



Fabricating Malleable Interaction-Aware Materials

Michael Wessely

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Fabricating Malleable Interaction-Aware Materials

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FABRICATING MALLEABLE INTERACTION-AWARE MATERIALS

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"It's when you begin to think about going to your dream that your dream is always outside of your comfort zone. It's always beyond what you've ever done."

— Bruce Wilkinson

ABSTRACT

Personal fabrication machines, such as 3D printers, allow casual makers to create custom objects, which may also contain soft, flexible, or shape-changeable parts. Making use of these mechanical properties and developing novel forms of interaction opens up new possibilities for research in Human-Computer-Interaction (HCI). However, embedding sensing and output capabilities into material is still challenging. Although research in materials science has introduced a range of methods for producing interaction-aware materials, these methods require significant domain expertise and often rely on specialized and expensive equipment. My dissertation focuses on casual makers, designers, and HCI researchers, and investigates how to support their design and physical modeling tasks with interactive, non-rigid materials that are stretchable, shape configurable, or cuttable.

I explore three directions on how such materials can enhance user interaction, with applications to wearables and ubiquitous computing, DIY product design, and interactive fabrication. First, I introduce a new fabrication method for embedding touch sensing, proximity sensing, and electroluminescent displays into stretchable silicone materials. Based on screen printing, the method allows for rapidly fabricating inexpensive and highly stretchable user interfaces that can be embedded in wearables and other everyday objects. Second, I present an approach for creating interactive paper-folded building blocks that we call Interactive Tangrami. Interactive Tangrami are made of flexible materials such as paper, folded and combined together to form modular 3D structures. They support touch sensing and actuation and can also integrate rigid electrical components, such as LEDs. We use a rapid ink-jet printing technique to apply sensors and circuits on paper. We also offer a software tool that helps makers to design the geometry and interactive behavior of their physical user interfaces and then print them on paper. Third, I introduce a method for fabricating shape-aware material, which is modeling material that captures and streams its own shape while being cut by an artist. The method is based on a novel inkjet-printable sensing technology that can be embedded into a variety of cuttable material such as foam-core. Our software toolkit helps makers produce 2D or 3D shape-aware material and customize its sensing topology for higher sensing accuracy. It also allows them to link the physical model with its digital copy in a 3D CAD environment, such as Blender and Unity. Overall, our approach supports a bi-directional fabrication workflow that combines both physical and digital modeling tools.

Les machines de fabrication personnelle, comme les imprimantes 3D, permettent au plus grand nombre, de fabriquer des objets personnalisés. Il est possible de créer des pièces rigides, mais aussi des pièces souples, flexibles ou malléables. Faire usage de ces propriétés mécaniques permettent de concevoir de nouvelles formes d'interaction et ouvrent des perspectives inédites dans la recherche en Interaction Humain-Machine (IHM). Un défi reste toutefois d'intégrer des capteurs ainsi que des retour visuels à ces matières. Les sciences des matériaux ont introduit plusieurs techniques pour rendre des éléments interactifs, mais leur application requiert une forte expertise ou la mise en oeuvre d'équipements très coûteux. Ma thèse se concentre sur les professions créatives, comme les professionnels du design, les architectes ainsi que les chercheurs en IHM. Elle vise à accompagner le processus de conception et de prototypage de ces derniers, en produisant des matériaux interactifs, flexible, possédant des formes reconfigurables ou des propriétés lors de leur découpage.

De tels matériaux peuvent enrichir notre interaction avec le monde numérique de trois manières différentes : - l'application dans la création d'objets portés et l'informatique ubiquitaire, - le design de produits personnels, - la fabrication interactive. J'introduis d'abord une nouvelle méthode pour intégrer des capteurs tactiles, des capteurs de proximité et des écrans électroluminescents dans des matériaux de silicone étirables. Je présente une approche de fabrication multicouche qui permet de superposer plusieurs couches de capteurs, des couches d'affichage et des couches de couleurs personnalisées dans une seule interface. Basée sur des techniques d'impression en sérigraphie, la méthode permet de fabriquer rapidement des interfaces étirables et peu coûteuses, qui peuvent être intégrées dans les vêtements et dans d'autres objets du quotidiens. La méthode de fabrication traite de l'hydrophobicité du PDMS (Polydiméthylsiloxane) et permet d'imprimer des encres à base d'eau telles que le PEDOT:PSS (Poly-3,4-éthylendioxythiophène) transparent et conducteur sur du silicone étirable. Deuxièmement, je présente une approche pour créer des modules de construction interactives, qu'on appelle "Tangramis Interactifs". Les Tangramis interactifs sont des matériaux souples, par exemple du papier, pliés et combinés ensemble pour créer des structures modulaires en 3D. Ils peuvent réagir au toucher, être actionnés, et intégrer des composants électroniques comme des LEDs. Nous utilisons une technique rapide d'impression par jet d'encre pour intégrer des capteurs et des circuits sur du papier. Nous avons également développé une interface graphique qui permet aux créateurs de con-

cevoir la forme et le comportement interactif de leur propres interfaces physiques avant de les imprimer sur papier. Une fois connecté à l'interface physique, le logiciel configure automatiquement le microcontrôleur connecté et transmet les données d'interaction via un protocole réseau (Open Sound Control) à des plates-formes de prototypage d'applications telles que Max/MSP ou Processing. Troisièmement, j'introduis une méthode de fabrication de matériaux capable d'identifier sa forme ("shape-aware material"). Ce matériau peut détecter et communiquer sa géométrie en temps réel durant son découpage par un designer. La méthode s'appuie sur une nouvelle technologie de capteurs de forme, imprimés par jet d'encre et intégrés dans du matériel de maquettage, comme de la mousse. Notre logiciel aide les designers à générer du matériel de prototypage en 2D ou en 3D qui peut identifier sa forme, en configurant la topologie des capteurs pour optimiser la précision du modèle. Il permet également d'établir le lien entre un modèle physique et sa représentation numérique dans un environnement CAO (Conception Assisté par l'Ordinateur), tel que Blender ou Unity. Notre approche soutient un processus de fabrication bidirectionnelle en intégrant des outils de modélisation à la fois physiques et numériques.

PUBLICATIONS

Some ideas have appeared previously in the following publications:

Chapter 3: Highly Stretchable User Interfaces

[1] Michael Wessely, Theophanis Tsandilas, and Wendy E. Mackay. 2016. Stretchis: Fabricating Highly Stretchable User Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST'16)*, 697–704.

Chapter 4: Modular, Paper-folded User Interfaces

[2] Michael Wessely, Nadiya Morenko, Jürgen Steimle, and Michael Schmitz. 2018. Interactive Tangrami: Rapid Prototyping with Modular, Paper-folded Electronics. In *the 31th Annual Symposium on User Interface Software and Technology (UIST'18 Adjunct)*, 143–145.

Chapter 5: Shape-Aware Material

[3] Michael Wessely, Theophanis Tsandilas, and Wendy E. Mackay. 2018. Shape-Aware Material: Interactive Fabrication with ShapeMe. In *Proceedings of the 31st Annual Symposium on User Interface Software and Technology (UIST'18)*, 127–139.

Chapter 6: Controlling Reflectance Properties of Screens

[4] Michal Piovarči, Michael Wessely, Michał Jagielski, Marc Alexa, Wojciech Matusik, and Piotr Didyk. 2017. Directional Screens. In *Proceedings of the 1st Annual Symposium on Computational Fabrication (SCF'17)*, 1–11.

[5] Michal Piovarči, Michael Wessely, Michał Jagielski, Marc Alexa, Wojciech Matusik, and Piotr Didyk. 2017. Design and Analysis of Directional Front Projection Screens. In *Computers&Graphics, Volume 74*, 213–224.

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INTRODUCTION

Personal fabrication machines allow casual makers to create their own physical objects. I argue that future technologies should move from the creation of passive components to the fabrication of highly interactive objects. I focus on inexpensive, highly accessible technologies for creating malleable interactive materials that can change shape by being flexible, stretchable, or cuttable. I identify three challenges that future fabrication platforms have to meet. My dissertation responds to these challenges with three main contributions that demonstrate interaction with stretchable, foldable, and cuttable materials.

Modern interactive devices, such as laptops, smart watches, mobile phones or fitness trackers, most often come in rigid shapes and materials. Their form factor is driven by the rigid electric components that they are made of, for example, the display, a micro-processor, and batteries. With the recent movement of personal fabrication, we see that certain communities like makers and HCI practitioners get access to fabrication technologies that can go beyond rigid interactive components. For example, flexible conductive ink can be printed on flexible paper [37] and is able to sense user input such as touch or deformations [26]. With these novel possibilities at hand, HCI researchers and future interaction designers have to think about how the mechanical properties of materials, such as their flexibility, elasticity, and foldability, can be effectively used to produce novel forms of interaction with physical devices and everyday objects.

In this dissertation, we focus on the fabrication of user interfaces that leverage a range of material properties that go beyond classic rigid form factors, e.g., they are stretchable, they can be folded and recombined to generate new shapes, or they can be reshaped by cutting.

1.1 OPPORTUNITIES FOR INTERACTION-AWARE MATERIALS

Traditional user interfaces sense user input and provide visual, audio or haptic feedback. For user interfaces that integrate tangible interactive parts, this often requires using integrated electric components like sensors or displays that must fit to the form factors of the tangible interface. Modern devices such as smart phones or tablets usually support interaction through a touch sensitive OLED display. Other more simple but still widely used devices, such as remote controls and coffee machines, use rigid circuit boards with mechanical

switches. What all these physical interfaces have in common is that they rely on rigid electronic components. Thus, they are bound to a rigid form factor.

On the other hand, recent developments in materials science enable the fabrication of physical user interfaces that offer novel possibilities of interaction with materials whose shape can change. For example, one stream of research focuses on stretchable interactive materials. Such materials can allow for novel application scenarios that take advantage of their stretchability to support user input. They can be applied, for instance, on the human skin [116] and sense pinch and pressure gestures [115]. Such forms of interaction are only possible because of the material’s stretchability.

Thill et al. [103] present a structured overview of materials that can change shape. This work focuses on applications related to aircraft morphing skins, but Quamar et al. [78] extend it and discuss applications of such materials in the context of Human-Computer-Interaction (HCI). More specifically, they provide a taxonomy of *shape-changing mechanisms* that include stretchable structures, deployable structures, variable stiffness materials, and shape memory materials. This dissertation investigates several of these categories, in particular stretchable and deployable structures, but also explores *cuttability* as an additional shape-changing mechanism. This mechanism is important for physical prototyping and fabrication scenarios. For example, many artists create design pieces through physical modeling and sculpting, where they often interact with material by removing and cutting parts. From a user’s perspective, cutting can be seen as a shape-changing interaction with the material of a physical model.

Taking advantage of such shape-changing mechanisms to make material *interaction-aware* brings new challenges for HCI research.

1.2 CHALLENGES FOR INTERACTION-AWARE MATERIALS

Digital fabrication machines, e.g., laser cutters and 3D printers, enable makers to create complex shapes with a variety of construction materials, including flexible, foldable, and soft materials. However, integrating sensing and visual capabilities into fabricated objects is still a challenge for current systems. For example, a user interface that is designed to be flexible as paper requires the use of flexible circuits and sensor technologies that do not hinder the mechanical properties and affordances of its underlying material structures. Our goal is to go beyond the design of flexible user interfaces – ideally, any change in the shape of a physical object must be sensed as well. For example, physical paper is flexible and thus offers new interaction possibilities. In particular, by sensing its deformations, we can design novel forms of interaction, such as folding or scratching, that rigid objects cannot support.

Furthermore, HCI research seeks inexpensive fabrication technologies that are accessible to novice makers and is also interested in novel form factors. Many advances in interactive materials like super thin and stretchable displays [2016:someya] that could be of high interest for the HCI community are developed by experts from materials science, who unfortunately use highly specialized machines to produce them. How to make these technologies accessible to larger communities is a challenge for HCI research but also a prerequisite for building research prototypes and studying their application in real use contexts.

Finally, makers need graphical user interfaces that aid the design of physical objects and their fabrication with interaction-aware materials. The integration of functional components may require special arrangements and constructions. A digital design tool should be able to support the user with *domain knowledge* [10] in building those interactive components. For example, embedding electrical components such as micro-controllers or displays into a 3D printed object requires knowledge on integrating circuits into these objects and adjusting their geometry accordingly. Tools that support this integration, such as Savage et al.'s Maker's Marks [89], let the artist focus on the creative parts of the design, e.g., where components should be placed, by delegating the required technical knowledge on *how* to integrate these components to the design toolkit.

Taken together, we identify three challenges for creating physical user interfaces with interaction-aware materials:

- **Support Novel Sensing Capabilities**

In order to support novel forms of interaction with non-rigid materials, we need sensing systems that are robust to material deformations, i.e., sensors must not break and remain functional even if they are strained. We further need sensors that extend the traditional input capabilities, such as touch sensing, by detecting changes in the material's shape. For example, if an object is cuttable, not only should integrated sensors be robust to cuts, they must also be able to determine how the object is cut.

- **Develop Affordable Fabrication Technologies**

Integrating circuits, sensors, and displays into non-rigid materials comes with new challenges. We need to develop cost-effective fabrication techniques that support rapid prototyping and are accessible to casual makers, professional designers, and HCI researchers.

- **Create Interactive Tools to Aid Design and Fabrication**

The integration of interactive components like sensors and displays into non-rigid materials may require specialized expertise and be subject to many technical constraints. To this end, de-

sign software can support makers in designing and fabricating their objects by abstracting the technical aspects of their internal construction.

1.3 SUMMARY OF KEY CONTRIBUTIONS

This dissertation investigates solutions for all these three challenges, focusing on interaction-aware materials that are *stretchable*, *foldable*, and *cuttable*. It presents a fabrication technique for embedding interaction in stretchable materials. It introduces *shape-aware* materials that allow physical model to sense their own shape as they are cut. Finally, it investigates an approach for constructing modular interactive 3D models from foldable pieces of paper. I summarize these three contributions of the thesis below.

Stretchability

We contribute a novel and inexpensive method for fabricating *Stretchis*, highly stretchable user interfaces that sense user input and provide visual feedback. We use the elastomer Polydimethylsiloxan (PDMS) as the base material for *Stretchis* and show how to embed touch and proximity sensing and visual output through stretchable electroluminescent displays. *Stretchis* are ultra-thin, flexible and transparent and can be applied on soft surfaces like the human skin, shape-changing objects, and elastic fabrics. We use screen printing, an inexpensive and accessible fabrication method, to create such interfaces. Our approach deals with the hydrophobicity of PDMS and investigates how to print water-based, transparent and conductive inks on silicone. The multi-layer components of *Stretchis* can be designed digitally with popular design tools such as Adobe Illustrator [Illustrator] or Eagle [7]. Finally, the interfaces are customizable by interleaving the interactive components with printed graphical elements that we call *aesthetics*.

This work offers the following key contributions:

- We show how to embed transparent sensors and visual output into highly-stretchable silicone. All interactive elements are printed using screen printing, an inexpensive fabrication method that even novice makers can use. The approach deals with the hydrophobicity of PDMS, allowing water-based inks to be printed on water-repellent silicone.
- We present a multi-layer fabrication approach that allows to interleave multiple layers of sensors, displays and aesthetics on a thin foil of PDMS. We demonstrate the usefulness of this approach with application examples that cover ubiquitous, mobile and on-skin interaction.

- Our technical evaluation shows that sensors and displays remain functional under strain levels of more than 100%.

Foldability

Popular construction techniques like Origami rely on *foldable* materials such as paper to construct 3D objects from 2D sheets. My dissertation presents *interactive tangrami*, modular paper-folded and reusable building blocks that offer input sensing and visual output. We support users in constructing 3D objects with a graphical user interface that helps them design their pieces by integrating internal wiring structures and interactive components, such as capacitive touch sensors and LEDs. The software generates the circuit patterns for fabrication with a rapid and inexpensive ink-jet printing technology that uses conductive silver ink. I can further stream interaction data, e.g., touch events, from the physical structure to other software platforms such as MAX/MSP [57] via OSC protocol [124]. Objects constructed with *interactive tangrami* can be easily modified, and their parts can be reused. This lightweight fabrication process through folding allows designers to prototype functional user interfaces within minutes and with little knowledge of the underlying technology.

Taken together, this work presents the following key contributions:

- We introduce *interactive tangrami*, modular, paper-folded building blocks that support user input through printed touch sensors and visual output with integrated electric components such as LEDs.
- We provide a software toolkit that helps users design modular interactive objects by integrating sensors, circuits, and rigid electric components into their structures.
- We present applications of *interactive tangrami* with scenarios from ubiquitous computing to wearables design.

Cuttability

Many artists often use subtractive fabrication techniques, or sculpting, where they remove material to shape a model. In such scenarios, they take advantage of the haptic feel of real materials and the stereoscopic feedback that they get through interaction with a physical 3D model. On the other hand, several artists make also use of digital design tools because of their high precision and speed. The dissertation introduces *ShapeMe*, a novel smart material that captures its own shape while being cut by an artist or designer. We offer a software toolkit that supports makers in generating customizable shape sensor that can be integrated into modeling material. As the artist makes physical changes on the material, the system streams a digital model of the object in real-time to a 3D CAD environment such as Blender or Unity. We show how to fabricate the shape sensors with a rapid and inexpensive ink-jet printing technology. We developed a linear

prediction model that estimates the sensor’s length from the received sensor data, and our technical evaluation shows a mean estimation precision between 2 and 3 mm. We show the benefits of shape-aware material with an application scenario on multi-object construction such as architectural models that consists of multiple shape-aware sheets and volumetric 3D objects that are build from multiple layers that are stacked on top of each other. *ShapeMe* is the first material-based sensor technology for 3D shape estimation and we present a novel technique for integrating physical and digital modeling.

In summary, the contributions of this work are:

- We introduce *ShapeMe*, a novel smart material that can sense its shape while being cut. The sensor technology supports 2D and 3D objects and can be embedded into a variety of modeling materials.
- We present a linear regression model that maps the sensor values to the sensor’s length. Our technical evaluation shows a mean precision of 2-3mm.
- We offer a software toolkit that supports the maker in customizing and fabrication the sensor technology. It also converts sensor events into geometric parameters, which are then streamed to 3D CAD environments.

Future Outlook: Material Reflection Properties

Future interactive systems could make use of material properties other than shape, such as dynamic color and reflectance. For example, a canvas that senses the color of the ink while being painted could support a range of artistic tasks. During my thesis, I have worked on *directional screens*, which can be customized to reflect light depending on a specific audience layout. We have shown how to computationally control the reflectance properties of a front projection screen in an office or cinema environment and have fabricated several fragments of such screens. Although I do not present this work in the main chapters of my thesis, I discuss future several interaction possibilities with dynamic reflectance properties (Chapter 6).

1.3.1 Collaborators

The core contributions of this thesis, *ShapeMe*, *Interactive Tangrami*, and *Stretchis*, were developed in close collaboration with my supervisors Theophanis Tsandilas and Wendy E. Mackay. The idea and implementation of interactive tangrami was done together with Nadiya Morenko (Academy of Fine Arts Saar). Feedback on the writing of the corresponding demo paper was provided by Jürgen Steimle (Saarland University) and Michael Schmitz (Academy of Fine Arts Saar). I

contributed to the work on directional screens with the software implementation, the fabrication, the evaluation and the writing of the paper together with Michal Piovarči and Michał Jagielski (Saarland University). The project was supervised by Piotr Didyk (Saarland University), Marc Alexa (TU Berlin), and Wojciech Matusik (MIT CSAIL).

1.4 METHODOLOGY

To present novel fabrication technologies, we had (1) to demonstrate their technical feasibility but also ensure that our sensors are reliable, precise, and robust enough for real use scenarios, and (2) to understand how it would benefit people, in particular novice or professional makers. The thesis methodology has largely focused on the first more technical part of this problem. However, we have also tried to involve people in the design process, in particular for the last parts of this thesis.

While this thesis only presents our final approaches to create malleable user interfaces, we went through several iterations in the design process until we reached a working solution. For example, to create stretchable user interfaces, we first experimented with various methods to print on silicone that were finally too complicated to serve as a technology that is accessible to novice makers. We therefore explored new materials that simplified the fabrication process.

Interactive Tangrami was developed in collaboration with an artist that informed with her working practices the system design. The *ShapeMe* platform was initially motivated by a series of interviews with expert users from the area of shoe making and architecture. Additionally, we conducted a workshop with novice maker to better understand how humans construct objects from layers of material. These findings motivated our approach on constructing *shape-aware material*.

1.5 STRUCTURE OF THE THESIS

Chapter 2 reviews related work on digital fabrication techniques and material-based interaction. Chapter 3 introduces our fabricating method for highly stretchable user interfaces. Chapter 4 investigates user interfaces constructed from foldable materials. It introduces our *interactive tangrami* approach for constructing interactive, modular 3D models from foldable pieces of paper with embedded electronics. Chapter 5 presents our technology of shape-aware materials and explains how to use such materials to support interactive fabrication through cutting. I conclude the dissertation and discuss future perspectives in Chapter 6.

RELATED WORK

I start with an introduction to the personal fabrication movement. I then discuss the HCI literature on the fabrication of interactive objects, starting with rigid materials and continuing with malleable, shape-configurable materials. I end with an overview of the state-of-the-art technologies for printing interactive materials.

Until recently, fabricating custom objects from digital models was only accessible to experts by using expensive industrial machines. The uprise of personal fabrication devices enable makers and designers to create custom objects rapidly and at a low cost. This chapter reviews previous HCI work on personal fabrication and discusses the state-of-the-art techniques for fabricating interactive devices and objects. I focus on material-driven technologies that allow to add interaction into both rigid and flexible (or shape-changing) objects.

2.1 DIGITAL AND PERSONAL FABRICATION

Fabrication technologies have made a shift from their exclusive use in industry to small machines that small laboratories or even individuals can afford and use. Making 3D printers, milling machines, and laser cutters available to large communities of makers and tech enthusiasts comes with new challenges. Such users are often not experts in engineering, electronics, or model design. Thus, there is a need for novel user interfaces that aid users in their design and fabrication tasks. The following section summarizes recent developments in this area and stresses the importance of fabricating not only passive, but also interactive objects with functional components.

2.1.1 *The Personal Fabrication Movement*

The power of digital fabrication remained, until recently, in the hands of a few experts who fabricate with expensive and complex machines. Designs created by such industrial workflows are usually intended for multiple copies rather than individually customized products. In contrast to this traditional model, Gershenfeld described personal fabrication as “the ability to design and produce your own products, in your own home, with a machine that combines consumer electronics with industrial tools.” Once consumers can access and control digital fabricators at home, it will reveal “the real expressive power of

machines that make things" [24]. These devices will be able to produce not only passive objects. There will be "machines that build machines" [24], meaning that these objects are themselves interactive and functional.

Baudisch and Müller [9] argue that the personal fabrication movement as described by Gershenfeld has reached a special group of users: makers and technology enthusiasts. While this is already an encouraging development, it has not yet had an impact to the life of millions of regular consumers. Taking further steps towards this goal requires us to first understand why other successful personal fabricators, such as the fax machine, had such a huge impact on society. Baudisch and Müller describe an Analog-to-Digital (AD) and Digital-to-Analog (DA) pattern that can be found in successful fabricators. In the example of a fax machine, the device is able to scan and digitize a physical page (AD), send the digital version to another peer and print this digital copy out again (DA). This pattern allows to bring physical objects to the digital realm, solve problems digitally and then materialize the solution again in physical form. Enabling consumers to make use of this pattern comes with six challenges:

- *Hardware and Materials.* Extending the functionality of hardware from analog to the AD-DA pattern enables a much wider range of functionality as features come "piggy-back" to personal computing. Digitizing a model for 3D printing allows to use a much larger spectrum of functions than a 3D "copy machine" that would only copy geometries without digitizing them.
- *Domain Knowledge.* Modifying digital models requires expert knowledge that consumers might lack. Developing interfaces that aid users in working with these models is a key element for a more wide spreading of personal fabrication devices. An example from image processing are modern programs like Adobe Photoshop Elements [2] that can automatically remove the red-eye effect without requiring the user to know how this is done with basic image manipulation tools.
- *Feedback through Interactivity.* Smart design tools can only aid the design process but not replace it. It will be still necessary for a user to iterate on the model before it is mature. To reduce the amount of iterations it is beneficial if users get immediate feedback on their changes and also have the possibility to undo actions. Getting early feedback on the physical model even during fabrication leads to *interactive fabrication* that interleaves the modeling and fabrication phases.
- *Machine Knowledge.* After designing a digital model, it is also necessary to have expert knowledge about the machine that will reproduce the model. A printer, for example, might work

with different color models, gamma values and paper types that users have to understand before they are able to reproduce the digital model exactly. A main challenge is how to abstract this technical knowledge to help users make the right choice.

