Fabricating Custom-Shaped Thin-Film Interactive Surfaces

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Abstract

Novel possibilities in digital fabrication empower end-users to design and fabricate custom objects and surfaces. But in order to equip these with interactivity, the user has to fall back on existing display and touch surfaces, which come in a predefined resolution and shape. This constrains the shape and consequently the application areas of the interactive device. This work presents three approaches, based on printed electronics, for designing and fabricating interactive surfaces with an individual shape and functionality on flexible materials.

The first contribution is a design and fabrication approach for custom and flexible touch-displays. We present display primitives to support their digital design. In order for the end-user to physically instantiate the design, we show two practicable printing processes for electroluminescent displays. Additionally, a technical solution for adding touch sensitivity is provided. In the second contribution, we extend this work with a novel design and fabrication approach for interactive folded 3D objects. In an integrated digital design environment, the user annotates 3D models with user interface elements. Based on the design, folding and printing patterns including interactive elements are automatically generated. The third contribution focuses on manual forming. We show a flexible multi-touch sensor foil, which can be cut using physical tools while remaining functional. We contribute novel patterns for the internal wiring of the sensor to support a variety of shapes.

Kurzzusammenfassung
Neuartige technische Möglichkeiten in der digitalen Fabrikation erlauben Endnutzern maßgeschneiderte Objekte und Oberflächen zu gestalten und zu erstellen. Um diese aber mit Interaktivität auszustatten, muss auf bestehende Displays und Touchoberflächen mit definierter Auflösung und Form zurückgegriffen werden. Das beschränkt die Form und damit auch den Einsatzbereich des interaktiven Geräts. Basierend auf gedruckter Elektronik, werden in dieser Arbeit drei Ansätze vorgestellt, um interaktive Oberflächen mit einer individuellen Form, Funktion und auf flexiblen Materialien zu gestalten und zu erzeugen.

Der erste Beitrag ist ein Design- und Fabrikationsansatz für maßgeschneiderte berührungssensitive und flexible Displays. Darin stellen wir Displayprimitive zur Unterstützung des digitalen Designs vor. Um diese physisch zu instantiieren, tragen wir zwei für den Nutzer durchführbare Druckprozesse für elektrolumineszente Displays bei. Wir zeigen außerdem eine technische Lösung, um dem Display Berührungssensitivität hinzuzufügen. Im zweiten Beitrag, erweitern wir dieses Vorgehen um einen neuartigen Design- und Fabrikationsanatz für interaktive gefaltete 3D Objekte. In einer integrierten digitalen Designumgebung annotiert der Nutzer 3D Modelle mit Userinterfaceelementen. Falt- und Druckmuster inklusive interaktiver Elemente werden automatisch generiert. Im dritten Beitrag zeigen wir eine flexible Multi-touch Sensorfolie, welche vom Nutzer zugeschnitten werden kann und weiterhin funktioniert. Darin tragen wir neuartige Muster für die interne Verdrahtung des Sensors bei um eine Vielzahl von Formen unterstützen.

Acknowledgements

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Contents

Chapter 1

Introduction

Interactive surfaces are a technical foundation for many human computer interfaces and are integrated in numerous devices that are in use today. Technically, the interactive surface is the component that senses user input and/or provides visual output. An example of an interactive surface is the touch-sensitive display of a smartphone or tablet computer. But it is also the touchscreen that is integrated into a modern fridge. These displays come with a well-known rectangular form factor, have a fixed and defined resolution and are planar.

At the same time, the shapes and material composition of products in our environment are becoming more and more personalized to the user. For example, the interior of a car is highly individualized to the customer. The user can customize the layout and material of a sports shoe, which is then fabricated for him. Machines that can fabricate various shapes in a variety of materials and are digitally controlled play a main role in these scenarios. Examples of these machines or fabricators are 3D printers and CNC mills. The digital aspect has the benefit that the shape can be digitally stored, customized and reused.

While the end-user can now create personalized static objects, it is very challenging for him to create custom interactive surfaces. The user has to rely on pre-fabricated interactive surfaces that might not fit in terms of their shape, resolution or material properties. Not only does this limit the sheer variety of potential interactive devices for e.g. ubiquitous, wearable and mobile computing, but these strict constraints also prevent users from realizing devices that are so deeply integrated into their personal environment that they are indistinguishable from it, or devices that closely match the individual shape of a personal object or the human body.

1.1 Printing Thin-Film Electronics

A digital fabricator that has been very successful worldwide is the computer-controlled desktop printer. The user specifies the content digitally and the machine handles the complex transformation from bits into atoms. It works with various highly flexible substrates and can print any shape the user specifies. Its impact has been profound: it allows anyone to fabricate and publish a physical document right from his desk. But besides the technical capabilities of the fabricator, a key to its success were also the user interfaces that made this complex fabricator accessible for the end-user.

Printing technology now makes it possible to print traces and sophisticated electrical components and even displays on thin-film substrates. Simply put, these use similar printing technology as is applied in regular printing, but use different inks and substrates. This paves the way for overcoming the rigid form factors of interactive surfaces and also allows mass-fabricating of non-rectangular shapes. This opens up many possibilities for applications in ubiquitous and mobile computing. For example, flexible displays and touch surfaces could be integrated into objects or attached as e.g. interactive stickers [68] to our surroundings. Their flexible substrates pave the way for more closely integrating form and functionality. Recent work has explored novel interactions and form factors for devices that can be realized with this technology [96, 40, 103, 36, 105, 43, 35, 24].

If we look at printed electronics analogously to regular printing, current machines resemble the professional high-volume printing machines that require experts to run them. But recent work has taken a similar approach to the desktop printer. It showed the first conductive desktop inkjet printer that can be operated by non-experts [34]. It enables the end-user to fabricate electrical circuits of a custom shape and custom complexity directly at his desktop. This highly personalized and direct way of fabricating functional surfaces has great potential. It would allow non-experts to create custom shaped interactive surfaces that exactly fit the individual shape of the product: for example, a wearable interactive device that exactly matches part of the user's body. It would also speed up the product development process, since iterations can be done faster. The independence from expensive equipment and expert knowledge enables people to create interactive surfaces that exactly fit their local set of problems [15].

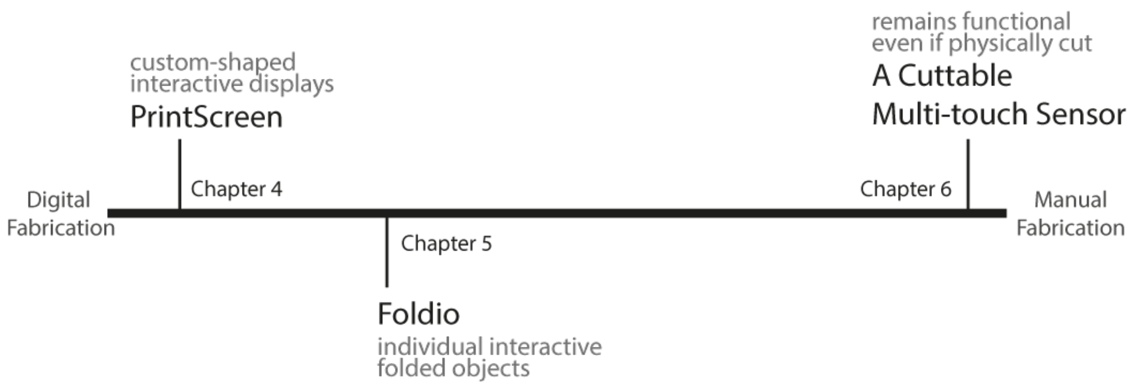


Figure 1.1: Overview of the chapters in this thesis

1.2 Towards Personal Interactive Surfaces

We see the movement of personal fabrication as just the beginning for an entire class of fabricators that empower the end-user to fabricate highly interactive custom-shaped interactive surfaces. Realizing this vision is highly challenging.

It demands novel user interfaces that enable the user to easily specify both functionality and shape while abstracting away from the technical complexity. These user interfaces transform the technical problem of creating a custom interactive surface into a design problem. This requires a conceptual understanding of the user interface elements necessary to define shape and functionality as well as concepts for how these should be integrated into a digital design environment.

It also requires technical fabrication processes that can physically instantiate custom interactive surfaces based on the end-user design. These processes should support various shapes (in 2D or even 3D), various materials and a wide range of interactive behavior. The end-user should thereby be capable of performing the fabrication process, which is challenging, since fabrication processes for e.g. mass-fabricated touch-screens require experts to perform them.

1.2.1 Addressing the Challenges

In order to transform these general demands into a systematic set of requirements, we conducted two complementary empirical studies (see Chapter 2). We aggregate the findings of each study and present a requirement analysis of the results in Chapter 2.3. We then reconcile requirements concerning shapes and interactivity with previous work in Chapter 3.

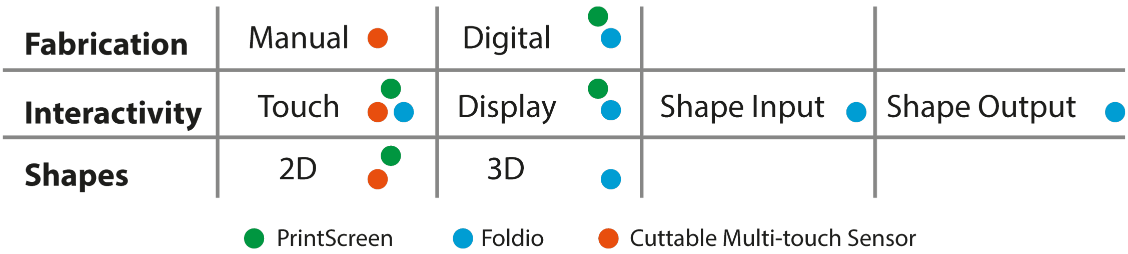


Figure 1.2: Coverage of fabrication styles, interactivity and shapes for each chapter

Based on these requirements, we created a series of solutions that enable end-users to fabricate custom-shaped interactive surfaces. We systematized them, by arranging them on a continuum between "digital" and "manual" fabrication (Fig.1.1). In digital fabrication, shape and interactivity are defined in the digital realm and are then physically instantiated using a fabricator. In contrast, in the manual approach the interactivity is predefined and the user just defines the shape of the object using traditional tools.

Both perspectives have their advantages: The digital design gives the designer more freedom regarding shape and interactivity. But it demands expertise in digital design and requires a fabricator. The manual approach is more constrained in terms of interactivity, but can be performed quickly, in an ad-hoc fashion, requiring no special equipment or knowledge of digital design tools.

Chapters 4 and 5 take a digital fabrication perspective, in which shape and interactivity are digitally designed and then physically instantiated. Chapter 4 presents *PrintScreen*, a fabrication process that enables non-experts to fabricate custom-shaped individual touch displays. In Chapter 5, *Foldio* extends this work to 3D objects that are folded. We directed this work slightly towards the manual approach, since the process of folding is done manually. Chapter 6 takes a completely manual perspective. We contribute a multi-touch sensor foil that can be cut to wide range of shapes while remaining functional. We envision this foil to be prefabricated and integrated into material so that users can shape-adapt it just using the tools they would normally use to shape-adapt the material.

Figure 1.2 complements the structure of this thesis by taking a design-space perspective. It visually aligns three dimensions that are intermixed in the approaches presented in this work. As shown in Figure 1.1, *Fabrication* can be done either manually or based on a digital model. The Interactivity dimension shows the types of interactive elements that can be integrated into an interactive surface. For example, the surface could sense if it is deformed or be actuated to actively deform itself. Lastly, the *shapes* dimension distinguishes between custom 2D shapes and 3D shapes. Figure 1.2 shows that this thesis covers the entire design space for custom shaped interactive surfaces.

1.2.2 Contributions

The main contributions of this thesis are the following:

- **PrintScreen** [70] is a digital fabrication process that enables designers, makers and end-users to fabricate custom-shaped interactive displays in low volume based on simple vector graphic files. We contribute a systematic overview of display primitives that the designer can fabricate. We contribute two complementary fabrication processes. One is based on conductive inkjet printing and enables instant displays. The other is based on screen printing for printing more advanced displays and displays on variety of substrates (such as wood, leather, PET, paper or stone). Lastly, we contribute a sensing framework that enables one to add touch-sensitivity without adding additional complexity to the fabrication process. The work is presented in Chapter 4.

- **Foldio** [66] enables the user to digitally fabricate 3D shaped interactive objects based on folding. These objects are very lightweight, cheap and can come in different sizes. This enables the user to create ubiquitous applications, such as an interactive lamp shade, or it can be used for novel packages with integrated interactivity. We contribute a fabrication process that abstracts away from creating crease patterns and printable electronic components. Instead, the user designs the object and adds interactivity in a standard 3D design environment. The shape is automatically unfolded and print patterns are generated by our algorithm. These are then instantiated using PrintScreen or conductive inkjet printing [33]. As a second contribution, we provide a set of controls that are added to the object during digital design to make the object interactive. These controls comprise surface input and output (e.g. touch or display) but also sensors to sense deformation and an actuator for moving the object. This work is presented in Chapter 5.

- **A cuttable multi-touch sensor** [65]. We developed a printed thin-film multi-touch sensor that can be cut in an ad-hoc fashion into a large number of shapes while remaining functional. The user can use standard tools, e.g. scissors, to cut the sensor sheet into a new shape. In order to realize the sensor, we contribute novel geometrical wiring layouts and analyze the space of shapes that the sensor can be cut into. We contribute approaches for combining individual layouts to further increase the robustness of the sensor. This work is presented in Chapter 6.

The work of this thesis has been published at international conferences. Chapter 2.1 is based on [107], while Chapter 2.2 is based on [69] and [68]. *PrintScreen* (chapter 4) is based on [70]. It received a best paper award and was selected as "Landmark 2015" by the German "Land of Ideas" initiative. In addition, it was exhibited at the CeBIT 2015 trade show and invited to the UIST Reprise track at SIGGRAPH 2015. *Foldio* (chapter 5) has been accepted at the UIST 2015 conference. Chapter 6 is based on [65]. The author contributed to a journal article [34] that covers the recent advances in printed electronics for applications in human-computer interaction and to a journal article focusing on the interaction perspective [106]. In addition, the author contributed to work that is closely related to this thesis: *PrintSense* [19] contributes a printed multi-modal sensor sheet that can be easily fabricated. Furthermore, the author contributed to work that investigated into the application space for flexible interactive surfaces: A mobile and resizable display that is used collaboratively is presented in [105] and the author contributed to a journal article that aggregates the work on interactions for resizable displays [104]. We show an exploration of the interaction space of a custom shaped display that is worn on the forearm of the user in [71]. The author contributed to a system for interacting with videos using multiple paper-like displays [48, 47]. Lastly, we contributed to work on pen & paper interactions [67, 28] to support knowledge work.

A full list of the author's publications can be found below:

- **Olberding S.**, Wessely M. and Steimle J.: PrintScreen: fabricating highly customizable thin-film touch-displays. In Proc. of UIST '14. (full paper, Best Paper Award)

- **Olberding S.**, Gong N., Tiab J., Paradiso J. A. and Steimle J.: A cuttable multi-touch sensor. In Proc. of UIST '13. (full paper)

- **Olberding S.**, Soto S., Hildebrandt, K. and Steimle J.: Foldio: Digital Fabrication of Interactive and Shape-Changing Objects With Foldable Printed Electronics. In Proc. of UIST '15. (full paper, Best Paper Award)

- **Olberding S.**, Steimle J., Nanayakkara, S. and Maes, P.: CloudDrops: Stamp-sized Pervasive Displays for Situated Awareness of Web-based Information. In Proc. of PerDis'15. (full paper)
- **Olberding S.** and Steimle, J.: Display Stickers: Enhance Your Environment with Tiny Interactive Stickers. CHI 2013 Workshop "Displays Take New Shape: An Agenda for Future Interactive Surface", 2013.
- **Olberding S.**, Yeo, K.P., Nanayakkara, S., Steimle J.: AugmentedForearm: exploring the design space of a display-enhanced forearm. In Proc. of Augmented Human. 2013. (note)
- Steimle, J. and **Olberding S.**: Verformbaren Mobilgeräten gehört die Zukunft: Wie gedruckte Elektronik und deformierbare Bildschirme die Interaktion mit mobilen Anwendungen verändern werden. Informatik Spektrum. 2014.
- Kawahara, Y., Hodges, S., Gong, N., **Olberding S.** and Steimle, J.: Building Functional Prototypes Using Conductive Inkjet Printing. Journal of IEEE Pervasive Computing. 2014.
- Gong N., Steimle J., **Olberding S.**, Hodges S., Gillian N. E., Kawahara Y., and Paradiso J. A.: PrintSense: a versatile sensing technique to support multimodal flexible surface interaction. In Proc. of CHI '14. (note)
- Steimle J., Weibel N., **Olberding S.**, Mühlhäuser M., and Hollan J. D.: PLink: paper-based links for cross-media information spaces. In Proc. of CHI EA '11.
- Hong, M., Piper, A. M., Weibel, N., **Olberding**, S. and Hollan, J. Microanalysis of active reading behavior to inform design of interactive desktop workspaces. In Proc. of ITS '12. (full paper)
- **Olberding, S.** and Steimle, J. Towards Understanding Erasing-based Interactions: Adding Erasing Capabilities to Anoto Pens. In Papercomp 2010 Workshop held in conjunction with UbiComp.
- Steimle, J. and **Olberding, S.** When mobile phones expand into handheld tabletops. In Proc. of CHI EA '12.
- Lissermann, R., **Olberding**, S., Petry, B., Mühlhäuser M. and Steimle, J.: PaperVideo: interacting with videos on multiple paper-like displays. In Proc. of MM '12. (full paper)

- Lissermann, R., **Olberding, S.**, Mühlhäuser, M. and Steimle, J.: Interacting with videos on paper-like displays. In Proc. of CHI EA '12.

