards Developing Real-Time Adaptive Building Skin Systems. *International Journal of Architectural Computing* 07, 04 (2007). DOI: http://dx.doi.org/10.1260/1478-0771.7.4.643
3. Stewart Brand. 1995. *How buildings learn: What happens after they're built*. Penguin.
4. Leah Buechley, David Mellis, Hannah Perner-Wilson, Emily Lovell, and Bonifaz Kaufmann. 2010. Living Wall: Programmable Wallpaper for Interactive Spaces. In *Proceedings of the international conference on Multimedia*. Firenze, Italy, 1401–1402. DOI: http://dx.doi.org/10.1145/1873951.1874226
5. Nicholas S Dalton, Emily Collins, and Paul Marshall. 2015. Display Blindness? Looking Again at the Visibility of Situated Displays using Eye Tracking. In *CHI'15*. ACM, Seoul, Republic of Korea. DOI: http://dx.doi.org/10.1145/2702123.2702150
6. Nicholas S Dalton, Holger Schnadelbach, Mikael Wiberg, and Tasos Varoudis. 2016. *Architecture and Interaction*. Springer.
7. Dalziel & Pow. 2015. Engaging Space. In *Exhibited at the Retail Design Expo (RDE) in 2015*. Exhibited at the Retail Design Expo (RDE) in 2015, London, UK.
8. DARLING QUARTER. 2016. Luminous | Darling Quarter. (2016). http://www.darlingquarter.com/luminous/
9. Simon Dodsworth. 2009. *The Fundamentals of Interior Design*. 184 pages. https://books.google.co.za/books/about/The
10. William Gaver, John Bowers, Andy Boucher, Andy Law, Sarah Pennington, and Nicholas Villar. 2006. The History Tablecloth: Illuminating Domestic Activity. *Dis 2006* (2006). DOI:http://dx.doi.org/10.1145/1142405.1142437
11. Sven Gehring, Elias Hartz, and Markus Löchtefeld. 2013. The Media Façade Toolkit: Prototyping and Simulating Interaction with Media Façades. In *UbiComp'13*. Zurich, Switzerland. DOI: http://dx.doi.org/10.1145/2493432.2493471
12. Ernst Giselbrecht. 2010. Kiefer Technic Showroom. Styria, Austria.
13. Mark Goulthorpe. 2000. Aegis Hyposurface. Cambridge, Massachusetts, USA. http://www.hyposurface.org/
14. Jens Emil Grønbæk, Henrik Korsgaard, Marianne Graves Petersen, Morten Henriksen Birk, and Peter Gall Krogh. 2017. Proxemic Transitions: Designing Shape-Changing Furniture for Informal Meetings. In *Proceedings of CHI '17*. Denver, CO, USA.
15. Erik Grönvall, Sofie Kinch, Marianne Graves Petersen, and Majken K. Rasmussen. 2014. Causing Commotion with a Shape-Changing Bench. In *Proceedings of CHI'14*. Toronto, ON, Canada. DOI: http://dx.doi.org/10.1145/2556288.2557360
16. Henning Larsen Architects. 2014. Kolding Building of SDU. Universitetsparken Kolding, Denmark.
17. Chuck Hoberman. 2004. Hoberman's Arch. Salt Lake City, Utah, USA.
18. Yannick Joye. 2007. Architectural Lessons From Environmental Psychology: The Case of Biophilic Architecture. *Review of General Psychology* 11, 4 (2007), 305–328. DOI: http://dx.doi.org/10.1037/1089-2680.11.4.305
19. Stephen Kaplan. 1995. The Restorative Benefits of Nature: Toward an Integrative Framework. *Journal of Environmental Psychology* 15, 3 (1995), 169–182. DOI: http://dx.doi.org/10.1016/0272-4944(95)90001-2
20. Chin Koi Khoo and Flora D. Salim. 2013. Lumina: A Soft Kinetic Material for Morphing Architectural Skins and Organic User Interfaces. In *Proceedings of UbiComp'13*. Zurich, Switzerland, 53. DOI: http://dx.doi.org/10.1145/2493432.2494263
21. Nadia Mounajjed and Imran A Zualkernan. 2011. From Simple Pleasure to Pleasurable Skin: An Interactive Architectural Screen. In *DPPI '11*. Milano, IT. DOI: http://dx.doi.org/10.1145/2347504.2347537
22. Sara Nabil, Thomas Plötz, and David S Kirk. 2017. Interactive Architecture: Exploring and Unwrapping the Potentials of Organic User Interfaces. In *Proc. of TEI'17*. Yokohama, Japan, 89–100. DOI: http://dx.doi.org/10.1145/3024969.3024981
23. Jean Nouvel. 1987. Institut du Monde Arabe. Paris, France.
24. Kas Oosterhuis and Nimish Biloria. 2008. Interactions with Proactive Architectural Spaces. *Commun. ACM* 51, 6 (2008). DOI:http://dx.doi.org/10.1145/1349026.1349041
25. Marianne Graves Petersen. 2007. Squeeze: Designing for playful experiences among co-located people in homes. In *Proceedings of the ACM 2007 Conference on Human Factors in Computing Systems*. San Jose, CA, USA, 2609–2614. DOI: http://dx.doi.org/10.1145/1240866.1241050
26. Philips Lighting. 2016. Philips Luminous Patterns. (2016). http://www.lighting.philips.com/main/systems/packaged-offerings/retail-and-hospitality/luminous-patterns.html
27. Ingrid Maria Pohl and Lian Loke. 2012. Engaging the Sense of Touch in Interactive Architecture. In *Proceedings of the 24th Australian Computer-Human Interaction Conference on - OzCHI '12*. Melbourne, VIC, Australia, 493–496. DOI: http://dx.doi.org/10.1145/2414536.2414611

28. Larissa Pschetz and Richard Banks. 2013. Long Living Chair. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*. ACM, Paris, France, 13–14. DOI: http://dx.doi.org/10.1145/2468356.2479590
29. Carolina Ramirez-Figueroa, Martyn Dade-Robertson, and Luis Hernan. 2013. Adaptive Morphologies: Toward a Morphogenesis of Material Construction. In *ACADIA 2013 Adaptive Architecture*. Cambridge, ON, Canada, 21–23.
30. Axel Ritter. 2015. *Smart Materials in Architecture, Interior Architecture and Design*. Vol. 1. Birkhauser. DOI: http://dx.doi.org/10.1017/CBO9781107415324.004
31. Francesca Rogers and Daniele Gualeni Design Studio. 2010. Light-Form. In *Designed for ILIDE (Italian Light Design) and Exhibited at the Milan Design Week in 2010*.
32. Holger Schnadelbach, Ainojie Irune, David Kirk, Kevin Glover, and Patrick Brundell. 2012. ExoBuilding: Physiologically Driven Adaptive Architecture. *ACM Transactions on Computer-Human Interaction* 19, 4 (2012). DOI:http://dx.doi.org/10.1145/2395131.2395132
33. Odilo Schoch. 2006. My Building is my Display. In *Proceedings of the the 24th Conference on Education and Research in Computer Aided Architectural Design in Europe: Communicating Space(s) (eCAADe'06)*. Volos, Greece, 610–616.
34. Nicolas Schöffer. 2005. Spatiodynamic, Luminodynamic & Chronodynamic. In *Nicolas Schöffer's Précurseur de l'Art Cybernétique Exhibition*. Paris, France.
35. Roel Vertegaal and Ivan Poupyrev. 2008. Organic User Interfaces. *Commun. ACM* 51, 6 (2008), 26. DOI: http://dx.doi.org/10.1145/1349026.1349033
36. Richard Weston. 2003. *Materials, Form and Architecture*. Yale University Press.
37. Bin Yu, Nienke Bongers, Alissa van Asseldonk, Jun Hu, Mathias Funk, and Loe Feijs. 2016. LivingSurface: Biofeedback through Shape-changing Display. In *Proceedings of the TEI '16*. Eindhoven, Netherlands, 168–175. DOI: http://dx.doi.org/10.1145/2839462.2839469

Appendix H. Paper 4: OUI Architecture and Interiors

Interactive Architecture: Exploring and Unwrapping the Potentials of Organic User Interfaces

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ABSTRACT
Organic User Interfaces (OUIs) are flexible, actuated interfaces characterized by being aesthetically pleasing, intuitively manipulated and ubiquitously embedded in our daily life. In this paper, we critically survey the state-of-the-art for OUIs in interactive architecture research at two levels: 1) Architecture and Landscape; and 2) Interior Design. We postulate that OUIs have specific qualities that offer great potential for building interactive interiors and entire architectures that have the potential to –finally– transform the vision of smart homes and ubiquitous computing environments (calm computing) into reality. We formulate a manifesto for OUI Architecture in both exterior and interior design, arguing that OUIs should be at the core of a new interdisciplinary field driving research and practice in architecture. Based on this research agenda we propose concerted efforts to be made to begin addressing the challenges and opportunities of OUIs. This agenda offers us the strongest means through which to deliver a future of interactive architecture.