- *Sustainability.* Personal fabricators require building material, produce waste, and consume energy. Building materials with many different material properties, interaction aware materials and systems that require less energy and produce less waste are key factors for personal fabricators.
- *Intellectual Property.* Making designs is a creative task that the author might want to share freely or protect from being copied. Handling rights in future systems will have impact on the success of personal fabrication on a broader consumer level.

Addressing these challenges will enable a larger audience of regular users to develop interest in using these fabricators. However, their success also depends on whether the fabricated objects are useful. I argue that being able to create functional objects that contain mechanical parts and interactive electric components will increase the usefulness of these fabricators. Both materials science and HCI research have made significant developments into this direction. The following section reviews HCI literature that studies the problem of how to fabricate interactive objects. Later, I will provide an overview of fabrication technologies for interaction-aware materials that focuses on the more recent advances on materials science.

2.2 FABRICATING INTERACTIVE 3D OBJECTS

Early HCI work in this area started by adding copper tape onto rigid objects, but advances in materials science has allowed to print conductive filaments and inks with digital fabrication machines. In this section, I review the state of the art for fabricating interactive 3D objects.

Adding Electric Components to 3D Objects

A common approach to sensing the user's interaction and providing visual, audio, or haptic feedback is to integrate off-the-shelf electronic components directly into the objects of interest. The electric components are often the driving form factor of an object's design, as the object has to enclose all its components [107, 113]. Maker's marks [89] brought more design freedom into this process as they aid the integration of electric components into custom 3D prints. The user can place stickers on a passive object to indicate the position and the type of the interactive component that should be added to the object. A 3D scanner captures the object's shape and the markers and automatically generates internal circuits and place holders in a digital model,

which can then be 3D printed. The electric components can be added manually after the print is finished. However, the created objects still have to be volumetric enough to contain all the components.

Another stream of research focused on placing bulky electronic components outside of the object and print internal structures that can transport interaction information such as light, air pressure, or conductive material. This helps to reduce the constraints on the object's shape. Printed Optics [14, 123], for example, integrates internal optical fibers in combination with external displays or photo sensors to enable touch sensing and visual output on the object's surface. Sauron [86] uses an internal camera and printable light reflecting material to sense various forms of user input controls like buttons, wheels and sliders. Another work by Savage et al. [88] helped the designer to embed internal hollow tubes into their prints. These tubes can be filled with conductive material, air under pressure to enable inflation and compression, or thin electroluminescent wires to provide visual feedback.

These approaches offer the advantage that makers can choose from a large variety of industrially fabricated components such as sensors, displays, and motors. On the flip side, these components are not customizable but come in fixed sizes and shapes. The object's design gets constrained by these components, their internal space, and the wiring structures they require. Alternatively, there is a stream of research that focuses on adding interactive materials directly, during the print process.

Printing Interactive Material

A more direct way of integrating electric components into 3D prints is to use conductive material directly during the fabrication. Unfortunately, commercially available conductive filaments for 3D prints show a high resistance and can be only applied to low-current applications (see section 2.4). Schmitz et al. [91] showed improvements to the manual application of touch sensor by offering a toolkit that lets designers digitally add touch sensitive areas that are automatically integrated and wired with 3D printable conductors. They later extended their system to also sense deformation of soft 3D printed objects [92]. PEP [68] circumvented this limitation of conductive filaments by stacking many pages of electronic paper on top of each other to create 3D shapes. Printed circuits on paper can have a much lower resistance than conductive filament and allow integrating thermochromic displays and connecting small sensors or LEDs.

These approaches enable the digital design and integration of interactive materials into digital models that can then be fabricated by using personal fabricators. Currently, they are limited by the available materials needed for adding conductive traces, as they often suffer

from low conductivity, or still require a manual assembly.

Spraying Interactive Material

Instead of integrating sensors during the print process, researchers investigated the alternative of spraying conductive material on an object's surface after its print. Ishiguro et al. [34] showed a 3D printed speaker with a sprayed conductive layer. Such a layer was later extended to also work as a multi-touch sensor on curved objects [130]. Even though these methods do not allow to add internal circuits but can only be applied to an object's surface, they offer the possibility to add interactive components to challenging surface geometries and already fabricated artifacts.

2.3 SHAPE-CONFIGURABLE INTERACTIVE OBJECTS

HCI researchers have also studied interaction with non-rigid objects with flexible and stretchable material properties. Quamar et al. [78] observed that HCI research has recently shown a great interest in novel interaction possibilities that such material offer, such as sensing the deformation of flexible materials or the strain of stretchable substrates. However, a much larger body of work from materials science reveals a wide range of useful technologies and opportunities. These are highly interesting for HCI research, but unfortunately, they are rarely accessible to casual makers or researchers from domains other than materials science. Inspired by Quamar et al. [78], I review the HCI literature on flexible, stretchable, and soft materials.

2.3.1 Flexible Materials

Thin and flexible interactive surfaces are an ongoing research field in HCI. They enable paper-like interactions on desktop computers [130], mobile computing [81], and tangible interaction [38, 99, 121] by being bendable, foldable, rollable, and highly deformable. The rapid and inexpensive fabrication of such devices is highly beneficial for quick prototyping and has been extensively studied by past HCI research.

Printing Flexible Circuits and Sensors

Early work by Savage et al. [87] used vinyl cutters to shape copper tape to form touch sensors and wires. Kawahara et al. [37] improved this approach by presenting an instant ink-jet method of printing conductive silver traces directly on paper or transparent PET, which is similar to regular document printing. The ink sinters at room temperature and offers a high conductivity (see section 2.4). The authors demonstrated the potential of this instant fabrication method with touch sensors and flexible PCB production. Hodges et al. built on

this instant fabrication method and extended it with Circuit Stickers [30]. These stickers let makers attach electric components like sensors, LEDs and more simply by gluing them on the printed traces. They are removable so that printed circuits can be reused and modified during design iterations. The works show advances in digitally designing functional components and rapid fabricate them with ink-jet print technologies or vinyl cutters.

These approaches focus on traditional interaction techniques, such as touch sensing, or on how to integrate rigid electronics. Previous work that makes use of the material's property of being flexible, trying to sense the substrate's deformation, will be discussed in the following section.

Deformation Sensing

The input modalities that I discussed so far handle direct input on the surface of a flexible object. However, a different stream of research has investigated shape-deformation as the source of user input. Such forms of interaction were shown to be useful in medical imaging [99] and interaction with deformable displays [38, 39, 49, 93]. This work requires external camera systems to track the deformation of the device. PrintSense [26] followed a different approach that supports multi-modal sensing by relying on ink-jet printed sensors. In particular, the authors demonstrated the implementation of multi-touch, proximity, bend and fold sensing on a flexible paper sheet. FlexSense [81] was able to sense its deformation by printing a sparse set of bend sensors directly on a thin sheet and using machine learning to identify its deformation. The sheet can be used as an overlay on tablets to change layers of a video or as a game controller on a console. Sensing continuous pressure on flexible sheets was shown with UnMousePad [84]. The authors implemented a grid of electrodes that changed their resistance under pressure but came with a limited resolution while their prototype was considerably thick. Later work by Rendl et al. improved these methods by implementing piezoelectric pressure sensors on a thinner and transparent sheet [80].

Attaching Flexible Interfaces on Physical Objects

Flexible interfaces were also used to enrich curved objects with interactive controls. Midas [87] provides a design and fabrication pipeline to add touch sensors on 3D objects. The user can select areas on a digital model to be touch sensitive. The system generates cutting patterns to shape copper tape that can be wrapped around the object and sense the touch after connecting to a micro-controller.

Folding Paper Electronics

Besides 3D printing, several researchers have explored various ways of creating 3D objects by *folding*. Sketch-a-TUI [121] are folded geo-

metric paper primitives that serve as tangible controls for tablets. Qi et al. extended paper pop-ups by integrating electric components [79]. Foldio [71] used origami techniques and ink-jet printed conductive traces on the sheets before folding. This construction technique enabled touch sensors, deformation sensing and visual output. These works benefit from advances in printing highly conductive traces on 3D sheets of foldable materials. Also their fabrication is light-weight and well established. However, they often result in limited stability when using flexible and foldable materials. Also, they have an upper limit in geometric complexity as fine details also increase the effort in folding them.

Printed Displays

Visual feedback is an important feature of most user interfaces. Integrating visual feedback has been largely supported by commercial components like LEDs or LCD displays, but this constrains the design of a user interface, as those are only available in certain shapes and sizes. Thermochromic displays are a passive display technology that causes materials to change their color under heat. They have been used in fabrics [17, 98] and hair colors [18] but also on flexible sheets [94, 105]. Unfortunately, these displays are heat-driven, which limits their resolution as they do not actively emit light. Olberding et al. [69] addressed these limitations by introducing a digital fabrication pipeline for customizable flexible touch-displays based on thin-film electroluminescence. Such displays can be fabricated with an inexpensive and fast screen-printing method and are printable on various substrates, including PET film, paper, leather, and stone. This technology was later applied to build smart paper in classrooms and security environments [41, 42].

2.3.2 *Soft Interfaces*

Stretchable and soft interaction aware materials offer novel possibilities for interaction. HCI research has used this special material property to build wearables in stretchable fabric, on-skin interfaces, and interactive deformable surfaces [125]. We can distinguish between two ways of creating stretchable interaction aware materials [83]: intrinsically elastic materials and auxetic materials.

Elastomers

Elastomers are stretchable materials. A widely used elastomer is Polydimethylsiloxane (PDMS) as it is inexpensive and simple to fabricate. It is also biocompatible, ensuring a safe contact with the human skin. Materials science research has shown how to embed conductive carbon and silver particles [67], nano-tubes [23, 52] and PEDOT:PSS [51] into or on the surface of this material. While these techniques have

a high potential, they require cleanroom environments that are not accessible to common makers. Lu et al. [55] addressed this issue with a rapid prototyping method for laser-cutting conductive carbon-PDMS (cPDMS) and a liquid metallic conductor. iSkin [116] built on this technique to fabricate customizable on-skin interfaces that sense touch and one-level pressure input. iSoft [128] further extended this approach by including multi-touch and strain sensing. cPDMS uses inexpensive carbon particles that need to be mixed into liquid PDMS to make it conductive (see section 2.4). This fabrication process is lightweight but also comes with limitations, in particular printed electronics demonstrate low conductivity and cannot be transparent.

To overcome the limitation of low conductivity, researchers have used liquid metallic conductors that are embedded inside PDMS with a grid of tubes [55]. Lu et al. [56] further presented an approach for fabricating micro-fluid circuits by patterning PDMS and filling micro-channels with liquid eutectic gallium-indium (EGaln). While these authors relied on expensive UV lasers for patterning the PDMS, Nagels et al. [66] simplified this process by using standard CO₂ lasers and allowing for multi-layer circuits. Their system allows to integrate high-current electric components like LEDs and micro-controllers.

Both approaches use opaque conductive materials. As a result, the sensors and wiring structures of a printed user interfaces are all visible. In addition, such materials cannot be used to print electroluminescent displays, which require one layer to be transparent to let their light pass. In response to these limitations, materials scientists found that PEDOT:PSS, a transparent conductive polymer, is also stretchable up to 188% [51, 108]. SkinMarks [117] presented an interactive tattoo foil for on-skin interaction with screen-printed PEDOT:PSS and printed EL displays. However, similar to other approaches that used tattoo foil with ITO [112], silver [54] and gold coating [36], such interfaces are only stretchable by less than 10%.

Auxetic Materials

In contrast to materials that exhibit elasticity through their material composition, auxetic materials gain this property by changing their internal structure. Cutting hinge-like cells (e.g. honeycomb cells) into flexible material let it expand and compress under force. The cutting patterns thereby define their strain behavior, which is most often anisotropic [104]. Although these patterns have been mainly investigated for 2D planes [27, 65], we can also find their application in 3D structures [127]. For example, Konaković et al. [43, 44] introduced a computational optimization to let flexible material stretch in an exact pattern to form specific 3D objects, e.g., for fashion applications.

Architectural and HCI research has used these principles to fabricate interactive objects. For example, Theodoros et al. [102] developed an auxetic structure that can change its curvature through pneumatic

pressure. Ion et al. [31] proposed a computational model to generate internal structures in 3D prints with flexible filament (NinjaFlex) that translates rotary movement of a door handle to linear movement of a latch. Ion et al. [32] extended these internal structures to mechanisms that behave like logical gates and, more recently, to mechanisms that can generate custom textures on 3D prints [33].

Research in HCI is still sparse in this field. A first reason is the limited communication between the fields of computer graphics and HCI. Furthermore, the fabrication of such materials was challenging for a long time. However, given the new opportunities of 3D printing high-resolution flexible structures, this field shows promising potential for future HCI research.

2.4 PRINTED ELECTRONICS

The term *printed electronics* characterizes several printing technologies used to deposit functional materials on a physical substrate. The most common printing technologies in personal fabrication are ink-jet printing, screen printing, and 3D printing. In contrast to classical fabrication methods for electric components, printed electronics offer the possibility to print on flexible and stretchable substrates while being inexpensive and fast.

The field of printed electronics is highly interdisciplinary. It requires knowledge from materials science on how to provide functional inks to print electrical components, sensors and displays, useful for fabricating interactive objects. Depositing such materials with digital fabricators further requires experience in mechanical engineering, as the goal is to create machines that are capable of processing various kinds of functional materials. This dissertation focuses on technologies (i.e., materials, equipment, and treatments) that are suitable for personal-fabrication scenarios. The following paragraphs discuss the most representative ones.

2.4.1 *Printing Technologies*

Depositing functional materials can be achieved with a range of printing technologies, including ink-jet printing, screen printing, and 3D printing. I review the state of the art of these techniques.

Ink-Jet Printing

While ink-jet printers are popular for making instant copies of documents and photos, recent work has also enabled this technology to print functional inks. The working principle is based on a controlled shooting of ink droplets on the surface of a flat printing substrate [48]. Conductive ink-jet inks that allow to print circuits are

available commercially. For example, Mitsubishi offers a flexible silver nano-particle ink [59] and Sigma-Aldrich, a conductive ink that is based on the polymer PEDOT:PSS [95]. We will discuss these materials in section 2.4.2.

The fact that the positioning of thousands of ink droplets on a surface can be computationally controlled is a strength of ink-jet printing but also comes with some disadvantages. The diameter of a printer nozzle is in the range of several microns [48]. In order to avoid clogging, the functional particles in the ink have to be much smaller than the nozzle, thus they are rather in the nano scale. Other functional materials like electroluminescent phosphor particles are difficult to print with this technology because of their large bulk particles of around 50 microns [40]. In addition, most modern ink-jet printers are based on two core technologies. These are piezoelectric and thermal printer nozzles [48]. The later ones heat the ink up to about 400°C, and only thermal stable inks can be used in such temperatures. In contrast, piezoelectric nozzles use an electrically controlled piezo crystal that pushes the ink out on demand. Functional inks that are solvent based or contain heat-sensitive particles have to be printed with piezoelectric printer heads.

These capabilities of instantly fabricating electronics made way for several works in HCI. Kawahara et al. [37] showed that silver ink can be used not only by industrial ink-jet printers but also by low-cost commercial printers to produce flexible touch sensors and flexible circuit boards. Later work extended the range of printable sensor with bend and proximity sensing [26].

Screen Printing

Screen printing is used for industrial printing and graphical arts since the 19th century. This stencil-based printing technology is nowadays mostly known for printing on fabrics but is also used in large-scale printing. Its popularity comes due to its relatively small installation costs for manual printing and its ability to process a wide range of inks and printing substrates [19].

Its working principle is to mask a stringed net with a pattern to be printed. The open areas are then soaked with an ink that gets pressed through the net on the printing substrate. Screen-printing machines exist for manual printing and can be also used by novice makers. They are inexpensive and simple to work with. At the same time, there exist partially and fully automatic screen-printing systems that allow for digitizing the printing process and ensuring a reproducible and constant printing quality.

Screen printing with manual equipment has been explored by researchers for printing a variety of interactive surfaces in workshops with art and HCI students [45]. Others have used this technology to print electroluminescent displays [69] or thin multi-touch sensors that

can be wrapped around everyday objects [130].

3D printing

3D printing is an additive manufacturing method where material is joined together to produce nearly any geometric shape. In personal fabrication, two main methods are used: fused deposit modeling (FDM) printers and stereolithography (SLA) printers.

FDM printers extrude a melted filament layer-wise on a working platform. The filament cools down and hardens almost instantly once extruded. After one layer is complete, the printer extrudes the next layer on top of the previous one until the full object is complete. Embedding electrical materials inside an object is currently very limited. Conductive filament contains carbon particles and can be printed as regular filament. Unfortunately, its conductivity is low ($0.1 - 1 \Omega\text{-m}$), which only allows to build low-current circuits such as capacitive sensors [46]. Recently, Voxel8 [109] presented an FDM printer that can extrude conductive resin in a regular 3D print with filament. The resin contains silver particles and offers a high conductivity ($5 \times 10^{-7} \Omega\text{-m}$) suitable for medium-current circuits. However, the printer can print horizontal and vertical conductive traces but is less reliable with three dimensional curves and diagonals.

SLA printers use directed light to harden a liquid resin. As with FDM printers, the polymers are hardened layer-wise until a full object is completed. SLA printers offer a higher print resolution than FDM printers, and there are resins available that are clearer, more flexible or stronger than FDM prints [22]. However, SLA printers are not capable of producing multi-material prints. This limits their usability for embedding interaction aware materials inside printed objects.

2.4.2 Functional Materials

Conductive Materials

Interactive objects can be created with internal mechanical components or by embedding electric components. The latter approach largely relies on the ability to print conductive materials. In personal fabrication, three materials are commonly used: carbon particles, silver nano-particles, and PEDOT:PSS.

Carbon particles are maybe the most popular choice for creating conductive inks due to their simple handling and their low price ($\approx \$1/\text{kg}$). For example, they are used for screen printing [35], 3D printers [46], stretchable conductors [101], and pens [8]. However, their low conductivity does not allow for high-current applications.

In contrast, silver nano-particles offer a high conductivity ($0.01 - 0.1 \Omega/\text{sq}/25\mu\text{m}$). Available pastes and inks based on silver nano-particles can support both ink-jet printing (e.g. Mitsubishi's silver ink [59])

and screen printing (Gwent's silver paste [28]). One of the key features of nano particles is that they melt together at much lower temperatures than regular bulk silver which has a melting point of 961°C. This allows printed patterns to create homogeneous layers of silver on heat-sensitive substrates such as paper or PET at curing temperatures of 120°C or even room temperature [75].

PEDOT:PSS is a conductive polymer that shows a slightly better conductivity ($50 - 150 \Omega/\text{sq}/25\mu\text{m}$) [96] than carbon particles but is also transparent, highly flexible and even stretchable [51]. This makes it applicable to fluorescent materials as it lets pass light [69]. This material can be screen printed [28], ink-jet printed [95] and even sprayed [100] on various surfaces. As we will see in the next chapter, our work on stretchable user interfaces relies on this ink.

Materials for Printing Displays

A large variety of display technologies can be used for tangible user interfaces [47], but this dissertation only examines displays that can be printed with personal fabrication devices. We can identify three common materials whose optical properties can be computationally controlled: electroluminescent (EL), thermochromic (TC) and electrochromic (EC) materials.

EL displays are a simple version of modern OLED displays and can be printed using screen printing. The EL ink contains phosphor particles that light up when activated through an alternating current [40]. The printed displays can be segments of high resolution or passive matrix displays for dynamic content. Previous work has shown that these displays can be printed on a variety of materials, such as wood, stone, and metal [69]. Other work uses this technology to create interactive and responsive paper for classroom exercises [42].

In contrast, a thermochromic material does not actively emit light, but its color changes under heat. A thermochromic display consists of two layer. The first layer consists of a heating structure that is often realized by a horse shoe pattern layer of conductive material that gets heated by applying a strong current. The second layer is the actual thermochromic material that changes color at the areas of heat. The switching time is slow due to the heating time required to reach the temperature threshold. HCI research showed that flexible TC displays are possible [53] and that this material can be embedded in artificial hair for public and social communication [18].

Finally, a electrochromic material behaves similarly to a thermochromic material but is activated with electric current. EC materials support different colors like green, blue and red [15]. They are inexpensive and simple to build but suffer from slow switching times [4]. So far, HCI research has not investigated their usage, so there are opportunities for investigating applications of such materials in the future.

FABRICATING HIGHLY STRETCHABLE USER INTERFACES

I present Stretchis, highly stretchable user interfaces that support touch and proximity sensing, as well as stretchable electroluminescent displays. Stretchis are based on a new method of printing stretchable conductive material onto silicone. Their interactive components can be stretched by more than 100% and are inexpensive to fabricate by novice makers. We demonstrate their applications to wearables, ubiquitous computing, and on-skin interfaces.

As discussed in the previous chapters, we can think of user interfaces that are not simply composed of rigid physical components. In particular, embedding interaction-aware materials in flexible and stretchable substrates would allow us to add interaction to a wider range of physical objects. For example, interactive stretchable materials can be integrated into fabrics, used as on-skin interfaces or applied to complex geometries and components with moving parts. Thereby, stretchable materials interleave seamlessly with physical objects, as they do not constrain their shape and material behavior.

However, fabricating stretchable user interfaces is still a complicated task. Embedding sensors and visual output into flexible and stretchable surfaces requires the use of conductive materials, sensors, and display technologies that can withstand strong forces. Previous work has simplified the fabrication of interactive flexible surfaces through ink-jet printed sensors and displays [26, 37, 69]. However, HCI research in fabricating *stretchable* user interfaces is still rather sparse. Although rapid fabrication techniques exist for touch and pressure sensors [116, 128], such approaches do not support visual feedback, while the strain level they handle is limited.

We address this problem with a novel fabrication technique for printing highly stretchable user interfaces that we call *Stretchis*. These *Stretchis* are customizable and can sense touch and proximity input. They provide visual feedback with stretchable electroluminescent displays. As other work, we use Polydimethylsiloxan (PDMS) for the stretchable base substrate. We present a set of key innovations to enable the printing of interaction aware materials on PDMS. Our approach deals with the hydrophobicity of PDMS and allows to apply a water-based transparent conductive material on hydrophobic substrate such as silicone. Layers of interaction aware materials can be arranged using common design tools such as Adobe Illustrator [Illustrator]

and Autodesk Eagle [7]. Additionally, we present artistic customization possibilities by printing graphics with stretchable colors that interleave with the functional components without interfering with them.

Stretchis can be ultra-thin ($\approx 200\mu\text{m}$), foldable and rollable. We show that our sensors and displays remain functional even under strain of more than 100% their initial length. Our fabrication framework allows to print in large formats and at low costs. To show their usefulness we implemented application examples in fabrics, on-skin interfaces and in ubiquitous computing.

Taken together, we show in this chapter the following contributions:

- We developed an inexpensive and accessible fabrication method to screen print stretchable capacitive sensors and displays onto PDMS. We found a novel method of applying hydrophilic inks on hydrophobic PDMS. This allows us to embed a water-based transparent conductive ink directly onto the stretchable substrate.
- We present a multi-layer fabrication approach to combine diverse interaction aware materials into PDMS which enables us to print and interleave sensors, displays and aesthetic graphics. We show their application with three examples from wearables, on-skin interaction and ubiquitous computing.
- We evaluate the behavior of our stretchable conductors, sensors and displays under various strains and show that they remain functional even under stretchings of more than 100%

3.1 STRETCHIS: REQUIREMENTS AND CHALLENGES

When exploring which requirements a stretchable user interface should fulfill, we found several factors that enable versatile application scenarios and allow for accessible and personal fabrication.

Form Factor

Stretchis should remain functional also under strain and stress. For instance, if makers want to apply a *Stretchi* on the movable neck of a lamp, a curved geometry like a cup or even their own cloth or skin, it should remain functional and adapt to the object's shape and deformation.