- Steimle, J., Lissermann, R., **Olberding, S.**, Khalilbeigi, M., Kleine, W. and Mühlhäuser, M.: Be-greifbare Interaktionen mit grössenveränderbaren Bildschirmen. i-Com. 2012.

1.3 Thesis Organization

This thesis is organized as follows:

- **Chapter 2** presents two technological probes, and an analysis thereof, in order to investigate the requirements for custom shaped interactive surfaces.

- We present related work in **Chapter 3**. Here, we also reconcile the findings of the technological probes with previous work. Based on these requirements, we present three approaches for creating custom shaped interactive surfaces.

- **Chapter 4** shows a digital fabrication process for custom shaped touch-sensitive displays. It enables non-experts to digitally design a display of a custom shape with the help of a set of display primitives. Then, we contribute a fabrication process with which the user can physically instantiate the design.

- **Chapter 5** extends Chapter 4 and presents a digital design and fabrication process for 3D objects by folding a custom shaped interactive surface. In this process, the user designs the 3D shape in a standard 3D modeling environment and annotates it with interactive controls. Foldio abstracts the technical complexity away by automatically generating printable controls, wires and crease patterns based on the 3D model. The user then just folds up the printout to use the object.

- **Chapter 6** presents a manual approach for creating custom-shaped interactive surfaces in an ad-hoc fashion. We present novel wiring layouts for a multi-touch sensor that can be physically cut but remains functional. The sensor can be cut into a large variety of shapes. The thin-film substrate of the sensor can be integrated into other materials, such as wood, to create interactive and shape-adaptable materials.

- We conclude this thesis in **Chapter 7** and show directions for future work.

Chapter 2

Technological Probes

Designing novel interfaces and fabrication processes for end-user fabricated thin-film interactive surfaces requires an understanding of their critical design dimensions from the end-user perspective. Getting these insights is itself challenging, because end-user-created and custom-shaped thin-film interactive surfaces are not widely available yet. Instead, we took two complementary technological probes that resemble important properties of custom interactive surfaces.

The first probe focuses on input for paper-thin interactive surfaces that come in different formats. The high flexibility and varying paper formats limited the opportunities for output, so the surfaces support input only. We deployed these surfaces within a long-term study in the area of knowledge work. The goal was to get insights into the implications of size and shape and the usage of space.

With the second probe, we aim to get a better understanding on display output, interactions and spatial arrangements. We applied a user-centered design approach for a system, consisting of a multitude of small, high-resolution and touch-sensitive displays. Similar to post-its, these can be attached in space or on objects to make them interactive or to structure information spatially. The resulting interactive surface — consisting of small tangible displays — is highly shape-adaptable. Since flexible small displays are not yet commercially available, we use rigid displays of the same size.

Finally, we aggregate the results and formulate requirements for printed surfaces.

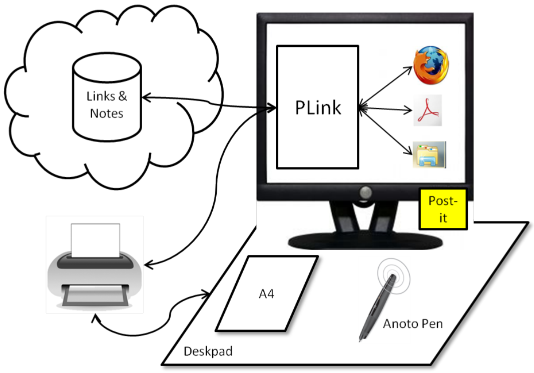


Figure 2.1: Overview of the system architecture

2.1 Input on Interactive Paper

With the first probe, we want to provide insights into the input space of interactive paper. In particular, we want to learn about the role of shapes, substrates and physical space for thin-film interactive surfaces.
To do so, we created a system called "PLink" that uses thin-film interactive paper as an input surface. It supports a large variety of shapes including large deskpads, letter-size sheets, post-its and very small link stickers. By using a digital pen, the user can create written hyperlinks of the interactive paper, which link to a digital resource (e.g. a file or website). PLink is a promising system to study, since its interactive surface comes in various sizes and shapes, the surface itself is thin-film and it can be distributed in space.
We deployed PLink[1] in the context of knowledge work, since there are various paper formats in use and space acts as an important way to structure information. Because it is immensely challenging to introduce a novel system into highly personal work practices, we deployed PLink in a multi-week field study.

2.1.1 System Design

Figure 2.1 shows an overview of PLink. PLink relies on Anoto[2] digital pens. These behave like ordinary ballpoint pens, but in addition capture all written traces in digital form by decoding a specific dot pattern, which is printed on paper. The position is streamed in real-time via a Bluetooth connection to the user's computer, on which the PLink application is running in the background. Links and notes are stored in a database.

[1]Side note: PLink itself is a novel system for bridging the gap between paper and digital media and extends earlier work [21, 39, 45, 51, 120, 102, 62, 119, 87]
[2]http://www.anoto.com

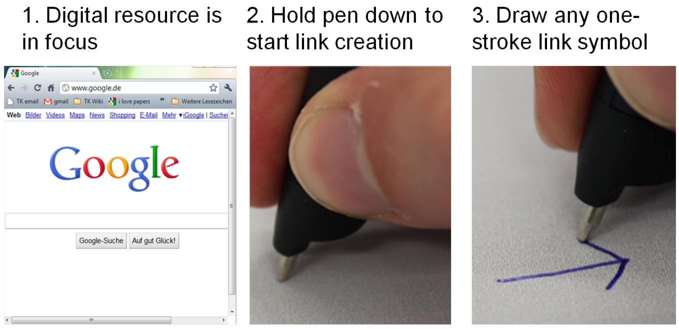


Figure 2.2: Steps for creating a link

PLink supports the use of different types and formats of paper media. The system can be used with any kind of paper which is covered by the Anoto pattern. This includes large sheets (A0 or A1 format) which we call deskpads, empty sheets of A4 or letter-sized paper and post-it stickers. Inspired by one participant, we added very small stickers (1.5 x 1.5 cm in size).

PLink enables linking regions on paper to digital resources. These include 1) web pages, 2) any folder or document in the local file system and 3) PDF files (including the page number). In the latter case, links can be used not only for accessing a document, but also for switching between its pages. Links are created using a simple pen gesture. This gesture links a region on paper to the digital resource of the currently active window.

We designed this gesture with the goal to be easily integrated into established notetaking practices. Figure 2.2 shows the steps for creating a link. In order to create a link, the user holds the pen down for a short moment (500 ms) until visual and auditory feedback is given by the system. Then the user can draw any one-stroke gesture. When the pen is lifted, the link is automatically created and status feedback is given. When this region is quickly tapped with the pen, the hyperlink gets activated and the target document is opened or sent to the foreground.

2.1.2 Field Study

In order to explore the role of shapes, substrates and physical space for interactive surfaces, we deployed PLink in a multi-week explorative field study.

Methodology

Participants: We recruited 10 volunteer participants (5 female, 5 male; 8 right-handers, 2 left-handers). All were experienced knowledge workers, from both technical and non-technical backgrounds. All had an office with personal work space at our university and used it daily during work days. Six of them were PhD candidates or senior researchers in computer science, 3 were PhD candidates or senior researchers in psychology and 1 was a secretary. Their ages ranged from 25 to 42 years with an average of 30. No compensation was provided.

Procedure: The participants used PLink over a period of four weeks at their desks. They were free to use the system in whatever ways and for whatever purposes they liked. On the first day, we installed the software on each participant's computer (9 PCs, 1 laptop). Each participant was given a personal Anoto pen (either Logitech io2 or Maxell DP-201). A large deskpad sheet in A1 size was placed onto the participants' desks at the position they desired and attached with removable strips of tape. The participants were told that they had the option to cut the deskpad into arbitrary smaller shapes. In addition, each participant was given 10 empty A4 pages and 10 post-it stickers (7.5 x 7.5 cm in size), also covered with the Anoto pattern. More pages and stickers were available if needed.
Each participant was individually introduced to the functionality of PLink (for about 15 minutes). We demonstrated how to write and link using the pen as well as how to access the digital representation of the documents and how to print documents.

Data Gathering and Analysis For gathering data, we conducted three semi-structured interviews with each participant, each between 15 and 45 minutes in length. These interviews were audio-recorded. A first interview was conducted before the system was installed, a second interview after 7-10 days of use and a final interview after 4 weeks of use. Each day, we took photos of the participants' desks.

2.1.3 Results

Shape and Size

The variety of shapes and sizes (deskpad, A4, post-it, stickers) was critical for participants to spatially organize information. We observed different usage behaviors for classes of shapes. Deskpads provided a large physical area for adding interactive links. We observed that only a subset of the paper area was made interactive. Individual spatial distribution of interactivity was important for participants. P9 showed the

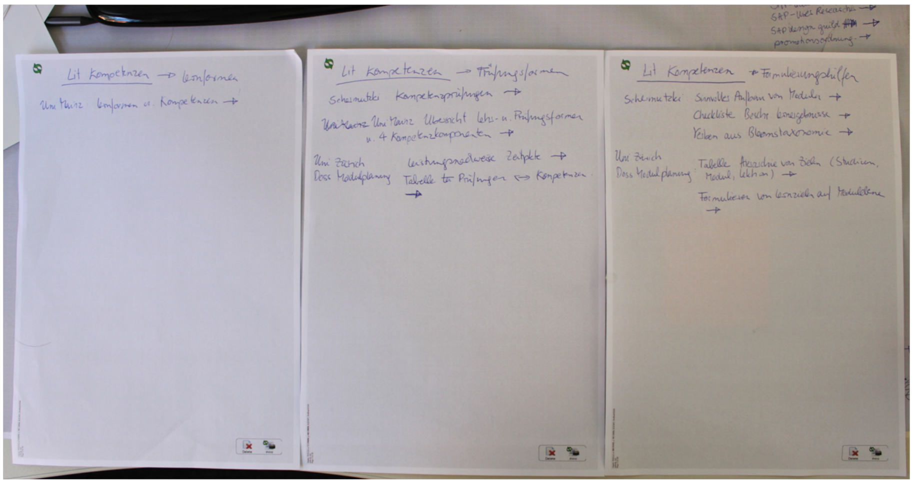


Figure 2.3: An example of how multiple A4 shapes supported information restructuring.

example of a link he had created when he was interrupted during a task on a web page. *"Yesterday I was about to leave and this was the most important link I wanted to see [the] next day. So I made a link there."* He created the link on his deskpad at a position next to the pen docking tray, which is used for charging the pen overnight, to ensure that he would see the link the next day.

We observed that users leveraged the dynamic spatial reconfigurability of A4 sheets to organize information within a digital document. P1 devoted one sheet for one central dimension that she wanted to address in an article that she was about to write (see Fig 2.3). To each dimension, she linked related documents or pages within documents. She concluded that *"I have a more permanent structure that I can refer to that [reminds me which] resources are in this topic, [and] which resources are in that topic."*

Post-its were placed on various locations at the desk and were mainly used as reminders, in which case they were often attached to objects. For example, P3 attached a post-it with links close to the phone. P3, P4 and P5 placed post-its at strategic positions so that they would stay aware of them. For example, P5 placed a post-it on the edge of their computer screen. The location was not necessarily fixed. P3 and P5 moved post-its to adapt their information environment.

We observed that the small interactive stickers were deeply integrated into the users' objects and in their information environment. They were integrated into notebooks (P1, P9), loose sheets of paper (P6, P10) and even on the cover of a notebook (P5). Within a period of 2 weeks, participants had created more links using stickers (23 links overall) and activated them more frequently (a total of 52 times) than on post-its in the entire period of four weeks (9 links, 20 activations).

Persistence of Information Across Shapes

We found that different paper sizes exhibit different degrees of persistence for the information written upon them. Four participants (P1, P3, P4, P10) perceived information on the large deskpad as static and sometimes too persistent, in particular for short-term information. P10 reported using the deskpad only for long-term information to avoid seeing outdated information all day. P4 did not make any notes on the deskpad because *"one cannot remove any note"*. P1 comments: *"If I had to reorganize something with this deskpad, it would not be so easy."*

Cutting for Shape Adaptation

Cutting paper was applied as a technique for adapting the shape of the interactive surfaces in a direct fashion. It was applied across different shapes and sizes and intuitively performed by the user. Two participants (P3, P5) cut the deskpad to make it better fit their desk. P4 reported that she likes the physical act of throwing a sheet of paper into the wastepaper bin. In order to be able to discard individual pages, she cut the deskpad into smaller sheets of paper (A5 size). One participant (P1) cut a patterned post-it into many small stickers and attached these into her notebook. She concluded: *"I was really happy because I have seen how flexible [the system] is. I attach [a sticker] into [the notebook] and then I can also use the system with my old notebook."*.

Substrate

We observed that the flexibility of the substrate was a key enabler for spatially distributing shapes (since they are light and thin), integrating them into other objects (since they can flex to adapt their shape to the object), for shape adaptation (since they can be cut) and for using them with traditional paper media (since they are based on the same material).

One finding was particularly interesting: Participants extended the expectations they have of interaction with paper to the *entire* system, including the digital part. Link activation with PLink added at most one second to the time which the participant's computer needed for opening a document. Nevertheless, many participants (P4, P5, P6, P9) perceived the system as too slow when activating a link. P5 commented

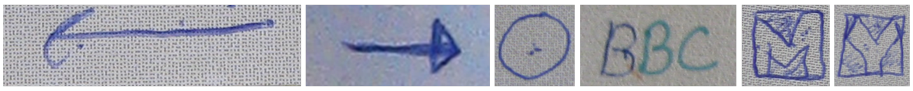


Figure 2.4: Custom shaped interactive areas

that *"It is not really natural. Paper is natural. I should not need to wait for it."*

These are strong indicators that users have different expectations of thin-film interactive surfaces than of traditional rigid interactive surfaces. This suggests that the expectations are closely connected to the affordances of the substrate that the interactive surface is printed on.

Visual Personalization of Links

We observed that interactive areas had a highly personal shape. Figure 2.4 shows some examples. P9 drew interactive links as personal artwork prominently on the deskpad. P1 drew links as a recurring symbol and independently of the type of the digital resource.
The participants had created custom groups of links at locations which were usually not occluded by other documents or objects (with the one exception of online banking links which the participant wanted to be hidden). This meant that the shape of the links became a permanently visual and also highly personal part of their working environment.

2.2 Output on Tiny Mobile Displays

With the second probe, we seeked to generate insights into the requirements for the design of thin-film interactive surfaces that include output capabilities. More specifically, we aimed at gaining an understanding of shapes, visualizations and interactions from an end-user perspective.
To achieve this, we performed a user-centered design process for an awareness platform that uses these tiny displays. The platform is called "CloudDrops" and is meant to enable the user to stay aware of dynamic digital data by using their entire architectural space.
We opted for multiple tiny displays, since thin-film interactive surfaces of a custom size and resolution are not yet commercially available. Tiny displays can approximate the shape space of custom interactive surfaces and serve as basic building blocks for creating a custom shaped surface. To closely resemble continuous thin-film interactive

surfaces, each stamp-sized display can technically connect to its neighboring displays to form larger surfaces.
We based the design of the platform on a set of usage scenarios that are derived from informal discussion with six potential users. Then, we created a prototypical version of the system and developed first example applications. Lastly, we evaluated the system with a user study.

2.2.1 Usage Scenarios

We performed informal discussions with six potential users (5 male, 1 female). We aggregated the results and present them as usage scenarios. Participants were told that they can assume that the display can be connected to any digital information item.