ACM Classification Keywords
H.5.m Information Interfaces & Presentation (e.g. HCI): Misc.; J.5 Computer Applications: Arts & Humanities – Architecture

Author Keywords
Organic user interfaces; Tangible user interfaces; Shape changing interfaces; interactive architecture; kinetic building skins; ambient displays

INTRODUCTION
Organic User Interfaces (OUIs) arguably represent the flexible, adaptive and malleable version of both Tangible User Interfaces (TUIs) and Shape-changing interfaces (SCIs). Initially introduced as 'organic tangible interface' or 'organic TUI' [33], OUI evolved offering radical new materialities and form factors that underpin both input and output interactions, coinciding with Ishii's vision for the future of UI as 'Radical Atoms' [34]. Therefore, over recent years OUIs have seen increased interest amongst HCI [11], Ubicomp [76] and TEI research communities [24].

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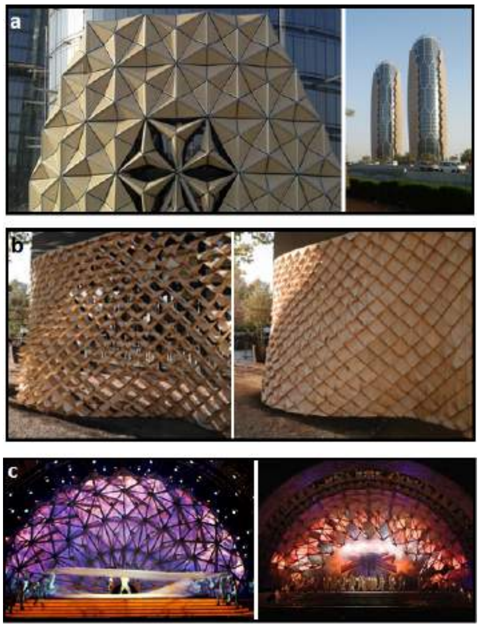

Figure 1. Examples of OUI Architecture: a) Kinetic sun-shade: Al Bahr Towers by Aedas Architects, Abu Dhabi 2012; Photo credit: Aedas.com. b) Climactive skin: Hygroscopic Envelope Prototype, 2010 [64]; Photo credit: Steffen Reichert. c) Shape-changing: Hoberman Arch by Chuck Hoberman, Salt Lake 2002 [28]; Photo credit: hoberman.com.

By definition, OUIs are non-planar interfaces taking any 3D shape and morphing either actively or passively, to support direct physical interaction [31, 33, 65, 76]. So, OUIs enable manipulative and bodily input (like TUIs) and kinetic interactions (like SCIs) facilitating flexible form and change of appearance as output, which matches their intended function and supports intuitive interaction. However, OUI conceptually depends on the 'shape' of the interface being the 'key' for interaction; that is: the physical 'form' conveys its function and invites users to familiar interactions such as deformable/non-deformable hand manipulations in addition to body gestures and movements, including hand, head, eye tracking, etc. [51] as means of user input; and multi-sensory auditory, visual or haptic feedback as means of output interaction. Early examples of OUIs range from surface computing, volumetric (spherical [3], polygonal [52], cylindrical [4], etc.) and bendable computers to flexible displays or paper computers [1]. Similarly OUI can utilize flexible, deformable, skin-changing and shape-changing materials in order to cover, embed and surround real-world objects and environments.

The concept of OUI builds on organic electronics or 'Transitive Materials' [11, 34] allowing displays/ devices to be malleable & actuated in an aesthetically pleasing way. Examples of such flexible and controllable displays include flexible Organic Light Emitting Diodes (OLED), Electrophoretic displays (EPDs), and Electroluminescent Lighting (EL). In addition to flexible displays, OUI can be designed using all ranges of flexible conductive materials; from paper or fabric to wood and glass that has embedded thin & flexible electronic sensors, microcontrollers and actuators, such as muscle wires, metal powder, conductives (thread, fabric and paint), optical fibres, thermochromic color-changing pigments and e-textiles. Such materials and technologies pave the way for rethinking user interfaces that can be embedded into everyday objects. Accordingly, OUI have great potential for radically new applications, e.g., dynamic artwork, pattern-changing fabrics, reactive architectural facades or even entire interactive spaces.

Examples of OUIs that have specifically explored new materialities include FuSA [53] the furry display, ClothDisplays [42], Hairlytop [56] and uniMorph [27] a curved actuated interface that enables designers to print custom responsive OUIs in various flexible and dynamic forms. In addition, one of the key potentials of OUI is their malleability, as seen in Follmer et al. [17], who introduced a technique for enabling programmatic control of a material's stiffness enabling actuated manipulations and deformations as both input and output interactions. Several other possibilities of deformable display materials have been motivating researchers for the past few years creating leading to innovative ideas and novel flexible design materials [2].

These kinds of interactive technology have enormous potential to not only change the nature of our interactions with technology but also to change the very environments we inhabit. Computational processes and interactivity will become increasingly embedded within the environment (as per the vision of ubiquitous computing). However, those environments will also increasingly react to our presence through embedded sensing, now with the additional potential to change form and function on demand. Accordingly, technologies such as 'Reactive Architecture' [68] and 'Kinetic Architecture' [39] offer substantial scope for redefining current architecture (see Figure 1). However, such architectural interventions are quite rare, and commonly only possible as new builds (thereby ignoring existing building stock) and largely neglect interior design, focusing more on dynamic structural features or interactive service layers within the building fabric.

We believe that OUIs have significant potential for opening up a new architectural design space for the development of interactive architecture and interior design. In this paper we make a case for this and encourage researchers & practitioners to adopt OUIs as key technology for future developments in this area. We begin by examining the state-of-the-art in OUI to lay out the play-of-possibilities that they offer, before looking at current applications in interactive architecture/ interior design. We then formulate a manifesto, i.e., our vision for the role of OUIs in architectural design and then finally present an articulation of the future challenges for researchers and practitioners to realize this radical pervasive computing agenda.

OUI: THE STATE-OF-THE-ART

Through contextualizing OUI with regards to the state-of-the-art we can formulate the research agenda for OUI as means for interactive architecture and interior design. In this section, we explore a specific subset of OUI application areas to demonstrate the general concept of Organic User Interfaces and to highlight advantages and benefits of designing interactive architectural spaces. We divide potential OUI applications into two levels matching the common classic design disciplines: 1) Architecture and Landscape; 2) Interior Design. Although, we do realize that both levels are not mutually exclusive or complementary, but are inter-related in many aspects, we tackle each level as to present OUI potentials from a holistic large-scale experience to the smallest ornamental detail. The first level focuses on the entire architecture of buildings and planning the landscape/environment around them, where OUI buildings could be reactive to people, environment or other buildings. The second level includes reactive surfaces, context-aware spaces within buildings and interactive interior elements.

OUI Architecture

Architectural history demonstrates early adoptions of 'Organic Architecture' emphasizing how organic designs (from buildings to ornamental details) could be flowing in harmony and blended naturally with our environment whilst fulfilling their essential structural, functional and aesthetic purposes [58, 41]. Decades ago, architect Frank Lloyd Wright's philosophy of 'Organic Architecture' focused on nature-inspired organic designs for buildings to be "not only convenient but charming" imagining both the exterior of buildings, the interior areas together with furniture and decorative accessories all integrated into a design that serves and contributes to users' values concerning usability and comfort. Although how literal the term 'organic' was used back then do refer to non-rectlinear architectural designs, OUI takes it further to focus on impacting aesthetics of interactive architecture or 'architecture as user interface' that should live, grow and adapt with users along their lifetime. We believe that Wright's ideas emphasizes the motivation and need for OUI architecture harvesting the value of designing any building or artefact -even a digitally augmented one- in real-world affordances and aesthetics.