Substrate Properties

The base material of a *Stretchi* should be safe to touch and wear. Also, it should be able to host all sensors, displays and aesthetics. We chose silicone (PDMS) as it is known to be bio-compatible and available in

various levels of stretchiness and color. PDMS is also inexpensive, customizable and is known to be suitable for embedding also electrical components [51, 55].

Input and Output Capabilities

Stretchis should be able to sense user input but also give visual feedback through customizable displays. PrintScreen [69] showed screen printing of touch-displays on flexible substrates but these interfaces are not stretchable. Also, they reused the display electrodes as touch sensors which limits the design freedom of the maker. For instance, it is not possible to have a multi-touch displays that contains various touch sensors.

Fabrication Process

It is our goal to develop a fabrication method that does not require cutting-edge technology and clean-room environments but is accessible as a personal fabricator to non-engineers and hobbyists. It should encourage customization and rapid prototyping for: i) HCI researchers who want to design and explore interactive devices for ubiquitous computing ii) designers who create artistic installations or develop novel interactions on cloth or the human body iii) hobbyists who want to experiment with interactive components on their fabricated objects.

3.2 MULTI-LAYER FABRICATION APPROACH

Our fabrication platform for *Stretchis* accommodates 4 functional layers that serve as building blocks for stretchable user interfaces:

Base Layer

This layer should define the basic structure and material behavior of a *Stretchi*. We chose PDMS because it is available in various scales of stretchability from being very stiff and robust to extremely soft, stretching up to 10 times its original length. The right choice of PDMS can constrain the stretchability in order to protect the embedded electronics. Also, PDMS is available in different colors or even complete transparency. As the material comes in contact with the human skin through interaction or because it is applied directly as an on-skin interface, it is important that the base layer is bio-compatible. PDMS is often used in medical context and known to be safe to touch and wear.

Sensing Layer

This layer consist of a stretchable conductor that can be patterned to house different types of sensors. Currently our system supports capacitive touch and proximity sensors. However, it can be extended to

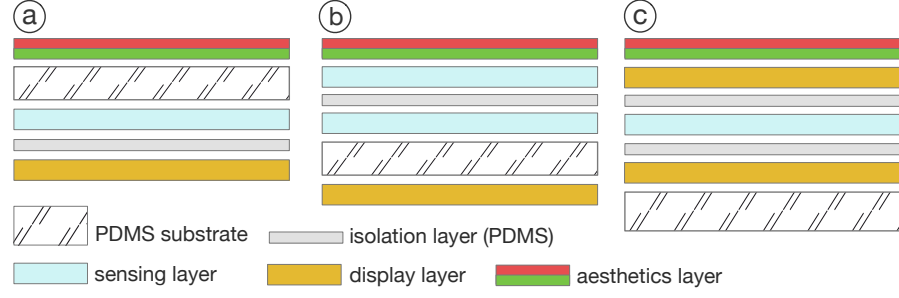


Figure 1: Examples of *Stretchis*'s multi-layer approach. The top layer is facing to the user. Layers can be arranged to optimize different interface functions. For instance, functional layers and aesthetics can be separated to isolate and protect the electronics (a), sensing layers and display layers can be separated by the PDMS substrate to shield the sensors from the display's electrical field (b), or on-skin *Stretchis* are isolated from the skin with the PDMS layer on the bottom (c).

support deformation sensing [26] and strain sensing [16].

Display Layer

We implement visual feedback with printed electroluminescent displays. They consist of a stretchable phosphor layer that gets sandwiched between two conductive layers. The displays can be freely shaped and customized. Also, the maker can choose the color using different kinds of phosphor particles.

Aesthetics Layer

This layer consists of colored inks. We found that screen printable colors that are used for textile printing also have stretchable properties. The maker can use practices from textile printing to embed multi-colored graphics into a *Stretchi*.

The multi-layer approach increases the designer's freedom when constructing a stretchable user interface. All mentioned layers can be printed independent from each other during the print process. This allows to mix and combine displays, sensors and aesthetics. Figure 1 shows some example configurations. For instance, several sensing layers can be stacked on top of each other (figure 1b) to sense different kinds of input or the PDMS base layer can be used to shield the conductive parts from the skin (figure 1a,c). The overall thickness remains thin even with multiple layers. A *Stretchi* has a thickness of around 200 μm and is mainly determined by the PDMS base layer. Sensing and display layers have a thickness of 50-100 μm .

3.2.1 Adding Stretchable Conductors to PDMS

Embedding conductive material into PDMS creates special requirements for the conductor used. Other conductive materials, for instance silver ink, fail under strain because the printed particles move apart from each other when the base substrate gets stretched. This makes them lose their connection and destroys the printed traces. Alternatives that remain functional under strain exist. For example, carbon-filled PDMS (cPDMS) and liquid eutectic Gallium-Indium (EGaIn) remain conductive even under stark strain but both of these materials are non-transparent. These methods rely on specialized equipment like laser engravers while it was our goal to present a fabrication technique that relies on inexpensive and accessible equipment. Also, being opaque makes them unusable for printing stretchable displays as at least one layer has to remain transparent to let the light of the display pass.

Materials scientists found that PEDOT:PSS, a conductive polymer, remains stretchable under strains of up to 188% and is even reversibly stretchable by 30% where resistance increases only by a factor of 5 after 1000 stretches [51]. Also, it is transparent which makes it suitable for our attempt to print stretchable sensors and displays. Unfortunately, PEDOT:PSS is hydrophilic while PDMS is hydrophobic. Printed shapes lose their homogeneity and form drops. This makes it impossible to print this ink without further treatment. This is also the reason that PEDOT:PSS hasn't been used in HCI research so far to print on silicone. Materials scientists use plasma [25] and corona [29] treatment to change the surface behavior of PDMS to become hydrophilic. After the treatment, it is possible to print PEDOT:PSS but the effect is only temporary. After several minutes the silicone returns to its initial state and repels the PEDOT:PSS layer. Only small stretches below 10% are possible before a critical breakdown occurs [51]. Lipomi et al. used in their tests a doping of PEDOT:PSS with Zonyl to increase the bonding between PDMS and the conductive ink. However, these materials are not available on the consumer market and therefore, they are not suitable for our goal to develop a maker friendly fabrication method.

We experimented with various surface treatments and developed a novel, inexpensive and permanent method to print hydrophilic inks on hydrophobic surfaces such as PDMS. Since direct application of PEDOT:PSS is not possible, we use a stretchable *binding layer* that acts as an interface between the PDMS and the conductive ink. We found that AQUAPLAST DIY BINDER shows excellent printing properties on PDMS. The fraction of water is lower than in PEDOT:PSS which reduces the repellent effect. Also, it is a liquid with a higher viscosity than water which prevents it from forming drops after printing but remains a homogeneous layer. It is also transparent, highly stretchable

and inexpensive(<\$15/kg). A layer of this binder serves as the basis to print patterns of PEDOT:PSS.

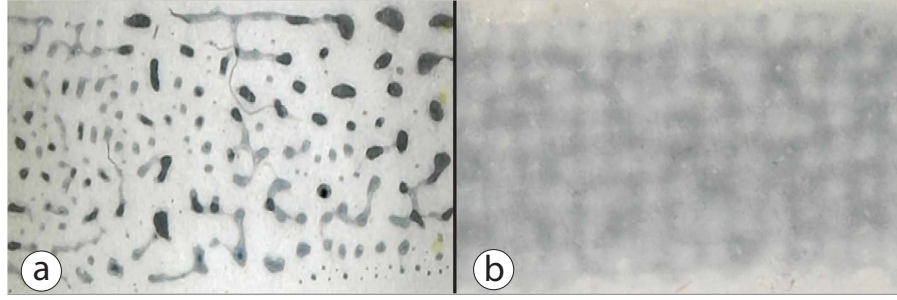


Figure 2: Examples of printing PEDOT:PSS on PDMS under 20X magnification. (a) shows the result of printing PEDOT:PSS directly on the PDMS without any further treatment. The ink forms drops and is not conductive. (b) shows the result with a binding layer between the PEDOT:PSS and PDMS. The ink forms a homogeneous and conductive layer. The print pattern of the screen printing net is visible.

Figure 2 shows the outcome of print tests with and without the binding layer. In the left image, we printed PEDOT:PSS directly on PDMS. The ink gets repelled from the surface and forms unconnected drops(similar to the Lotus effect). Electricity cannot flow through this layer. In the right image, we first printed a layer of the binder liquid. It spreads homogeneously over the PDMS and creates the basis to print PEDOT:PSS on. The visible blue pattern is a layer of the conductive ink. One cannot observe a drop creation anymore but PEDOT:PSS is distributed over the whole surface. The chess board pattern of the PEDOT:PSS originates from the screen printing net used. However, also between the darker areas there is a thinner film of conductive ink that transports the current.

3.2.2 *Embedding Stretchable Displays*

Now, that we are able print conductive patterns on PDMS, we can extend the PrintScreen approach [69] to stretchable displays. Electroluminescent display are a simple version of OLED displays. They consist of a phosphor layer which can be activated by a strong electrical field to emit light [40]. To create this field, the phosphor layer is sandwiched between two layers of conductive material. Applying an AC current on the electrodes creates the electric field. The electrodes and the phosphor can be printed in any shape and at high resolution which offers great degree of freedom in customization for interface design [69].

The phosphor layer in PrintScreen is not stretchable. Therefore, we adapt Wang et al.'s approach [111] to mix phosphor particles (KPT

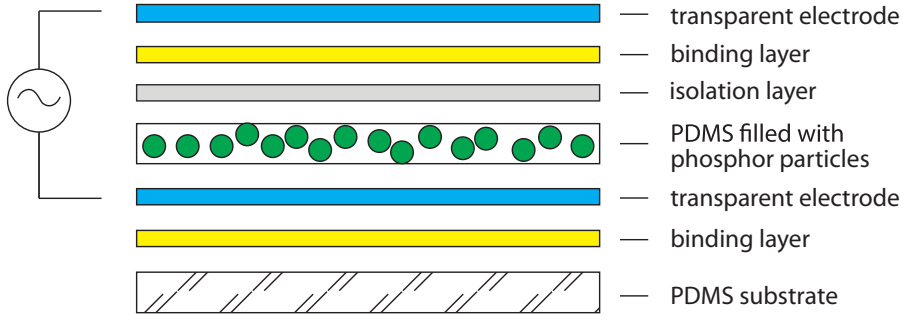


Figure 3: Schematic of *Stretchis*'s electroluminescent displays. A layer with phosphor-filled silicone gets sandwiched between two electrodes of PEDOT:PSS. Each conductive layer also requires a binding layer before printing. To ensure perfect isolation between the two electrodes, we print an PDMS isolation layer between the two.

D310B) directly into silicone. To do that, we use a two component liquid silicone mixture (Smooth-On Sorta-Clear 18) and add the particles in a 2:1 ratio to the mix. While liquid, the phosphor can be used as regular ink. After screen printing, the phosphor-silicone mixture cures and solidifies to a stretchable layer.

To build a fully functional electroluminescent display, we also need to sandwich the phosphor layer between two electrodes. Each electrode also needs a binding layer to enable printing directly on silicone. To make sure that the two overlapping electrodes do not get short-circuited, we recommend to add a layer of pure, transparent PDMS on top of the phosphor to ensure perfect isolation. Taken together, printing an EL display takes 5-6 individual layers (see figure 4). To also increase the robustness of the displays under strain and touch we also recommend to encapsulate the entire displays with another clear silicone layer on top.

3.2.3 Sensing

It is our goal to interleave displays also with user input sensing. Unfortunately, activated electroluminescent displays emit a large electromagnetic field that interferes with any capacitive sensing method. To be able to sense touch and proximity even with an EL display in proximity, we adapt Olberding et al.'s method [69] of time-multiplexing. We deactivate the power source of the displays and set both electrodes to high impedance. Internal capacitors of the AC generating inverter have a long discharge time of several hundred microseconds. Thus, we also shortcut the inverter to trigger a rapid discharge of the display's electrodes and the inverter. Using this method, we can reduce the discharge time after deactivating a display to $1.7\mu\text{s}$. The *Stretchi* is

then free of any electric noise and can be used for a variety of sensing methods.

We use Arduino's capacitive sensing library to sense interaction by touch and proximity [6]. Sensing with this library takes in our implementation 2ms which gives an overall sensing cycle duration of 3.7ms. To avoid any flickering of the displays, we let the display activated for 10ms. This allows to reach a refresh rate of 73Hz which is not visible to the human eye. Deactivating the display during the sensing cycle reduces the brightness of the displays by 27% which can be compensated by increasing the input voltage or frequency of the display's power source. Increasing the sensor's sensitivity can be necessary for proximity sensing. We achieved that by adding the sensor values of multiple sensing cycles. We found that using the values of 5-10 sensing cycles lets the system sense a user's proximity by up to 10cm.

Our current system only supports touch and proximity sensing. However, the sensing cycle can be used to accommodate a variety of other sensing modalities for printed electronics. For example, we could use single layer [26] and multi-layer [16] conductive layouts to sense bending, stretching or folding. In contrast to Olberding et al.'s approach [69] we do not reuse the electrodes of the display for sensing. A major advantage of our multi-layer fabrication approach is that all functional components are designed and printed independent from each other. This does not constrain the shape, position or amount of displays and sensors in a *Stretchi*.

3.3 FABRICATION PROCESS

Digital design and fabrication of a *Stretchi* takes 5 basic steps. The section concludes with design and fabrication recommendations.

3.3.1 Design a *Stretchi*

The maker uses common digital design tools like Adobe Illustrator [Illustrator] or Photoshop [2] to design a *Stretchi*. Routing of functional components and wiring to a connector can be done with a PCB design software such as Autodesk Eagle [7]. The layers in the design software can be structured according to the multi-layer fabrication approach (see section 3.2). Each layer consists of sublayers. For example, the sensor layer requires one binding layer and on PEDOT:PSS layer. Binding layers and insulation layers should be designed slightly larger than the corresponding functional layer to simplify the registration of consecutive layers during the print and ensure perfect insulation and protection.

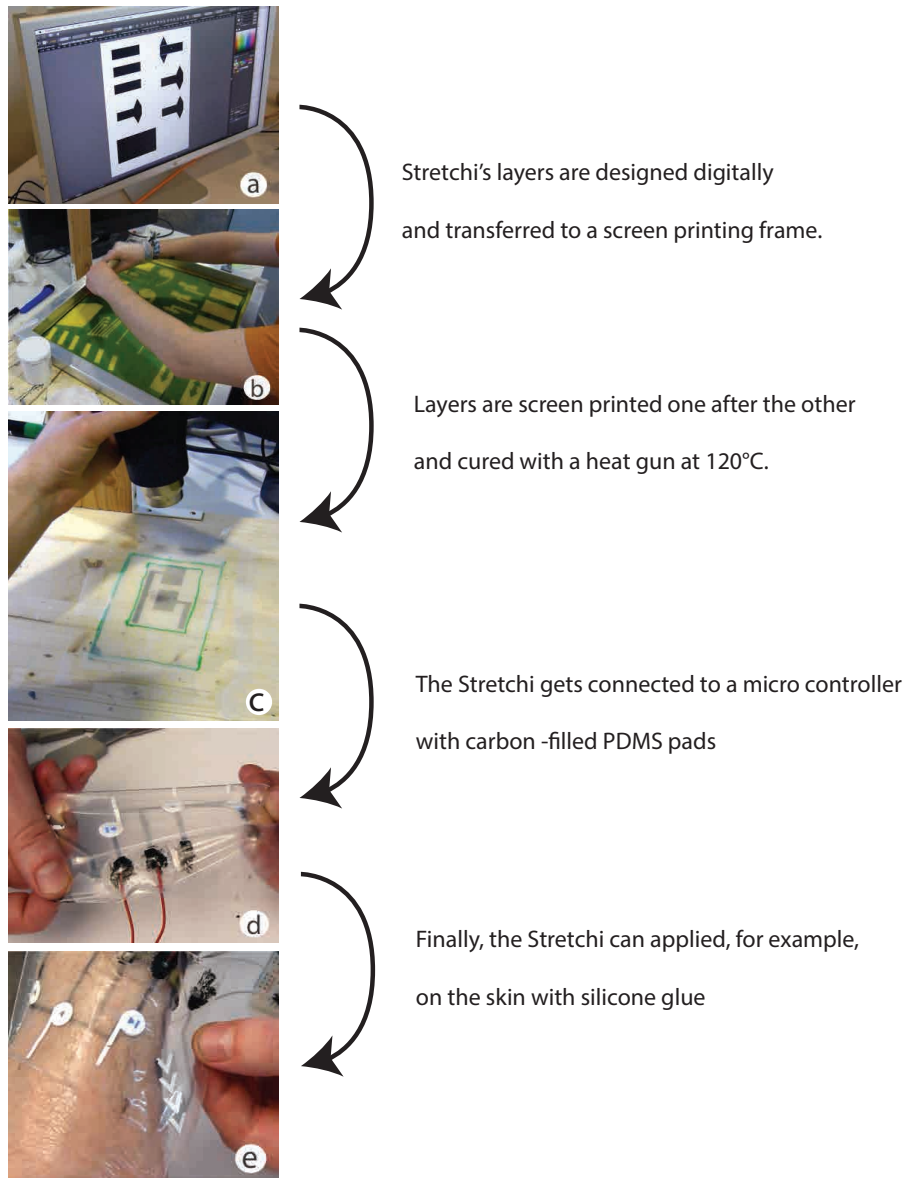


Figure 4: Fabrication pipeline for *Stretchis*. Each layer gets designed digitally (a). The patterns then get transferred into a screen printing frame and can be used to print layers (b). After each layer, the print has to be cured using, for example, a heat gun at 120°C (c). The stretchable sensors and displays are connected to a micro-controller with carbon-filled PDMS pads (d). Finally, the *Stretchis* can be applied to objects or the human skin (e).

3.3.2 Creating the Base Material

Thin sheets of PDMS are commercially available and ready-to-use, for instance, from Wacker GmbH [110]. They can be bought in different colors, levels of elasticity and thickness (20 μm - 400 μm) for less than \$10 per sheet. Alternatively, it is also possible to fabricate

custom-shaped PDMS base layers with simple materials and tools. We use liquid two-component PDMS (Sorta-Clear 18). After mixing, the compound stays liquid for 1 hour and can be further customized by adding color pigments to the mix. A thin layer of PDMS can be created by spin-coating, molding or with a thin-film applicator to achieve the desired shape and thickness. When the PDMS is shaped, it fully cures within 24 hours at room temperature or it can be heated up to 90°C with a hot plate, oven or a heat gun to cure in about 20 minutes. Since the air flow of a heat gun can change the layer thickness of the liquid silicone by its pressure, we recommend to reduce the strength of the air flow by keeping a sufficient distance to the PDMS layer.

3.3.3 *Printing Sensors, Displays, and Aesthetics*

We use screen printing to apply all functional layers on the PDMS base layer of a *Stretchi*. This printing technology is easy to use and widely known for printing on fabrics. HCI researchers used this technique for printing functional inks on various substrates, for instance, on flexible interfaces [69], on-skin interfaces [117] and in educational context [45]. We use a standard, off-the-shelf screen printing table for less than \$200. The screen printing nets should have a high resolution but should not be too dense to block larger particles like the phosphor. Therefore, we recommend densities of 100T-140T.

The maker prints each layer of ink one after the other. Between each layer, the inks have to be cured with a heat gun and temperatures between 90°C (for the silicone) to 120°C (for all other inks). After curing, the *Stretchi* might be still hot. Some layers like the binding layer can be sticky during the time and might break if the next layer gets printed on top. Thus, we recommend to let each layer cool down to room temperature. Also, we noticed that the prints become most homogeneous if the maker moves the squeegee with high speed and low pressure over the substrate. We also noticed that colored inks like TEXPRINT AQ have similar properties as the binding layer but are already colored with pigments. The designer can create various graphical effects by layering colors on the PDMS before adding sensors and displays.

3.3.4 *Shaping the Stretchi*

The designer can shape a *Stretchi* with common cutting tools like scissors or digitally with a vinyl cutter or a laser cutter. *Stretchis* can also be bent to form 3D shapes like a cylinder. The ends of one or multiple *Stretchis* can be glued together with liquid 2-component PDMS or with silicone glue.

3.3.5 Adding Electronics, Power, and Control

Stretchis are able to contain various rigid electronics like additional sensors, integrated circuits or LEDs. Connecting those components requires a conductive material to connect the rigid components that remains robust under stretch. We use carbon-filled PDMS (cPDMS) for this purpose. We create a mix of 7% carbon particles (e.g. Cabot Black Pearls 800) with fluid two-component PDMS. While still liquid, this mix can be applied on a *Stretchi* by using an aluminum stencil or by manual application. The electrical component or a regular wire can then be pressed in the cPDMS pads. Finally, the cPDMS is then cured like regular PDMS with heat as describe earlier in this section. The connections remain stretchable and enable a stable connection between rigid and stretchable electronics.

The designer has various options to control and power a *Stretchi*. We use an Arduino Uno controller for our application examples. The stretchable displays require a high voltage but low current AC power supply (100V - 220V). We generate this AC current with a compact inverter (WY-ELI) that takes an input voltage between 3.3V-12VDC. The electric components can be made mobile by using smaller inverter ICs (e.g. SIPEX SP4405) and smaller controllers like the Arduino Nano or Intel's Curie controller.

3.4 APPLICATION EXAMPLES

Stretchis can be used to embed interaction in various objects and locations. To show their potential we implemented several application examples.

Awareness Sleeve

We fabricated a stretchable sleeve that notifies the user about incoming calls and social media events (see figure 5). The sleeve can be stretched to fit on various objects and can be reused if the user prefers the notifications on another object. The awareness sleeve is equipped with multiple stretchable displays that give visual feedback to the user. On top of each display is a transparent touch sensor. The sensor can read the interaction of the user and can, for example, accept a call if the corresponding displays has alerted the user. We also printed a graphic with stretchable colored ink on top of the displays and sensors to show its visual customizability.

On-Skin MP3 Player

Another application area are on-skin interfaces. We fabricated a *Stretchi* to be worn on the back of the hand. It contains several touch-displays that work as controls for an MP3 player (see figure 6). Each display is covered with a layer of colored ink that forms the visible shape of the

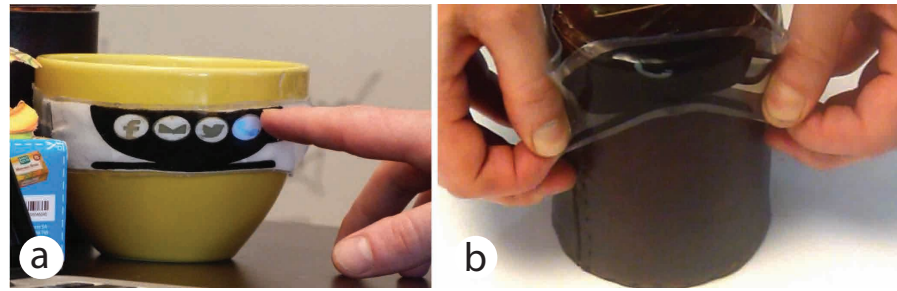


Figure 5: Awareness Sleeve. It contains four stretchable displays and touch buttons that inform the user in its proximity about incoming calls or social media actions (a). The user can interact with the notifications with touch. The awareness sleeve can be removed from an object and stretched over another object of different size and shape (b).

touch-displays. While the hand and especially the thumb is moving, the interface adapts its shape to the movements by stretching. The functional part of the interface are connected via wires to a micro-controller that is embedded into a wristband close to the interface.