Information Worker: Jack arrives at his office. Groups of displays are attached to the wall, next to his computer screen and scattered on his desk. A picture of his family is held in place by two displays that are associated with his wife and his daughter. More toward the periphery of his desk is a group of displays associated with news blogs. Close to it is a group of displays, each of which shows the daily offerings of a food delivery service. Jack glances over the displays on the wall. Each group corresponds to a project that he is involved in. One of the typical groups consists of displays that are associated with shared documents or persons. He immediately sees that one of the international projects got updated overnight and that some co-workers from other projects sent him an email. He decides to take care of it later. On the side of his screen a display is attached, showing the number of unread emails.

Smart Home: Jack arrives at home. On the kitchen fridge are display magnets attached next to various postcards and other paper documents. The displays show the special offers for the next two hours in his local supermarket. While opening the fridge door, Jack notices that his mother has sent a recipe to one of the displays. He smiles into the camera of the display, takes a picture and sends it back to her. Next to his sofa, some displays that are associated with Jack's online music service are pinned on the wall. Some of them show album covers for music albums that are recommended by the music service, while others are directly linked to Jack's favorite songs. These are grouped and pinned closer to his sofa to have them directly in reach. Jack is in the mood to listen to something new, so he glances quickly over the corresponding displays and taps on one of them. The song starts playing on his stereo. He particularly likes the new song. Jack touches the favorite icon on the

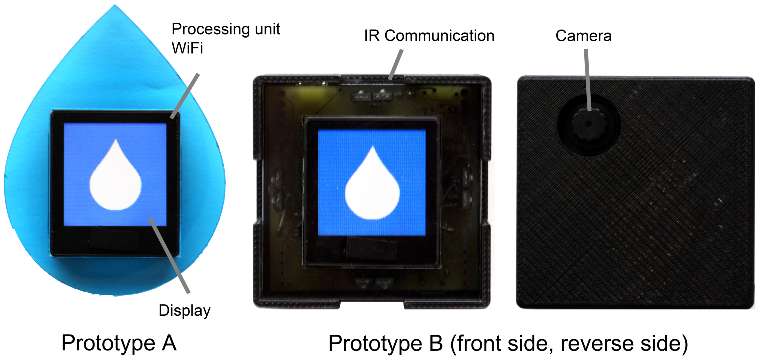


Figure 2.5: CloudDrop Prototypes

display to add the song to his favorites.

2.2.2 System Design & Implementation

Device Concept

Based on the usage scenarios, we realized the concept of a CloudDrop in two prototypical versions (Fig. 2.5). A CloudDrop contains a small touch-sensitive display. Users can personalize the appearance of a CloudDrop with custom cases or skins (e.g. with a drop-like shape). Similarly to how magnets are used on whiteboards or fridges, a CloudDrop can be attached to various objects, sticking to them with its magnet and adding additional information to those objects. Our prototype B has a camera on the back (see Fig. 2.5 reverse side), which is used for easy association between the CloudDrop and the underlying object by taking a picture of the object.

Implementation

In our prototypical implementation, each CloudDrop has a full-color touch-sensitive screen with a diagonal of 1.5 inches and a resolution of 160x160px. It features a 600Mhz processor, a built-in accelerometer and WIFI connectivity, and an attached RFID tag. Prototype A weighs 32 grams and measures 2.1 x 2.9 x 0.5 inches. Prototype B weighs 73 grams and measures 2.1 x 2.1 x 1.25 inches. It features an infrared sensor on each side with a maximum range of 4cm for neighbor detection. Once a neighbor is detected, they exchange their ID and the side along which they are facing each other via a custom infrared protocol. All CloudDrops are connected to a central server. Other computing devices recognize a nearby CloudDrop using an RFID reader.

Our implementation is compatible with standard Web protocols and major application platforms. CloudDrops can display and communicate with content from Web pages,

a) Website b) Document c) Inbox d) Email e) Person

Figure 2.6: Content types and their visualizations that are supported by a CloudDrop

Gmail, Google Docs and Skype. For associations with the Google Chrome browser and Skype, the nearby computing device runs a client application that communicates with the CloudDrops server.

Content and Interactions

We learned in the usage scenarios that CloudDrops should be designed to be visible at a glance. Therefore, all available screen real estate is devoted to content. To maximize the flexibility for possible shapes, each CloudDrop displays only one type of content at a time. This includes web documents, or content related to people or places (see Figure 2.6). Not only do CloudDrops show content, the user can also touch the display to interact with the content in a lightweight fashion (e.g. tag an email or open the associated website on a nearby screen).

The screen of a CloudDrop is too small to browse for content as is done on larger mobile devices (e.g. on smartphones). In order to associate content, the user selects content on a nearby device (e.g. a dynamic part of a website) and holds the CloudDrop close to it.

2.2.3 Example Applications

To get insights into custom interactive surfaces with output capabilities, we created a set of example applications that are based on the usage scenarios. These applications provide an integrated view of the role of space, interactivity and shape for custom shaped interactive surfaces.

Custom Shapes for Displays

The tangible nature of CloudDrops empowers the user to create custom interactive display surfaces that exactly fit his needs. Figure 2.7 shows a variety of examples. CloudDrops can be arranged as a symbolic shape that extends the shape of the underlying object (Fig. 2.7a). They harmonize with traditional ways in which the

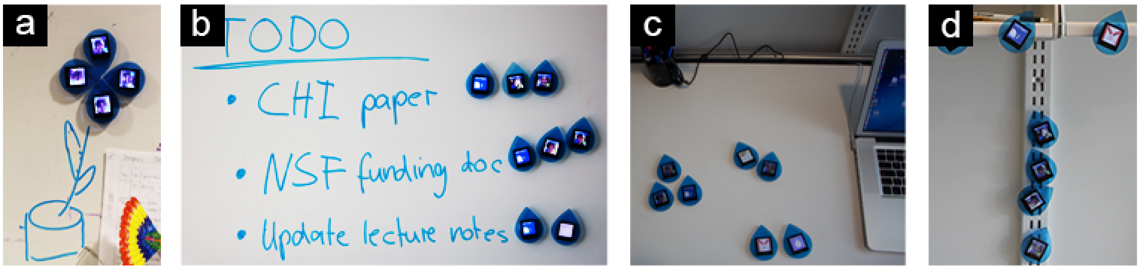


Figure 2.7: CloudDrops support custom display shapes and can be scattered around the entire architectural space

user structures information (Fig. 2.7b,c). Their form factor allows display shapes that fit well into architectural space (Fig. 2.7d).

The user can create custom shaped continuous displays in an ad-hoc fashion by placing CloudDrops in close proximity to each other. For instance, adding a CloudDrop next to the user's inbox displays the most recent email; each additional CloudDrop adds one more recent message (Fig. 2.8). Thus, each display remains interactive. This application case shows the large number of individual shapes of interactive surfaces. It also shows that it can be beneficial if the user is both the creator of the shape and its user.

Enhancing Passive Objects

The tiny form factor of CloudDrops can extend a passive object with dynamic digital functionality. An example application allows users to associate a CloudDrop with a printed schedule of a bus stop or subway/commuter rail station.
The display then continuously updates information such as the arrival time of the next bus/train or status updates such as delays and cancellations (Fig. 2.9). This principle applies to a wide range of objects, including a restaurant flyer on which the CloudDrop shows the menu of the day or a postcard to which the CloudDrop adds live images of that location. This application case shows that the interactive surface and an underlying passive object build a rich interactive structure that comprises a

Figure 2.8: Creating an interactive surface of a variable size by placing CloudDrops close to each other

custom shape and functionality.

Remotely Accessible Interactive Surface

CloudDrops can be attached and associated to locations such as walls, doors or desks. This application case shows a potential use of interactive surfaces for accessing these locations remotely. In the example shown in Figure 2.10, the user had selected a textual description of the location on the CloudDrop (e.g. "office door"). This location information is automatically propagated to other CloudDrops that are added in its close vicinity. The user can then send content via email to the CloudDrops associated with the location.

Visualization of Dynamic Digital Elements

The general purpose display allows both static and dynamic content to be shown. For example, the visualizations that were presented include a more static and a more dynamic part. This makes it possible to display a wide variety of content including people, documents and locations (see Figure 2.6). The touch sensitivity is critical to directly manipulate the content. This implies that custom interactive surfaces should enable the user to integrate content of various dynamics and they should be touch sensitive.

2.2.4 User Study

We were interested in deepening our understanding of the locations to which users would attach the interactive surfaces in their architectural space and what the intended use would be. In order to gain these insights, we performed a user study.

Methodology

We conducted an explorative user study in 5 households with a total of 8 persons (4m, 4f). We visited the participants at their homes. We gave a short introduction into the system's functionality. The participant's task consisted of using CloudDrops

Figure 2.9: Adding dynamic information to a paper document.

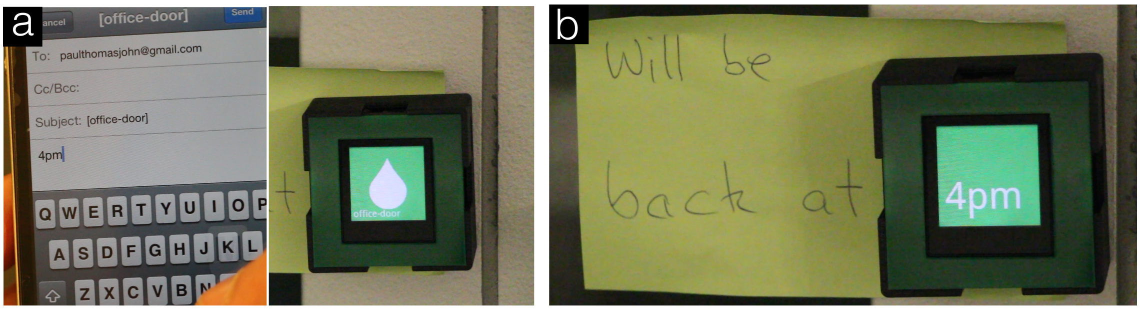


Figure 2.10: An interactive surface associated with a location. The user can update the information by sending an email to that location.

in his/her home. We asked the participant to associate CloudDrops with persons, applications and websites and place them at any suitable location in the apartment. We used a think-aloud protocol. Field notes and photos were taken. Each session was concluded by a semi-structured interview and lasted approximately 2 hours.

Results

All participants were very positive about CloudDrops and enjoyed using them. For instance, P7 reported: "[It makes digital things] distinct, in flux, tangible and spatial."

CloudDrops were intuitively placed at many different locations in the home. This included highly visible locations that participants pass by frequently, e.g. the fridge, desk, and bathroom. It also included dedicated objects that were augmented with specific digital functionality. For instance, one participant augmented her guitar with a CloudDrop that directly links to her guitar teacher. CloudDrops were also placed into existing information ecologies, e.g. to add digital information to paper documents on the fridge.

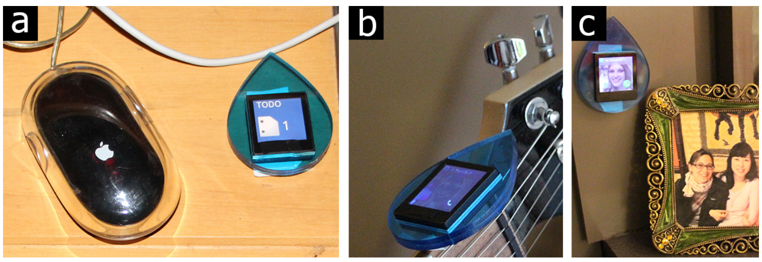


Figure 2.11: Emerging practices performed by users. a) P7 placed a CloudDrop associated with a TODO document prominently on her desk. P3 attached a CloudDrop of her guitar teacher onto the guitar. c) P1 attached a CloudDrop onto a picture frame to stay aware of her friends.

CloudDrops associated to websites and applications were used in very versatile ways, taking the contextual richness into account. For instance, P2 placed a CloudDrop as a shopping list on the fridge. P1 attached a CloudDrop on her fridge to stay aware of a blog about recipes. CloudDrops with documents were often placed on the table in the living room or close to the desk (see Fig. 2.11a). P7 commented: "It has the potential to return the [digital] desktop to the tangible space of my desktop." After spatially placing multiple CloudDrops around her desk: "it relieves the temptation to be distracted by the multiple tabs [in my web browser] that I have always open."

In particular, the association with a person increases social presence, as reported by P7 after looking at a status message: "It so nice to be with somebody without being physically there [...] we can leave the channels to our homes open." We observed that CloudDrops associated with persons were prominently placed in the field of view of the participant or on objects that are closely connected to that person (see Fig. 2.11b, c).

2.3 Requirement Analysis

In this section, we analyze the results of the technological probes and draw implications for the design of thin-film interactive surfaces. We start by providing a set of observations, which are then taken as a basis for deriving the requirements.

2.3.1 Observations

Shape as reference frame for digital data

We observed that the physical shape of the interactive surface acts as a reference frame for digital data and vice versa. The motivations for adapting the reference frame can be divided into two classes:

First, the reference frame can be adapted to fit the shape of another object or in order to integrate it into the environment. Both in PLink and in CloudDrops, it was important that the entire environment could be potentially interactive. The thin-film form factor of the substrate and the size-adaptable printing was critical in PLink. With PLink we observed that a user cut a post-it into multiple small stickers to make it fit into her notebook. The large deskpad was adapted by cutting it to fit onto the user's desk. The small form factor of CloudDrops was crucial for their integration into existing environments.

Second, the reference frame can be adapted to fit the content. In this way, the content benefits from the specific affordances of the shape:

- In PLink, users put long-term information (such as portals) on the large deskpad whereas more short-term information was written on smaller surfaces. This allows the user to influence the persistency and dynamics of content through the physical shape.
- Shapes support flexible spatial organization. Due to the different shapes, users can organize information spatially on a macroscopic and microscopic level. For example, users can organize information by scattering CloudDrops through physcial space and can use the large surface of a deskpad e.g. for organization within written lists.
- Shape adaptation was used to more closely connect digital information with the physical. In PLink, a user extended the interactive area by adding more sheets to fit the content.
- The shape influences the mobility or stationary nature of content. Content in CloudDrops was more mobile than what was written on the large deskpad in PLink. Flexible thin-film surfaces have the potential to be both mobile and stationary. By adapting the shape through rolling or folding, the surface can be made small for transportation and large for interaction. This aspect was heavily used in [36, 35, 79, 24, 43].

Shape as the content

The physical shape is not necessarily a frame of reference; rather, it can also be the content itself. For example, CloudDrops can be arranged to a heart shape in order to transmit a symbolic meaning. In PLink, users can draw individual interactive areas that exactly fit their needs. Hand-drawn interactive areas have been used in previous work as well, such as [115]. Not observed in the tech probes were folded 3D paper shapes to support prototyping, such as presented in [101]. Here, the shape itself is an integral part of the content.

Creation of Shapes: At design time and at use time

Both CloudDrops and PLink enabled the user to be the creator and the user of custom shaped interactive surfaces. Furthermore, the probes showed that it is beneficial if interactive shapes can be created quickly and directly. Taking the tech probes as a point of departure, we want to contrast two extremes on a continuum.

Creating the shape at design time: The shape of the interactive surfaces is defined at design time. For example, in PLink, users were given shapes of interactive paper that were pre-defined and created at the design time of the system. In a second step, these shapes were then used by the participants. In CloudDrops, the shapes of the visual representation were defined at the design time of the system.

Creating the shape at use time: The shape is defined at the time of use. For example, while using the system, participants adapted the shape of the interactive surface by cutting. In CloudDrops, the user could spatially reconfigure individual displays to create custom interactive surfaces at use time.

Each of these strategies has its advantages. Creating shapes at design time often includes a digital specification of the shape. This allows it to be reproduced easily. If we consider the content of a CloudDrop as a specific visual shape, then we can argue that the digital model also allows sharing of the same visualization across users. But this strategy requires a second step for creating the shape according to the model, which also requires additional technical expertise. Adapting the shape at use time has the benefit of directly manipulating the shape in a similar fashion as adapting the shape of a material. It allows for quick and ad-hoc adaptation of the shape. On the other hand, due to the absence of a digital model, the shape cannot easily be reproduced or shared.

Distribution of interactive areas on the surfaces

The interactive parts on the surfaces that were shown in the studies are not equally spatially distributed. In PLink, only a part of the entire shape was actually made interactive by writing links to it. The same observation can be made in CloudDrops. But in both probes, it was important that the entire shape could be potentially interactive. That means that any part of the shape could have interactive content.
The dynamics of the content on a shape were not equally distributed. In CloudDrops, the display showed very static content that rarely updated as well as very dynamic content that updated frequently. Content on the deskpad in PLink was rather static, while content on post-its was more dynamic.