Evident ecent literature of architecture ('Dynamic Buildings' [40], 'Interactive Architecture' [36, 18, 25] and 'Responsive Landscapes' [8]) and practice (Diller & Scofidio, Jean Nouvel, Chuck Hoberman, Ned Kahn) architects started envisioning the future of architecture using smart materials that can sense, react and integrate with their architectural designs. Some authors even proposed the integration of physical computing, robotics and sensor technologies. However, collaboration with HCI communities, UI and UX designers and researchers to fully realise the potential of these novel interfaces is still quite limited. For example, 'Kinetic Facades' [49] started to be adopted in architecture as means for energy-efficiency using flexible sun-shade envelopes that cover several buildings nowadays around the world. This is one kind of interaction with the environment. OUI Architecture concept incorporates a broader meaning and understanding of dynamic architecture in a way that would be more interactive and organic. For example, climactive architectural skins that react to environmental changes such as sun light/shadow, temperature, humidity, rain, wind, etc to create dynamic forms that would essentially change how people perceive and feel their surroundings. Figure 1 shows different examples for OUI Architecture.

In HCI, recent studies around architecture such as 'Kinetic Organic Interfaces' (KOI) [39] and 'Proactive Architecture' (ProA) [57] have developed notions of responsive actuated buildings with mass customization designed in entirely new aesthetic (curved surfaces, bent lines, organic designs, and unusual innovative structures) and responsive to both users and its surrounding environment (temperature, wind, solar radiation, etc), emphasizing the need and possibility for buildings to be dynamic and interactive enough in order to change physical form autonomously thereby reflecting context-awareness. Oosterhuis et al. describe the concept of proactive architecture as buildings that are "organic, ever-changing vehicles for processing and displaying information" [57].

Similarly, studies of 'Adaptive Architecture' [5, 68] attempted to create a self-sustaining, user oriented and real-time interactive 'skin' where building designs involve entire dynamic facades that are flexible in two opposite curvatures during their movement, with embedded sensors (light, energy, humidity) and actuators to generate kinetic adaptations that respond to, store and regulate environmental factors (sun, wind, precipitation) enhancing comfort level, social interaction and environmental conditions within the living environment. ExoBuilding [68] is an example of adaptive architecture, exploring potential biofeedback relationships between buildings and users.

Alternatively, the term 'Interactive Architecture' has been used. For example, Acacia [44] is a platform developed for the design of interactive building facades using organic smart materials allowing interactivity between users, buildings and the environment. In this sense, responsive architectural facades are thought to bring opportunities that redefine building skins offering impactful values being both architecturally aesthetic and interactive surfaces at the same time. Similarly, other researchers [50, 61, 39] have been motivated to study and design interactive architectural facades using OUI arguing how the visibility and size of building facades together with possible embedded capabilities create potential for utilizing them as public displays or interactive architectural surfaces.

Others envisioned 'Display Buildings' [69, 21] where buildings and cities will become gigantic multi-dimensional, frameless displays and entire architectural surfaces can become interactive media facades using huge screens in building scale, wrapped around surfaces that are possibly curved facades. Schoch [69] suggested that architects should design interactive buildings that can significantly change its appearance, using novel materials, describing such interface as changing 'curtain' covering the entire building than a distinct display.

More sustainable designs has considered the use of organic and natural materials that are responsive to different environmental conditions. Responsive materials such as hydromorphic, hygromorphic [47, 32] , photomorphic [14] or thermomorphic materials can sense changes in moisture, humidity, light or temperature respectively and autonomously react by changing their physical shape or colour. For example, Climactive wood [47, 13] that is physically programmed to respond to rain through shape-changing hygromorphic natural thin wood (see Figure1.b) and SynthMorph [62] that uses synthetic biological materials such as morphological bacteria [63] as construction elements for shape-changing architectural structures. Such OUI Architecture does not require electronic or mechanic control, or even energy-consumption but are engineered to autonomously react to certain environmental conditions creating novel dynamic spatial experiences.

Again, we refer to OUI Architecture as not just 'literally' organic in form or materialism, but as user interfaces that are ambient, and dynamic in a way that allows buildings and architectural structures (from bridges to sculptures) to react, express or heal us through changing their appearance or shape similar to the way humans and animals are able to communicate by simple speechless gestures or subtle reactions. OUI architectural designs can shift the appearance of exterior facades/skins, physically transform position, orientation, colour, lighting or curvature of either small modules or large blocks. Such organic interactions can be subtle, slow transformations, or reactive to people's needs and contextual situations. Think of a stadium that autonomously reacts to spectators' cheers or a bridge that illuminates in a way that expresses its traffic load or rain-sensitive convertible pedestrian walkways, or city skyline towers that can together chant a silent melody to celebrate.

OUI Interior Design

Although interior spaces are typically of static nature that require an interior designer and/or architect to facilitate any changes to their appearance and function, the idea of dynamic interiors has recently gained popularity. Interior elements such as surfaces (walls, floors, ceilings) and openings (doors, windows) can be augmented with digital technology to enhance both their aesthetic impact and potential dynamic functionalities. Examples of interactive interior walls are Smartwall [16], LivingWall [7] and LivingSurface [78], while GravitySpace [6] is an interactive floor. However, ceilings seem to be neglected from similar interaction design in spite of all opportunities and potentials that could potentially be addressed especially in bedrooms where users lie down facing their normally plain ceilings.

In general, research on building interactive surfaces and walls has taken two approaches: either wall-sized emissive displays or subtle ambient designs. Wall-sized displays are either light-emissive (i.e. LED displays) or projection-based, while subtle tactile designs focus on embedding interactivity in normal coating, lighting or different finishing materials, such as wood panels, ceramic tiles, wallpaper, ..etc. An example for the first approach is Smartwall [16] where the wall display is divided into large pixel-like, reconfigurable cells that users can select

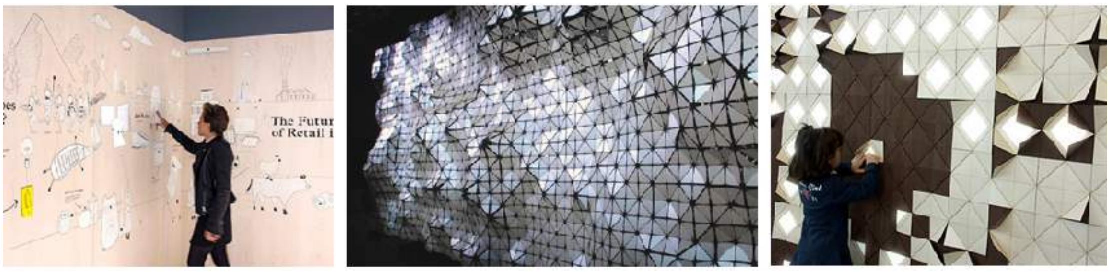

Figure 2. Examples of OUI Interior. Left to right: a) Engaging Retail Space, Dalziel & Pow, 2015 [dalziel-pow.com] b) Aegis Hyposurface, Mark Goulthorpe, 2000; Photo credit: Mark Burry c) Light-Form interactive wall, Francesca Rogers, 2010; Photo courtesy: Daniele Gualeni Design Studio.

and/ or drag each cell representing a certain function, utilizing room dividers and interior walls in user interaction design. Similarly, GravitySpace [6] is an interactive floor designed for smart rooms using real-time tracking, detecting multiple users, their positions/ orientations, and furniture through the pressure-sensitive, back-projected floor.

On the other hand, LivingWall [7] is an interactive wallpaper that uses conductive paint layers connected to microcontrollers and LEDs for interactivity. Users not only interact with it by touching it, but also through walking beside it, which creates a playful experience for interactive interior and a large ambient dynamic wallpaper. Likewise, LivingSurface [78] is a shape-changing surface that interacts with users through its non-emissive material that rather changes its physical shape in response to sensed user physiological data, reflecting their internal body processes such as heart rate and blood volume pulse. The shape-changing interaction of LivingSurface is designed using cutouts in the wallpaper that is actuated to form different interesting 3D shapes. Actuation is deployed in a back layer embedded with hidden servo-motors, vibration motors and small fans controlled using Arduino microcontrollers. The same effect could be implemented without motors using non-mechanical linear actuators such as muscle wire or Shape-Memory Alloys (SMA) that are light-weight thin wires with strong and silent actuation capabilities.

We believe that non-emissive responsive surfaces are much more appropriate to be widely adopted in our environments as they do not constantly stand out and capture attention like with emissive wall displays. Therefore, non-emissive materials and ambient ubiquitous interaction are more appropriate to designing and creating entire interactive interior spaces rather than just a single actuated surface or wall. Still, some examples have used lighting techniques in ambient interactivity such as Light-Form by Francesca Rogers (see Figure2.c) and Luminous by Philips [59] creating interesting playful experiences. Figure 2 shows examples of interactive interiors.

Likewise, other interior elements that range from furniture and decorative art to soft furnishing such as cushions, curtains and carpets can be transformed into OUI devices employing haptic interactions they already afford, serving both beauty and function. Previous work on interactive furniture includes interactive tabletops [35] and shape-changing furniture such as EmotoCouch [48] and shape-changing bench [26]. Other interior elements have also been investigated in OUI research creating haptic interior artefacts such as interactive Tablecloths [20, 72], interactive curtains [19, 71], wall art [75], lampshade [37] and other interior 'Soft User Interfaces' [70].