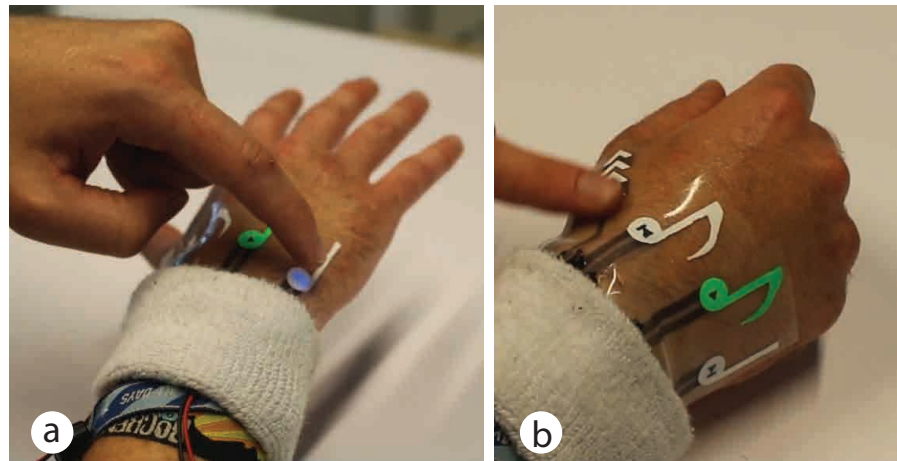


Figure 6: On-Skin MP3 Player. We implemented an on-skin MP3 player that contains 3 touch-displays for skipping and starting a song. A slide sensor consisting of three touch electrodes on the thumb lets the user control the volume. The interface naturally adapts its shape through stretching to the hand's movements.

Interactive Headband

Stretchis can also be integrated into wearables. We added a stretchable touch sensor and a rigid vibration motor into a sports headband (see figure 7). It can notify the wearer on incoming calls through vibration even while being occupied by sportive activities. She can accept the incoming call by tapping on the band even though the sensor is on the

inside of the band well hidden using the sensors proximity sensing capabilities. The *Stretchi* withstands strain of the head band while being taken on and off. The encapsulation with an additional layer of PDMS saves the integrated electronics from friction and sweat during sport sessions.



Figure 7: Interactive Head band. We integrated a stretchable touch/proximity sensor (1) and a vibration motor (2) into a stretchable head band. It notifies the wearer on incoming calls through vibration and the user can accept the call by touching the head band in proximity of the integrated sensor.

3.5 TECHNICAL EVALUATION

We run a series of tests to study reliability, technical behavior and robustness of *Stretchis*. We start with a study on the reliability of touch- and proximity sensing under strain. Next, we test the robustness of electroluminescent displays under repeated stretching. We conclude this section with a test of a PEDOT:PSS trace under several thousands of stretches.

3.5.1 Capacitive Touch- and Proximity Sensing

Reliable sensing of touch- and proximity is an important feature for a user interface. We test these sensing technologies under up to 120% of strain. Note, that earlier work in HCI on stretchable touch sensors [116] showed reliable sensing under stretch only up to 30%.

Apparatus

We printed a touch sensor shaped as a 15mmx15mm square of PEDOT:PSS on a silicon layer according to the fabrication method described in section 3.3. We connected the square with a 1mm thick PEDOT:PSS trace to our sensing circuit. We collected the sensing data with an Arduino Uno micro-controller and used Arduino's capacitive

sensing library [6] to sense touch and proximity values.

Participants

We recruited 12 volunteers (6 female) at ages between 21 to 30 years. All participants did the test with the same sensor throughout the entire experiment.

Procedure

The participants positioned their index finger in normal direction above the sensor in 7 discrete distances from 6cm to 0cm, where 0cm means direct touch of the sensor. For each distance they were asked to let their finger rest for 3 seconds. We captured in this time 63 values ($SD=10$) on average using Arduino's capacitive sensing library [6].

This process got repeated five times with the sensor being stretched by 0%, 30%, 60%, 90% and 120% of its initial length. To stretch the sensor, we put both ends of the PDMS base layer into clamps and fixated the clamps on the experiment table after each stretch.

Results

Figure 8 shows the results of touching the sensor directly and figure 9 shows the 6 proximity sensing results. The plots show the median of all measurements for each combination of participant, strain level, and distance to the sensor. The key result from the experiment is that the sensor is robust to strain. Both the touch sensing and the proximity sensing values show reliable values even up to 120% of strain.

The touch sensing results in figure 8 show a high variance. This is because participants touched the sensor with different pressure and some missed the sensor, only touching the sensor partially. However, the difference between direct touch and the sensing values for proximity at 1cm distance differ by a factor of at least 4.53 (24 on average). This allows to clearly detect touch and differentiate to proximity sensing with a perfect (100%) recognition accuracy.

The proximity sensing results are consistent for all levels of strain (see figure 9) and the sensing values are clearest at 1cm distance and becomes less precise with growing distance. This is expectable for capacitive proximity sensing as the influence of noise becomes strong with greater distance of the interacting finger. The accuracy could be increased by printing a larger sensor area. However, even though 12 participants tested the same sensor over the course of two days, we did not observe any degradation in the sensing values over time.

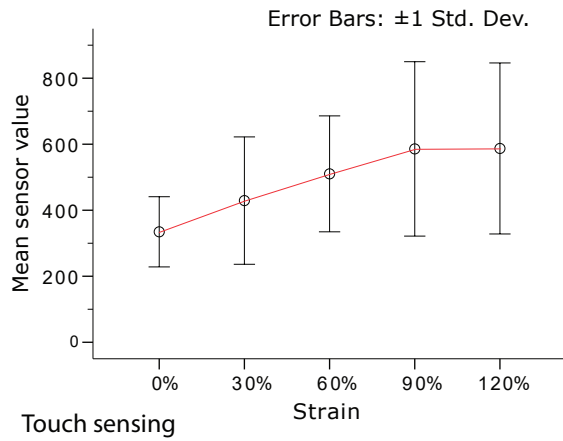


Figure 8: Results of touch sensing under strain between 0% and 120%. We show between-participant standard deviation for 12 participants.

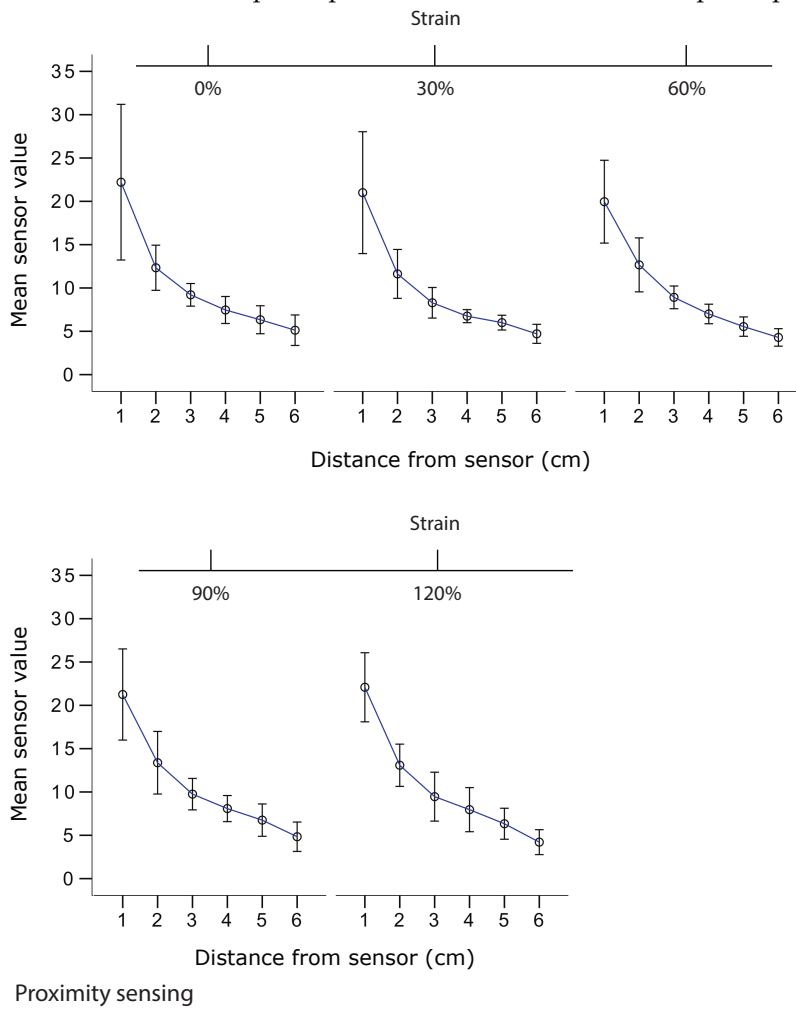


Figure 9: Results of proximity sensing under strain between 0% and 120%. We show between-participant standard deviation for 12 participants.

3.5.2 Luminosity of Displays

In the experiment, we want to find out how strain influences the brightness of stretchable electroluminescent displays.

Apparatus and Procedure

We fabricated an 40mm x 20mm EL display according to the fabrication procedure in section 3.3. To ensure precise and repeatable stretches, we fixed the EL display with clamps on the movable head of a CNC milling machine (Roland MDX-40A, 10 μ m step resolution in x and y direction). We used the device to stretch the display 10 times from 0% strain up to 50% and back. The display was powered by the PYL-ELI-ISC inverter that provided 150V AC at a frequency of 1.3kHz. We use a photo diode to capture the light intensity of the EL display. More precise measurements of luminosity require specialized equipment like a photometer. However, our setup allows for an initial assessment of the brightness level when putting *Stretchi's* displays under strain.

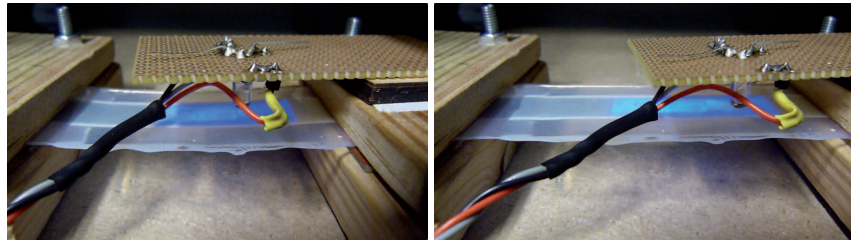


Figure 10: Stretchability test for printed displays. The display was stretched 10 times to 50% its original length. The relative brightness was measured with a photo diode.

Results

The EL display remained functional over the whole duration of the experiment. We measured brightness values of 13 (0% strain), 17 (30%) and 16 (50%) which remained highly stable over the 10 stretch repetitions. The brightness gain under stretch is caused by phosphor layer becoming thinner when stretched. This lets the two conductive layers of an EL display move closer to each other which increases the strength of the electrical field. The estimated luminous intensity derived from our measured values ranges between 150-200cd which is comparable to the measured values of Olberding et al. [69]. Note that the printed display is transparent and emits light in both directions towards the viewing and the hidden surface. It is possible to increase the brightness in one direction by printing a reflective white layer on one side of the display.

3.5.3 Durability of Stretchis

Finally, we wanted to know if our stretchable conductors can also endure long-term usage without breaking. Thus, we stretched a conductive trace 6000 times from its initial length up to 50%. For most use cases as on-skin interfaces or wearables this is a reasonable upper bound. In comparison, Lipomi et al. [51] and iSkin [116] both tested the durability of their stretchable interfaces only up to 30% strain.

Apparatus and Procedure

We printed a 60mm x 6mm conductive trace with PEDOT:PSS on a 1mm thick stripe of PDMS (SORTA-CLEAR 40) using the printing method described. To increase its durability we also sealed the printed PEDOT:PSS with a layer of PDMS as recommended in section 3.3. We measured the initial end-to-end resistance of the virgin test stripe to be 2.7k Ω . As in the previous experiment we use the controllable head of a CNC machine (Roland MDX-40A, 10 μ m step resolution in x and y direction) to stretch the test pattern from 0% to 50% and then back to 0%. This procedure is repeated 6000 times.

Results

The resistance of the printed pattern increased non-reversibly after 10 stretches to 177k Ω . Lipomi et al. [51] explained this behavior with microscopic cracks in the PEDOT:PSS layer when it gets initially stretched. These cracks increase the resistance of the conductive layer but remain small and do not hinder electric current to flow through the PEDOT:PSS layer. The resistance did not increase considerably in the subsequent stretches and reached 350k Ω after 6000 cycles. This slight increase (29 Ω per stretch) is negligible for most capacitive methods in interaction sensing.

However, detecting the amount of strain was not possible with this material as the increase of resistance when being stretched is small and behaves non-linear. Capacitive methods like in [16] have to be used for that. An increase in resistance can also affect the brightness of a printed display. This loss has to be compensated by increasing the power supply voltage of the display.

Break Point

After finishing the previous test, we stretched the conductive traces until we reached the break point of the conductive film. We reached it at 153% of strain where the resistance exceeded 20M Ω . Lipomi et al. [51] reported a higher break point in their experiments at 188%. However, we did this test on an already used *Stretchi* after 6000 strains while Lipomi et al. did their experiment with a virgin conductive film.

3.6 DISCUSSION AND FUTURE DIRECTIONS

Stretchi's fabrication platform enables the printing of various interaction aware materials on stretchable silicone. We would be interested to extend its current range of materials to also other displays technologies. For example, it is possible to mix thermo-chromic powder (WO_3) into PDMS similar to the phosphor-PDMS mix in the display layer. Together with an underlying heating structure it is possible to fabricate stretchable thermo-chromic displays [126]. The insulation layer of a displays could also be improved to have better dielectric properties by mixing Barium-Titanate powder (BaTiO_3) into the mix. This material reduces the attenuation of the electric field in electroluminescent displays while it passes through the layers which could improve the brightness and energy-efficiency of printed displays.

We presented in this chapter a multi-layer fabrication approach that enable the integration of various functional layers like sensors and displays into a stretchable silicone. Adding interactive areas to a silicone layer, however, still requires the maker to design each layer individually. Instead, we would like to develop a digital design toolkit that aids makers in designing and automatically generating all functional layers based on the proposed mutli-layer fabrication approach.

Materials science research also presented interesting novel materials that could be integrated into the *Stretchi* framework. Silver nano-wires (AgNW) can be mixed into PDMS to produce stretchable conductive layers (up to 70% strain) [3]. They are also transparent and have a lower resistance than pure PEDOT:PSS. Most interestingly, they can be used as strain sensors which is a challenging task with pure PDMS. AgNW show a reversible resistance change under strain while our current approach with printing pure PEDOT:PSS changes its resistance non-reversibly after stretching.

3.7 CONCLUSION

This chapter presented a novel fabrication method for *Stretchis*, highly stretchable user interfaces that enable integrated sensors and visual output with printed stretchable displays. *Stretchis* are able to sense user input through touch- and proximity sensing and can give visual output with stretchable electroluminescent displays. Inspired by state-of-the-art research on stretchable electronics [51, 55, 111], we developed a novel and inexpensive fabrication method based on screen printing that does not require special treatment, clean-room environments or expensive machines. We demonstrate that the presented sensors and displays are highly stretchable to more than twice their initial length, stretch by more than 100%. We implemented three application examples that show the usefulness of *Stretchis* for on-skin interfaces, wearables and ubiquitous computing. Our introduced multi-

layer fabrication apporach is capable to be extended to a variety of other sensing technologies and interaction aware materials.

MODULAR FABRICATION WITH PAPER-FOLDED ELECTRONICS

I present a modular fabrication method that is based on folding paper pieces into 3D building blocks. Those may contain circuits, sensors, rigid electric components and can also support actuation. We print conductive traces on paper by using a rapid ink-jet printing technology. We also offer a software toolkit that supports makers in designing and fabricating fully interactive objects from their pieces. I demonstrate applications of our approach with examples from fashion design and ubiquitous computing.

In the previous chapter, I examined stretchability as an interesting material property for interaction. This chapter investigates foldability as the enabling material property. By using foldable materials, one can turn 2D sheets into complex 3D geometries. This property has been successfully used in *Origami* [11] techniques but also by commercial products such as postal cardboard boxes. Here, we will explore how foldability can be useful for rapidly prototyping applications with interactive objects.

Makers and artists can easily fabricate prototypes of tangible user interfaces [91] with the help of personal fabrication machines and simple electronic prototyping platforms, such as Arduino. Unfortunately, such prototypes are most often fabricated out of one main piece, which introduces challenges for a rapid-prototyping design process. If the artist only wants to modify a specific part of the design, it is hard to remove and replace certain pieces while individual segments cannot be reused. The maker has to fabricate a new object from scratch after making the appropriate modifications digitally. This results in longer workflows and an unnecessary waste of resources.

Past HCI researcher has developed several approaches to support the reuse of functional components. For instance, Roumen et al. [85] let makers extract mechanisms from digital models and adapt them to their individual design. Mueller et al. [64] interleaved 3D printing with Lego-like building blocks that can be reused, which accelerates the fabrication process. Folding has also been shown to be a powerful tool for fabrication. LaserOrigami [61] supports fabrication of 3D objects by folding 2D acrylic sheets. It creates fold lines by using a laser cutter that heats the material at these lines and lets them bend under their own weight. However, these approaches do not support the fabrication of interactive prototypes. In contrast, Foldio [71] sup-

ports interaction through sensors and flexible displays printed on paper. Those can be folded in a subsequent step to create 3D interactive objects.

Inspired by these works, we present *Interactive Tangrami*, paper-folded building blocks (*Tangramis*) that include printed sensors and other electronic components. Their fabrication is inexpensive and rapid based on ink-jet printing of conductive silver traces. Each building block can be reused and replaced during prototyping without having to fabricate a prototype from scratch. We offer a design toolkit that supports the planning and programming of interactive tangrami prototypes. Taken together, this work presents the following contributions:

- We present *interactive tangrami*, modular paper-folded building blocks that support input and visual feedback.
- We implemented a design toolkit that supports makers in designing and integrating functional tangrami pieces into their design artifacts.
- We show the interaction possibilities of *interactive tangrami* with two application examples from ubiquitous computing and fashion design.

4.1 REQUIREMENTS AND CHALLENGES

Based on our exploration of fabrication methods that support reuse, waste reduction and offer input and output capabilities, we found several requirements that such a platform should fulfill.

Construction Mechanism

Our goal is to offer makers the possibility to perform quick modifications on a physical object and try out different functionalities without having to reproduce the entire prototype from scratch. Also, they should be able to reuse functional parts in other prototypes. Avoiding to recreate every design iteration with a new prototype also helps to reduce waste. We found that removing or adding parts from or into a physical object requires mechanisms that allow to attach and detach certain parts similar to Lego bricks. Thus, we focused on exploring modular fabrication with reusable building blocks.

Input and Output Capabilities

Objects built out of tangrami pieces should be able to sense user input and should be able to integrate electrical components, such as LEDs and sensor ICs, in order to support both input and output capabilities. The functional components should be easy to connect and control even though an object's building blocks are not permanently

connected but can be attached and detached.

Inexpensive and Rapid Fabrication

The fabrication of *interactive tangramis* should be rapid and inexpensive. Also, they should be able to contain electronic components, sensors, and visual output. Because integrating such electronics into 3D printed objects directly is difficult, we chose an inexpensive ink-jet printing method that can pattern conductive silver traces on paper [37]. To create three-dimensional volumetric objects from these sheets we explored the possibilities of folding building blocks from the printed sheets. Thus, we adopted an established folding technique, tangrami [60], to create 3D building blocks out of paper.

4.2 PAPER-FOLDED BUILDING BLOCKS

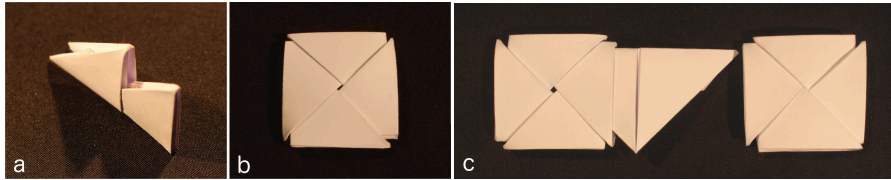


Figure 11: Tangramis are paper-folded building blocks. Tangramis have pouches to connect to other tangramis (a). 4 tangramis can be combined to a meta-tangrami which is useful to build larger structures with less tangramis (b). Meta-Tangramis are connected with normal Tangramis (c).

Tangramis are folded out of a rectangular sheet of paper with an aspect ratio of $\sqrt{2}$. The size of a tangrami can be scaled from very small sizes, which result in high resolution objects with fine details, up to large tangramis that can form large objects. One obtains a triangle with two tips and two pouches (see figure 11a) after a few simple folds in about 30 seconds. With this basic building block it is possible to create a large variety of 3D volumetric objects.

However, large prototypes can consist out of hundreds of tangrami elements. To reduce the amount of required tangramis for large artifacts, we use *meta-tangramis*. By combining four tangramis into a rectangle (see figure 11b), one gets a larger structure which offers pouches in all four directions. Each meta tangrami can be connected with a single tangrami to another meta-tangrami (see figure 11c). By that, larger prototypes can be realized with fewer elements.

4.3 INTEGRATING ELECTRONICS

We developed a set of circuit patterns that can be integrated into a tangrami. Currently our system features touch sensing, embedding of

electric components, wire tangramis and actuation. Figure 12 shows an overview of the supported patterns.

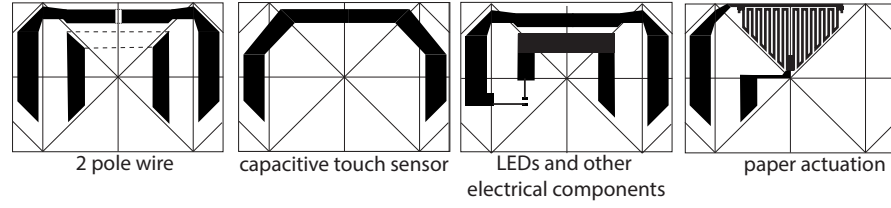


Figure 12: Tangramis are paper-folded building blocks. Tangramis have pouches to connect to other tangramis (a). 4 tangramis can be combined to a meta-tangrami which is useful to build larger structures with less tangramis (b). Meta-Tangramis are connected with normal Tangramis (c).

Wire tangramis can transmit electric signals through a tangrami construction. They are invisible from the outside and can contain one electrode for touch sensing or two electrodes to power and control electric components like LEDs. Touch tangramis have only one electrode in the flaps of a tangrami triangle. Building blocks that can contain electric components are designed to use one flap to hold the electronics and the other to connect to a wire tangrami.

Similar to that, actuated tangramis also connect with one flap to a wire tangrami but contain a heating structure that facilitates the actuation. Inspired by [20] we apply polyethylene Tape (Workzone PE Tape) on the heating structure. This tape expands under heat and can bend paper when glued onto it. The strength of this bend is rather weak. Thus, we remove one layer of paper at the fold line in the middle of the tangrami where the heating structure is printed. This reduces the bending resistance and lets the paper be actuated with the PE tape. The heating structure is designed as a horse shoe pattern that heats up by letting current pass through it. Once it reached 90°C the expanding PE tape bends the tangrami up to 70° in our tests.

Connecting Tangramis

Connections are formed by plugging one tangrami into the other. To ensure stable connections, we designed the conductive traces to be large enough such that it is safe for two electrodes to touch.

Fabrication

We use the instant ink-jet printing technology to print silver traces on paper as in the previous chapter using an Epson ET-2550 printer and Mitsubishi's silver ink (NBSIJ).

Electronic components are connected to the printed traces using double-sided conductive tape (z-tape by 3M). We attach 3x3mm neodymium magnets on the conductive tape. Metallic components can then simply be attached to the magnets and are also removable. One can also

apply electric components directly on the z-tape if they are not metallic and would not stick to magnets.

Folding Conductive Traces

Printed silver traces are robust to bending but can break if they are folded sharply. Thus, we recommend to fold the paper without applying much force. If a trace breaks, it can be healed by applying silver ink on the fold line.

Finalizing the Design Artifact

While working with tangrami artists, we found that they use the modularity to try out different designs and rearrange certain parts. Once their artifact is finished, it is common practice to make the connection between tangramis permanent using paper glue. This improves the stability and robustness of the piece. To also make the electric connections between the tangramis permanent, we recommend to use conductive silver epoxy or copper tape to bind two pieces.

4.4 DESIGNING INTERACTIVE TANGRAMIS

During our explorations with tangrami artists, we found that integrating and assembling interactive objects can be challenging for non-technical users. Also, connecting the art piece to a micro-controller and programming the functional components requires understanding of the underlying technology. To facilitate a rapid prototyping design process, we developed the *interactive tangrami toolkit*.

4.4.1 Workshop on the Toolkit Design

The design of the toolkit is inspired by our first explorations on constructing an interactive tangrami dress together with an artist. In the first attempt, she built up the entire dress without any initial planning. This strategy revealed problems when we wanted to integrate the functional components, for example, touch tangramis that required a series of wire tangramis to connect to a microcontroller. She then created a simplified version of the dress' structure on paper by representing each tangrami as a square on a regular grid. She drew wires from the controller to an interactive tangrami with strokes and indicated LED-tangamis and touch tangramis by marking the squares with a different texture. Our digital toolkit is directly inspired by these findings.