2.3.2 Requirements

Based on the observations, we derived the following requirements for the fabrication of thin-film interactive surfaces:

R1: Individual Shaped Display Output with Touch

Visual output on thin-film interactive surfaces in combination with touch input is only available in standard shapes and with a predefined resolution. Thus, interactive surfaces cannot benefit from the rich semantics of shapes. Novel fabrication processes are necessary to enable the end-user to fabricate individual shaped touch displays.

R2: Highly Interactive 3D Objects

Interactive surfaces were attached to 3D objects. But the surface itself did not create the shape, as is done with e.g. folded objects. Novel user interfaces and fabrication processes are necessary to leverage the potential for forming 2D interactive surfaces into 3D interactive objects.

R3: Creation of Shapes

The creation time of shapes can positioned between two extremes of a continuum: *"at design time"* and *"at use time"*. Both extremes have their strengths. Thus, both creation strategies should be supported.

R3a: Creation of Deformable Shapes at Design Time

Defining the shape digitally at design time is beneficial, since the process is easily repeatable due to an existing digital model. The downside is that it often requires technical skills for the design and fabrication. Novel fabrication processes are necessary to lower these technical requirements.

R3b: Creation of Deformable Shapes at Use Time

Defining a shape at use time is beneficial, because no technical hardware skills or complex machinery are involved. The user shape adapts a prefabricated interactive surface in a direct and ad-hoc fashion. Based on our observations, we require that the interactive surface can be modified in the same way as the user would modify the substrate that the shape is printed on.

R4: Support for Various Materials

Shapes for interactive surfaces are highly individual. This means the *flexibility* of the substrate is crucial to easily adapt the surface to fit on objects, into the environment and to combine it with various materials. The interactive surface has been integrated into or could be combined with specific substrates. For example, in PLink the substrate was regular office paper. Merging substrates and interactivity is a promising way to interweave technology into our everyday life [118]. This requires enabling designers, makers and end-users to create interactive surfaces that can be *embedded into various materials*.

R5: Custom Spatial Distribution of Interactivity

The spatial distribution of interactive areas and the kind of interactivity on the surface varies. This requires that the user should be empowered to decide on the *location* of interactive areas and on the *type* of interactivity within each location.

2.3.3 Conclusions

In this chapter, we derived first requirements for custom shaped interactive surfaces based on two technological probes. In the next chapter, we present related work and consolidate the requirements with the previous work.

Chapter 3

Related Work

This thesis touches on work from three major fields (see Fig. 3.1). Printed electronics is used as a technical foundation. Since printed electronics is a research field in itself, we will give only a brief overview of the knowledge that is relevant for this thesis. Since this work is concerned with shape-adaptable interactive surfaces, we will also present existing approaches within the HCI community. A further basis for this work is the area of novel user interfaces for fabricating objects and interactive surfaces. We will show research findings that have been presented in HCI so far. As shown in Fig. 3.1, there are intersections between these individual fields. Where appropriate, we will highlight intersecting work.

3.1 Printed Electronics

There are several definitions of printed electronics. “Printed electronics is a technology that merges electronics manufacturing and text/graphic printing. By this

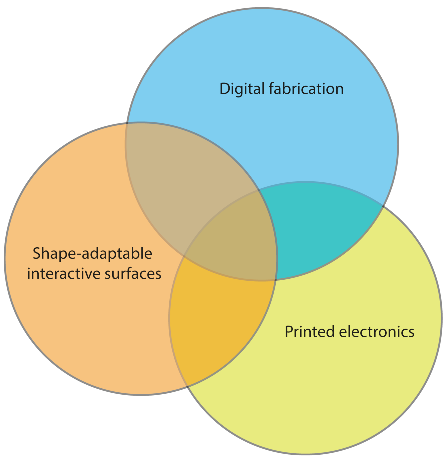


Figure 3.1: Related fields of this thesis

Printed Electronics	Traditional Electronics
inexpensive	high fabrication cost
large area	small area
simple fabrication	sophisticated fabrication
flexible substrates	rigid substrates
long switching time	short switching time
high volume	

Table 3.1: Differences between printed and traditional electronics based on [7]

combination, one can manufacture high-quality electronic products that are thin, flexible, wearable, lightweight, of varying sizes, ultra-cost-effective, and environmentally friendly" [108]. The term organic electronics is often used interchangeably: "Organic electronics is based on the combination of a new class of materials and large area, high volume deposition and patterning techniques. Often terms like printed, plastic, polymer, flexible, printable inorganic, large area or thin film electronics or abbreviations like OLAE or FOLAE (Flexible and/or Organic Large Area Electronics) are used, which essentially all mean the same thing: electronics beyond the classical integrated circuit approach" [7].

These definitions make it clear that printed electronics literally means to print electrical components with similar methods as those used to print text or visuals. It thus combines the advantages of printing (high speed, large volume, cheap and simple fabrication, flexible substrates) with electronics. On the flip side, electronics are not as small or high-performing as those on rigid circuit boards. We listed the most notable differences in Table 3.1.

Printed electronics is a highly interdisciplinary field of active research. It basically merges three disciplines: electrical engineering for building novel electrical components and sensors, chemical engineering for creating functional inks with defined electrical properties as well as substrates to print on, and mechanical engineering to facilitate printing methods that can process the inks. Since this is important background for this thesis, we will describe these topics in more detail.

3.1.1 Printing Technologies

There are several printing technologies available (see Fig. 3.2). Since only two of them are of particular relevance for this thesis, we will describe them in more detail.

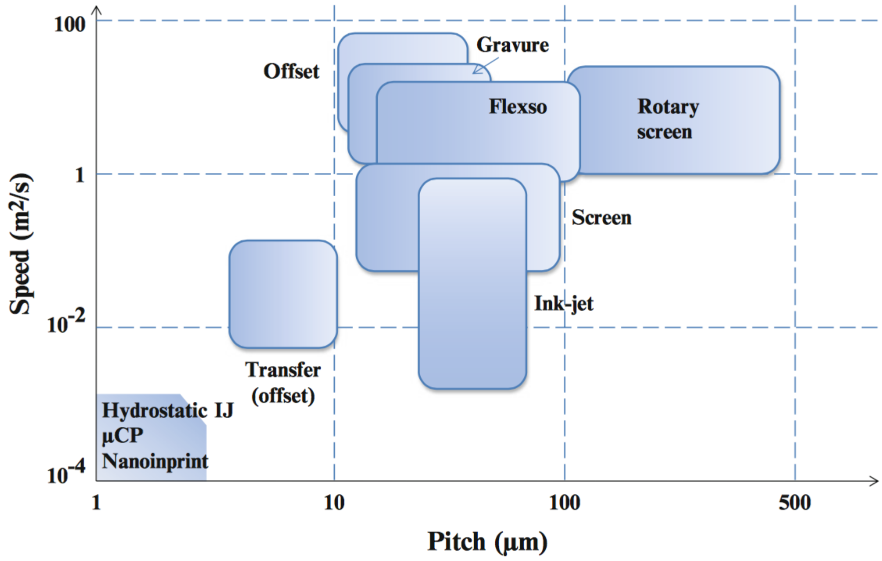


Figure 3.2: Printing methods ordered according their printing accuracy and speed [108]

A detailed explanation of the other printing methods can be found in [108].

- **Inkjet printing**: The working principle of an inkjet printer is to deposit multiple tiny dots of inks onto the substrate [108] in a computer-controlled way. The control over individual droplets is the big advantage of inkjet printing: Individual prints in low volume can be done at little cost. But it comes with limitations: To achieve small dots on the substrate and to avoid clogging of the printing nozzle, the conductive particles in the droplets need to be tiny. This constrains the choice of ink. For example, phosphor for fabricating electroluminescent displays cannot be inkjet printed because of its large particle size (30-50 microns [38]).

- **Screen printing**: The working principle of screen printing is to mask a fine mesh with the shape that should be printed, then press ink through it and deposit it onto an underlying substrate. Screen printing has the advantage that it can print large aspect ratios [108] and it provides flexibility in terms of the level of automation. It can be done completely manually even by hobbyists. Semi-automatic, 3/4 or fully automatic machines are available to control the printing process more accurately and to reduce manual work. Screen printing is unique in the sense that it is possible to print on a large variety of substrates and with a large variety of inks [10]. Thus, it is interesting for many applications in HCI where electronics need to be embedded into the environment, e.g. by large scale prints, or into objects, e.g. by printing on different substrates.

3.1.2 Basic Electrical Components

In order to realize circuits, basic electrical components are necessary. While it is possible to add traditional rigid parts to printed circuits, this has the disadvantage that they are not flexible and their attachment to the flexible substrate is not integrated into the printing process. Therefore, previous work in printing technology and materials science attempted to develop components that are completely printable.

Many passive and active components, including capacitors, resistors and transistors, are already printable [108]. Printing of passive conductive circuits is already offered commercially[1].

Components are fabricated by printing inks with special electrical properties on a substrate. The chemical composition of inks is an active research field in itself. From an HCI perspective, inks can be roughly distinguished by their electrical properties, printability and possible combination with substrates. For example, there are inks that have conductive or dielectric properties [108], inks that can be embedded into elastic 3D structures [61] and inks that chemically react with the underlying substrate to receive their electrical functionality [33].

Although similar technology is applied as in traditional printing, the requirements for the substrates are different. Inks may require post-processing, in which the printout is heated up to high temperatures to sinter the inks. The substrate must also prevent the occurrence of micro cuts which will damage the circuit. Recent work [114] investigated paper as a suitable candidate for printed electronics. Other materials are often based on PET (e.g. mylar).

3.1.3 Advanced Components: Displays

There is a vast range of display technologies available [8] and it would be far beyond the scope of the thesis to present all of them. In this section, we provide a short overview of the most common technologies. A detailed description can be found in [8].

[1] http://www.conductiveinkjet.com

Electrophoretic Displays

Electrophoretic displays [8] have high contrast, a large degree of viewing angles and appear like "ink on paper". Thus, they are often called e-ink displays. The displays are flexible and consume a very low amount of energy, but have a slow update rate and support only a small amount of color. In many HCI applications dual-particle displays are used [16, 40, 17]. They work as follows: The display surface is filled with tiny microcapsules. Each of the capsules is filled with an oily fluid and contains two particles, normally a white and a black one. Depending on the position of the particles, the display will show a black or a white dot. For example, if the black particle is on top, the display will show a black dot. To move colored particles, an electric field is applied.

Electrochromic Displays

Electrochromic displays switch their color when a charge is applied. Different colors such as red, green and blue are also supported [8]. They consist of three layers: a top and a bottom electrode and an electrochromic layer in the middle. Electrochromic displays consume little power and are cheap to build. However, they have slow switching times [2].

Thermochromic Displays

Thermochromic displays have a low contrast and a slow update rate. But they can be made flexible [49] and are fairly easy to build. The display consists of two components: a temperature sensitive ink that is applied on a surface and a heating element that can heat up the surface. When the temperature reaches a certain threshold, the ink changes its color.

OLED Displays

OLED displays have several advantages: They can be made flexible, have a short switching time and are multi-color [8]. They can also be created in custom shapes. However, the fabrication of OLED displays is complex and cost-intensive due to their multi-layer structure and the sensitivity of the materials.

Electroluminescent Displays

Electroluminescent displays are mostly known from backlighting applications (e.g. in car panels). Displays can be produced in multi-color and have a short switching time [8]. Since the internal structure is less complex and the materials used are more robust compared to those used in OLED displays, displays are relatively cheap and easy to fabricate [70]. A more detailed description can be found in chapter 4.

3.2 Digital Fabrication

With the emergence of 3D printers, laser cutters and milling machines, fabrication of surfaces and objects has been emancipated from the traditional mass fabrication approach towards custom fabrication. This shift puts the human into the center of fabrication and as a consequence demands novel interfaces that lower the entry point for fabrication [15, 60].
In a parallel movement, the surfaces and objects to be fabricated emerge from being passive towards becoming interactive [123], which requires novel fabrication processes [93, 92, 91, 6, 122, 19, 30] and accessible fabricators [33, 63, 74, 126].

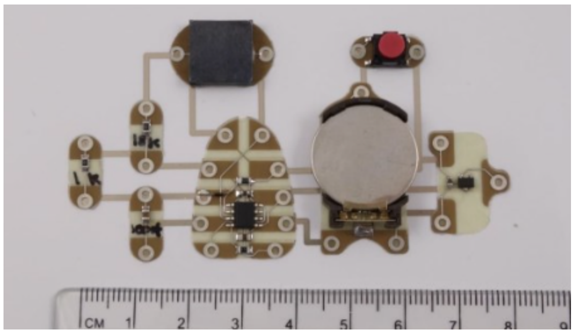
In the following sections, we provide a background on personal fabrication. Then we present fabrication approaches for interactive surfaces and objects.

3.2.1 Digital and Personal Fabrication

Neil Gershenfeld historically aligned digital fabrication to digital communication and computation. Digital fabrication is at its core very similar to digital computation, since it is about reliably symbolizing physical behavior.

Personal fabrication is seen as the *killer application* for digital fabrication by Gershenfeld [15]. He observed that “the real expressive power of machines that make things has remained firmly on the manufacturing side rather than on the consumer side.” To understand this critique, we have to take a look at the manufacturing side: Complicated CAD programs are used to design products, along with machines that are specialized and complex to control. Therefore, machines have been intended to fabricate multiple copies or variations of a single item and thus are often expensive. Both the process of design and the control of machines require experts and are — because of their complexity — out of reach for the unskilled user. This “reduces the machines to produce products for profane consumption." Gershenfeld takes a radically new perspective on this: In his eyes, “fabrication is a fundamental aspect of liberation." The “real expressive power” of machines is then unveiled, if they are available for the individual.

(a) Fast fabrication of printed traces using an off-the-shelf printer filled with conductive silver ink [33].



(b) Circuit stickers contain non-printable electronics and are attached on top of printed traces [25].

Figure 3.3: Fabricating printed electronics in low volume

Bringing fabrication down to the individual has implications.

- Individuals can invent solutions that exactly fit their needs and work in their local context. This changes the process of invention from a top-down approach, in which institutions with big resources solve problems, to a bottom-up approach.
- Anyone can realize his own ideas for the sake of personal expression. He can create products with a market of one.

3.2.2 Interactive 2D Surfaces

Low-cost and fast fabrication of flexible conductive traces is beneficial for quick iterations in prototyping. Previous solutions required expensive and complicated hardware and inks. Kawahara et al. [33] address this issue by demonstrating how a regular off-the-shelf printer filled with liquid silver ink can be used to inkjet-print conductive circuits (see Fig. 3.3a). The ink dries within minutes at room temperature. The traces have a high conductivity ($0.19\,\Omega/\square$), and can be printed in high resolution (600dpi). The authors demonstrate the capabilities with a number of applications: They show a flexible circuit board consisting of pre-fabricated components with printed traces. Printed input sensors are demonstrated with a single touch sensor pad.

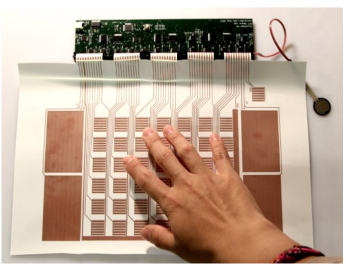
Attaching pre-fabricated electrical components on flexible conductive substrates is often time-consuming and technically complicated. But it is often necessary, since hardware components such as microprocessors or certain sensors are not possible or not trivial to print. Hodges et al. address this issue with Circuit Stickers [25]. These are attached on top of printed traces and have a pre-defined embedded functionality

Figure 3.4: Midas enables users to fabricate custom-shaped touch sensors [93].

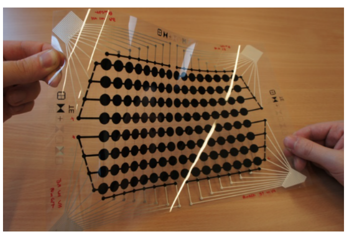
(see Fig. 3.3b). Thus, Circuit Stickers contribute a tangible interface for non-printable functionality. The authors provide a range of Circuit Stickers with varying technical capabilities. This includes stickers for batteries, Hall effect sensors or accelerometers.

Creating custom-shaped input components that fit on an object is often necessary in prototyping applications. But it is a laborious task to digitally design, fabricate and control these components. Midas [93] simplifies the entire process, by providing a pipeline from digital fabrication to physical fabrication (see Fig. 3.4). Paperpulse [80] showed an integrated approach for creating applications based on printed electronics while requiring no programming expertise.