The above examples form rich inspiration for artists, designers and architects, but only scratch the surface of possibilities for promising smart and dynamic interiors yet to come. General benefits of interactive interiors have been discussed in related prototype installations [20, 46, 48]. By generalizing the concept, we come closer to the vision of ubiquitous computing where technology quite literally weaves into the fabric of everyday life [77], providing inhabitants with potential benefits at both the emotional and physical level. The emotional and psychological effect of changing interiors, e.g., colours, lights, shapes and textures, can have significant impact on inhabitants, potentially leading to improved quality of life through novel, possibly serendipitous experiences and sensory stimulations.

A MANIFESTO FOR OUI ARCHITECTURE

Although previous work on OUI has mentioned art and architecture as interesting applications of OUI, e.g. [12, 31, 65, 76], no systematic research has been undertaken investigating, questioning and discussing how 'OUI Architecture and Interior' can be designed, perceived and lived with. This is a missed opportunity, as instead of having our built environments as static structures built from static materials, designing them as OUIs can create dynamic, responsive and thus context-aware architecture. OUI Architecture can be actuated to modify its appearance, spaces and surfaces as a response to interaction with users, other devices (or buildings), and the surrounding environment. All of which emphasizes the motivation, opportunities and potentials of designing architectural elements that can be interactive, responsive and, consequently, have the potential for fundamentally changing the way architecture and interior design is done leading to radically different ways of interacting with the built environment.

In the sections above we have identified the potential of OUI for substantially opening up a design space that offers new opportunities for Interactive Architecture and Interior Design. Adopting this direction would emphasize how technology can support future architecture in a way that is beyond contemporary techniques of Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM) and Computer-Aided Engineering (CAE) applications.

In the following we present a manifesto outlining the key considerations for OUIs as a core technology underpinning our vision for the future of architecture and interior design.

1. **Ubiquitous Interaction**: OUI interaction is defined as intuitive and familiar affordance of everyday objects in our physical world[23, 22, 30]. This allows to employ both explicit and implicit interactions we perceive and perform on a daily basis into the fabric of future interactive spaces, fulfilling Weiser's vision of ubiquitous computing [77]. OUI explicit input interactions could range from physical hand manipulations (both deformable and non-deformable) to in-air gestures, body motions and speech [22] resembling more intuitive human-physical and human-human interactions [65]. Implicit input may be triggered by other activities, motion or presence, psychological or physiological sensing or environmental stimuli. Output interactions range from simple visual and haptic feedback such as light, sound or motion to richer sensory and morphological actuation, e.g., skin-change or shape-change. In this sense, people will engage effortlessly through their normal daily interactions with real-world objects and environment, and step into immersive experiences of a ubiquitous dynamic world.

2. **Context-Awareness**: With OUIs, architectural and interior designs can be context-aware for both occupants and the surrounding environments. A user's environment can be seamlessly embedded with technology that captures, analyses and understands different situations and contexts changing around. Earlier work on smart environments has led to robust but not necessarily non-intrusive sensing and inference systems (e.g., [66, 67]). Morphological natural or manufactured responsive materials [47, 32] that sense changes in humidity or temperature and react -by transforming their shape or colour- are rich materials for context-aware building envelopes and fabrics, at no energy cost. Equally, there is clear potential to leverage the strength of the emergent Internet of Things (IoT) to support this seamless networking of OUIs (e.g., [74, 38]). This furthers the vast potential to leverage interaction with everyday objects as sources of data and user input to interactive environments and offers opportunities for interactive interfaces to be based on our interactions with familiar objects. For example, OUI Walls can expect user actions and therefore emerge hidden parts or layers, i.e. bring out a hidden shelf when user holds something needs to put down; or bring out a hidden seat when user seams tired and looking to sit down. In this sense, a new generation of context-aware smart buildings and smart homes can emerge, i.e., rooms that can change their size based on occupants and context of use, decorations that can change their skin based on temporal or social events, and exteriors that can be interactive as well.

3. **Dynamic Nature**: Advances in organic smart materials will allow interfaces to be malleable, deformable, change colour or shape, and be actuated, giving us unprecedented opportunities to design dynamic architecture and interior designs that are not necessarily static like most contemporary designs. OUIs will offer the flexibility of dynamically changing structures and spaces, either on demand (passively) or autonomously (actively). Changing tastes or interests will be accommodated instantaneously. And likewise with exterior architecture, which no longer has to be fixed, using smart OUI materials, a building will be able to alter its facade or even dynamically reconfigure its internal spaces to suit the needs of inhabitants. Essentially, this vision requires re-thinking current architectural methodologies in different ways as it is not that obvious yet, but would also solve historical dilemmas for architects such as orientation towards sun light, view and natural ventilation through dynamic adaptive architecture. Some are already considering buildings that rotate with the sun [49]. So we can foresee the future of having skin-changing and shape-changing architecture being feasible, practical and efficient.

4. **Seamless and Seamful Sensing**: Possibly complete houses and entire buildings can be embedded with intelligence through technology to allow seamless and spatial data sensing. Such embedded intelligence when employed in our everyday objects, furniture and surfaces will allow them to do much more than they already afford. OUIs can eventually replace current health sensor devices in a ubiquitous and seamless implicit interaction [60, 29]. The simplest example could be a duvet/blanket that can measure heart rate, blood pressure, etc. or a sofa arm that senses stress levels. A bigger picture is where –through OUI spaces– architects can design buildings that are able to capture different neurophysiological and psychological data for both the analysis and better understanding of user behaviour and user experiences within interior spaces, buildings and landscapes. On the other hand, seamful ubiquity [9] is also necessary for solving issues of ambiguity and uncertainty of interaction and sensing that might occur in some seamless systems [10]. For example, to design interactive interior spaces, we don't have to achieve completely seamless interaction in every surface and object but could exploit the representation of seams allowing the user to understand the edges of connectivity. Not only is this approach useful for user interaction regarding awareness, ambiguity and control challenges of ubiquitous interaction [15]. It will also provide flexibility for designing both public and private spaces in terms of social concerns such as privacy and personal data. Therefore, incorporating both seamful interation and implicit or seamless data collection through proper appropriation can together support a better user experience and simpler acquiring of the information and knowledge needed to improve the quality of living experience. In addition, such appropriation will support efficient management of urban flows aimed by researchers of smart cities and smart grids, who are already open to such opportunities through big data capabilities and tackling personal data protection challenges[45, 73].

5. **Visualizing the Unseen**: OUI buildings open frontiers for visualizing hidden data in new ways by translating the unseen data into visual, peripheral and tangible representations in the space. For example, displaying energy consumption of a house or a building through colour-changing interior elements. Another application might be for office buildings where the OUI space can visualize employees' satisfaction or engagement through sensing work loads, social interaction or stress levels and giving feedback through ambient texture-changing OUIs. Applications for healthcare spaces (patient rooms, senior homes, etc) can be similarly designed

to give biofeedback to certain health conditions and thresholds through peripheral OUIs. Even gentle breezes can be sensed and interpreted by wind-responsive architecture [43] or an actuating force, such as the work of Ned Kahn [54] (facades of flexible metal panels moving with wind force revealing impressive patterns of wind turbulence).

6. **Aesthetic Computers**: Concomitant with the third generation of computing is the desire to explore how computational devices can be made more aesthetically engaging. The rise of lifestyle brands such as Apple demonstrate consumers' desires for aesthetically pleasing products. OUI provides a design space allowing both researchers and designers to collaborate and innovate around new, dynamic forms of decorative artefacts, harvesting the potential of creating aesthetic computers that can exist in any shape. These devices embed both digital technology -with all its capabilities- and decorative beauty -with all its artistic values- together in one integral interface that can live, engage and influence people's lives over years. Using this paradigm, a lace tablecloth, a shaggy cushion or a Persian rug can become a computational device. Furthermore, aesthetic interaction -which is similarly important and impactful- aligns well with OUI interactions being more intuitive, familiar and manipulative than earlier user interface paradigms. Additionally, OUI can provide a user-friendly interface alternative for complex embedded systems in simple metaphors. For example, tangibilizing power utilization trends through colour-changing tangible clouds hanging as decorative elements.