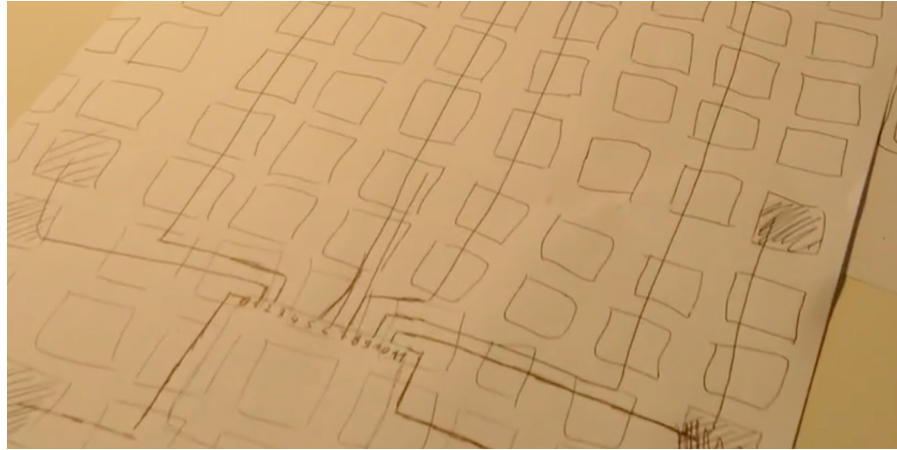


Figure 13: Paper schematic of a tangrami dress. An artist sketched the dress by representing each tangrami as a square on a regular grid. She drew wires as strokes and marked functional components such as touch tangramis by painting a different texture on the squares.

4.4.2 *The Tangrami Toolkit*

Figure 14 shows the design tool. The artist can choose from a library of functional tangramis that can be placed by drag-and-drop on the working area. The tangramis are connected through green wires to a micro-controller connector. Once the design is complete, the system can export the circuit patterns to a pdf file that can be printed using the silver ink-jet printer. The toolkit also exports the outline of the tangramis in the same file, which can be sent to a laser cutter.

Tangrami Library.

The left panel of figure 14 shows the types of tangramis currently available in our system. The user can choose between (a) a blank tangrami with no embedded circuits, (b) a touch tangrami that contains a touch sensor, (c) a hover tangrami that contains a larger, more sensitive hover sensor, (d) an actuated tangrami that has an integrated heating pattern, and (e) and EL tangrami that supports additional electronic components such as LEDs or printed electroluminescent displays. The footprint of these tangramis correspond to those shown in figure 12.

Pin Icon

The right panel of the interface contains a pin icon. This icon can be dragged and dropped on the working area and informs the user interface which tangrami should be used to connect the interactive object with a controller pin. The user has to place a green wire from one tangrami to the pin icon to mark it as the one that should connect to the controller.

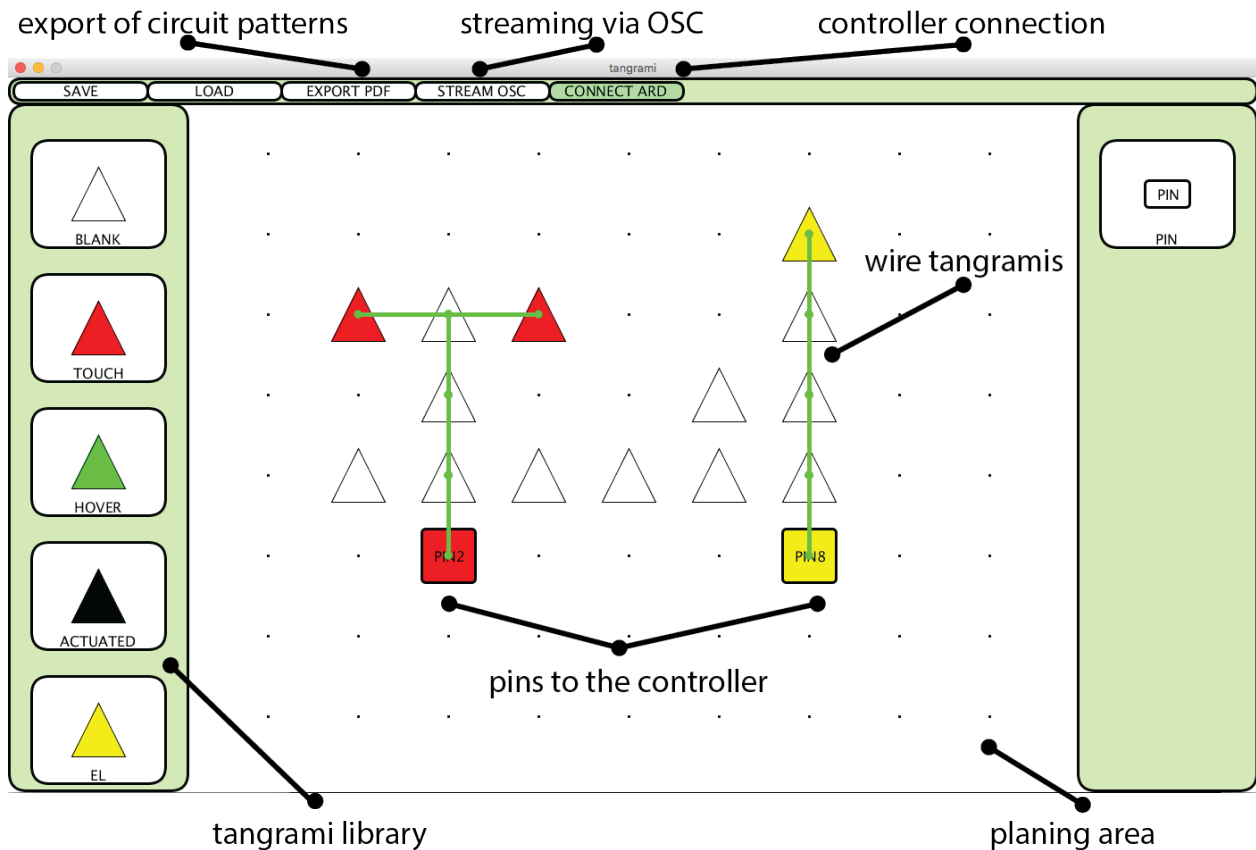


Figure 14: Tangrami toolkit. Functional tangramis can be dragged to the planning area in the middle. Green wires indicate which components are connected to which controller pin. The finished design can be exported for fabrication. The tool configures the microcontroller and streams the interaction data to external prototyping tools via the OSC protocol.

Working Area.

The white area in the center of the interface is the working area to construct interactive tangrami objects. Tangramis can be dragged from the tangrami library on the left onto the working area. They snap to the grid outlined by the black dots. The added tangramis can be rearranged and tested inside this working area until the designer is satisfied with the current design. Green wires can be drawn to indicate which tangramis should be connected to functional tangramis, for example, for touch or hover interaction. Finally, they have to be connected to a pin icon to let the system know which tangrami connects to the microcontroller.

Control Panel.

The panel at the top of the interface contains several controls to han-

dle the communication of the toolkit with the tangrami object and application prototyping systems:

- a. *CONNECT ARD* handles the communication between the toolkit and the physical tangrami object. First, the system checks which pin icon is connected over green wires to a functional tangrami such as a touch tangrami. Then, it assigns a pin id and colors the pin icon in the color of the connected tangrami type. For example, touch tangramis are red in our interface. Thus, a connected pin icon would be colored in red. This visualization should support users in understanding which tangrami is connected to which pin and also indicates to which pin the user should plug in the physical wires of the tangrami object. Figure 14 shows the toolkit after clicking on the *CONNECT ARD* button. Note, that the pins are colored and show the pin id. With this information known, the toolkit sends a command to the micro-controller (e.g. Arduino Uno) that configures all used pins as defined by the user and handles the interaction data between toolkit and tangrami object. For example, a touch tangrami streams a binary number over Serial communication to the toolkit (1: touch, 0: no touch).
- b. *STREAM OSC* activates the streaming of the captured interaction data (such as a touch event) via the OSC protocol. Application prototyping systems such as Processing [77] or MAX/MSP [57] support this protocol and can read the interaction data from the toolkit. We used this system to implement the application examples in the next section.
- c. *EXPORT PDF* creates a pdf file that contains the circuit patterns of the functional tangramis added to the working area. Additionally, the file contains the outlines of each tangrami, for example, to laser cut the paper parts. It is also possible to rescale tangrami objects by changing the size of the tangramis with a vector program such as Adobe Illustrator [Illustrator].
- d. *SAVE/LOAD* lets the user store or reload a working area.

4.5 APPLICATION EXAMPLES

Interactive Tangramis can be used for prototyping tangible user interfaces. We implemented one example that shows its application for rapid prototyping and quickly exchanging and reusing parts. The second example shows that tangramis can also be used to build more complex objects in fashion design.

Paper Pets

We constructed a versatile paper pet out of 4 tangramis. The base consists of two wire-tangramis and contains the connection to the micro-controller. The paper pet's "head" can be exchanged with two different versions. The first is a cow made from two touch tangramis. The user can play and cuddle with the cow. The functional tangramis

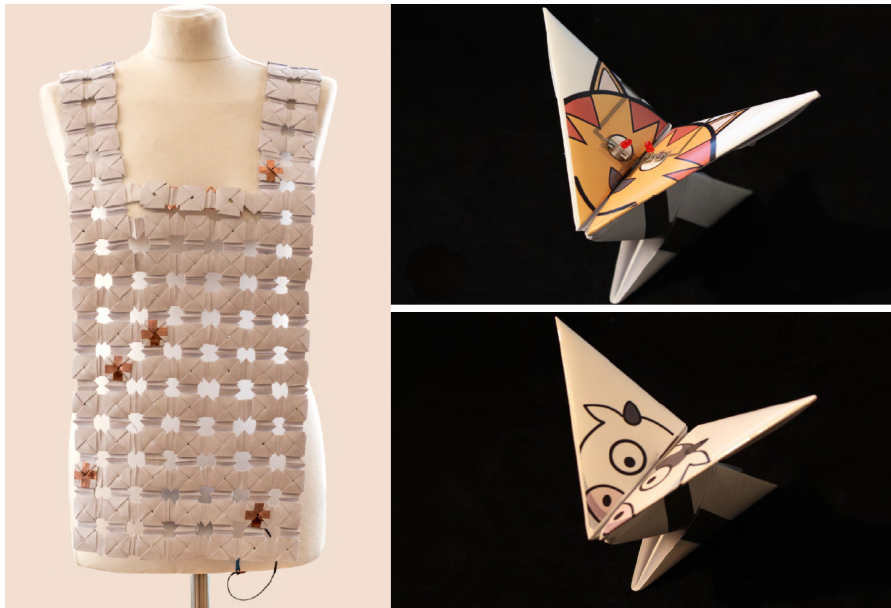


Figure 15: Application examples of interactive tangrami. (a) is a modular paper dress that houses 3 LEDs and several touch sensors. Interactive components of the dress can be removed or replaced. (b) and (c) show a paper pet. Both examples use the same wire tangramis at the base but the head can be replaced with a lion head containing LEDs (b) or a cow head with touch tangramis (c).

recognize the interaction and send the touch event to a Processing application that reacts with a "Moo"-sound on the cuddling. The cow tangramis can be replaced by a lion head which contains two red LEDs at the position of the eyes. The LEDs can be turned on using the *Tangrami Toolkit* to leave ambient notifications. Both applications reuse the two wire-tangramis at the base of the object.

Interactive Paper Dress

We built an entire dress out of tangramis that contains a set of three LEDs at the collar and five touch-tangramis distributed at several locations over the whole dress. The touch-tangramis can sense various body postures and trigger an audible response by an integrated speaker. The interactive tangramis can be removed or replaced to reflect the current emotional situation of the wearer and as an ambiguous communication channel. For example, red LEDs may communicate that the wearer feels uncomfortable and wants to be left alone while green signals the wish to engage in social activities. The piece has been nominated for the Hager Award and has been exhibited at the Saarland Museum in Berlin, Germany and the Academy of Fine Arts, Saarbrücken, Germany.

4.6 CONCLUSION AND FUTURE DIRECTIONS

We presented *interactive tangrami*, modular paper-folded building blocks to create tangible user interfaces. We used the material property of paper to fold 3D objects from 2D paper sheets. This enabled us to print sensors and circuits using an instant ink-jet fabrication technology and subsequently, folding 3D building blocks that can be combined to shape volumetric tangible user interfaces. We presented a design toolkit that supports the construction of tangrami objects and manages the communication to the micro-controller via Serial communication and to prototyping software via the OSC protocol. We showed the usability of this construction platform with two application examples from ubiquitous computing and fashion design.

In the future we want to experiment with alternative folding techniques and materials to create different geometries and explore novel uses. Also, our current implementation is not robust to sharp folding lines. We want to increase its robustness by printing the integrated circuits with the conductive polymer PEDOT:PSS which shows a higher robustness to strain [51] and could also improve its robustness to folds. Finally, we want to test our design toolkit in a study with novice and professional tangrami artists and learn more about their design practices to support creativity and functionality with this construction platform.

I present ShapeMe, a shape-aware modeling material that streams its own shape while it is being cut by an artist. Our approach is inspired by interviews with professional makers and a design workshop with novices. I describe our sensing approach, discuss its accuracy and limitations, and give an overview of optimal sensor topologies for different shapes. I then present our software toolkit that helps makers design and fabricate 2D or 3D ShapeMe models. I demonstrate how our technology can be used for architectural modeling with a walkthrough scenario.

I presented a method for fabricating *stretchable* user interfaces (see Chapter 3). I also showed how to use *foldable* paper pieces to create interactive 3D prototypes by following a modular fabrication process (see Chapter 4). In this chapter, I investigate a third material property, *cuttability*, and demonstrate its application to personal fabrication.

In many professions like architecture and industrial design, it is necessary to create several prototypes in order to explore alternative designs. For instance, architects produce miniature house models out of cardboard, foam-core or other materials to get a three dimensional stereoscopic vision of their designs and experience their model under real-world light conditions [118]. Using cuttable materials for their models gives them the possibility to make changes directly on the model, view the result and continue modeling. This rapid *cut-view-cut-view* approach gives them immediate feedback on the new model and may inspire new ideas. Unfortunately, making physical changes can be time-consuming and errors can hardly be undone. Also, the physical artifact will not be identical to the digital model anymore and recapturing the geometry can be difficult or time-consuming, in particular for soft, deformable materials.

Some practitioners learn modeling with 3D CAD tools and fabricate their intermediate prototypes directly, given a suitable 3D printer or laser cutter. However, 3D modeling software is difficult to master and often not optimized for rapid prototyping. Taking the trade-offs into account, makers often take a compromise between the rapid and direct interaction with a physical model, and the precision and versatility of its digital counterpart.

While the transition from a digital model to a physical one can be realized with an appropriate fabrication device like a 3D printer, the counter direction is more difficult. Creating a digital model from a physical artifact requires the maker to take numerous measurements

according to the objects geometry, or the maker has to use a camera setup to capture the object's geometry. This may come with difficulties if parts are in the object's interior or hidden.

We argue that makers need *shape-aware* material that is able to capture its own geometry and trace physical cuts while sculpting. This material given, the maker could easily switch between physical and digital modeling in the early phases of prototyping. In this chapter, we present *ShapeMe*, a self-aware material that can track the maker's physical cuts and stream a digital model of itself to a 3D CAD environment. The user can continue working on the model digitally and reproduce the updated shape with a fabrication device. We show how shape-aware material can be produced using printed electronics techniques [37, 69].

We utilize a lossy capacitor system to determine the length of printed line sensors. Using grids of these sensors allows to recompute 2D and 3D shapes. We offer the *ShapeMe* toolkit that takes into account the user's knowledge of the expected cut to optimize the *ShapeMe* sensor grid. The toolkit generates a printable pattern that can be fabricated with rapid and inexpensive ink-jet printing and screen printing. The sensors can be integrated in a variety of different modeling materials. Contrary to external scanning systems [76, 114], our approach does not suffer from occlusion and does not require external camera setups.

Taken together, we show the following key contributions:

- We present *ShapeMe*, a novel smart material that captures its own geometry while being cut and streams its own geometry to a digital model. The sensing technology supports both 2D and 3D geometries and can be embedded into a variety of modeling materials.
- We developed a linear prediction model to estimate the length of printed line sensors. Our technical evaluation shows the accuracy of the model
- The *ShapeMe* toolkit supports users in designing the sensor layout. It also converts the captured sensing data to a digital model and streams it to 3D CAD environments.

5.1 BACKGROUND ON INTERACTIVE FABRICATION

With current design tools, modeling and fabrication are two strictly separated steps. The digital design is done on a computer with mouse and keyboard in front of a 2D screen. Physical testing and a stereoscopic impression of the design requires one to fabricate the model. Errors cannot be undone on the fabricated prototype and the designer does not get immediate feedback from the physical model during the digital design process. To address these problems it is necessary to improve the underlying interaction model to direct feedback and

interactive fabrication. The term *interactive fabrication* was first introduced in 2011 by Willis et al. [122]. They propose tangible feedback while digital modeling. HCI researchers developed several systems that are inspired by this concept.

Camera-based systems

Applying digital tools on a physical object requires the system to capture the objects geometry during the design process. One stream of research used camera based systems to do that. CopyCAD [21] captured the shape of the object with a 2.5D scanner enabling the modeler to remix the original shape with individual designs. Weichel et al. extended this approach with ReForm [114] by 3D scanning a clay model and modifying its shape manually or with a combined milling and extrusion system. RealFusion [76] uses a depth camera and mid-air gestures to capture and modify a digital model. Savage et al. [89] annotate objects with stickers that indicate the position for interactive components. Both the object and the stickers get captured with a 3D scanner. The system integrates the interactive components in the interior of the object which can then be printed with a 3D printer.

Interaction with the fabricating device

Other approaches focused on direct interaction with the fabricating machine to design and shape objects. Constructables [62] is an interactive laser cutting device. The designer uses laser pointers to sketch 2D shapes directly in the fabricator. A camera captures the strokes and executes them with the laser cutter. Later, Müller et al. [61] extended this approach to 3D shapes by melting joints of polymer sheets with a laser cutter and let them bend under their own weight. DCoil [72] supports the fabrication of wax proxies with an actuated hand-held extruder. On-the-fly Print [73] fabricates wireframe proxies [63] while the designer is modeling with a CAD tool on the computer. Peng et al. [74] extended this approach later with an augmented reality system that allows to design a virtual model directly on the print bed of a FDA extruding robotic arm. The device fabricates parts while the designer continues to model on the virtual model.

Guidance systems

In contrast to CNC machines, researchers proposed guidance systems that support manual sculpting and shaping with hand-held tools and devices. Rivers et al. [82] use a 3D scanner-projector combination to show visual cues on the object to support manual sculpting. FreeD [131] has a guidance system integrated in a hand-held mill. The system tracks the position of the tool and guides the maker to sculpt according to a digital model without reducing the artist's freedom to make creative changes. WireDraw [129] supports modeling with a 3D

extruder pen with a augmented reality overlay.

Physical Proxies

Another stream of research supports *interactive fabrication* with tangible proxies that aid digital design or specialized tools that capture the interaction with a physical object. ModelCraft [97] captures annotations on architecture prototypes for edits on a digital model using the Anoto pen [5]. DressUp [120] lets designers work on a mannequin to create a digital model of a dress. Weichel et al. [114] implemented a tangible measuring tool that adds object constraints to the digital design process. StrutModeling [50] lets makers build physical models with building blocks that sense their own shape and stream the configuration to a digital model.

Our work on shape-aware materials relates to the last category, but unlike camera-based system, our modeling material can sense its own shape with internal, printed sensors. The artists can sculpt with her own preferred tools and does not require external camera systems but the shape-aware sensors can be integrated in a variety of classic modeling materials.

5.2 EARLY STUDIES WITH EXPERT AND NOVICE MAKERS

ShapeMe is inspired by a series of initial interviews with expert makers and an informal workshops with novices. We present in the following section the key findings from these explorations.

5.2.1 Interviews with Expert Practitioners

In order to better understand the challenges between combined digital and physical modeling, we started with interviewing a chief architect and two professional modelers from a large architectural company. The modelers presented a selection of physical models that were build both with digitally modeled parts but also parts that were created manually with traditional cutting tools. The chief architect explained that the high quality models were often used for communication with customers, stake holders or with the jury in a design competition. Nowadays, they are often replaced with computer-aided presentation tools. Physical models are, however, still used in design iterations. The architect explained that these iteration require multiple models at different stages of the design process and close communication between the modelers and the architect. He also stated that he often does changes himself on the models with traditional cutting tools to get immediate visual feedback on his ideas.

Physical modeling by shaping with cutting tools is also frequently used in shoe making. We interviewed a professional shoemaker in

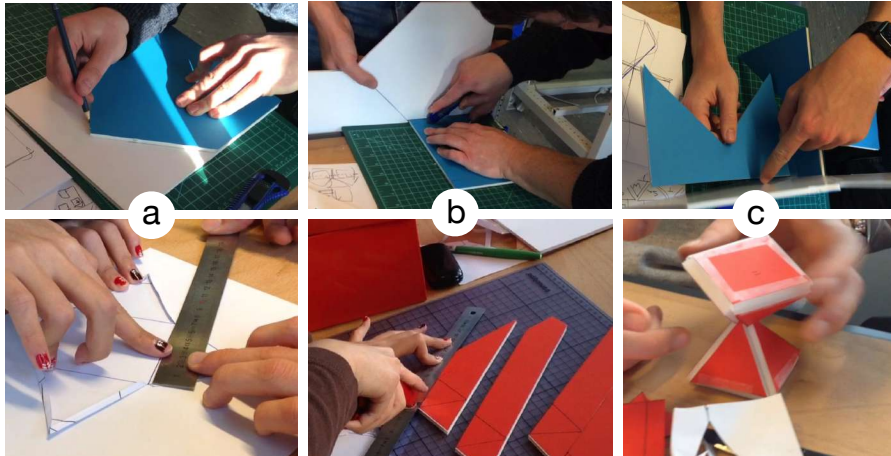


Figure 16: Prototyping strategies during a design workshop. Participants use an existing piece as a template for a new part or copy the side lengths by measuring it (a). They also shape pieces by using a building block reference or reuse a ruler to cut straight lines (b). Finally, they try alternative cuts and assemble pieces to explore different dimensions and to test their prototype for stability (c).

a specialized craft shop for customers with special needs. The fabrication of a shoe involves both digital and physical design where creating the shape of the sole is a core element of the design process. Each sole consists of 3 to 5 layers that are stacked on top of each other. Each layer must be shaped to the customer's individual needs. The perfect shaping requires the experience of the shoemaker and is done manually with traditional cutting tools. It is a major challenge to capture the shape of the first layer to get a template for the subsequent layers. This process requires multiple manual steps and is highly time-consuming.

Our system design for *ShapeMe* is directly inspired from these initial findings. Manual cutting a prototype is still widely used in design. Also, the examples from the architect and the shoemaker often involve 3D objects that are build by layered sheets.

5.2.2 Design Workshop with Novice Makers

In order to better understand the practices and challenges in physical prototyping, we ran a workshop with 11 novice user (6 women) including 2 post-docs, 7 PhD students, an intern, and a graphics designer. With the workshop taking place in December, we decided to frame the workshop around a prototyping competition with the goal to build a "ginger bread advent calendar" house. The winning design was later recreated with real ginger bread.

We assigned each participant to one of four groups. Each group got color-coded foam-core sheets for prototyping (blue, green, red, and

yellow). We offered the participants a set of tools to use. The toolkits included pen and paper for the first sketching phase and 8 foam-core sheets (size A4) in the corresponding color of their group. Also, they had access to scissors and cutters for shaping the foam-core, scotch tape and glue to assemble the parts, and rulers for measurements. The workshop consisted of two parts. The participants started with a short paper sketching session (30 minutes) to develop their initial design ideas. In the second part, they realized their ideas with a foam-core prototype. Altogether, the workshop took 4 hours and was video taped by three members of the research team who did not take part in the prototyping.