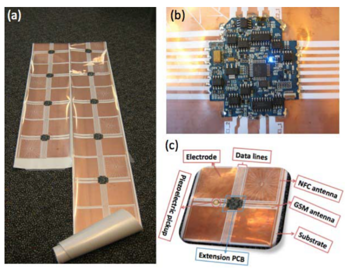
PrintSense [19] followed the philosophy of empowering end-users to fabricate custom touch sensors (see Fig. 3.5a), but focuses on a more sophisticated input sensing technique. Its authors contribute a multi-modal input sensor that is fabricated with an



(a) Multi-modal input on a single layer printed flexible surface [19].



(b) Pyzoflex is a flexible printed pressure-sensitive foil [83].



(c) The scalable printed surface detects users and nearby devices [18].

Figure 3.5: Input sensing for printed surfaces

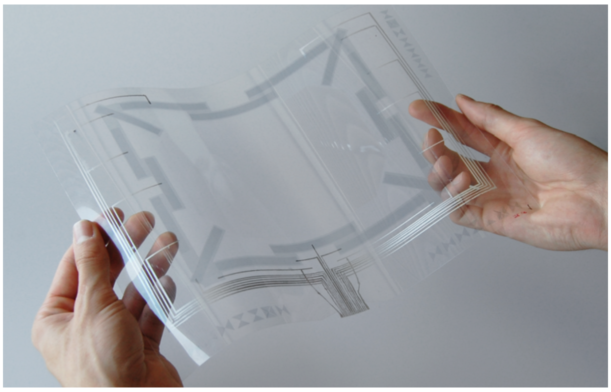


Figure 3.6: FlexSense is a deformable surface that measures its deformation [84].

off-the-shelf printer based on the approach presented by [33]. The sensor can detect pressure, touch, hover and bend actions with just a single-layer print. But due to its simple fabrication, the resolution of pressure was limited to three identifiable states.

A more accurate printed and flexible pressure sensor was presented by Reindl et al. [83]. They present an input device that consists of a thin foil with piezoelectric sensors printed on it (see Fig. 3.5b). Each sensor tile is pressure-sensitive. The sensor sheet consists of four layers that are printed on top of each other. The sensor response is highly linear to force, which allows accurate readings. However, compared to Gong et al., this approach requires multiple printed layers and custom inks, which makes it more time-consuming to fabricate.

Printed electronics is a promising technology for fabricating surfaces of a large size that can be integrated into floors or walls in order to make them interactive. Gong et al. [18] present a first printed, scalable multi-modal sensor (see Fig. 3.5c). The sensor consists of individual tiles, each capable of capacitive and electromagnetic sensing. These make it possible to detect users walking over the sheet.

So far, the work in this section has focused on novel technologies for surface input. Next, we present approaches for printed sensors to detect shape input. These are solutions for detecting the deformation of the sheet itself. Detecting the deformation of the sheet itself has been shown to be useful for many applications [36, 103, 35, 24, 43, 96]. These solutions used optical tracking methods, limiting the mobility of the sheet. To overcome this, Gong et al. presented a printed bend sensor that can measure bending along one axis [19]. While it had the advantage that it required only a single layer to print, the sensing resolution was limited. Reindl et al.

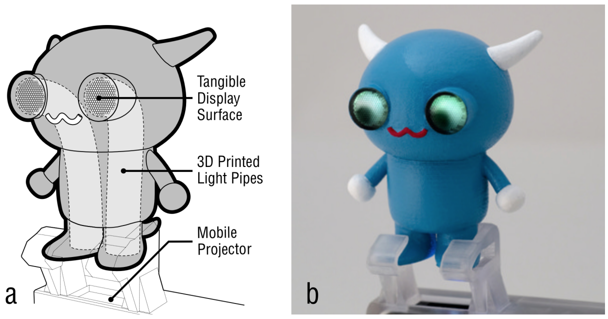


Figure 3.7: Printed Optics makes 3D printed objects interactive with printed light pipes [122].

increased the resolution of deformation by printing multiple bend sensors directly onto the sheet [84]. They demonstrate a foil with a sparse set of piezo sensors printed on them (see Fig. 3.6). They contribute algorithms for reconstructing the complex deformation of the substrates based on the pressure that occurs when the sheet is deformed.

All of the presented approaches require power for sensing and for processing. PaperGenerators [32] presented an energy harvesting technique in which users rub, touch or slide on a printed conductive sheet to generate electricity.

3.2.3 Interactive 3D Objects

Typical fabrication methods for shaped and shape-changeable objects are 3D printing or assembly of multiple components.
3D printing allows production of objects with complex 3D geometry and fine detail. To add interactive functionality to the 3D print, a stream of prior work has proposed sensing and output principles that leverage specific 3D printed (passive) geometries in conjunction with electronic components, which are added after printing:sssss Printed Optics [122, 6] has shown how the combination of 3D printed passive light guides with external display or image sensors can enable touch input and visual output on

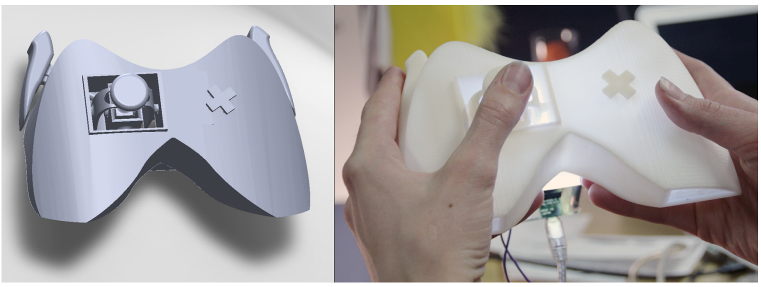


Figure 3.8: Savage et al. presented concepts for using a camera and embedded mirrors to make low-end 3D prints interactive [91].

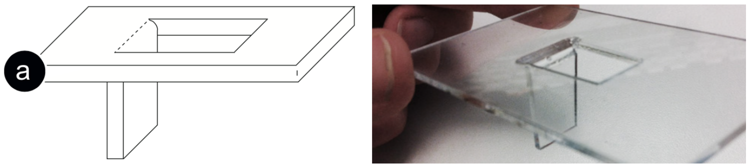


Figure 3.9: LaserOrigami lets users build 3D objects with a laser cutter by bending substrates instead of cutting them [59].

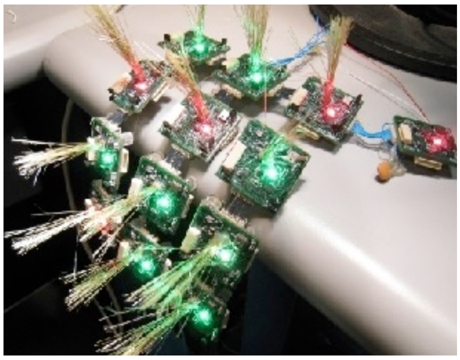
the object's surface (see Fig. 3.7). Sauron [91] auto-generates structures inside a 3D object which, together with manually added cameras and mirrors, enable sensing of user input (see Fig. 3.8). An alternative approach generates cavities inside the object, which can be filled with various materials, including liquids or gases, to enable interactivity [92]. While versatile and well-suited for curved geometries, all these approaches require an inner volume of the object, which is problematic for thin and shape-changeable geometries.

Printing functional electronic components in 3D, along with the 3D geometry, is very challenging for various reasons, including the need for extrudable functional materials, printing in the z-direction and sintering. To date, only conductors and very simple touch sensors can be 3D printed, with conductivities far below and minimal feature sizes far above those reached in 2D printable electronics [44]. A workaround consists of manually adding conductive layers using conductive spray paint, as demonstrated for 3D-printed custom-shaped speakers [30].

Instead of 3D printing, folding was used as a technique to construct a 3D shape out a of 2D surface. Folding of sheets and manual assembly of auto-generated planar building blocks have been demonstrated to be powerful approaches for fabricating passive 3D objects [4, 59]. LaserOrigami [59] shows concepts for using a laser cutter to extend surfaces to 3D objects. This is accomplished by bending parts instead of cutting them (see Fig. 3.9)

Folding has also been investigated extensively as a means for interaction. A stream of research has explored interaction techniques for foldable displays [35, 79]. Moreover, paper-folded 3D objects have been proposed as tangible input devices. ModelCraft [101] allows the user to annotate an auto-generated paper model to modify the underlying digital CAD model. Sketch-a-TUI [121] enables user-folded paper objects to be used as tangible controls on touchscreens. Interactive pop-up books have been realized through added conventional electronic components [77]. Lastly, folded paper

(a) **Building sensate floors out of multiple pressure sensitive Z-Tiles [85].**



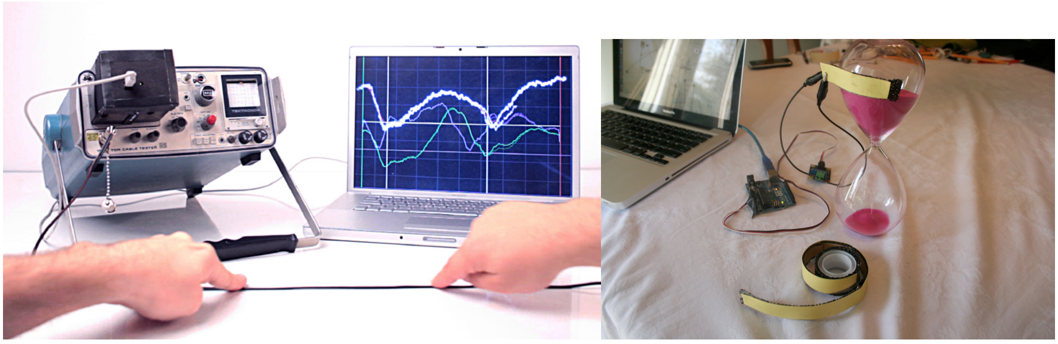
(b) **Multi-modal sensor tiles to create flexible sensate surfaces [55].**

Figure 3.10: Additive shape customization

structures have been actuated with shape-memory alloys to realize animated paper crafts [78, 127] and post-it notifications [76]. All this work has in common that sensing and output is either realized through projection-mapping or by using conventional electronic components, which limits interactivity and foldable geometries.

3.3 Shape-Adaptable Interactive Surfaces

Interactive surfaces of a custom shape have been recognized as being useful for e.g. creating sensate environments [85, 55], interactive objects [98, 50] or novel mobile devices [125, 113]. We identified two complementary streams of research for shape-adaptable interactive surfaces that are both of particular interest for this thesis. The first stream that we will discuss is concerned with adapting the contour of the interactive surface. We divide this work into two styles of contour adaption, which we will present individually: (1) Additive shape creation supports shape customization by combining multiple interconnected active tiles [3, 85, 73, 55]. (2) Subtractive approaches support customization by cutting [124, 27]. Next, we discuss the type of shapes within a geometric perspective. The second stream is about altering the shape of an existing surface. Roudaut et al. used NURBS as a geometric foundation to describe the dimensions in which the shape can be changed [89]. Within the scope of this work, we will show work in which the interactive surface itself alters its shape. Lastly, we show applications for shape-adaptable interactive surfaces.



(a) Applying time domain reflectometry to measure touch on modular surfaces [124].

(b) Touch-sensitive tape that can be cut to a custom length [27].

Figure 3.11: Subtractive shape customization

3.3.1 Additive Shape Customization

The contour of the surfaces is altered by combining multiple sensitive tiles to build an interactive surface.
Z-Tiles [85] focus on creating custom shaped interactive floor spaces (see Fig. 3.10a). To achieve custom shapes, the authors propose connected pre-fabricated sensor tiles, which form an ad-hoc network when connected. Each tile is capable of measuring pressure and propagating this information through the tiled network.

Chainmail [55] follows a very similar approach: Sensate modules are interconnected to form a sensate surface. Each module is capable of sensing pressure, sound, proximity/airflow, light, temperature and bending (see Fig. 3.10b). Unlike Z-Tiles, it uses flexible wires as interconnectors. This integrates to a partially flexible surface.

Gong et al. presented a tiled sensate surface with tiles that consist of a small rigid part and a large sensate flexible part [18] (see Fig. 3.5c). It has the advantage that particularly large surfaces can be made interactive easily.

Streitz et al. presented ConnecTables [111] as part of their Roomware concept. ConnecTables are movable mobile rigid displays that can be connected in an ad-hoc fashion to form a bigger display. Similarly, Siftables [54] used close physical proximity to connect multiple stamp-sized displays. There has also been work on the interaction topologies of how displays are connected with each other. Most notably, Hickley et al. showed gesture concepts for connecting mobile handheld computers [23]. Marquardt et al. contributed concepts for connecting displays based on social distance and social situation [53].

Figure 3.12: Tekscan [113] is a pressure sensor for shoe insoles. It can be cut along the predefined silver lines to fit the size of the foot.

3.3.2 Subtractive Contour Customization

In the subtractive approach, the contour is adapted by removing parts of the shape. Wimmer et al. present a sensor wire (see Fig. 3.11a) that is adapted in shape by cutting it to the desired length and laying it out using a space-filling curve [124]. This concept has been recently applied for printed surfaces [33]. While this elegant solution supports virtually any sensor shape, it is limited to single-touch input and requires a complicated sensing technology, time domain reflectometry.

Holman et al. presented a sensor tape (see Fig. 3.11b) that is based on resistive sensing [27]. It acts as a linear potentiometer and supports single touch recognition. The tape can be cut to adapt its shape.

Both works force the user to create a spatial layout out of a single wire with custom length. Tekscan presented a different approach in which the user directly shape-adapts the interactive surface. They presented a shoe insole [113] that can sense pressure and can be cut to fit to the size of the foot. The sensor has predefined sizes to which it can be cut (see Fig. 3.12). The degree of shape adaptation is therefore limited.

Tekscan integrates the arrangement of the sensors with the contour of the surface. Villar et al. present an approach in which the shape of the contour of the surface is independent of the components that are attached on it [117]. The user can shape-adapt an intelligent foam mat and populate it with standard rigid user interface components. The foam mat automatically connects these components together. However, the flexibility of the foam mat itself is limited and the interface components are rigid and non-flexible.

Additive	**Subtractive**
Connecting tiles can be complicated [55, 18]	Cutting is easy to perform [124, 113, 27]
Large areas can be covered [85, 18]	Covering large areas is complicated with a single wire [124] and the variation of shapes are limited [113]
Large variety of sensing modalities [55, 18]	Only single touch [124] and pressure [113]
Individual tiles can be expensive [55]	Sensing surface can be made cheap [124]
Surface is only partially flexible [55] or rigid [85]	Sensor surface is highly flexible [124, 113]
Surface has no sharp contours [55, 18, 85]	Contours can be made sharp [113]

Table 3.2: Additive vs. subtractive shape creation

Additive and subtractive shape creation have different characteristic properties, which we extracted from the related work. Table 3.2 shows them alongside.

3.3.3 Discussion on the Geometric Aspects

The purpose of this section is to highlight the geometric properties of shaped interactive surfaces. This includes the geometric space of shaped interactive surfaces as well as the shape space of shape-adaptable surfaces.

Static-shaped interactive surfaces: Traditionally, interactive surfaces are not shape-adaptable and offer only a rectangular shape. This has a technical benefit: The wiring of the internal sensor or display can be done efficiently in a matrix-style fashion. DiamondTouch [9] was among the first multi-touch tables introducing a wiring pattern that looks like many displaced diamonds but is essentially a variation of the matrix. Rekimoto's Smartskin [82] introduces a novel sensing approach for matrix-based touch sensors, namely projected capacitance.
The matrix-style touch sensor was also applied for flexible PCBs. Mouse 2.0 [116] augmented the surface of a mouse with a multi-touch sensor to make it interactive. Song et al. [98] attached a rectangular multi-touch sensor on the grip area of a pen and presented interactions for different grasps (Fig. 3.13a). FlexAura [50] also augmented the grip of a pen but used optical sensing to include the space above the surface as well (Fig. 3.13b).

Convex Polygons: Gong et al. overcame the fixed size of the rectangle by present-

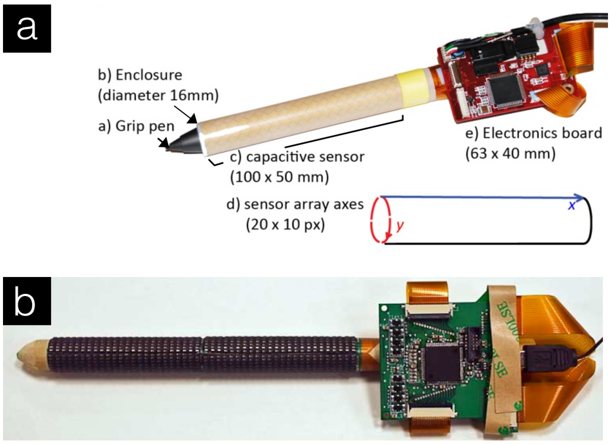


Figure 3.13: Flexible rectangular multi-touch sensor wrapped around a pen to (a) detect grips and gestures on the surface [98] and (b) above the surface [50]

ing a multi-modal sensor consisting of multiple tiles [18]. The tiles can be stitched together by the user in one dimension in order to vary the width of the rectangle. However, the sensor does not support multi-touch input.