7. **Sustainability**: OUI architecture contributes to sustainability on four different levels. First, less need for re-design or refurbishment, if interiors and/or exteriors of spaces and buildings are able to change their appearance (colour, shape, pattern, state, texture, etc) either autonomously or responding to occupants' interactions and/or needs. Second, OUI materials such as flexible bendable OLEDs, energy-efficient RGB LEDs and other organic electronics and polymers offer low-power alternatives and energy-efficient technologies [17, 50, 76] that do not compromise energy sustainability. Third, OUI responsive materials that sense and react to changes in humidity, light or heat requires zero energy consumption and can be physically programmed to solely act as sensing, processing and actuating complete system of adaptive architecture. Finally, we've got a missed opportunity of utilizing wasted energy sources that are literally pouring, facing and blowing towards every architectural structure anyway. Such natural resources can be either directly utilized as actuating stimuli [54, 47] creating natural behavioural patterns or employed in a more complicated processes. Nature powers of wind, sun radiation, wasted rain water (storm drain) and even greywater drains are all considered nature's gift to sustainable architecture researchers and should inspire interaction designers as well.

8. **Expressiveness**: Both personalization and playfulness are two important aspects of interaction design in general and in OUI design in particular. OUI interactive and manipulative interfaces have been found to be playful and enjoyable by users. Ubiquitous computing environments are believed to add a pleasure dimension leading to more user-friendly architectural design [50]. OUI interactions such as air gestures and direct hand manipulations are not only intuitive but pleasurable as well. This explains how children nowadays often enjoy playing with technology more than ever before. In her study of interactive architecture in a pleasure-based methodology, Mounajjed [50] stated that "accommodating aesthetic elements that appeal to the emotions is critical to the development of a user-centric design", where the pleasure factor influences the behavioral patterns of users. Therefore, OUI interactions accommodate pleasure as both a cause and an effect in where it encourages user participation and enhances the user experience in an enjoyable and pleasurable flow, influencing their emotions and visceral responses. On the other hand, expressing personalization -in some cases- is beneficial. When tangible art pieces and decorative surfaces become OUIs that are digitally aware of occupants' presence, and perhaps identity, then profiling and real-time customization can be easily implemented so that the same artefact or room can look differently for different occupants as they use a space. Moreover, OUI materials can help transform the same object into different other personalized appearances that suit its owner/user.

9. **Expand Creativity**: Art and architecture are about inspiration, questioning and creativity, provoking people's curiosity and thinking differently. When augmenting an artifact with actuated capabilities, allowing it to dynamically transform, creativity fosters conversations that alter meanings and aesthetics conveyed each time it generates a new form or appearance. OUI Architecture enables such creativity in different designs not only in residential interiors, but also in public spaces such as museums, galleries and showrooms. Commercial spaces are also a candidate for designers who consider technology in their installations to incorporate tangible and tactile interactions to draw innovative, surprising, experimental and engaging user interaction experiences. For example, retail designers Dalziel and Pow recently designed the 'EngagingSpace' at Retail Design Expo 2015 (Figure 2.a) where they installed an interactive animated space to engage visitors in an entertaining novel user experience through simple tactile interactions with interactive wallpaper. In this sense, we have to promote that technology should not be means to performing tasks, solving problems and improving efficiency and productivity only, but rather as well support us to be human, expanding the unique human abilities of vision, creativity and imagination and thus enhancing our quality of living and potentials.

10. **Tangible Decor**: Because domestic environments are required to be both comfortable and beautiful for a lifetime, architecture and interior design (including furniture, decorative accessories, fabrics, e.g., curtains, linens, upholstery) need to serve and contribute to the usability values of occupants in simple synthetics and impacting aesthetics that could live with occupants for years, interact and adapt with them along their lifetime. Domestic decorations can be designed and manufactured as OUIs with slow technology that allows them to respond and interact with occupants calmly and seamlessly over the years, manifesting their physical

pre-existing function and form, in addition to all their potential contribution to enhancing the quality of domestic living, being embedded computers; moreover, provoking inspiration, anticipation and self-reflection. Another important aspect of home decoration is the problem of habitual blindness. Over long periods of time, decorative home artefacts tend to lose their ability to 'stand-out' as they do when first brought-in and blend in a way that stops attracting our attention by time [20] losing a lot of their intended aesthetic values. OUI decorative artifacts that change their appearance, create subtle movements or form alterations, avoid blindness towards them, and create a renewable sense of awareness and perception of these decorative elements and thus a charming atmosphere influencing people's perception of value and meaning of such artefacts over time [55].

WAY FORWARD

We have explored the need, motivation and opportunities OUI provide for developing interactive architecture, both exterior and interior. However, the vision of OUI as key technology for interactive architecture requires substantial efforts to become a reality, which effectively defines the research agenda for the field. In what follows we outline what we have identified as the most important aspects that future research on OUI for interactive architecture has to address.

a) **Radical Interdisciplinarity**: Bridging the gap between involved parties, e.g., computer scientists, material physicists, architects, interior designers, OUI and UX researchers is an essential requirement for realizing the vision of OUI for interactive architecture. More than in any other domain truly interdisciplinary collaborations are essential meaning that where researchers and practitioners from different core subject areas need to go out of their way and work together on creating what eventually will turn into an entirely new research area. Such radical interdisciplinarity needs to be formalized and -more importantly- "lived" in everyday practice of researchers and practitioners. Staying in -certainly comfortable- silos of core disciplines will not lead to the realization of OUI-based architecture be it related to either interiors or exteriors. Although it may sound obvious to some, we have identified this as a key problem for the development of this research area: both architecture and HCI researchers and academics work separately from one another, yet with the same vision. What is ultimately necessary is that, for example, classical architects not only utilize new materials and technologies but rather also actively contribute to their research and developments. Conversely, core technical research disciplines need to engage in thinking like architects and appreciate OUI from a UX and general user perspective. As such a new generation of researchers and practitioners will be able to develop and employ radically new methods, tools, and materials and thus be able to transform both architecture and interaction technologies.

b) **Appropriation and Retrofitting**: An interesting design space emerges not only for designing new buildings with embedded OUIs, but also for retrofitting existing buildings and interior spaces. This requires less structural intervention and allows new OUI layers to cover entire pre-existing interior or exterior surfaces. Considering that interior elements (furniture, decorative accessories and soft furnishings etc) can be appropriated as interactive surfaces through the design of OUIs there is a broad space through which interior designers and OUI researchers can come to collaborate. Similarly, utilizing OUI in architectural exterior facades creates numerous possibilities for exploration. The design space for OUI in architecture is unique in the sense that it bears an intrinsic conflict of conceiving, designing, and developing new objects that effectively implement Organic User Interfaces vs the need for altering, adapting and extending existing objects that are not necessarily straightforward to modify. Especially the latter is the predominant case for existing buildings, which requires retrofitting and approaches of opportunistic modification.

c) **Tackling Scalability**: Addressing scalability of OUI is a fundamental challenge for the field. Scalability hereby refers to moving on from prototypical or exemplary developments to large scale uptake of OUI in everyday scenarios of interactive architecture & interior design. Scalability of large interfaces, e.g., building exteriors, is much more challenging than small-sized interior interfaces. Designing OUIs in ways to be skinned on architectural structures requires many different considerations and functional testing than just lab research. Such considerations are required due to the large scale and reliability required for building envelopes in addition to surviving different environmental conditions. As any newly introduced building material, OUI architectural skin materials must prove durability in terms of sun, rain, wind and fire resistance. If designed as a structural material (holding some building weight), it needs to be tested for load resistance as well, as architecture is non-risk tolerant. Other considerations that require further research and testing are lifespans, vandalism and maintenance approaches of such subtle materials. Once OUI materials are proved to stand such testing and be produced into building components with qualified and quantified specs for architects and structural engineers, pioneers can start using them with confidence and we can start witnessing a new era of responsive and organic architecture as reality.

d) **Re-defining the User**: As somehow different than usual interfaces, defining who would be users of OUI architecture is rather vague and not straightforward. Traditionally, users of an indoor interface system are thought of as the inhabitants, while users of an outdoor interface are considered as the public passing-by. On the other hand, architects and interior designers may consider their users as the contractors, project owners or funding bodies of the designed building/space. In either cases, rethinking who is the user is an important point to be tackled and explored by OUI research when it comes to entire buildings as application/ design space. This is crucial from both perspectives: HCI and Architecture disciplines, both depend on building their design 'concept' on defining the users. More importantly, defining the actual users will essentially push forward a user-centric design and a post-occupancy testing or long-term evaluation of such designs/interfaces that can potentially constantly change, transform and react.