Results

Each group successfully created a ginger bread house prototype. The developed designs differed largely from each other and the groups faced different challenges during the prototyping. However, we observed common strategies that most groups shared (see figure 16): (1) Participants used already created parts as templates to create subsequent parts that fit in their dimensions to the construction or served as a base shape for further customization; (2) Participants used pencil annotations, measurements with a ruler or reused edges of another part as reference when cutting and sketching; (3) Participants tested the visual impression by moving pieces around to explore symmetries. Also, they tested the stability of their design by placing and combining pieces at different positions.

All participants reported that working with the physical prototype helped them to develop their design ideas and solve construction and stability problems. For instance, the red team constructed their ginger bread house out of modular geometric shapes. Their transition from the paper prototype to construction was straight-forward. First, they cut and folded their drawings on paper to get an initial idea before realizing their construction with foam-core sheets. However, participants also identified several shortcomings in this fully manual process: cumbersome reproduction of identical pieces, working with symmetries, correcting mistakes, making repeated measurements, and rescaling already fabricated pieces. These findings motivated the *ShapeMe* approach to aid the transition from physically modeled prototypes to a digital model. We base our approach on a novel sensing technology to create shape-aware material.

5.3 APPROXIMATING SHAPE: APPROACHES AND CHALLENGES

Streaming the changing geometry of an object while it is being shaped by an artists is a challenging task. Camera-based systems often suffer from occlusion problems because of the hidden parts in the object's geometry or because the maker is occluding certain parts while

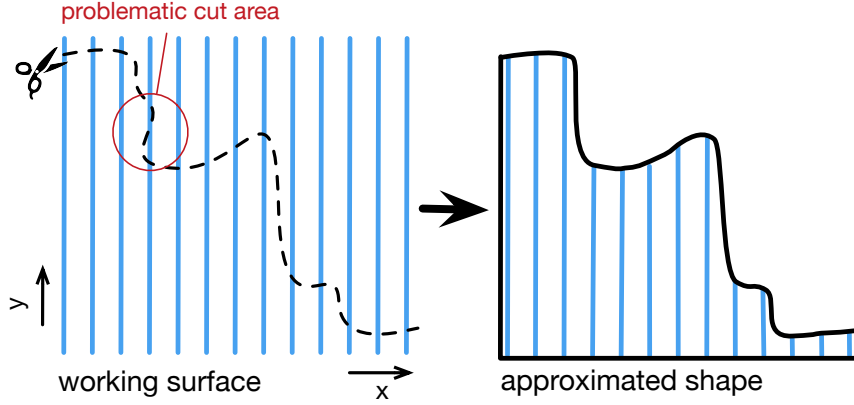


Figure 17: Illustration of our approach for 2D curve reconstruction with parallel length-aware sensors. The red circle highlights a situation where the sensors layout cannot precisely reconstruct the cutting edge.

working on the piece. Smart tools [131], on the other hand, require the object to remain fixed to estimate the cutting path or they require additional external tracking and calibration. Additionally, the artist cannot use their traditional cutting tools which might hinder learned fabrication skills. We address these limitations by integrating the shape-sensing technology into the interior of the modeling material.

Material-based sensing technologies to capture the shape of 2D or 3D objects and can additionally stream changes of the object's geometry instantly to a digital model do not exist to the author's knowledge. We engage this problem by focusing on a solution that allows to approximate 2D and 3D shapes by sampling.

Figure 17 shows an overview of our approach. We distribute a grid of line sensors in a two-dimensional space. Each line sensor can capture its length. Since the position of each line is fixed, we can recompute the shape of the plane. In the example of figure 17, we have parallel line sensors perpendicular to the x-axis. The shape can be cut with an arbitrary 2D curve. To recompute the cut, we use the position of the line sensors as the x-coordinate and the captured length of a line sensor as the y-coordinate. The 2D curve can be approximated using an interpolation algorithm (e.g. linear interpolation) and the sampled cut points of the line sensors.

This principle can be extended to 3D geometries. By stacking shape-aware material layers on top of each other, we can also sample 3D shapes. Creating volumetric shapes out of thinner layers of material is common practice in many areas. We observed this practice in the interviews with the shoemakers and also with the building of architectural models [118].

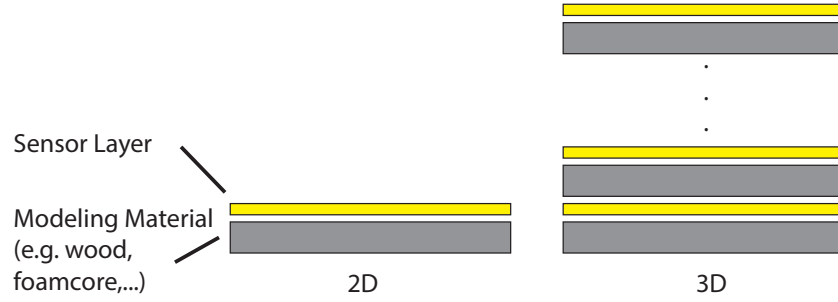


Figure 18: Extension of 2D geometry sensing to 3D. Each sensor layer is attached to a sheet of modeling material. Stacking several layers allows for reconstructing 3D volumetric objects.

Taken together, we observe three main challenges to create shape-aware material:

- There are no material-based shape-sensing technologies available up to date of publishing this work. We had to develop our own sensing technology
- Achieving a reasonable shape approximation resolution requires a sufficient amount of sensors for sampling. We had to develop hardware that is able to control larger amounts of sensors.
- The arrangement of the sensor grid determines which cutting edges can be reconstructed without approximation errors. The cutting edge in figure 17 shows a singularity where the edge goes along the sensor orientation in y-axis direction. This shape cannot be precisely reconstructed with a parallel sensor layout. We address this issue with the *ShapeMe* design toolkit that supports makers in generating alternative sensor layouts that are optimized for different cutting scenarios.

5.4 FABRICATING SHAPE-AWARE MATERIAL

Our sensing technology is based on printed capacitors that can be embedded into modeling material such as wood or foam-core. We show in this section how we derive the length of a sensor from its capacitance, how we measure the capacitance and how such sensors can be fabricated with inexpensive and rapid fabrication technologies

5.4.1 Expressing Length through Capacitance

We realize length-aware sensors by creating a parallel-plate capacitor system. As shown in figure 19, our capacitor consists of two plates with length l and width w . When a voltage V is applied to the capacitor, opposite charges $+q$ and $-q$ form on the surface of both plates.

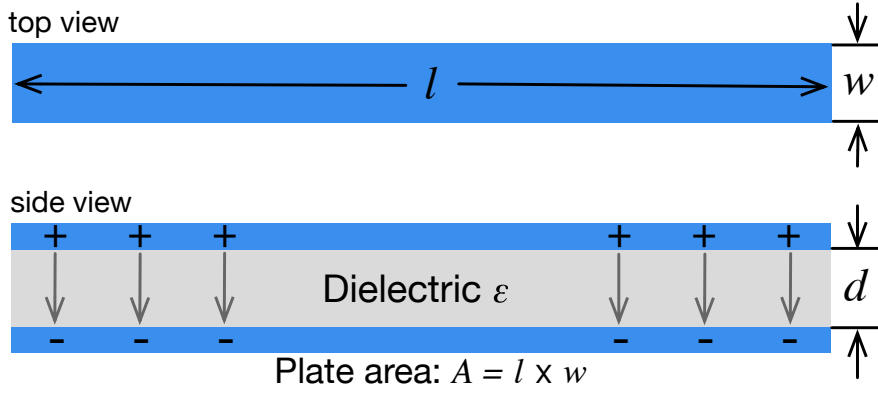


Figure 19: Schematic of a parallel plate capacitor setup showing top and side view.

This induces an electric field between the two plates. The strength of the charges is proportional to the capacitance C of the capacitor system. Given that the distance d between the two plates is relatively small, the capacitance is considered proportional to the overlapping surface area A of the two plates [90].

$$C = \epsilon \frac{A}{d} \quad (1)$$

where ϵ is the permittivity of the dielectric medium that lies between the two plates.

If we assume that the distance between the plates, their width and the dielectric coefficient of the material between the plates remain constant, we can simplify the equation to compute the capacitance to be proportional to the length of the capacitor

$$C(l) = c \cdot l \quad (2)$$

where c is a constant that expresses the capacitance per unit length. This linear relationship between the capacitance of the two plates and their length is the foundation of our length sensing approach. By applying two parallel conductive layers on a dielectric material, we create a parallel plate capacitor that is able to sense its length. When the capacitor is cut and has a new length Δl , the overall capacitance must also change to ΔC

$$\Delta C = c \cdot \Delta l \quad (3)$$

The relation between the capacitance and the size of the parallel plates is a more complex phenomenon as the electric field spreads also to the sides of the plates and not only in the space between the plates. Yet, in our scenario where we deal with long capacitors with constant width, the stated relation ship in equation 2 is not affected.

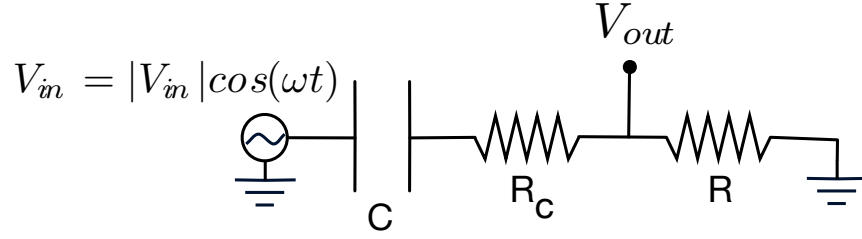


Figure 20: Voltage divider circuit used to measure the length of a sensor.

5.4.2 Length Estimation

We use a voltage divider to measure the capacitance of a sensor. A voltage divider can consist of a capacitor C and a resistor R (see figure 20). An imperfect capacitor (as in our case) can act like a resistor [90]. We name the resistance of the capacitor R_c . The total resistance of the circuit depicted in figure 20 can be expressed by a simple sum $R_{total} = R + R_c$. We can reformulate the total resistance as $R_{total} = \beta R$, where β describes the total resistance as a multiple of the resistor R , thus $\beta \geq 1$.

If we connect the voltage divider to an AC power source that outputs a voltage of V_{in} with an amplitude of $|V_{in}|$ and angular frequency ω , the ratio $r_v = |V_{out}|/|V_{in}|$ of the amplitude of the output voltage V_{out} and the input voltage can easily be shown as

$$r_v = \frac{\omega RC}{\sqrt{1 + \beta^2(\omega RC)^2}} \quad (4)$$

The length of the capacitor can be expressed by inserting equation 2 and solving for l

$$l = \frac{r_v}{\omega R c \sqrt{1 - \beta^2 r_v^2}} \quad (5)$$

where c is the capacitance per length unit. This parameter can be considered as constant as in our setup the dielectric constant of the material between the plates, their distance and the width of the traces does not change as explained earlier.

We can further assume that $\beta \approx 1$ if the resistance R of the voltage divider circuit is much larger than the internal resistance of the capacitor ($R \gg R_c$). Taking that into account, we can directly infer on the length l of the sensor from the ratio r_v and the measured output voltage V_{out} . Figure 21 depicts the ratio r_v for different combinations of $\omega R c$. The choice for the resistor and the applied frequency of the AC power source have to be adapted to the targeted sensor length. In our setup, we aim for a linear relationship between l and r_v to simplify the computation process and gain a more accurate estimation of the sensor's length.

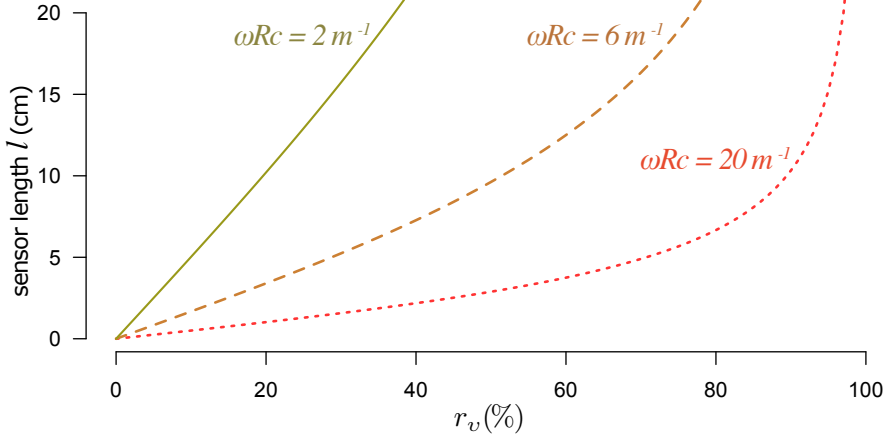


Figure 21: plots of r_v for different values of ωR_c .

5.4.3 Printing the Sensors

To fabricate shape-aware sensors, we print two parallel layers of conductive material on both sides of a dielectric material (e.g. paper). The dielectric material has to be easily cuttable for our approach such that it does not hinder the modeling process. Our first idea was to print silver layers with an ink-jet printer on paper similar to [37]. The ink-jet printable silver requires a coating on the paper to chemically sinter and become conductive. Unfortunately, there is no paper commercially available that is coated on both sides. Our next attempt was to print each layer on single-coated sheets of paper and then glue both sheets together. This approach works fine for rough prototypes. However, we noticed that the glue between the sheets creates uneven distances between the layers and reduces the sensing accuracy. Our final solution was to print silver with an ink-jet printer on the top layer. The back layer gets screen printed with a conductive material such as PEDOT:PSS [69, 119]. Alternatively, other conductive materials can be used that are simple to apply. For instance, Electrick [130] showed that conductive carbon ink can be efficiently applied with a color roller.

Wiring Scalability

We also had to deal with wiring scalability issues when large numbers of sensors have to be connected to a micro-controller as the accuracy of the cut reconstruction strongly depends on the sensor resolution. In a straight-forward implementation, each sensor consists of 2 conductive layers that each has to be connected to the controller circuit. To reduce the overall amount of connectors, we simplified the construction by printing one common back electrode that gets shared by all sensors on the top layer. We did several tests to find out if this construction has an influence on each sensors capacitance but could

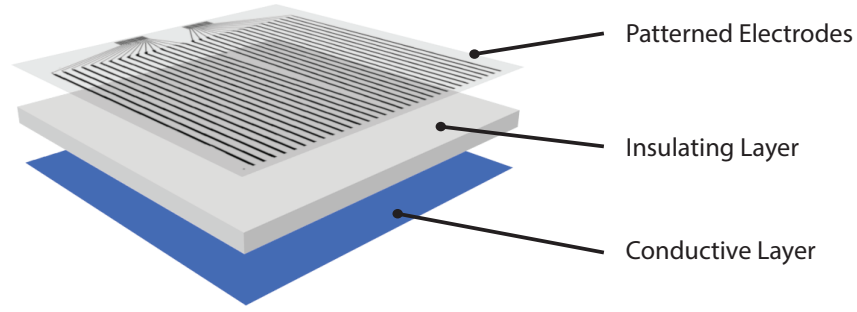


Figure 22: Schematic of a *ShapeMe* sensor grid. The top layer gets silver ink-jet printed and contains the individual sensor grid topology. The back layer is a homogeneous conductive layer that gets screen printed with PEDOT:PSS.

not find clear effects.

Compensating for Unstable Power Sources

We could observe a slight increase of the sensing values when parts of the shape-ware layer gets cut and removed. We found that inexpensive inverters, as we use them in our setups, cannot deliver constant input voltage but increase with a smaller bottom electrode to be charged. We address this problem by printing a small sensor of constant length on the sheet. This sensor serves as reference value to the system and allows to compensate for variations in the supply voltage. Our technical evaluations shows that the compensation for this variation is linear. Each time we measure sensor values, we multiply the ratio of the reference sensor's value change to the values of the other sensors. This cancels out any variations in the supply voltage.

Sensor Density

We also conducted tests to determine the minimal distance between two sensors. We found that the sensed values get distorted below a minimum distance of 1mm. The sensors even become non-functional below a distance of 0.25mm. We recommend a minimal distance of 1.5mm or greater between two sensors to avoid any interference effects.

5.5 THE *shapeme* BOARD

Our implementation currently supports printing of 64 sensors per layer. This number can also increase if we want to sense multiple layers in volumetric objects. We encountered scalability issues if such a high number of sensors have to be connected to a micro-controller. Thus, we developed the *ShapeMe* board, a printed circuit board (PCB) that can multiplex 64 sensor signals into one analog output channel.

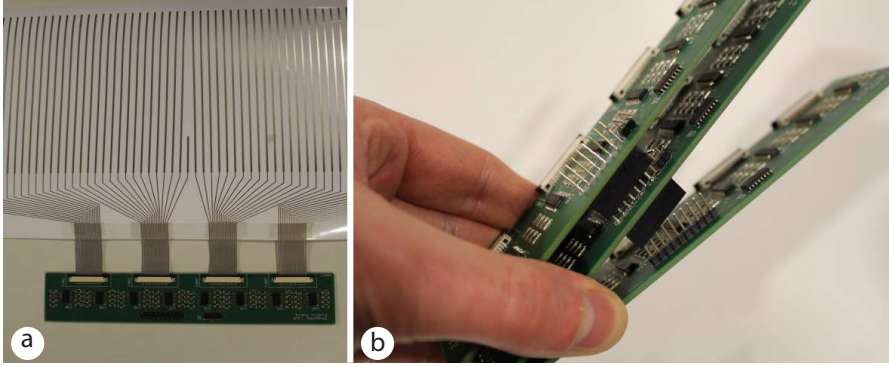


Figure 23: The *ShapeMe* board. The board can connect with 64 sensors via FPC connectors (a). Multiple boards can be stacked to increase the number of processable sensors (b).

The amount of readable sensors can be increased by stacking one board on top of the other for the cost of one additional analog output channel. To connect printed sensors effectively, we added four 16-pin FPC connectors to each board. We tested several types of FPC connectors and found that type 1-84952-6 works well with our printed traces. With this implementation, an Arduino Uno micro-controller can control with its 6 analog pins up to 384 individual sensors. The amount of readable sensors can be increased by using a micro-controller with more analog pins such as the Arduino Mega, or by multiplexing through several *ShapeMe* boards in a recursive manner.

5.6 TECHNICAL EVALUATION

In the following section, we report on the results of an experiment to determine the accuracy of our sensing technology and the correctness of our model.

5.6.1 Materials

Our test setup consists of two groups of sensors on the same sheet, 15 test sensors and 11 reference sensors. All sensors are shaped as parallel lines. The test sensors have all an identical length of 250mm and the reference sensors ranges between 250mm to 0mm which decrease in 25mm steps. We printed two versions of this layout with sensors of 1mm width and the second with sensors of 0.25mm width. The configuration of the sensors is depicted in figure 24.

We printed the sensors on a transparent foil (Mitsubishi NB-TP-3GU100). The top layer containing the sensor layout was ink-jet printed using an Epson ET-2550 printer and Mitsubishi's conductive silver ink (NBSIJ). We screen printed PEDOT:PSS ink (Gwent C2100629D1) on the back side of the sheet as the shared back electrode.

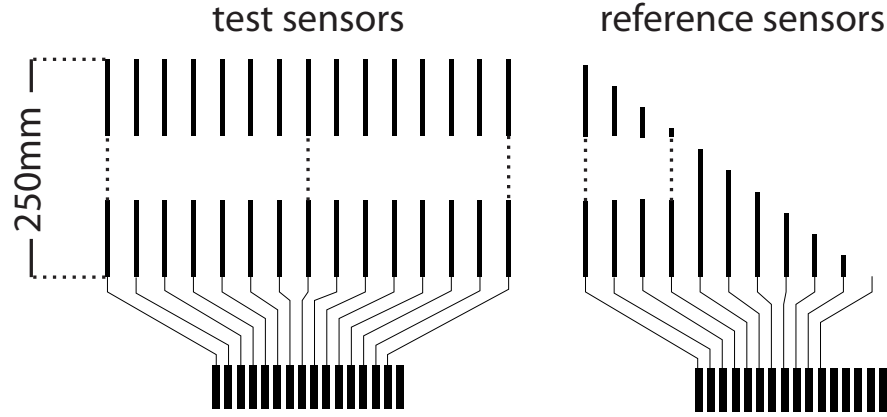


Figure 24: Sensor pattern of our experimental setup. The test sensors on the left get cut during our experiment. The reference sensors remain untouched during the procedure.

5.6.2 Procedure

The set of test sensors was cut simultaneously in 5mm steps from 250mm down to 0mm length. We used a laser cutter (Epilog Fusion M2 40) to ensure precision and repeatability of the experiment. The reference-sensors remained untouched during the entire experiment.

We captured 100 sensor values after each cut using the *ShapeMe* board and an Arduino Uno micro-controller. The back electrode got charged by an inverter (WY-ELI) that generates an approximated sine wave. We scaled the output voltage of the inverter to 72V for the 0.25mm sensors and 37V for the 1mm sensors. The inverter generates alternating current at a frequency of 1.6 kHz. This allows in our current setup to capture 320 sensor values per second if we average five measurements per sensor.

5.6.3 Results

We first analyzed the sensor values that we obtained from cutting the test sensors from 250mm to 0mm in 5mm steps. Our goal was to describe the relation between the measured sensor values and the physical length of the line sensors. Thus, we fitted a simple linear regression model to the sensor values. We describe the goodness of fit using the adjust R^2 value for regression analysis.

The captured sensor data shows nearly perfect linear relationships both for the 0.25mm thick sensors and the 1mm thick sensors. The adjusted R^2 value is 99.7% for the sensors of width = 0.25mm and 99.9% for the sensors of width = 1mm. However, the captured values reveal a non-constant slope over the course of cuts. As we have discussed previously, this is because the power supply of the back

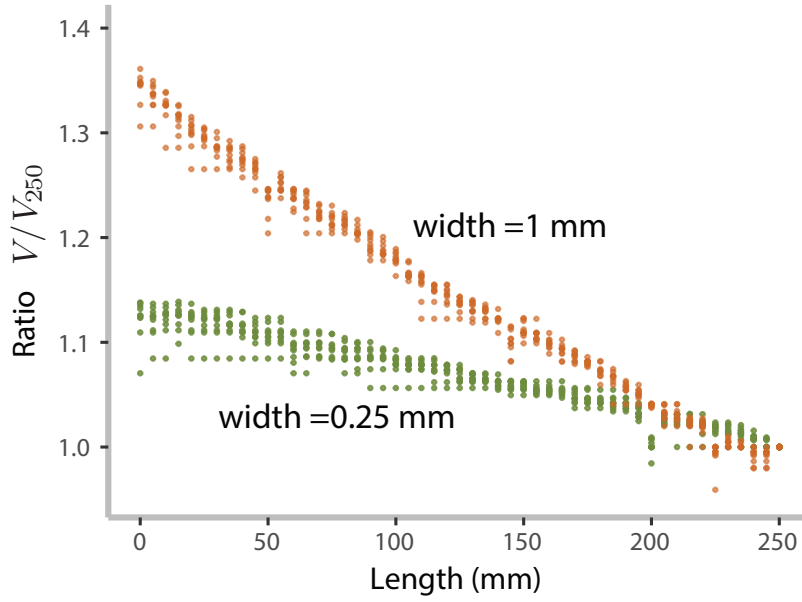


Figure 25: Relative voltage change of the reference sensors (green: 0.25mm sensors, red: 1mm sensors) while cutting the test sensors from 250mm down to 0mm.

electrode does not provide constant voltage when parts of the sensor sheet get cut away. Fortunately, we can measure this effect using a reference sensor and calculate out the deviations from the model. Given that the linear relationship is preserved, the ratio of voltage increases linear and equally for all printed sensors. Figure 25 depicts the behavior of the 11 reference sensors while the test sensors get cut. One observes an increase of the sensor's values due to the voltage increase by 12% (SD=2%) for the 0.25mm sensors and an increase of 34% (SD=2%) for the 1mm sensors.

We calculate the ratio of voltage change from one or multiple reference sensors that remain uncut during the whole process. This ratio is multiplied to the test sensors to correct their value. Figure 26 shows the measured sensor values for the 15 test sensors over the course of cutting. The uncorrected, raw sensing values are displayed in orange. These corrected values are displayed in red. They were obtained by multiplying the voltage increase ratio of one reference sensor (length = 250mm) to the raw values. Any other or even multiple reference sensor could have been used here.