Monotone Polygons: The flexible shoe insole sensor by Tekscan [113] can be cut into polygons that are a small number of predefined variations of the original sensor. All of these sensors have a monotone shape.

Arbitrary Polygons: The author did not specify the sort of polygons that can be created with Z-Tiles [85]. We can assume that a large variety of arbitrary polygons can be created. Chainmail [55] and Gong et al. [18] use square tiles which are interconnected. Thus, Chainmail can expand in two dimensions, which enables sensor grids and can approximate a large range of simple polygons. But the size of an individual tile determines the size of the smallest polygon. Very large interactive polygons are effectively inefficient to create. The single-wire touch-sensor by Wimmer et al. [124] can be formed into virtually any shape. But the layout strategy for the sensor can be highly complex and is individual to the polygon.

3.3.4 Shape Changing

Until now, we have discussed geometries for interactive surfaces and showed principles for how the shape can be adapted by altering the contour. In this section, we present a complementary stream of work, in which the shape of the surface is actuated and can be programmatically altered. Rasmussen et al. conducted a review of the work on

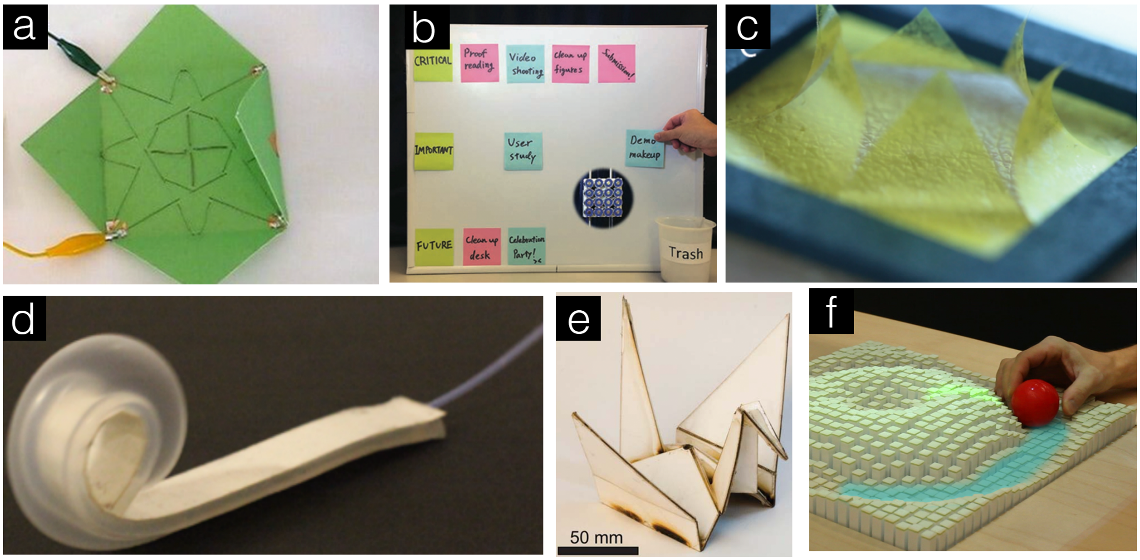


Figure 3.14: Different techniques for shape changing presented in HCI. Images (a)-(f): [78, 64, 126, 125, 12, 13].

shape-changing objects [81]. We will focus on actuated thin-film interactive surfaces. Roudaut et al. [89] systematized the space for flexible self-actuated mobile devices by introducing the term *screen resolution* to describe the dimensions of actuation. Qi et al. presented actuation concepts for shape changeable interactive paper folds using shape memory alloys [78, 77] (Fig. 3.14a). There, the user tailors a flexinol wire to fit the paper, and it is heated up to actuate the structure. Based on the same technology, MorePhone [17] studies notifications for an actuated mobile e-ink display. Probst et al. [76] provide actuated sticky notes that can give physical notifications about changes in the digital realm. Saul et al. show folded paper devices with manually attached flexinol wires [90].

Ogata et al. [64] used magnetic actuation for moving post-it notes on a surface. Small magnets are printed on the back of a post-it note. Behind the surface, electromagnets move the post-it note (Fig. 3.14b). Yao et al. presented bioLogic [126], which is an actuator based on the living *Bacillus subtilis natto* cell that reacts to humidity (Fig. 3.14c). Pneui [125] is a technology based on pneumatically-actuated soft composite materials. Depending on how the material is patterned, it can actively change its shape (Fig. 3.14d). Similarly, Sticker Actuators [63] are computer-controlled attachable planar actuators that change in volume once air is inserted. Inflatable Mouse [37] is a volume-adjustable mouse that can be inflated during use and flattened for transportation. Felton et al. [12] presented shape-memory composites that can fold themselves. They demonstrate these principles with a self-folding robot. Shape memory polymers (e.g. stretched polystyrene) are

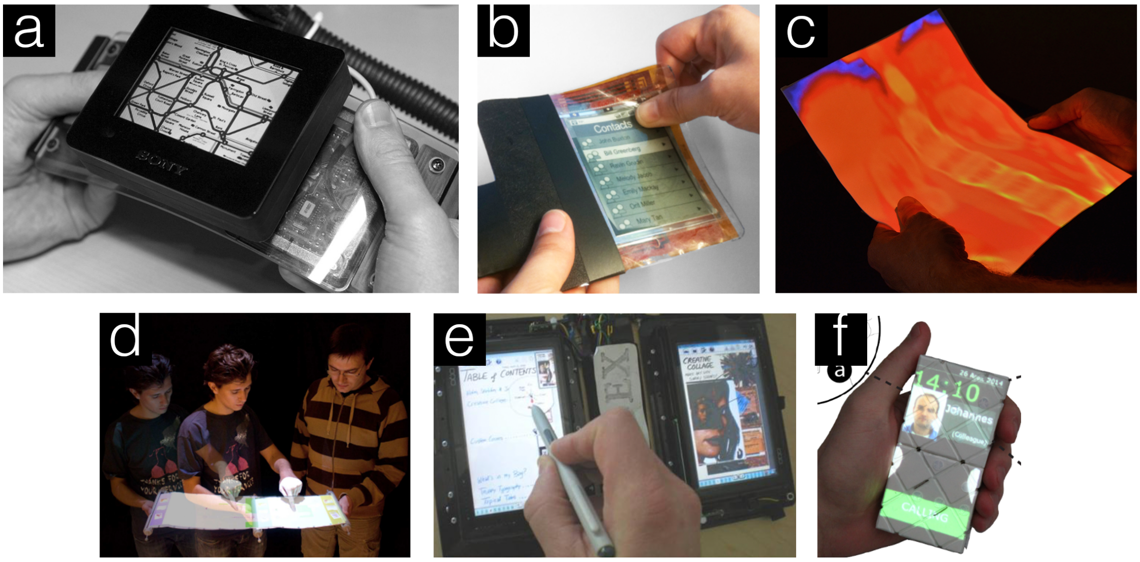


Figure 3.15: Applications of mobile interactive surfaces. Images (a)-(f): [96, 40, 103, 105, 24, 79].

used to actuate the shape. The actuator responds to heat, which can be locally generated by an underlying printed structure (Fig. 3.14e). inForm [13] is a statically mounted shape-changing display. Its UI dynamically adjusts to the shape change. It allows the user to interact by providing dynamic physical affordances or provides guidance to manipulate physical objects by actuating them (Fig. 3.14f).

3.3.5 Applications for Shape-Adaptable Interactive Surfaces

Flexible interactive surfaces are shape-adaptable by default. Like regular paper, they can be structurally deformed by e.g. bending or flexing, or resized by rolling and folding. Mollerup [57] provides a good insight into the space of deformation. These physical deformations as such are often not novel and are well-known from paper. But due to their ubiquity, they were good candidates for use as ways to interact with the digital realm. In the following, we give an overview of the work that has been done:

Mobile and Wearable Context

Schwesig et al. [96] presented interaction techniques for a bendable mobile device (Fig. 3.15a). Bending was found to be a means for continuous and discrete interaction. For example, it was shown in the context of physical map zooming or for text entry. Paperphone [40] is a flexible phone (Fig. 3.15b). The authors studied mappings for physical deformations and basic digital commands. Steimle et al. [103] contributed

Flexpad, an interactive system that features a highly deformable interactive surface, which is spatially-aware (Fig. 3.15c). This enables highly expressive interactions that go beyond the deformations themselves by integrating them with the physical space that they take place in. Song et al. presented a pen with a multi-touch sensitive grip [98]. They contributed the detection of different grips and gestures. An actuated post-it note [76] was presented by Probst et al. The post-it bends in order to reflect a change to a digital data item.

Lee et al. were among the first to explore the combination of shapes as a fan or a paper roll for interaction [43]. Khalilbeigi et al. [36] provided interaction concepts for a future mobile device that could be rolled up for transportation and rolled out to provide a large interaction space when needed. They showed that rolling is not only useful for resizing the surface but that rolling itself is a valuable interaction technique for navigating in maps or in data. We extended this concept to collaborative work [105] (Fig. 3.15d). The device is held collaboratively by both users. Since it is rollable, users can dynamically adjust their social distance according to the situation. In addition, the device automatically detects the positions of users around the device and adjusts the orientation of the contents accordingly.

Hinckley et al. provided insights into individual and collaborative work, but for foldable devices. They presented Codex [24], a dual-screen tablet computer, which can be folded in the middle. Hinckley et al. also contributed relationships between the physical configuration of the device and the support of individual and collaborative work (Fig. 3.15e). Khalilbeigi et al. [35] researched a related device type. They showed that the physical act of folding is a beneficial interaction for navigating in digital content and adjusting digital controls. Ramakers et al. presented Paddle [79], a mobile device concept with pre-defined folds on the surface, which allowed it to remain flexible and also transform its shape (Fig. 3.15f). Lastly, Girouard transferred the concept of stacking of physical documents to flexible displays [16].

Crafting

Shape-adaptable interactive surfaces have been used for interactive crafts. Qi et al. actuated [78] paper crafts using shape memory alloys and paper crafts with visual output in low-resolution LEDs [77]. ModelCraft [101] uses passive paper crafts in combination with a digital pen as an input device for CAD design tools. Sketch-a-TUI [121] uses folded paper tokens with hand-drawn circuitry as an input device for touch screens.

Interactive Surfaces of a Custom Shape and Size

Organic user interfaces [26] present the concept of interactive surfaces that are non-planar and of a custom shape so they can e.g. fit the object that they are integrated into. Using projection mapping, Lee [43] explored different form factors for rollable and foldable surfaces (e.g. an interactive fan or paper roll). Xpaaand [36] presented a device concept for a rollable mobile device. Yeh et al. [87] presented the combination of large static printouts together with a dynamically projected interface. Mouselight [100] and Penlight [99] use a mobile projector to create spatial dynamic overlays on top of static paper printouts. The A-book [120] provides location-based overlays using a PDA, which is placed on top of the printout by the user. Pacer [46] tracks the printout using a mobile phone and provides dynamic information on its displays. DisplayBlocks [75] are a set of cubic displays for multi-perspective and tangible data exploration. inForm [13] is an actuated surface that provides dynamic affordances (Fig. 3.14f).

Interactive Surfaces of Custom Resolution

Custom shaped interactive surfaces provide only limited visual output. Circuit Stickers [25] are an end-user friendly way to add LEDs to printed circuits. Alternatively, LEDs can be manually integrated as done in [77]. Higher resolution interactive surfaces use off-the-shelf hardware components [40, 17, 89] or projection mapping [36, 79, 103, 105].

3.4 Discussion and Conclusions

Having presented a body of work about printed electronics, fabrication and shaped interactive surfaces, we want to interweave these with the requirements that were presented in Chapter 2. Therefore, Table 3.3 shows which parts of the requirements have been addressed. Next, we discuss the requirements in the context of the related work.

R1: Custom Shaped Display Components: Visual output on thin-film surfaces requires highly sophisticated technical equipment to offer flexibility for the designer in terms of shape, resolutions and substrates. This forces the designer to use rigid LEDs that have to be manually attached to the substrate and offer only a low resolution. Otherwise, the designers must use off-the-shelf components [25, 77], which are only available in a small set of shapes and come in standardized resolutions.

Requirement		Supported by Related Work	Our Contribution
R1	Custom shaped display output	-	Digital fabrication pipeline for custom touch-displays
R2	Highly interactive 3D objects	[91, 92, 6, 122]	Wide variety of interactive controls for folded objects
R3a	Creation of flexible shapes at design time	[93, 33, 91, 122, 101, 80]	More degrees of freedom in terms of shape and interactivity
R3b	Creation of flexible shapes at use time	-	Wiring topologies for a flexible multi-touch sensor that is resistant to cuts with physical tools
R4	Support for various materials	-	Material explorations for embedded printed interactive surfaces
R5	Custom spatial distribution of interactivity	[93, 19, 80]	Rich ways for the end user to add custom interactivity to a location of choice

Table 3.3: Matching the requirements from Chapter 2.3 with related work

This constrains the creative freedom for combining form and interactivity. Novel fabrication processes should enable the designer to create printed visual output in an integrated and easy-to-control manner that does not require sophisticated equipment.

R2: Highly Interactive 3D Objects: 3D printing offers the designer great freedom in terms of the shape of the object. But interactivity is technically complicated to integrate into a printout, since it requires sophisticated functional inks. Therefore, previous work made use of printed passive pipe structures [91, 92, 6, 122] to bypass that problem. Printed electronics is quite different from 3D printing. There is a large variety of functional inks and solutions for printing conductive traces and components on thin-film sheets. But shapes are currently limited to 2D. This opens up an exciting possibility for merging the best of both worlds by creating highly interactive and individual 3D objects and using printed electronics as a technical foundation.

R3a: Creation of Deformable Shapes at Design Time: Examining the related work reveals a considerable body of work that follows the philosophy of first digitally designing the shape and its interactivity and then physically instantiating it [93, 33, 91, 122, 101, 80]. The approaches differ in terms of their support for the fabrication process and later usage. On one end of the spectrum are Midas [93] and PaperPulse [80]. They support the user during the digital design, the physical fabrication process (by e.g. generating instruction manuals) and in using the interactive surface. For example, in PaperPulse the user can express interactive behavior using a simple “if this than that” logic. Slightly less support is offered by Sauron [91], since the logic of each printed widget needs to be programmed manually. On the other end of the spectrum are Kawahara et al. [33] and Willis et al. [122]; they do not provide support beyond the digital design of the shape.

Much of the work addresses product developers and makers as potential users. A common methodology for developing novel products is iterative design. Except for Modelcraft [101], none of the approaches feed information about the usage or the shape itself back into the design tool to improve the next iteration.

R3b: Creation of Deformable Shapes at Use Time: Shape-adapting interactive surfaces in an ad-hoc fashion is valuable for users, because of the short fabrication time and because only a low technical skill level is required. Currently these ad-hoc approaches require rigid components, which are attached together using technical connectors. Single wire sensors [124, 27] address this problem and they can be flexibly laid out in space. However, their resolution is limited to single touch and in practice it is complex for end-users to cover a 2D space with a single wire sensor. Other solutions [9, 82, 116, 98, 50, 18] that provided a flexible surface were highly constrained in terms of the possible shapes. Our requirements call for novel sensor surfaces that can be modified in an ad-hoc fashion, requiring only low technical expertise (e.g. by cutting the sheet to the appropriate size), but they should also provide a high spatial resolution.

R4: Support for Various Materials: The support for various materials in the context of printed interactive surfaces is limited. Recent advances in printed electronics showed first results for printing on regular paper [114]. Kawahara et al. used photo and PET paper. Although it did not apply methods from printed electronics, PneUI [125] showed a material composite based on silicone that is stretchable and contains liquid conductors. However, the available set of printable materials contrasts with the rich set of materials that are used for surfaces and objects. For example, previous work did not embed interactive surfaces into materials such as stone, wood or metal.

R5: Custom Spatial Distribution of Interactive Areas: From a fabrication perspective, Midas [93], PrintSense [19] and PaperPulse [80] enable the user to spatially distribute interactive areas on a flexible sheet. While these solutions provide a good support for the digital design of input sensors, the options for custom visual output are limited. For example, PaperPulse only allows the user to attach rigid LEDs at user-defined locations. In this thesis, we provide approaches that enable the user to design and fabricate custom shaped visual output on flexible 2D surfaces (Chapter 4) and folded 3D objects (Chapter 5).