e) **Immersive Interaction Design**: as much as OUI Architecture sounds revolutionary and promising, it also triggers the need for essentially a new generation of interaction design. When re-defining architecture as user interfaces, we need to start reconsidering many interaction design fundamentals. User interaction will be immersive rather than focused, when interacting with spaces rather than devices or building-sized interfaces rather than tabletops. Crowd interaction would replace the traditional 'multiuser' notion, and would require creative methods and tools to study and evaluate. Even with small decorative OUIs, HCI research needs to create and evaluate new arrays of interaction techniques that are immersive, playful and engaging, together with designers. Several challenges require careful design for OUI interactions that would need to be ubiquitous and ambient but not entirely hidden, intuitive but not basic or mundane, surprising and enchanted but at the same time not -perceived as- completely random. Moreover, as OUI Architecture is realized, opportunities for social actions in these interactive spaces would also become an important topic in HCI. But what are the consequences of shifting users' expectations for their surroundings? When would embedded OUIs be appropriate? When would 'smart' be needed? How can we design long-term interactions?

f) **Ethical and Behavior-Shaping**: when building interiors and exteriors that can dynamically transform their shape or appearance either autonomously or interactively, new challenges for ethics and security will emerge. Sensing environments in general are advanced systems that involve complex scenarios and thus are potentially subject to 'hacking' activities as well. Special security procedures might need to emerge to protect one's wallpaper or moving furniture. An essential step forward for OUI Architecture would be considering BIM (Building Information Management) as means of embedding security techniques into OUI software not only for creating anti-hacking systems but defining who has the rights to interact -thus change- the physical appearance and form of interior elements or exterior facades. We are aware that such implications are applicable for any embedded system, yet we need to highlight this here as it would require new methodologies and considerations impacting people in their very own bedrooms. Another challenge is designing the appropriate skin-changes of the original architectural design and their possible emotional effects on residents. In theories of architecture, different colors, materials and textures have definite meanings, feelings and uses, thus consequently emotional effects on the building occupants and often the entire surrounding ecosystem. In OUI Architecture, the materials and methods of sensing, actuation and interaction will be an essential part of the architectural design, requiring careful studies in each context to control and avoid any implications that might result on families either physiologically or psychologically. When designing for domestic spaces, more challenges emerge on different technical, social and ethical levels. Since some early challenges of domestic ubiquitous computing [15] have been resolved, it seems that it is a matter of continuous studies and research to find ways to overcome more.

g) **Sustainability Dilemma**: Currently, sustainability research predominantly focuses on exploring means of building resource-efficient, energy-conservative and environment friendly architecture through Green Building and Sustainable Architecture practices. OUI exteriors can contribute to sustainable buildings through 'modularity' where component-parts can be replaced easily. In addition, any kinetic interaction employed in the interface can contribute to energy-harvesting in a way that allows micro-scale energy production that will support self-sustainable buildings. Not only buildings, but other architectural structures from bridges, tunnels and motorways to narrow streets, parks and transportation facilities. Together they form the urban glue in which indeed shapes our daily lives, is a rich space for OUI, converting them from mute structures to possible 'urban actors'. Yet, creating new urban actors would raise more sustainability challenges, and opportunities.

CONCLUSION

Technology is converging to bring together a new generation of devices and interactions built around smart OUI materials. The vision of smart homes and ubiquitous computing environments (calm computing) has never been closer to realization. Previous visions of interactive architecture have been just that, visions, largely unrealizable at a scale that would actually impact people in an everyday context (being largely restricted to specific experimental builds). The advances in networked technology and new materials mean that it is now possible to make architectural interventions at both the exterior and interior scale, in affordable and sustainable ways. Older building stock can be retrofitted with technology to dynamically alter spaces and make environments responsive in ways not possible before. No longer do we need to make the case for building entirely new reactive architecture when older buildings can be adapted with technology to make them smart. The imminent proliferation of smart home controls is making the general populace more switched on to the idea of technologically enhanced and reactive environments. Now is therefore the time to invest in thoroughly exploring a new future of interactive, dynamic and reactive architecture. This requires a fundamental attack from multidisciplinary and interdisciplinary researchers to begin to address the challenges and opportunities of OUIs, which offer us the strongest means through which to deliver a future of interactive architecture. In this paper we have sought to outline some of those challenges and to begin to galvanize a community that might seek to explore how OUIs can fundamentally alter the way we live.

REFERENCES

1. Eric Akaoka, Tim Ginn, and Roel Vertegaal. 2010. DisplayObjects: Prototyping Functional Physical Interfaces on 3D Styrofoam, Paper or Cardboard Models. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction - TEI '10*. Cambridge, Massachusetts, USA, 49. DOI: http://dx.doi.org/10.1145/1709886.1709897

2. Jason Alexander, Viljakaisa Aaltonen, Johan Kildal, Andrees Lucero, Kasper Hornbæk, and Sriram Subramanian. 2012. Interaction with Deformable

Displays. In *MobileHCI*. San Francisco, CA, USA. DOI: http://dx.doi.org/10.1145/2371664.2371723

3. Hrvoje Benko, Ad Wilson, and Ravin Balakrishnan. 2008. Sphere: Multi-touch Interactions on a Spherical Display. *UIST '08* (2008). DOI: http://dx.doi.org/10.1145/1449715.1449729

4. Gilbert Beyer, Florian Alt, Jörg Müller, Albrecht Schmidt, Karsten Isakovic, Stefan Klose, Manuel Schiewe, and Ivo Haulsen. 2011. Audience Behavior Around Large Interactive Cylindrical Screens. In *SIGCHI Conference on Human Factors in Computing Systems ACM CHI*. Vancouver, BC, Canada, 1021–1030. DOI: http://dx.doi.org/10.1145/1978942.1979095

5. Nimish Biloria and Valentina Sumini. 2007. Performative Building Skin Systems: A Morphogenomic Approach Towards Developing Real-Time Adaptive Building Skin Systems. *International Journal of Architectural Computing* 07, 04 (2007). DOI: http://dx.doi.org/10.1260/1478-0771.7.4.643

6. Alan Branzel, Christian Holz, Daniel Hoffmann, Dominik Schmidt, Marius Knaust, Patrick Luhne, Rene Meusel, Stephan Richter, and Patrick Baudisch. 2013. GravitySpace: Tracking users and their poses in a smart room using a pressure-sensing floor. In *SIGCHI Conference on Human Factors in Computing Systems*. Paris, France. DOI: http://dx.doi.org/10.1145/2470654.2470757

7. Leah Buechley, David Mellis, Hannah Perner-Wilson, Emily Lovell, and Bonifaz Kaufmann. 2010. Living Wall: Programmable Wallpaper for Interactive Spaces. In *Proceedings of the international conference on Multimedia*. Firenze, Italy, 1401–1402. DOI: http://dx.doi.org/10.1145/1873951.1874226

8. Bradley E Cantrell and Justine Holzman. 2015. *Responsive Landscapes: Strategies for Responsive Technologies in Landscape Architecture*. Routledge.

9. Matthew Chalmers. 2003. Seamful Design and Ubicomp Infrastructure. 4. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.61.6779

10. Matthew Chalmers and Ian MacColl. 2003. Seamful and Seamless Design in Ubiquitous Computing. In *Proc. Ubicomp 2003 Workshop At The Crossroads: The Interacton of HCI and Systems Issues in Ubicomp.* Seattle, WA, USA, 8. DOI:http://dx.doi.org/10.1.1.104.9538

11. Marcelo Coelho, Ivan Poupyrev, Sajid Sadi, Roel Vertegaal, Joanna Berzowska, Leah Buechley, Pattie Maes, and Neri Oxman. 2009. Programming Reality: From Transitive Materials to Organic User Interfaces. In *CHI 2009 Workshops*. Boston, MA, USA. DOI: http://dx.doi.org/10.1145/1520340.1520734

12. Sandra Coelho. 2011. Art Evolves through Technology: Haptic after the Hegemony of Visual Art. In *LNICST*, Vol. 101. 171–176. DOI: http://dx.doi.org/10.1007/978-3-642-33329-3{_}21

13. David Correa, Oliver David Krieg, Achim Menges, and Steffen Reichert. 2013. HYGROSKIN: A Climate Responsive Prototype Project Based on the Elastic and Hygroscopic Properties of Wood. In *ACADIA 2013 Adaptive Architecture*. 33–42.

14. Michael Dickey, Ying Liu, and Jan Genzer. 2012. Light-induced folding of two-dimensional polymer sheets. *SPIE* (2012), 3–4.