After correction with a reference sensor ratio, the captured sensor values fit well to the linear prediction model. The sensor accuracy is highest for short sensor and decreases for longer sensors. We observed less deviations from the model for the 1mm sensors. The slightly stronger variation of the 0.25mm mainly comes from a single sensor that deviated strongly from all other sensing values. This can

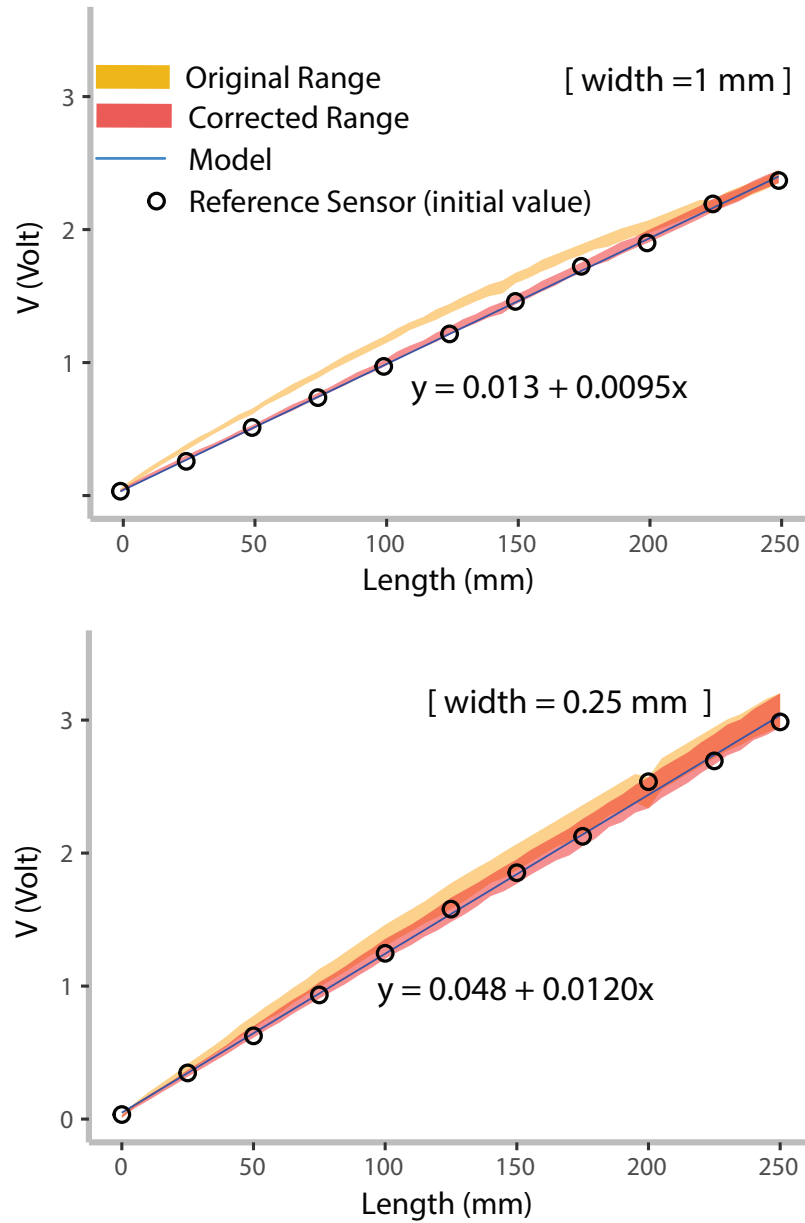


Figure 26: Range [min, max] of test sensor values when being cut from 250mm down to 0mm. The yellow range shows the raw sensor values during the progressive cuts. The red range is the corrected value when multiplying the voltage change ratio to the raw values. The circles depict the voltage levels of the 11 reference sensors before the cuts.

be explained by errors in the fabrication process. Unfortunately, printing errors can affect the sensors with our current fabrication method.

Table 1 reports on the length estimation error for the printed test sensors. We applied two estimation methods on the data. The first uses a common reference model as shown in figure 26 where all test sensors are corrected by multiplying the voltage ratio of a reference

sensor. The second method uses a per-sensor calibration. We calibrate each sensor with an individual linear length estimation function that is derived from the initial value at full length at 250mm. Both estimation methods reveal a similar mean error ($\approx 2.5\text{mm}$). However, the per-sensor calibration shows smaller discrepancies between the sensors.

Table 1: Average error for two length estimation methods

Width	Average Sensor Length Error	
	Common Reference Model	Per-Sensor Calibration
0.25 mm	1.0 – 8.2 mm (M = 2.7 mm)	1.3 – 4.3 mm (M = 2.1 mm)
1 mm	0.7 – 4.7 mm (M = 2.1 mm)	1.8 – 2.9 mm (M = 2.4 mm)

5.7 DESIGNING *shapeme* MODELS

Combining physical and digital modeling requires new ways of interacting with material. We envision the following scenario: A modeler, let's call her Sally, starts with a rough model or idea which she should would like to realize as a shape-aware object. This requires two steps. First, she has to choose an initial shape of her idea. Second, she has to integrate a sensor configuration that accurately extracts the geometry of the object when being cut. When this initial draft geometry is ready, she has to export it to a pdf that contains three patterns: (1) The top layer with the sensor pattern has to be ink-jet printed with conductive silver ink to the front side of a cuttable sheet such as paper or transparent foil, (2) the back electrode has to be screen printed on the other side of the sheet using PEDOT:PSS. This electrode can also be ink-jet printed once double-coated sheets become available. Another possibility is to roller paint or spray the back electrode with carbon ink [130]. (3) The drafted shape is included as a vector graphic and can be sent to a fabrication device such as a laser cutter or a milling machine. When the *ShapeMe* object is prepared, Sally connects the model to the *ShapeMe* board and starts exploring and modifying the object using her preferred manual cutting tools. Her modifications are streamed continuously to a digital model in a CAD environment. Sally frequently switches to the digital model to try out symmetries, observe the model with different material textures and in different 3D scenes. She also uses the history tool to observe earlier version of her model. If she wants to restart at a certain state of her project, she exports an earlier version and recreates a physical model representation.

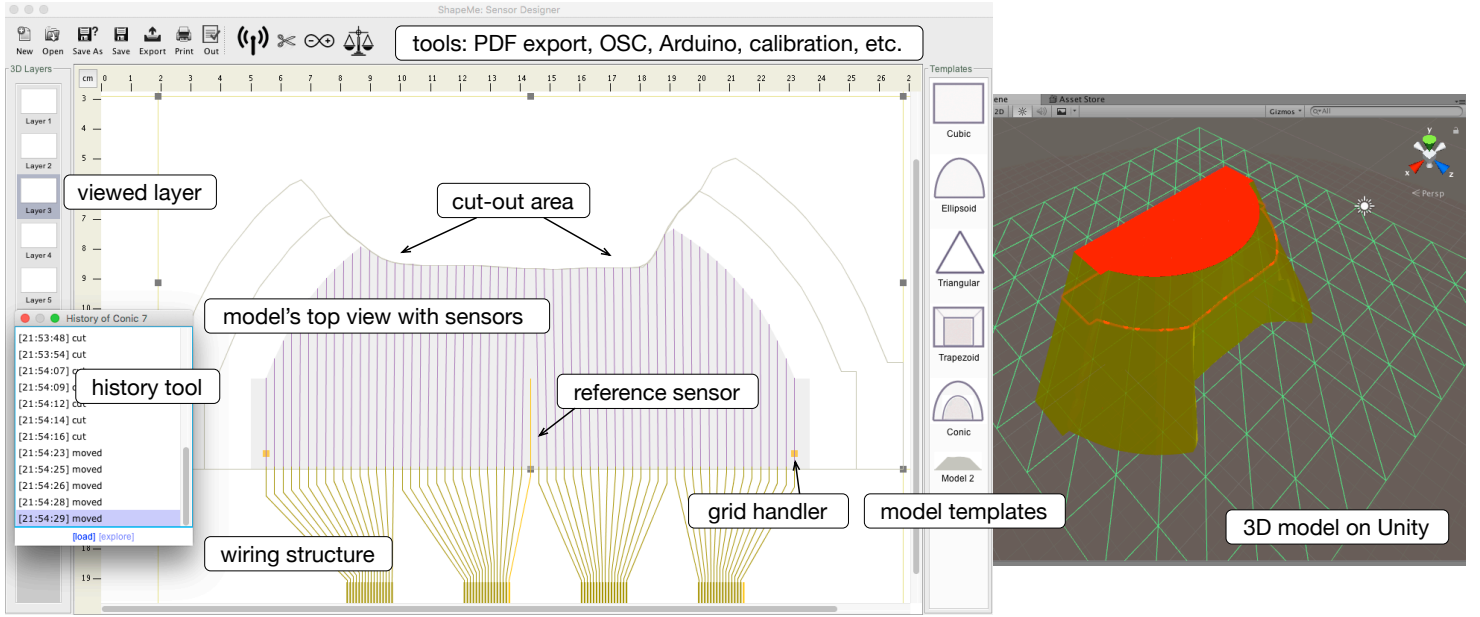


Figure 27: The *ShapeMe* toolkit (left) lets the designer choose an initial model template that can be customized in shape and size. It also embeds a customizable sensor topology into the template and automatically generates the wiring structure from the *ShapeMe* sensors to the connectors. The software captures the communication from the physical material, generates the digital shape and sends the fully digital model to Blender or Unity (right) using the OSC protocol. The history tool records all shape changes and allows the maker to return to a previous shape.

5.7.1 The ShapeMe Software Toolkit

Realizing such a workflow as described above requires a software solution that offers these features. Thus, we implemented the *ShapeMe* toolkit to enable designing *ShapeMe* objects and streaming physical changes of an object to a 3D CAD environment. Figure 27 shows our toolkit as it communicates the current shape changes to the Unity platform [106]. The toolkit offers the following functions:

1. **Create an Initial Geometry.**

The maker can choose from a predefined set of shapes or from personal templates. She can customize the shapes individually and creates an initial geometry for a *ShapeMe* object. A 2D model consists of one single layer that might represent a wall or the floor of an object. 3D shapes contain multiple layers where each layer contains one sensor grid (see figure 18). Our system currently support A4 and A3 sized sheets.

2. **Design a Sensing and Wiring Structure.**

The design toolkit offers a selection of sensor structures from which the maker can choose. The sensors can be further cus-

tomized by selecting the sensor density and width. An additional reference sensor can be added and specified to correct the captured values. Also, the maker can select the wiring structure that connects the printed line sensors to the *ShapeMe* board and choose additional specifications such as the minimal sensor and wire distance to support also low resolution prints. Finally, one can pick which 16-pin connector of the *ShapeMe* board to use which can be helpful to optimize the wiring structure (see figure 27).

3. Export and Print a *ShapeMe* Model.

The software can generate all necessary patterns to fabricate a fully functional shape-aware object. This contains the top layer with all sensor layers that got design through the toolkit, the shape and size of the back electrode and finally, the outlines of the object itself that can be fabricated with a laser cutter layer-wise. Alternatively, the 3D shape can also be exported to a 3D CAD software such as Blender [12]. From there, the 3D geometry can be send to a milling machine for fabrication.

4. Detect Cut Events to Update the Model

The toolkit reads the sensing values directly from the Arduino board via serial port communication. It allows to initially calibrate all sensor to improve their accuracy and subsequently apply the described linear regression model on the raw values. The length of each sensor can then be updated continuously. By taking advantage of the sensor configuration, it can generate the 2D or 3D shape of the physical object. The toolkit also supports a virtual scissor tool to simulate potential cuts. This can help to test sensor layouts if they accurately capture the planned cuts before fabricating the shape-aware material.

5. Communicate with 3D Modeling Environments

Our toolkit streams the geometric data of the read sensor values via the Open Sound Control (OSC) [124] protocol to the system where a 3D CAD environment with a suitable OSC plugin can read the geometric data and render it. We have implemented plugins both for Unity [106] and Blender [12]. The interface to Unity allows an easy port also to Augmented Reality (AR) platforms that support Unity such as the Microsoft HoloLens [58]. The extension to Blender enables the integration into a powerful 3D CAD environment including all native tools that come with it. For instance, Blender allows to quickly explore symmetries with the mirror tool or a powerful rendering engine to preview the object in different materials or complex scenes. It also features a bi-directional communication channel with the *ShapeMe* toolkit. This enables the designer to send her modified digital

model back to the toolkit, add grids of sensors and recreate the physical object with shape-aware material.

6. Fabrication History

We store the entire history of all cuts during the physical modeling process. The maker can access it with the history tool (see figure 27) and load earlier versions of her design. This enables to *undo* [62] mistakes, start from an earlier version to try a different idea or apply a different sensor grid pattern on the prototype. The current session can also be saved or used as a template for future reuse.

The *ShapeMe* toolkit is implemented using Java 8 and Java Swing. The export of the printable patterns uses the Text 7 library. The Unity plug-in is programmed in C# and the Blender plug-in in Python 3.

5.7.2 Choosing an Appropriate Sensing Structure

The accuracy of the shape reconstruction depends on the resolution and the structure of the selected sensor pattern. Each length sensor can only capture the point where it got cut. This constrains the shape reconstruction to a certain family of detectable shapes for a specific sensor topology. For instance, the parallel vertical sensors in figure 27 can detect horizontal cuts very well but decrease in quality for vertical cuts parallel to the sensors and even fail completely for holes.

We explored several solutions to this problem including alternative sensor shapes, for example, curved and complex line shapes or matrices of square-shaped sensors. Unfortunately, these early experiments revealed that the change in capacitance is affected by many complex factors in addition to the surface area of a sensor. These sensor shapes show a non-linear behavior when cutting them which would require more complex models to infer on the actual change in shape. Instead, we found that straight line sensor show a linear change in capacitance when being cut. Additionally, we observed that a limited amount of angular corners do not affect the linearity of the voltage change as well. Thus, we focus in our sensor topologies on straight lines or line shapes that contain only few corners.

The *ShapeMe* platform currently supports 3 sensor topologies that are optimized for specific cutting scenarios (see figure 28). Each topology can be selected and customized in shape and size through the controls in the toolkit (see the grid handler in figure 27). The first topology in figure 28a consists of parallel vertical lines and is best suited for horizontal cuts parallel to the x-axis. The second grid structure in figure 28b is constructed from star-shaped line sensors that are optimized to sense peripheral cuts around the center of the sheet. The last sensor layout in figure 28c is useful to sense vertical cuts and in particular also holes. We achieve this behavior by printing sensors

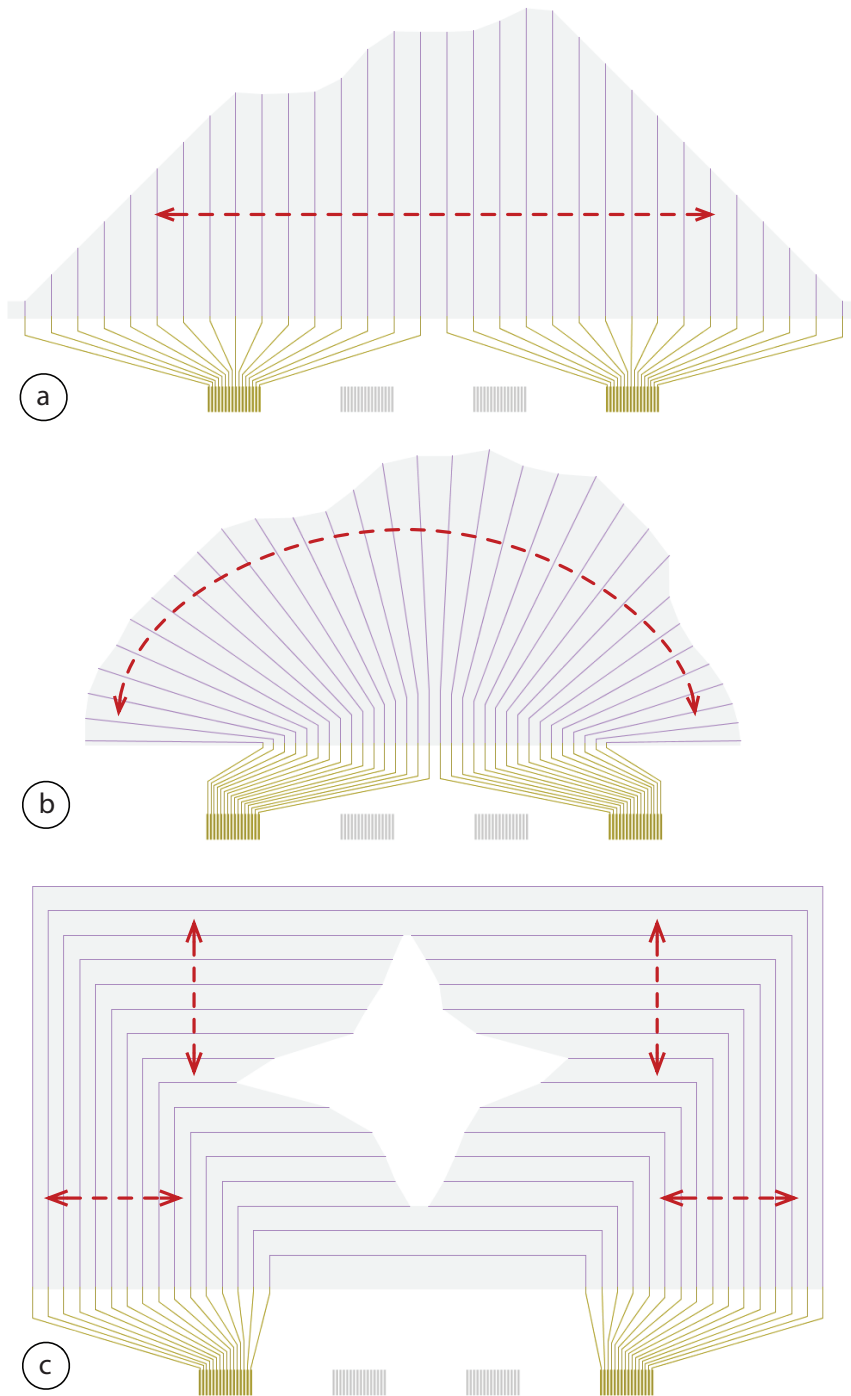


Figure 28: Variants of sensor topologies. (a) A grid of parallel, vertical line sensors is optimized to sense horizontal-shaped cuts. (b) The star-shaped layout works best for peripheral cuts around the center of the shape-aware material. (c) Finally, the toolkit offers a topology of doubly connected sensors that are able to capture holes and vertical cuts. The red arrows indicate the supported cut directions.

that have two connection points. When they are cut, the system treats them as two individual sensors that then sense different values each and can capture both sides of a hole individually.

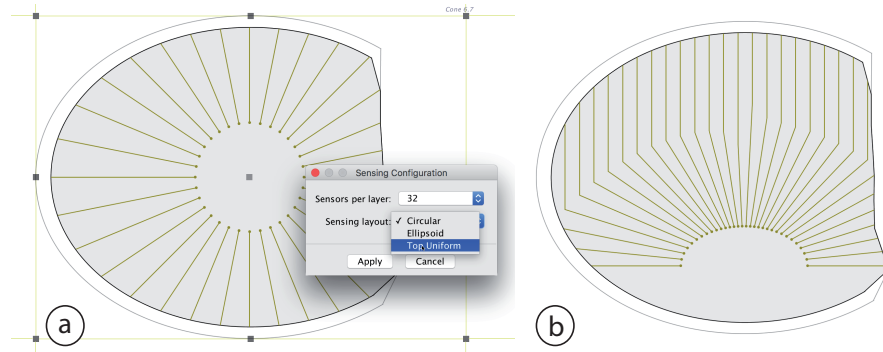


Figure 29: Alternative sensor structure with the connectors in the middle of the layer. The user first use a star-shaped sensor topology to capture shape-changes from all directions (a). Later, she can replace the topology with a mixed star-parallel one that offers a higher resolution on the top-side of the object(b).

Makers can also generate their own sensor layouts tailored to their individual needs using the *ShapeMe* toolkit. Figure 29 shows alternative configurations where the connector is located in the middle of the sensor structure. This enables makers to make cuts and sculpt all around the shape-aware material. The toolkit also supports makers to keep their current object's shape but replace the embedded sensor topology with a different one to explore alternative shapes. For example, the circular sensor grid in figure 29 got replaced with a denser, forward-facing topology without changing the shape of the *ShapeMe* object. Taken together, the toolkit offers more general sensor topologies to do early explorations without knowing the future cuts precisely. When the modeling idea is more refined, the maker can use customized sensor topologies that increase the resolution and sensing accuracy at exactly those areas that the maker plans to work on next. This practice is consistent with other approaches [131] and our own observations when working with professional designers.

5.8 WALKTHROUGH SCENARIO

We demonstrate the usage of shape-aware material and the *ShapeMe* toolkit through a scenario that is inspired from our early studies with architects and novice makers. The scenario consists of two parts. First, a modeler creates an architectural model of the house. This is derived from our gingerbread-house prototyping workshop with novice makers where the physical model consists of multiple 2D elements. In the second part, a modeler works on a terrain for the house. This shows

how *ShapeMe* can be used to model with 3D prototypes that consist of multiple layers of shape-aware sheets.

5.8.1 Part 1: Modeling the House Structure

A modeler, Sally, wants to design and fabricate a model of a house with both digital tools and with physical modeling. First, she uses the *ShapeMe* toolkit to generate a wall of the house in the size of 26 x 14 cm and a layer thickness of 1cm. She streams the generated layer to the 3D CAD software Blender [12]. The *ShapeMe* plug-in for Blender receives the sent geometric data and generates a 3D mesh of the wall. Sally mirrors this wall and adds the remaining two walls with Blender's digital tools.

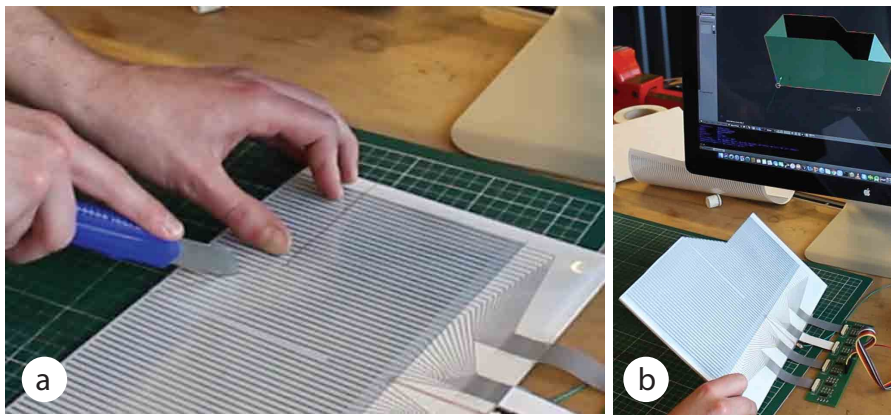


Figure 30: The physical shape of a wall can be designed with traditional cutting tools (a). The changes are streamed to a house model where they modify two mirrored walls (b).

To give the house parts a more detailed shape, Sally wants to model physically and watch how her changes influence the overall structure of the digital model in Blender. She returns to the *ShapeMe* toolkit and adds a sensor topology to the shape. Because she expects mainly horizontal cuts, she chooses the parallel line layout with vertical sensor orientation. The layer is now complete and can be exported as a pdf file. She ink-jet prints her design and adds the shape-aware sensor to a sheet of foam core. Finally, Sally connects the shape-aware foam-core wall to the toolkit using the *ShapeMe* board. The toolkit calibrates the printed sensors and streams its current geometry to the digital model in Blender. All shape changes are displayed instantly on the digital model and the history tool captures all modifications continuously.

Sally uses a regular cutter knife to model the first wall of the house (see figure 30a) and observes her cuts that get instantly reflected on the digital model. Changes are also mirrored on the parallel wall of the house which helps Sally to better imagine the full object even though she is just working on one single piece of the structure (see

figure 30b). She continues to tweak the wall's shape and uses the stereoscopic impression of the physical wall piece and the more complete digital model to gain a better understanding of her modifications.