In this chapter, we reviewed previous work that is related to this thesis. We investigated three areas of research: printed electronics, digital fabrication and shape-adaptable interactive surfaces. Then, we connected the work to the requirements that were presented in Chapter 2. In the next three chapters, we address these requirements. The first presents a novel digital fabrication approach that enables end-users to fabricate custom-shaped, interactive and flexible touch-displays. It addresses the requirements R1, R3a, R4 and R5. We extend this and provide a fabrication technique for folded highly interactive 3D objects to address R1, R2, R3a, R4 and R5. Lastly, we present a printed multi-touch sensor foil that can be shape-adapted using regular tools such as scissors while remaining functional. The fact that it can be adapted at use time addresses R3b and R4.

Chapter 4

PrintScreen: Fabricating Highly Customizable Thin-film Touch-Displays

As seen in the requirement analysis (chapter 2) and related work (chapter 3), there is a need for custom shapes visual ouptut on flexible 2D surfaces. This is in stark contrast to how displays are traditionally fabricated. Current fabrication concepts require experts to design displays and highly sophisticated machinery. In this chapter, we show a new empowering technology called "PrintScreen" for the light-weight fabrication of thin-film touch-displays .

The platform proposes a novel perspective on displays: instead of buying an off-the-shelf display, the designer can create a custom digital design, which meets the specific demands of the application, and then simply print the display. Printing customized flexible displays empowers makers and designers to create customized interactive print products, digital signage, smart objects, personalized computing devices and crafts with embedded display. For HCI researchers and practitioners, this is a powerful enabling technology for mobile, wearable and ubiquitous computing interfaces. It enables rapid and high-fidelity prototyping of functional HCI devices with embedded displays of highly custom shapes, on deformable and on unconventional materials.

PrintScreen is an enabling technology for digital fabrication of customized flexible displays using thin-film electroluminescence (TFEL). It enables inexpensive and rapid fabrication of highly customized displays in low volume, in a simple lab environment, print shop or even at home. We show how to print thin (120 μm) segmented and passive matrix displays in greyscale or multi-color on a variety of deformable and rigid

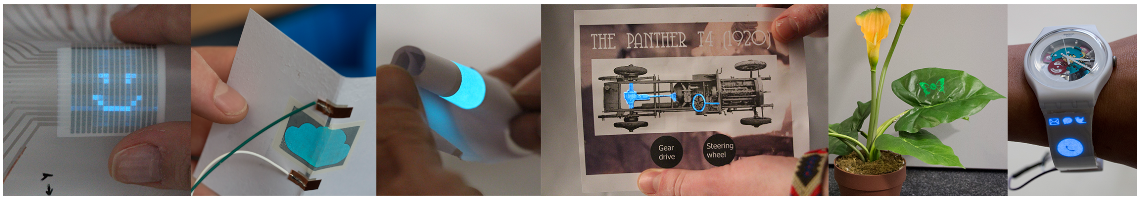


Figure 4.1: PrintScreen contributes a digital fabrication approach to enable non-experts to print custom flexible displays. They can be fully folded or rolled and enable manifold applications in ubiquitous, mobile and wearable computing.

substrate materials, including PET film, office paper, leather, metal, stone, and wood. The displays can have custom, unconventional 2D shapes and can be bent, rolled and folded to create 3D shapes (see Fig. 4.1). We contribute a systematic overview of graphical display primitives for customized displays and show how to integrate them with static print and printed electronics. Furthermore, we contribute a sensing framework, which leverages the display itself for touch sensing. To demonstrate the wide applicability of PrintScreen, we present application examples from ubiquitous, mobile and wearable computing.

Based on a holistic five-dimensional view on customized displays, we present the following main contributions:

1. We present *two methods for non-expert printing* of customized thin-film displays, using either screen printing or conductive inkjet printing. The approach is rapid, inexpensive, and does not require much hardware nor technical knowledge. Despite the restrictions stemming from manual fabrication, the display features a high luminance, is only 120 µm thick, bendable, fully rollable, and even foldable at arbitrary positions. It can contain custom-defined high-resolution segments (resolution of contours comparable to 250 dpi laser print) and/or a low-resolution passive matrix (up to 30 pixels per inch). Each segment or pixel can have a color defined at design-time from a wide palette of possible colors. At run-time, it has adjustable brightness intensity. We show that the display can be printed on a *large variety of substrates*, such as paper, plastic, leather or wood, making it ideal for mobile, embedded and wearable applications. PrintScreen can be used to fabricate displays of *irregular and unconventional shapes*, including 2D shapes, folded 3D shapes and adaptable shapes.

2. We propose a digital design approach for displays, which is based on conventional 2D vector graphics. We contribute the first systematic overview of

display primitives for user-printed displays, which act as basic building blocks in the graphical design. Moreover we show how to integrate printed display primitives with static printed artwork and with printed electronics.

3. We contribute a *sensing framework*, which allows using the printed TFEL display itself for a variety of input sensing. We demonstrate this principle for integrated touch sensing.

To demonstrate how PrintScreen can be used and to show its wide applicability, we present five example applications from ubiquitous, mobile and wearable computing. Results from a technical evaluation show that the displays are bright and very robust to bending and folding. We conclude by discussing benefits and limitations of PrintScreen.

4.1 Background in Thin-film Display Technologies

Organic light emitting diodes (OLEDs) and electrophoretic displays (electronic paper) can be printed on flexible substrates. Both technologies enable high-resolution displays, in addition OLED displays support a wide color spectrum. However, they are still complicated to produce. For instance, an OLED display typically requires six layers [38]; moreover it is very sensitive to oxygen during fabrication and requires proper permanent sealing during use. Therefore, a high-end print lab environment is required. While rollable and fully foldable OLED and electronic paper displays have been demonstrated as prototypes, they are not commercially available yet.

Thermochromic [49] and electrochromic [2] displays are less complicated to manufacture. However, they have very long switching intervals and precise control of thermochromic displays is challenging, as the ink is influenced by the ambient temperature. Electroluminescent (EL) displays are very robust, have fast switching times and a long lifetime of up to 50,000 hours [20]. Therefore the technology is often used for lighting applications [14] and fabricated light panels are commercially available[1]. Inspired by [14], we propose electroluminescence for custom-printed displays. The technology, a simple form of OLED, is based on phosphoric inks, which act as luminescent material. The print process requires only 4 layers [38]. Recent chemical advancement allow for inks that can be easily processed and need low curing temperatures. EL displays require higher AC voltages but very little current to operate. Previous work proposed creating simple EL displays by cutting

[1] http://www.oryontech.com

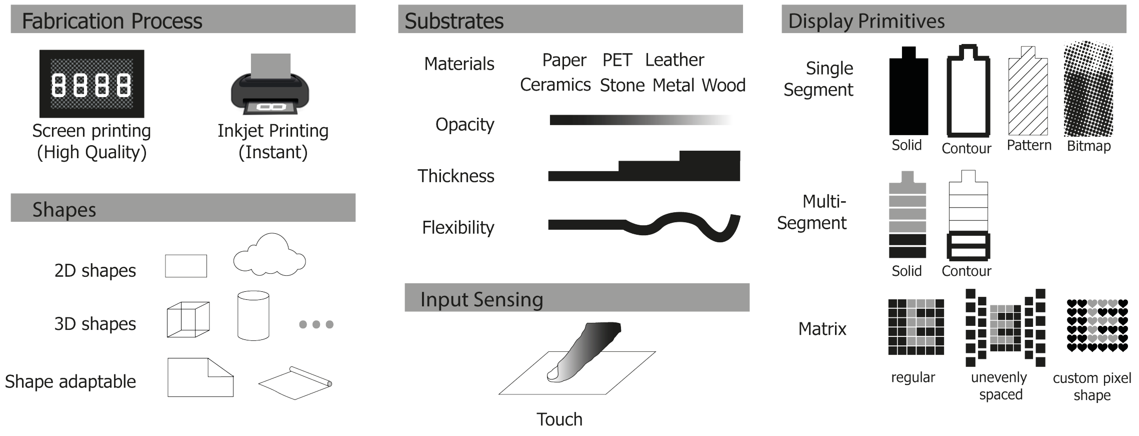


Figure 4.2: Five-dimensional design space for digital fabrication of customized displays

out segments from an EL film [1]; in contrast, our approach relies on high-resolution printing and therefore enables fabrication of a much wider spectrum of displays.

4.2 Design Space Of Customized Displays

Custom-made displays open up considerably more degrees of freedom for the design than off-the-shelf displays. We identified five key dimensions for digital fabrication of customized displays, which systematize the design options. This section provides an overview of these dimensions, which form the foundation of the PrintScreen platform. The design space is illustrated in Fig. 4.2.

4.2.1 Fabrication Process: How to Print

We propose a digital fabrication approach for production of customized displays. The designer generates a digital model of the display and then prints this model. Ideally, printing is as instant and easy as sending a document to an office printer. This would enable prototyping with rapid and many design iterations. We introduce an instant fabrication process based on conductive inkjet printing, which comes close to this ease of fabrication. Moreover, we propose a second fabrication approach, which requires screen-printing on a beginner's level. While it takes longer to fabricate a display, it is of higher quality and supports the full set of substrate materials, display primitives and sensing modes presented in this chapter.

4.2.2 Substrate Materials: On What to Print

Customized displays may be printed on various materials that vary in thickness, flexibility, texture and opacity. PrintScreen supports many substrate materials, including highly deformable and foldable office paper, transparent or nontransparent PET film, leather, wood, ceramics, stone.

4.2.3 Display Primitives: What to Print

Customized displays offer a large variety of design options regarding the display contents, far more than the regular matrix which one would intuitively think of. If contents are known at design time, segmented and multi-segmented displays are a compelling option. They feature very sharp contours and homogeneous fill, even if printed in large sizes, while nevertheless being easy to control. In addition, we introduce segments that feature an arbitrary bitmap pattern which is defined at design-time. For very dynamic applications, matrix displays are the preferred option. PrintScreen allows for printing conventional matrices in a custom resolution, but adds options for customization by offering unevenly spaced matrices and pixels in custom shapes.

4.2.4 Display Shapes: What Form Factors are Possible

A key question for any application is the size and shape of the display. With off-the-shelf displays, the designer has relatively little choice. Non-rectangular outlines, extreme aspect ratios, curved or 3D shapes are typically not available. However, such non-standard shapes are important to make an embedded display fit within an object or the physical environment. PrintScreen offers the designer a much higher degree of design flexibility. It supports custom 2D outlines; moreover it enables custom 3D shapes, which are created by bending and folding. Moreover, displays can be made shape-adaptable and resizable, using bending, folding or rolling, but are not stretchable.

4.2.5 Integrated Input Sensing: How to Interact

User input is a key property of interactive display surfaces. We contribute a generic platform for sensing of user input, which is directly integrated with the printed display. As examples we demonstrate touch input.

In the following main part of the chapter, we will discuss each of these dimensions.

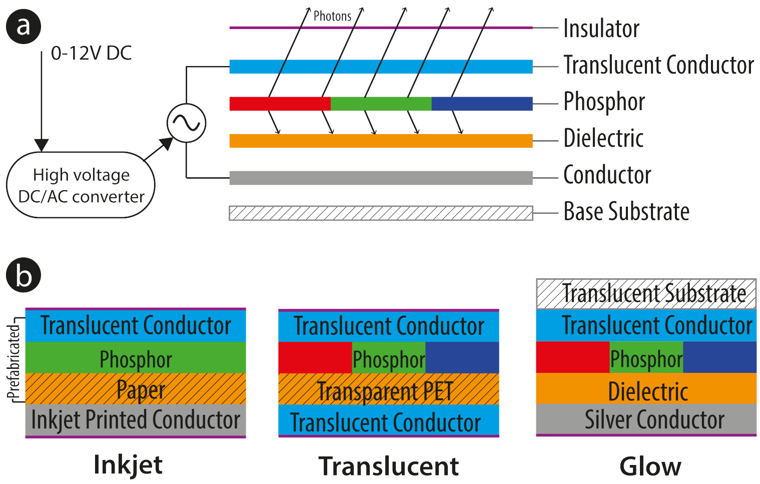


Figure 4.3: a) Composition of the printed layers of an electroluminescent display: Silver Conductor (C2131014D3, 100m Ω/□), a barium titanate based dielectric (D2070209P6), phosphor (e.g. C2101125P4) and a PEDOT based translucent conductor (D2070209P6, 500-700 Ω/□). b) Variations of the standard structure to create translucent displays, display glowing through materials or inkjet-printable displays.

4.3 Fabrication Process

We contribute two approaches to allow non-experts to fabricate customized thin-film electroluminescent displays: a high-quality and an instant process. Both are easy to learn and perform for non-experts and require only off-the-shelf tools and consumables.

4.3.1 Printed Electroluminescent Displays

Thin-film electroluminescent displays actively emit light. A segment of a TFEL display consists of two overlaid electrodes, which act as a capacitor. Inside the capacitor is a layer made of phosphor and a dielectric layer. If a high voltage, low current AC signal is applied, the phosphor emits photons (see Fig. 4.3a). TFEL displays are used in many commercial products, e.g. as backlight for car dashboards.

4.3.2 Digital Design

The designer of the display first creates a digital design in a standard 2D vector graphics editor, such as Adobe Illustrator. Each segment or pixel is created as if it was ordinary visual artwork, using the application's tools for creating lines, polygons, text, fills, etc. Hence, designing an interactive display is pretty much comparable to

Figure 4.4: Dual sided print on office paper

designing conventional 2D graphics.

For screen printing, the designer generates four adjacent identical copies of the design - one for each print layer (see Fig. 4.3). If segments and pixels shall be printed in more than one color, one more layer is added for each additional color. Laying out the copies adjacently allows to create one single print mask that contains all print layers, making screen printing cheaper and faster. For inkjet printing, only one copy is required. Next, the designer lays out the wires that are required for controlling the segments. The minimum width is 300 microns. On the first copy (bottom electrode), each segment is connected with an individual input pin. For screen printing, all segments on the fourth copy (top electrode) are connected to a shared ground pin. Alternatively a grid of segments or pixels can be wired as a matrix.

4.3.3 Screen Printing for High Quality

For screen printing, we used off-the-shelf equipment for hobbyists (approx. 200 €). We follow a standard multi-layer screen-printing process [10], which is commonly used for printing on paper or on fabrics and can be easily learned by non-experts. Each layer of the display stack is printed successively, from bottom to top. Details on the inks, available colors, mesh density of the screen and the instructions of use can be found in [20]. For multi-color displays, two or more layers of differently-colored phosphor are printed. Finally, the top layer is insulated with acrylic insulating spray (dielectric strength 80kV/mm). Overall, the display adds 110 µm to the substrate. We successfully printed a display on a 10 µm thick PET film (Gwent, F2111117D1), resulting in 120 µm as the minimal thickness of the final printed display. To create a dual-sided display (see Fig. 4.4), the same process can be repeated on the reverse side of the substrate.

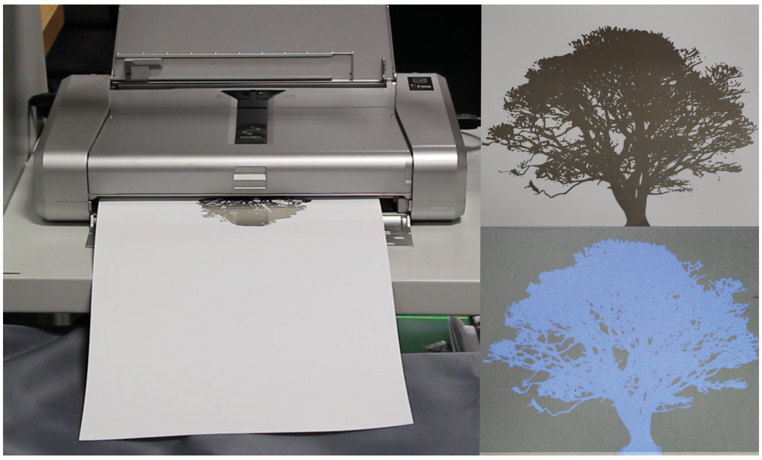


Figure 4.5: Instant inkjet printing. A printed electrode (left, upper right) is illuminated (lower right).