15. W.K. Edwards and R.E. Grinter. 2001. At Home with Ubiquitous Computing: Seven Challenges. In *Proceedings of the 3rd international conference on Ubiquitous Computing*. 256–272. DOI: http://dx.doi.org/10.1007/3-540-45427-6

16. Nicholas Farrow, Naren Sivagnanadasan, and Nikolaus Correll. 2014. Gesture Based Distributed User Interaction System for a Reconfigurable Self-Organizing Smart Wall. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction - TEI '14*. Munich, Germany. DOI: http://dx.doi.org/10.1145/2540930.2540967

17. Sean Follmer, Daniel Leithinger, Alex Olwal, Nadia Cheng, and Hiroshi Ishii. 2012. Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-Changing Devices. In *Proceedings of UIST'12*. Cambridge, Massachusetts, USA, 519. DOI: http://dx.doi.org/10.1145/2380116.2380181

18. Michael Fox and Miles Kemp. 2009. Interactive Architecture: Adaptive World. *Architectural Design* Novak (2009), 256. DOI: http://dx.doi.org/10.4018/978-1-61350-180-1.ch015

19. Markus Funk, Stefan Schneegaß, Michael Behringer, Niels Henze, and Albrecht Schmidt. 2015. An Interactive Curtain for Media Usage in the Shower. *Proceedings of PerDis'15* (2015). DOI: http://dx.doi.org/10.1145/2757710.2757713

20. William Gaver, John Bowers, Andy Boucher, Andy Law, Sarah Pennington, and Nicholas Villar. 2006. The History Tablecloth: Illuminating Domestic Activity. *Dis 2006* (2006). DOI:http://dx.doi.org/10.1145/1142405.1142437

21. Sven Gehring, Elias Hartz, and Markus Löchtefeld. 2013. The Media Façade Toolkit: Prototyping and Simulating Interaction with Media Façades. In *UbiCompâĂŹ13*. Zurich, Switzerland. DOI: http://dx.doi.org/10.1145/2493432.2493471

22. Atef Ghalwash and Sara Nabil. 2013. Organic User Interfaces: Framework, Interaction Model and Design Guidelines. *International Journal of Ad hoc, Sensor & Ubiquitous Computing (IJASUC)* 4, 4 (2013). DOI: http://dx.doi.org/10.5121/ijasuc.2013.4404

23. Audrey Girouard, Roel Vertegaal, and Ivan Poupyrev. 2011. Second International Workshop on Organic User Interfaces. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction - TEI '11*. Funchal, Portugal, 381. DOI: http://dx.doi.org/10.1145/1935701.1935791

24. Audrey Girouard, Roel Vertegaal, and Ivan Poupyrev. 2013. Special Issue: Organic User Interfaces. *Interacting with Computers* 25, 2 (2013). DOI: http://dx.doi.org/10.1093/iwc/iws001

25. Ruairi Glynn. 2014. Animating Architecture: Coupling high-definition sensing with high-definition actuation. *Architectural Design* 84, 1 (2014), 100–105. DOI: http://dx.doi.org/10.1002/ad.1707

26. Erik Grönvall, Sofie Kinch, Marianne Graves Petersen, and Majken K. Rasmussen. 2014. Causing Commotion with a Shape-Changing Bench. In *Proceedings of CHI'14*. Toronto, ON, Canada. DOI: http://dx.doi.org/10.1145/2556288.2557360

27. Felix Heibeck, Basheer Tome, Clark Della Silva, and Hiroshi Ishii. 2015. uniMorph - Fabricating Thin-Film Composites for Shape-Changing Interfaces. In *Proceedings of UIST'15*. Charlotte, NC, USA. DOI: http://dx.doi.org/10.1145/2807442.2807472

28. Hoberman Associates - Transformable Design - Hoberman Arch. 2002. Hoberman Arch. (2002). http://www.hoberman.com/portfolio/hobermanarch.php?projectname=HobermanArch

29. Jesse Hoey, Thomas Ploetz, Dan Jackson, Andrew F Monk, Cuong Pham, and Patrick Olivier. 2011. Rapid specification and automated generation of prompting systems to assist people with dementia. *Pervasive and Mobile Computing (PMC)* 7, 3 (2011), 299–318.

30. David Holman, Audrey Girouard, Hrvoje Benko, and Roel Vertegaal. 2013. The Design of Organic User Interfaces: Shape, Sketching and Hypercontext. *Interacting with Computers* 25, 2 (2013). DOI: http://dx.doi.org/10.1093/iwc/iws018

31. David Holman and Roel Vertegaal. 2008. Organic User Interfaces: Designing Computers in Any Way, Shape or Form. *Commun. ACM* 51, 6 (2008), 48. DOI: http://dx.doi.org/10.1145/1349026.1349037

32. Artem Holstov, Ben Bridgens, and Graham Farmer. 2015. Hygromorphic Materials for Sustainable Responsive Architecture. *Construction and Building Materials* 98 (2015), 570–582. DOI: http://dx.doi.org/10.1016/j.conbuildmat.2015.08.136

33. Hiroshi Ishii. 2008. The Tangible User Interface and its Evolution. *Commun. ACM* 51, 6 (2008). DOI: http://dx.doi.org/10.1145/1349026.1349034

34. Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Jb Labrune. 2012. Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials. *Interactions* XIX, February (2012), 38–51. DOI: http://dx.doi.org/10.1145/2065327.2065337

35. Hiroshi Ishii, Daniel Leithinger, and Sean Follmer. 2015. TRANSFORM: Embodiment of "Radical Atoms" at Milano Design Week. In *CHI'15 Extended Abstracts*. Seoul, Republic of Korea. DOI: http://dx.doi.org/10.1145/2702613.2702969

36. Taysheng Jeng. 2012. Interactive Architecture: Spaces that Sense, Think and Respond to Change. *Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education: Applications in CAD, CAM and CAE Education* (2012), 257.

37. Heekyoung Jung, Youngsuk L Altieri, and Jeffrey Bardzell. 2010. SKIN : Designing Aesthetic Interactive Surfaces. *Proceedings of the fourth International Conference on Tangible, embedded, and embodied interaction* (2010), 85–92. DOI: http://dx.doi.org/10.1145/1709886.1709903

38. Aftab Khan, James Nicholson, Sebastian Mellor, Daniel Jackson, Karim Ladha, Cassim Ladha, Jon Hand, Joseph Clarke, Patrick Olivier, and Thomas Plötz. 2014. Occupancy Monitoring using Environmental & Context Sensors and a Hierarchical Analysis Framework. In *Proc. ACM BuildSyS*. Memphis, TN, USA. DOI: http://dx.doi.org/10.1145/2674061.2674080

39. Chin Koi Khoo and Flora D. Salim. 2013. Lumina: A Soft Kinetic Material for Morphing Architectural Skins and Organic User Interfaces. In *Proceedings of UbiComp'13*. Zurich, Switzerland, 53. DOI: http://dx.doi.org/10.1145/2493432.2494263

40. Branko Kolarevic and Vera Parlac. 2015. *Building Dynamics: Exploring Architecture of Change*. 304 pages. DOI:http://dx.doi.org/10.4324/9781315763279

41. Hanno-Walter Kruft. 1994. *A History of Architectural Theory: From Vitruvius to the Present*. Princeton Architectural Press.

42. Julian Lepinski and Roel Vertegaal. 2011. Cloth displays: interacting with drapable textile screens. *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction* (2011). DOI: http://dx.doi.org/10.1145/1935701.1935765

43. Lorenzo Lignarolo, Charlotte Lelieveld, and Patrick Teuffel. 2011. Shape Morphing Wind-Responsive Facade Systems Realized With Smart Materials. In *Adaptive Architecture Conference*. London, UK, 1–14.

44. Daniel Cardoso Llach, Avni Argun, Dimitar Dimitrov, and Qi Ai. 2014. Acacia: A Simulation Platform for Highly Responsive Smart Facades. In *SimAUD Symposium on Simulation for Architecture and Urban Design*. Tampa, Florida, USA.