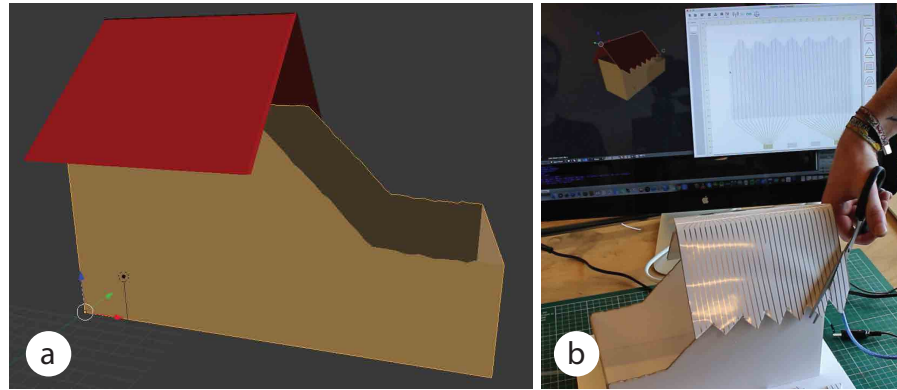


Figure 31: The modeler adds the roof digitally (a) and produce a shape-aware counterpart with the *ShapeMe* toolkit. She adds the final details of the roof with a cutting tools (b).

When she is happy with the intermediate prototype, she returns to Blender and adds a roof to the digital model (see figure 31a). She wants to add details to the roof but prefers to add them on the real object to get a better impression of the final model. Therefore she exports all parts of the house to a pdf file using the *ShapeMe* toolkit. She uses a laser cutter to fabricate all house parts and assembles them manually. Additionally, she adds a shape-aware sensor grid to the roof part, ink-jet prints the sensors and adds them to the roof foam-core sheet. When all is assembled, she cuts a free-form pattern with a scissor (see figure 31b).

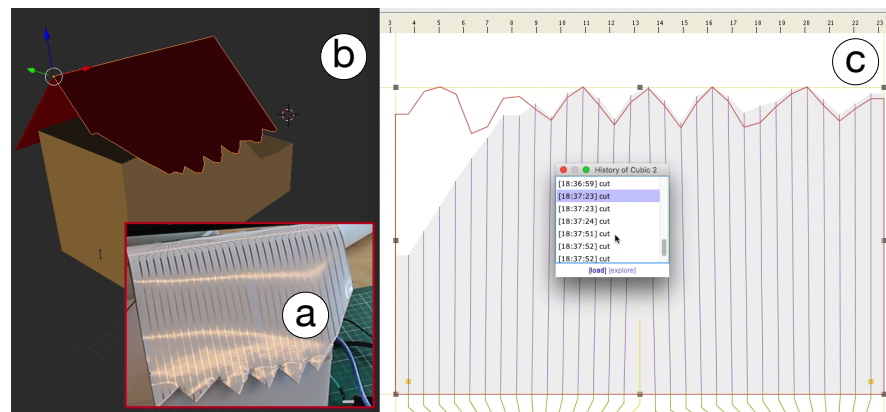


Figure 32: Correcting errors with *ShapeMe*'s history tool. A large part of the roof got cut away accidentally (a,b). The history tool captured all changes during the cutting process and can recover an earlier, undamaged version of the design (c).

At this stage, Sally makes a mistake and accidentally removes a large part from the roof and destroys her entire design (see figure 32ab). Thus, she uses the captured data of *ShapeMe*'s history tool and finds an earlier version of the roof part before she did the mistake (see figure 32c). She exports the recovered roof version and fabricates a new *ShapeMe* model. She proceeds, back and forth between the physical and the digital designs, until she finishes her model.

5.8.2 Part 2: Modeling the Terrain

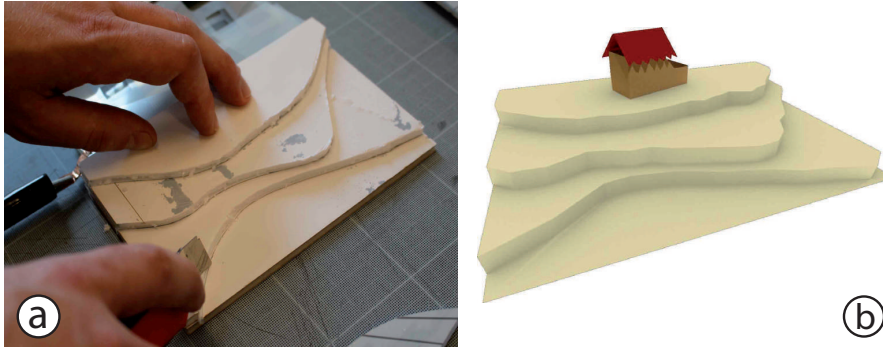


Figure 33: Correcting errors with *ShapeMe*'s history tool. A large part of the roof got cut away accidentally (a,b). The history tool captured all changes during the cutting process and can recover an earlier, undamaged version of the design (c).

After finishing her model, Sally wants to place the house into a decorative terrain. Unfortunately, she is not trained in such designs. Thus, she asks Yeo, a befriended landscape artist, to help her and sends him the digital model. Yeo prefers working with real prototypes to benefit from the stereoscopic impression of the model and to use his preferred physical tools (see figure 33a). However, he also requires a digital version to combine the landscape and the house in the end. First, he creates a volumetric object out of multiple foam-core layers. When he is satisfied with its dimensions, he creates a multi-layer objects in the *ShapeMe* toolkit that corresponds to his physical model. Because he expects also vertical cuts around the periphery of the model, he chooses the star-shaped sensor topology and adds it to the layers. After printing the shape-aware sheets, he adds them to the foam-core layers and glues them together. Creating volumetric objects by gluing layers is a common practice for practitioners such as architects [118]. He connects the model to the toolkit using multiple, stacked *ShapeMe* boards and streams it to the Blender plug-in.

He creates a first version of the terrain design and renders it together with Sally's house. He notices that his design is too small for the house. Thus, he rescales his model until the house fits well to the scene (see figure 33b). He then sends the complete design back to

Sally who can now fabricate both parts in the right scale with a laser cutter and finish her design piece.

5.9 LIMITATIONS AND FUTURE DIRECTIONS

The *ShapeMe* platform still has several limitations. One issue is the limited sensing accuracy that currently shows a mean error of about 2.5mm. The main reason for that are errors in the fabrication process that can lead to an inconsistent construction of the printed length-aware line sensors. One problem is that the silver ink-jet printing technology requires a coating on the paper to chemically sinter and become conductive. Currently, only paper with one side coated is commercially available. Thus, we have to manually screen printing a back electrode using PEDOT:PSS ink in our current setup. This process requires additional work and introduces a source for errors. We expect the sensing quality to improve once double-sided coated paper becomes available and the fabrication can be done fully automatic without any manual steps.

Also, the sensing accuracy depends heavily on a constant distance between the two capacitor plates. In our current implementation we use a sheet of paper or transparent foil as dielectric between the plates. On the one hand, we have to trust that the paper or foil has constant thickness over the whole sheet area. Second, paper has a low dielectric constant ($\epsilon \approx 2$) which means that the material attenuates the electric field between the two capacitor plates of a *ShapeMe* sensor. Thus, thickness variations have a greater impact because of the additional attenuation factor. In a future iteration, we intend to replace the paper with a printable dielectric layer that can be screen printed or sprayed and offers a guaranteed constant thickness due to the fabrication method and has a high dielectric constant to let the electric field establish without attenuation. We are also interested in integrating functional layers directly into materials like wood or foam-core by screen printing both conductive and dielectric inks on top of each other.

Makers use physical tools to model on a *ShapeMe* object. Often, those tools can have metallic blades which can destabilize the sensing values on direct contact. We found that these fluctuations are present only during contact but return quickly to their initial values once the cut is finished. The sensing values can also be influenced by direct touch. Thus, we recommend to insulate the sensing layer with insulation spray or by laminating the sheets.

Studies on design strategies [13] show that makers not only rely on shaping objects through cutting but also design with other tangible manipulations such as bending, folding or stretching the material to bring it into shape. In future work we want to extend the *ShapeMe* approach also flexible and stretchable substrates. Even though the

ShapeMe sensors are robust to bending they cannot sense the strength and position of the bending deformation. We expect that capacitive sensing methods [26] can be integrated to the *ShapeMe* fabrication approach. Strain sensing on stretchable substrates like silicone could be realized with a sensing approach by Cohen et al. [16] and the fabrication approach on stretchable electronics present in chapter 3. It will be a future challenge to find out how to best combine these methods.

Another challenge is to explore novel sensor topologies that can sense even more shape configurations, for instance, by stacking multiple topologies in one layer similar to [70]. Finally, our shape-aware material and the software platform were not evaluated with users. Further studies are required to assess whether and how such shape-aware materials supports novices and professionals in their creativity and object design.

5.10 CONCLUSION

Artists use digital modeling tools because of their high precision and because they offer features that are impossible with physical modeling such as instant rescaling, mirroring, undoing and creating copies. On the other hand, working with physical prototypes enables artists to experience the subtle feel of real material and they can use traditional, well-established modeling and cutting tools. To link these two worlds, we introduced *ShapeMe*, a novel smart material that captures its own geometry as it is physically cut by a maker. We presented a novel sensing technology that can capture 2D or 3D geometries by using grids of line-shaped capacitive sensors. Our technical evaluation shows that we can detect the length of the printed sensor through a linear regression model. We implemented the *ShapeMe* toolkit to facilitate the design of shape-aware sensor layers, add a wiring structure, export them for fabrication and send the captured shapes to 3D CAD environments such as Blender and Unity for live interaction. We show the use of shape-aware material through a application scenario walk-through that uses the present technology and tools. Even though the sensing resolution is still imperfect, we expect improvements on the sensor's accuracy in future iterations.

DISCUSSION AND CONCLUSION

In this dissertation, I argued that user interaction will become richer and more powerful if we go beyond rigid user interfaces that solely rely on touch input and OLED displays. Future interactive systems will be based on deformable interaction-aware materials and user interfaces that can be bent, stretched or even cut. Leveraging such material properties and capturing their changes opens new opportunities for HCI research. Future work has to come up with new fabrication technologies that are inexpensive and accessible to larger communities of makers and crafters. We also need software toolkits that aid the design of physical user interfaces but also sensor technologies that can make a range of construction materials interactive. Developing software, hardware and versatile fabrication machines requires us to combine knowledge from different domains: computer science, hardware engineering, and materials science.

My dissertation investigated three directions for shape-configurable materials with applications in DIY product design, wearables, interactive fabrication, and ubiquitous computing. First, I showed how to embed touch sensing, proximity sensing, and electroluminescent displays in stretchable silicone substrates. The fabrication of such highly stretchable user interfaces is based on an inexpensive and rapid screen-printing approach. I then examined how flexible, foldable materials such as paper can support creative design and fabrication. I presented a folding technique called *Tangrami*, which consists of modular building blocks that can be attached and detached to form 3D volumetric objects. We have extended tangrami to integrate touch sensing, paper actuation, and electric components, e.g., LEDs, into their structures. To this end, we use a rapid ink-jet based fabrication technique that allows us to print flexible conductive circuits on paper. Our software toolkit assists makers in designing interactive tangrami structures, printing their conductive patterns, and then streaming the received interaction signals to external applications. Finally, I presented a method for creating shape-aware material, modeling material that can sense its own shape while being cut by an artist. Our software toolkit supports makers in generating sensors that can be embedded into 2D and 3D shape-aware objects and lets them choose sensor topologies to adapt the accuracy of the sensing to their own needs. The software captures the sensor signals and streams them as digital models to 3D CAD environments, such as Blender or Unity. Overall, the system supports a bi-directional fabrication workflow that combines physical and digital modeling.

6.1 LIMITATIONS OF INTERACTION-AWARE MATERIALS

Shape-configurable materials such as paper and stretchable silicone open up new opportunities for interaction design. However, their interesting mechanical properties come at the cost of a lower stability, which makers have to carefully consider. For example, highly stretchable silicone cannot support itself and relies on the stability of the object it is applied on. For example, the support object can be the human body for an on-skin interface or the coffee mug for an awareness sleeve (see Chapter 3).

We expect that future personal fabricators will be able to produce multi-material prototypes. The challenge in such scenarios is how to combine rigid, flexible, and stretchable materials, being able to leverage the mechanical properties of each. A direction to this goal is to simulate the materials' physical behavior with a digital modeling tool and assist the user with suggestions about how to optimally combine materials to ensure the stability of their target geometries.

6.2 EXTENSIONS TO OTHER MATERIAL PROPERTIES

My dissertation has investigated how to embed interaction and shape sensing in objects with a range of mechanical material properties, including stretchability, flexibility, and folding. However, other material properties are equally interesting for HCI research, such as magnetic, haptic, and optical properties. I will concentrate on optical properties here.

6.2.1 *Future Outlook: Interactive Optical Material Properties*

Optical properties are, for example, the color of a material and its reflectance. Being able to computationally control such properties or change them interactively can enable HCI research to come up with novel interface designs, such as a canvas that senses color while an artist is painting and interactively reacts to this color. During my thesis, I worked with a computer graphics group in Saarland University on a computational model for controlling the reflectance properties of a surface. This model can be used to direct the light in a cinema to the audience's position. The advantage of the approach is that the projector requires less energy and can provide brighter projections because no energy is wasted to empty regions with no viewers, such as the floor, the walls, or the ceiling. In addition, one could fabricate private screens that show video to a single person in front of the screen but remain dark for all other angles.

Directional Screens are physical surfaces that can redirect light from a projector to a user-defined area in front of the screen. The reflectance behavior can be defined by the user who selects the position of the

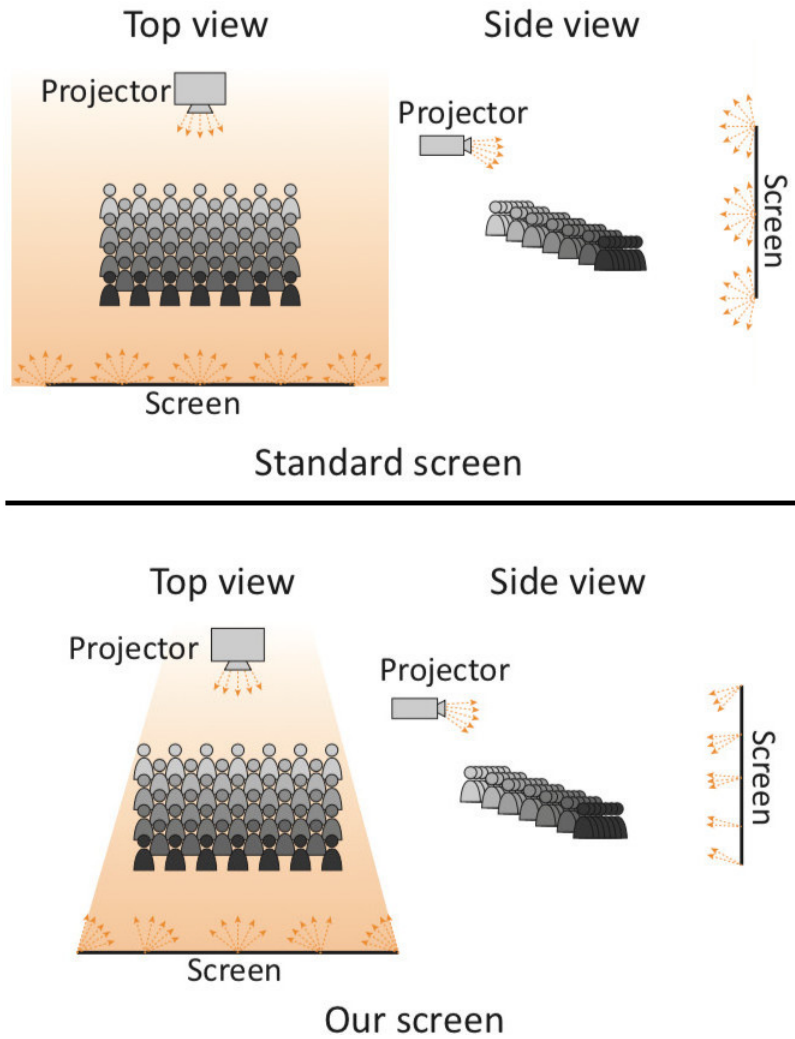


Figure 34: Application example for directional screen in a cinema setup. Traditional mate screens reflect light uniformly also to areas with no audience, such as the floor, walls and ceiling (left). Our directional screens can reflect light only in the direction of the audience, reducing energy waste and providing brighter projections with lower energy (right).

light source (projector), the position and size of the screen, and the space in front of the screen that the light should be directed to (see figure 35a). Next, the screen area gets sampled with a regular grid. For each pixel in the grid, we generate a microgeometry that consists of hundreds of reflective micro-facets that behave like mirrors. Each mirror is optimized to reflect the incoming light to sampled points in the audience (see figure 35b). The grid of microgeometries gets aligned on a curved screen to avoid self-shadowing using Poisson's equation (see figure 35c). The final screen geometry gets fabricated with highly glossy aluminum using a milling machine (see figure 35d).

The presented approach only allows to define a certain reflection in advance that can be fabricated in a subsequent step. After that, the

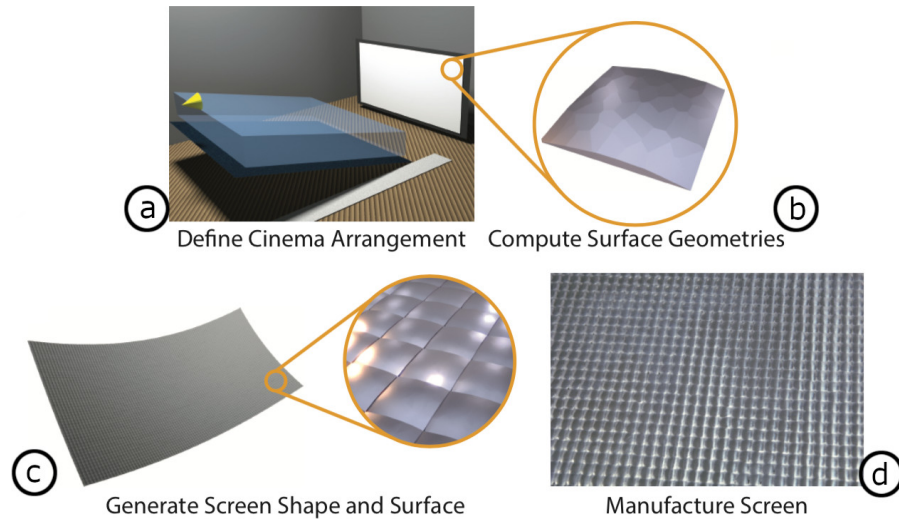


Figure 35: Construction of a *directional screen*. First, the position and size of the audience, screen and the projector get arranged by the user (a). For each pixel on the screen, we compute a microgeometry that reflects light to the audience (b). A matrix of microgeometries is distributed on a curved screen to reduce self-shadowing (c). The final digital model can be manufactured with mirror-like aluminum using a high-resolution milling machine (d).

surface cannot interactively change its reflectance properties again. In future work, I would be interested in technologies that allow to interactively change the reflection properties of a surface. These can be, for example, a shape-changing display that controls its surface geometry with actuated pins through pneumatic pressure or electric motors. Other work uses liquid droplets that are placed on a matrix of electrodes [Umapathi:2018]. Charging pixels of this matrix allows to attract and repel droplets and lets a system digitally control their position. Combining droplets of different materials could allow to digitally control the surface reflectance of such a matrix.

6.3 CONCLUDING REMARKS

The work presented in this thesis demonstrates that knowledge in materials is important for research on fabrication and interaction design. Nonetheless, many advances in material science never reach the HCI community and remain largely undiscovered. We formulated three main challenges for opening up this knowledge not only to HCI researchers but also to professional designers, crafters, novice makers, and other users. These are: (1) discovering inexpensive and accessible fabrication technologies, (2) engineering advanced sensing technologies that can capture the interaction of users with the material of physical objects, and (3) developing user interfaces that deal with the computational aspects of material properties and help users focus on

their creative parts of their tasks. I hope that this thesis will motivate future scientists to seek stronger collaborations between materials science and HCI.

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Titre : Fabrication de matériaux malléables et sensibles à l'interaction

Mots clés : Fabrication personnelle, Fabrication de prototypes, Aide à la créativité, Electronique imprimée

Résumé : Les machines de fabrication personnelle, comme les imprimantes 3D, permettent aux créateurs occasionnels de fabriquer leur propres objets. Il est possible de créer des pièces rigides, mais aussi des pièces souples, flexibles ou malléables. Le défi reste toutefois d'intégrer des capteurs et du retour visuel dans ces matières. Les sciences des matériaux ont introduit plusieurs techniques pour produire des éléments interactifs, mais leur application requiert une expertise spécialisée ou la disposition d'équipements très coûteux. Ma thèse se concentre sur les professions créatives, comme les professionnels du design, les architectes, ou les chercheurs en IHM. Elle vise à accompagner leur processus de conception et de prototypage avec des matériaux souples et interactifs, produisant des objets élastiques, des modèles avec des formes reconfigurables, ou même des maquettes qui peuvent être découpées. De tels matériaux pourraient enrichir notre interaction avec le monde numérique de trois manières différentes : - les dispositifs prothétiques et l'informatique ubiquiste, - le design de produits personnels, - la fabrication interactive. J'introduis d'abord une nouvelle méthode pour intégrer des capteurs tactiles, des capteurs de proximité et des écrans électroluminescents dans des matériaux de silicone étirables. Basée sur des tech-

niques d'impression en sérigraphie, la méthode permet de fabriquer rapidement des interfaces étirables et peu coûteuses, qui peuvent être intégrées dans les vêtements et dans d'autres objets ordinaires. Deuxièmement, je présente une approche pour créer des modules de construction interactives, qu'on appelle "Tangramis Interactifs". Les Tangramis interactifs sont des matériaux souples, par exemple du papier, pliés et combinés ensemble pour créer des structures modulaires en 3D. Ils peuvent réagir au toucher, être actionnés, et intégrer des composants électroniques comme des LEDs. Troisièmement, j'introduis une méthode de fabrication de matériau capable à identifier sa forme ("shape-aware material"). Ce matériau peut détecter et communiquer sa géométrie en temps réel durant son découpage par un créateur. La méthode s'appuie sur une nouvelle technologie de capteurs de forme, imprimés par jet d'encre et intégrés dans du matériel de maquettage, comme le carton mousse. Notre logiciel aide les créateurs à générer du matériel de prototypage en 2D ou en 3D qui peut capter sa forme, en configurant la topologie des capteurs pour optimiser la précision du modèle. Notre approche soutient un processus de fabrication bi-directionnelle en intégrant des outils de modélisation à la fois physiques et numériques.

Title : Fabricating Malleable Interaction-Aware Materials

Keywords : Personal fabrication, Prototyping, Creativity support, Printed electronics

Abstract : Personal fabrication machines, such as 3D printers, allow casual makers to create custom objects, which may also contain soft, flexible, or shape-changeable parts. However, embedding sensing and output capabilities into material is still challenging. Although research in materials science has introduced a range of methods for producing interaction-aware materials, these methods require significant domain expertise and often rely on specialized and expensive equipment. My dissertation focuses on casual makers, designers, and HCI researchers, and investigates how to support their design and physical modeling tasks with interactive, non-rigid materials that are stretchable, shape configurable, or cuttable. I explore three directions on how such materials can enhance user interaction, with applications to wearables and ubiquitous computing, DIY product design, and interactive fabrication. First, I introduce a new fabrication method for embedding touch sensing, proximity sensing, and electroluminescent displays into stretchable silicone materials. Based on screen printing,

the method allows for rapidly fabricating inexpensive and highly stretchable user interfaces that can be embedded in wearables and other everyday objects. Second, I present an approach for creating interactive paper-folded building blocks that we call Interactive Tangrami. Interactive Tangrami are made of flexible materials such as paper, folded and combined together to form modular 3D structures. They support touch sensing and actuation and can also integrate rigid electrical components, such as LEDs. Third, I introduce a method for fabricating shape-aware material, which is modeling material that captures and streams its own shape while being cut by an artist. The method is based on a novel inkjet-printable sensing technology that can be embedded into a variety of cuttable material such as foam-core. Our software toolkit helps makers produce 2D or 3D shape-aware material and customize its sensing topology for higher sensing accuracy. Overall, our approach supports a bi-directional fabrication workflow that combines both physical and digital modeling tools.