45. Antoni Martinez-Balleste, Pablo Perez-Martinez, and Agusti Solanas. 2013. The pursuit of citizens' privacy: A privacy-aware smart city is possible. *IEEE Communications Magazine* 51, 6 (2013), 136–141. DOI: http://dx.doi.org/10.1109/MCOM.2013.6525606

46. Rupert Meese, Shakir Ali, Emily-Clare Thorne, Steve D Benford, Anthony Quinn, Richard Mortier, Boriana N Koleva, Tony Pridmore, and Sharon L Baurley. 2013. From Codes to Patterns: Designing Interactive Decoration for Tableware. In *Proceedings of CHI'13*. Paris, France, 931–940. DOI: http://dx.doi.org/10.1145/2470654.2466119

47. Achim Menges and Steffen Reichert. 2012. Material Capacity: Embedded Responsiveness. *Architectural Design* 82, 2 (2012), 52–59. DOI: http://dx.doi.org/10.1002/ad.1379

48. Sarah Mennicken, A.J. Bernheim Brush, Asta Roseway, and James Scott. 2014. Finding Roles for Interactive Furniture in Homes with EmotoCouch. In *Ubicomp'14*. Seattle, WA, USA. DOI: http://dx.doi.org/10.1145/2638728.2641547

49. Jules Moloney. 2011. *Designing Kinetics for Architectural Facades: State Change*.

50. Nadia Mounajjed and Imran A Zualkernan. 2011. From Simple Pleasure to Pleasurable Skin: An Interactive Architectural Screen. In *DPPI '11*. Milano, IT. DOI: http://dx.doi.org/10.1145/2347504.2347537

51. Sara Nabil and Atef Ghalwash. 2013. Perspectives and Application of OUI Framework with SMaG Interaction Model. In *AmI 2013 (Ambient Intelligence) Workshops - Communications in Computer and Information Science CCIS*, Vol. 413 CCIS. Dublin, Ireland. DOI: http://dx.doi.org/10.1007/978-3-319-04406-4{_}29

52. Sara Nabil and Atef Ghalwash. 2015. Organic Interactive Displays: A Bridge from History. *The 5th International Symposium on Frontiers in Ambient and Mobile Systems (FAMS 2015) - Procedia Computer Science* 52 (2015). DOI:http://dx.doi.org/10.1016/j.procs.2015.05.109

53. Kosuke Nakajima, Yuichi Itoh, Takayuki Tsukitani, Kazuyuki Fujita, Kazuki Takashima, Yoshifumi Kitamura, and Fumio Kishino. 2011. FuSA2 Touch Display: A Furry and Scalable Multi-touch Display. In *Proceedings of ITS'11*. Kobe, Japan. DOI: http://dx.doi.org/10.1109/VR.2012.6180852

54. Ned Kahn Studios. 2016. Wind | Ned Kahn. (2016). http://nedkahn.com/wind/

55. William T. Odom, Abigail J. Sellen, Richard Banks, David S. Kirk, Tim Regan, Mark Selby, Jodi L. Forlizzi, and John Zimmerman. 2014. Designing for Slowness, Anticipation and Re-visitation: A Long Term Field Study of the Photobox. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*. Toronto, ON, Canada, 1961–1970. DOI: http://dx.doi.org/10.1145/2556288.2557178

56. Yoshiharu Ooide, Hiroki Kawaguchi, and Takuya Nojima. 2013. An Assembly of Soft Actuators for an Organic User Interface. In *Proceedings of the adjunct publication of the 26th annual ACM symposium on User interface software and technology - UIST '13 Adjunct*. St. Andrews, UK. DOI:http://dx.doi.org/10.1145/2508468.2514723

57. Kas Oosterhuis and Nimish Biloria. 2008. Interactions with Proactive Architectural Spaces. *Commun. ACM* 51, 6 (2008). DOI:http://dx.doi.org/10.1145/1349026.1349041

58. David Pearson. 2001. *New Organic Architecture: The Breaking Wave*. Univ of California Press.

59. Philips Lighting. 2016. Philips Luminous Patterns. (2016). http://www.lighting.philips.com/main/systems/packaged-offerings/retail-and-hospitality/luminous-patterns.html

60. T Ploetz, P Moynihan, Cuong Pham, and P Olivier. 2010. Activity Recognition and Healthier Food Preparation. In *Activity Recognition in Pervasive Intelligent Environments*. Atlantis Press.

61. Ingrid Maria Pohl and Lian Loke. 2012. Engaging the Sense of Touch in Interactive Architecture. In *Proceedings of the 24th Australian Computer-Human Interaction Conference on - OzCHI '12*. Melbourne, VIC, Australia, 493–496. DOI: http://dx.doi.org/10.1145/2414536.2414611

62. Carolina Ramirez-Figueroa, Martyn Dade-Robertson, and Luis Hernan. 2013. Adaptive Morphologies: Toward a Morphogenesis of Material Construction. In *ACADIA 2013 Adaptive Architecture*. Cambridge, ON, Canada, 21–23.

63. Carolina Ramirez-figueroa, Luis Hernan, Aurelie Guyet, and Martyn Dade-robertson. 2016. Bacterial Hygromorphs: Experiments into the integration of Soft Technologies into Building Skins. In *ACADIA 2016 Posthuman Frontiers, Programmable Matter*. Acadia Publishing Company, 244–253.

64. Steffen Reichert, Achim Menges, and David Correa. 2015. Meteorosensitive Architecture: Biomimetic Building Skins Based on Materially Embedded and Hygroscopically Enabled Responsiveness. *CAD Computer Aided Design* 60 (2015), 50–69. DOI: http://dx.doi.org/10.1016/j.cad.2014.02.010

65. Jun Rekimoto. 2008. Organic Interaction Technologies: From Stone to Skin. *Commun. ACM* (2008), 38–44. DOI: http://dx.doi.org/10.1177/1464700109355214

66. J Richarz, T Ploetz, and Gernot A Fink. 2008. Real-time Detection and Interpretation of 3D Deictic Gestures for Interaction With an Intelligent Environment. In *Pattern Recognition, ICPR 2008 19th International Conference on IEEE*.

67. B Schauerte, J Richarz, T Ploetz, C Thurau, and Gernot A Fink. 2009. Multi-Modal and Multi-Camera Attention in Smart Environments. In *Proc. ICMI*. 261–268.

68. Holger Schnadelbach, Ainojie Irune, David Kirk, Kevin Glover, and Patrick Brundell. 2012. ExoBuilding: Physiologically Driven Adaptive Architecture. *ACM Transactions on Computer-Human Interaction* 19, 4 (2012). DOI:http://dx.doi.org/10.1145/2395131.2395132

69. Odilo Schoch. 2006. My Building is my Display. In *Proceedings of the the 24th Conference on Education and Research in Computer Aided Architectural Design in Europe: Communicating Space(s) (eCAADe'06)*. Volos, Greece, 610–616.

70. Yuta Sugiura, Gota Kakehi, Anusha Withana, Calista Lee, Daisuke Sakamoto, Maki Sugimoto, Masahiko Inami, and Takeo Igarashi. 2011. Detecting shape deformation of soft objects using directional photoreflectivity measurement. In *Proceedings of UIST '11*. Santa Barbara, CA, USA, 509. DOI:http://dx.doi.org/10.1145/2047196.2047263

71. Tomomi Takashina, Kotaro Aoki, Akiya Maekawa, Chihiro Tsukamoto, Hitoshi Kawai, Yoshiyuki Yamariku, Kaori Tsuruta, Marie Shimokawa, Yuji Kokumai, and Hideki Koike. 2015. Smart Curtain as Interactive Display in Living Space. In *SIGGRAPH Asia 2015 Posters*. Kobe, Japan. DOI:http://dx.doi.org/10.1145/2820926.2820971

72. Sarah Taylor and Sara Robertson. 2014. Digital Lace: A Collision of Responsive Technologies. In *In ISWC'14 Adjunct: Proceedings of the 2014 ACM International Symposium on Wearable Computers*. New York: ACM, 93–97. DOI:http://dx.doi.org/10.1145/2641248.2641280

73. Omer Tene and Jules Polonetsky. 2013. Big data for all: Privacy and user control in the age of analytics. *Northwestern Journal of Technology and Intellectual Property Volume* 11, 5 (2013), 240–273. http://heinonlinebackup.com/hol-cgi-bin/get

74. Edison Thomaz, Vinay Bettadapura, Gabriel Reyes, Megha Sandesh, Grant Schindler, Thomas Ploetz, Gregory D Abowd, and Irfan Essa. 2012. Recognizing Water-Based Activities in the Home Through Infrastructure-Mediated Sensing. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*. ACM.

75. Kohei Tsuji and Akira Wakita. 2011. Anabiosis: An Interactive Pictorial Art Based on Polychrome Paper Computing. In *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology*. Lisbon, Portugal, 80:1–80:2. DOI: http://dx.doi.org/10.1145/2071423.2071521

76. Roel Vertegaal and Ivan Poupyrev. 2008. Organic User Interfaces. *Commun. ACM* 51, 6 (2008), 26. DOI: http://dx.doi.org/10.1145/1349026.1349033

77. Mark Weiser. 1991. The Computer for the 21st Century. *Scientific American* 265, September 1991 (1991), 94–104. DOI:http://dx.doi.org/10.1145/329124.329126

78. Bin Yu, Nienke Bongers, Alissa van Asseldonk, Jun Hu, Mathias Funk, and Loe Feijs. 2016. LivingSurface: Biofeedback through Shape-changing Display. In *Proceedings of the TEI '16*. Eindhoven, Netherlands, 168–175. DOI: http://dx.doi.org/10.1145/2839462.2839469