Segments can be printed in a resolution of up to 30 lines per inch (lpi). As a rule of thumb, this corresponds approximately to 60 pixels per inch (ppi). For comparison, a conventional office laser printer has between 35 ppi (300 dpi) and 75 ppi (600 dpi). We use printed guidelines to improve inter-layer alignment. However, the manual printing process introduces an offset between individual layers. We analyzed 10 display samples and measured the maximum offset between individual layers. We found the designer can ensure the full segment be functional by enlarging the top and bottom electrodes as well as the dielectric by 300 µm to each side.

Printing of the application examples presented in this chapter one person between two and four hours. The time depends not on the complexity of the display contents, but on the display size and the number of different colors. The cost of consumables for printing a completely covered A4-sized display is approx. 2 € for the screen mesh and 19 € for the inks. Many applications require segments only on some locations on the substrate, which can further reduce cost quite considerably.

4.3.4 Conductive Inkjet Printing for Instant Fabrication

The second fabrication process ensures instant fabrication, which is important for design iterations in rapid prototyping. No screen print equipment is required. However, it offers fewer design options.

The designer uses a prefabricated display film (Fig. 4.3b and Fig. 4.5). This film contains all printed layers except the bottom electrode. It consists of a sheet of coated paper (Mitsubishi NB-WF-3GF100), which acts as substrate and dielectric. On top of it, a fully filled layer of phosphor (in one color) and a fully filled layer of transparent conductor is printed. This film can be fabricated in bulk using screen printing, as describe above; in the future a paper manufacturer could make it commercially available for purchase.

The designer uses conductive inkjet printing [34] to print the digital design (aka. the bottom electrode layer) on the reverse side of the prefabricated display film. We use an off-the-shelf, consumer-grade inkjet printer (Canon IP-100) with Mitsubishi NBSIJ-MU10 silver ink. Finally, to seal the bottom electrodes, insulating spray is applied, or a thin layer of dielectric (e.g. office paper) is glued or laminated onto the reverse side of the display.

In the prefabricated film, the top electrode, phosphor and dielectric cover the entire surface. This restricts what types of display can be realized. In particular, the display is unicolored. Only segments, but no matrix can be designed. Segments always have a solid fill, and wires used for tethering the electrodes with the controller light up on the display. Touch sensing is restricted to a single touch contact on the entire display. However, contours and surface patterns can have a high resolution, which is defined by the resolution of the inkjet printer (600 dpi).

4.3.5 Controller

To light up a display segment, the controller applies a high-voltage, low current AC signal between the upper and lower electrodes. The luminance of a display segment or pixel is controlled using pulse-width modulation, a standard method for controlling the luminance of LEDs.

For mobile applications, our prototypical controller uses a small driver IC (Model Durel D356B, sine wave, 220 Vpp, 230Hz to 390Hz). This driver IC generates the high-voltage AC signal from a 1.0-7.0V DC power source. If a higher luminance is required, a stronger 0-12.0V driver IC with a slightly bigger footprint can be used (Model Sparkfun DC12V10M, sine wave, 220Vpp, 800Hz to 3.5KHz). A microcontroller (ATMega2560) triggers optocouplers (MOC3063) for multiplexing the high-voltage signal between display pins.

The TFEL-specific ghosting effect in passive matrix displays can be significantly reduced by using a slightly modified controller design [31], thus further increasing the contrast of the matrix. To interface the display with the controller, we solder

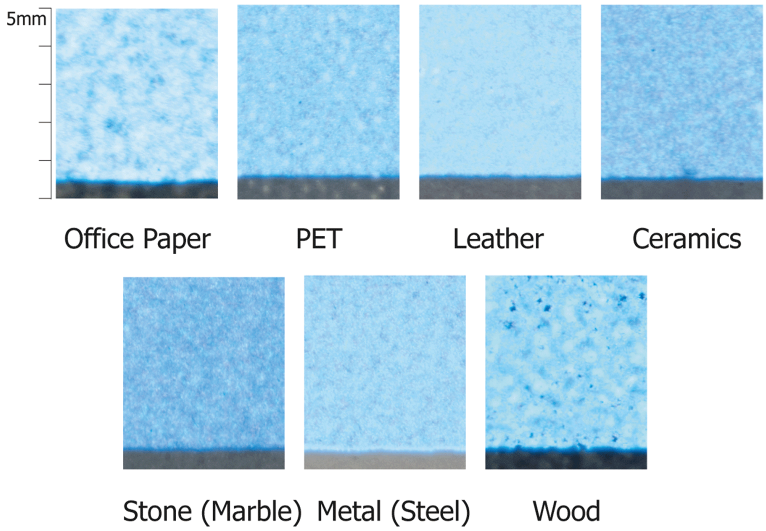


Figure 4.6: Enlarged view of an illuminated segment and its contour, printed on various substrates.

copper wires onto printed pin areas. For a larger number of pins, a flat-ribbon cable and 3M Electrically Conductive Adhesive Transfer Tape 9703 can be used.

The number of output pins of the internal microcontroller restricts our controller to up to 40 separate segments or a 20x20 matrix with passive matrix time-division multiplexing. However, the number of segments or pixels can be substantially increased by using multiplexers to increase the number of output pins of the microcontroller and additional optocouplers to switch high voltages. To keep the size of the controller (currently 5x7cm) small, small optocouplers (TLP266J) can be used.

Despite high voltages, the approach is safe and energy efficient, and even usable for fully mobile applications, because the current is very low and the TFEL display is very energy efficient (2.6 mW/cm^2 in highest luminance, using DC12V10M). The inkjet method uses a thicker dielectric; therefore power consumption increases to 38 mW/cm^2 .

4.4 Substrate Materials

For applications in ubiquitous, embedded and wearable interaction, it is of high importance that the display can be integrated with a variety of materials. Our screen printing approach allows for printing the display right onto the substrate material, integrating it fully with the object and making additional carrier materials and lamination obsolete.

We successfully printed displays on a wide variety of materials, including highly flexible, translucent and transparent materials (see Fig. 4.6). Among them was office paper, PET, leather, ceramics, marble, steel and untreated wood. Figure 4.6 shows that the surface structure, contours and color saturation of an illuminated display segment varies depending on the material; the contours of the printed segment are more or less crisp.

We experienced that successful prints largely depend on the (ideally high) smoothness of the material's surface, leading to a homogeneous display surface and crisp contours. We could not print on extremely uneven surfaces, such as cotton fabrics or suede leather. But we could successfully print on quite porous materials, such as office paper and untreated wood, with some decrease in homogeneity and crisp contours. In our experience the absorbency of the material is not decisive: we could print even on steel and stone in a very high quality.

Since the phosphor inks are not transparent, printing on the material inherently changes its visual properties. To fully hide the display components, the display can be printed on the reverse side of translucent materials. We also successfully printed the display on the backside of translucent materials, such as PET (see Fig. 4.8), paper (see Fig. 4.9), and wood veneer (see Fig. 4.6 lower right).

4.5 Display Primitives

Custom displays come in a large variety, ranging from easy to control segmented displays to highly generic matrix displays. In this section, we contribute a systematic overview of display primitives, structuring known primitives and contributing new ones. This acts as a graphical inventory from which the designer can combine elements to design the visual contents of the display. As PrintScreen applies principles from 2D vector graphics for the digital fabrication approach, the designer has extensive design flexibility and can make use of the powerful tools of modern vector graphics editors.

4.5.1 Single Segment

A single segment features an area or a contour, or a combination of both. A TFEL display homogeneously lights up the element, even over a large surface area. A

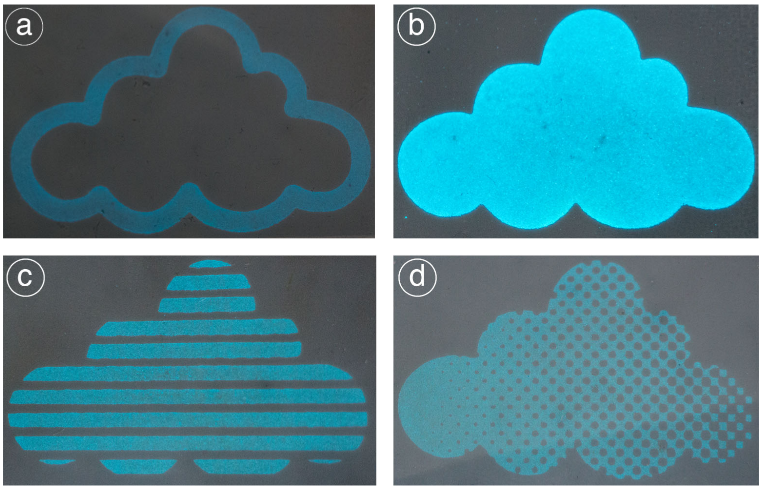


Figure 4.7: Display segments: (a) contour, (b) solid fill, (c) line pattern fill, (d) bitmap fill.

segment features sharp contours, even if printed in large size. A segment can be printed with a high resolution of 60 ppi with screen print and 75 ppi with conductive inkjet print.

We contribute over previous work on display segments by allowing the designer to very flexibly vary the shape, the fill and the contour of the segment in the digital design. This is illustrated in Figure 4.7. The fill can be either empty (not lighting, fully transparent), solid (lighting homogeneously in one color), can contain line art or line patterns as a visible structure, or can show a predefined greyscale bitmap image. For bitmap images, we use half-toning, a method that produces greyscale with one color by printing dots of different density and size on the substrate.

A non-solid fill is realized as follows: like for a solid fill, the top and bottom electrodes and the dielectric are kept solid, covering the entire area of the segment. In contrast, phosphor is printed only at locations that should light up, i.e. lines for line patterns or dots for half-toning. In our experience modifying the phosphor layer is preferable to modifying one of the electrode layers, as the former approach ensures that the full electrode remains conductive, independently of the pattern.

The contour of a segment can be solid or made of a dashed pattern. If realized as two separate electrodes, contour and filled area can be separately controlled. Displayed dots should have a minimum diameter of 300 microns.

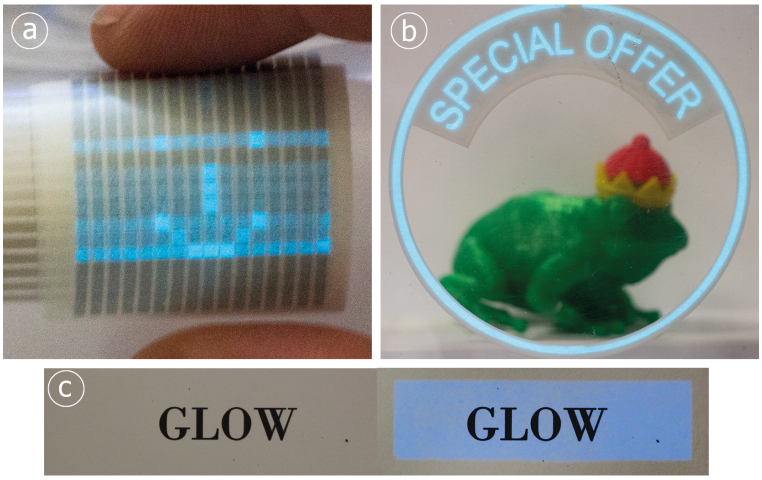


Figure 4.8: a) Passive Matrix Display. b) Translucent displayed on transparent PET film, in front of an object. c) Integration with laser-printed static visuals.

4.5.2 Multi-Segment

A multi-segment splits a single segment up into several sub-segments that can be independently controlled. Examples include a seven-segment display for numerical values or a progress bar. The principles introduced for single segments fully apply to multi-segments.

4.5.3 Matrix

PrintScreen supports printing a regular matrix display (Fig. 4.8a). We print the rows of the matrix as the bottom electrode and the columns of the matrix as the top electrodes. The phosphor layer and dielectric are continuous. Time-multiplexing between rows and columns allows for addressing individual pixels. The designer can define the size of the matrix and the pixel density. The maximum density is defined by the resolution of the screen printing equipment, in our case 30 parallel lines per inch, leading to 30 pixels per inch.

We extend the design possibilities for matrix displays in two ways: (1) Unevenly-spaced and -sized pixels allow for varying the information density, e.g. higher resolution in the center and lower resolution in the periphery of a display. (2) Custom-shaped pixels allow for creating a unique visual appearance of the display, e.g. for digital signage or artistic installations. Both these options come at virtually no extra cost, as it is very easy to modify these parameters in the digital design.

4.5.4 Translucent Display Segments

To fabricate translucent display segments, the back electrode is printed with translucent conductive ink on the reverse side of a transparent PET film (see Fig. 4.3b). The film itself acts as the dielectric, eliminating the need for nontransparent dielectric ink. The phosphor and top electrode layers are printed on the front side. The conductor and phosphor inks are translucent, leading to a translucency of 32% at positions where segments are printed. Note that the display is fully transparent at locations without segments. Fig. 4.8b shows an application example for a shop window showcase.

4.5.5 Integration with Static Visual Print

A display can be printed alongside and integrated with static visual print. The designer uses an office laser or inkjet printer to print static visuals onto the paper or PET substrate. Next, display primitives are printed with screen printing onto the same substrate. This enables the following functionality:

- *Adjacent:* Display primitives can be adjacent to printed visuals, for instance allowing for underlines or pop-out elements that light up on demand.
- *Contour:* They can be more directly integrated. For instance, a static printed headline can be augmented by a luminescent contour. As long as the segment is not filled, visual print inside the segment remains fully visible.
- *Highlight:* If the display primitive is printed at the reverse side of a slightly translucent substrate (see Fig. 4.3b), it can glow though static print on the front side and act as a dynamic highlight. The example in Fig. 4.8c demonstrates a highlight printed on the reverse side of office paper.

4.5.6 Integration with Printed Electronics

PrintScreen enables integrating display primitives with additional printed electronic applications on a single substrate. The bottom electrode layer can be used for designing additional electronics next to display primitives. Using silver ink for the bottom electrode, users can design printed traces and components. The principles for silver-ink printed components from previous work directly transfer to this case, e.g. for printing sensors [19, 25, 33]. Moreover, additional surface-mount components can be soldered onto the substrate.

4.6 Display Shapes

PrintScreen offers the designer a high degree of design flexibility, supporting custom 2D and 3D shapes as well as reshapeable displays.

4.6.1 2D Shapes

Virtually any (rectangular, circular, irregular) 2D contour of the display can be realized in the digital design and then cut out of the fabricated display substrate. The only restriction is that each segment must be connected with the controller. The size of a display can range from only a few square centimeters up to large sizes. Screen printing of up to A2 size is feasible with hobbyist's toolkits.

4.6.2 3D Shapes

Screen printing does not allow for printing on curved objects. However, it supports printing on flexible substrates. Once printed the substrate can be deformed to create curved or folded 3D surfaces (see the examples in Fig. 4.1 and Fig. 4.10).

4.6.3 Shape Adaptable

The flexibility of the substrate even allows for resizable and deformable displays. In technical experiments, we could demonstrate that the printed display can be folded anywhere on its surface and remains fully functional. It can also be rolled up on a scroll with a radius of 3 mm; this enables for applications for rollout displays. A technical evaluation shows that the displays are very robust to repeated bending or folding.

4.7 Integrated Sensing of User Input

Sensing of user input is a key requirement for interactive display surfaces. We contribute an approach for integrating different modalities of input sensing with a printed TFEL display, using the same set of electrodes both for display and for sensing. It is not necessary to print additional sensing elements on top or behind the display, as it would be necessary for LCD screens. We demonstrate the principle with capacitive touch sensing.

The approach is based on the key insight that the phosphor layer only lights up when a high AC voltage is applied on one electrode while the electrode on the other

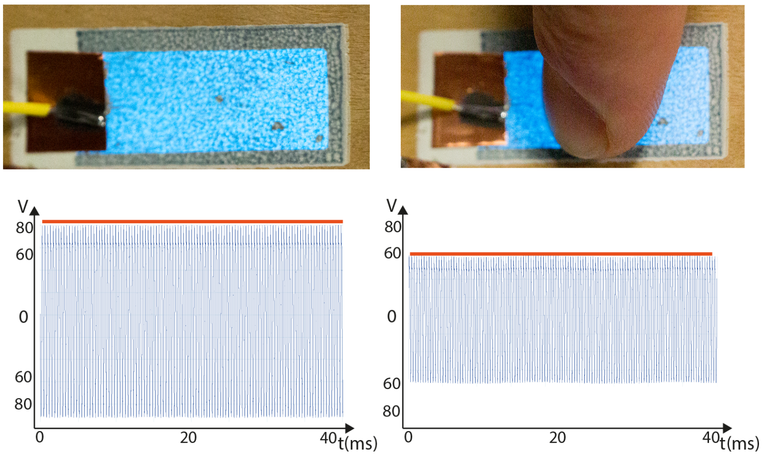


Figure 4.9: Touch sensing. The amplitude of the AC signal drops when the segment is touched.

layer is grounded. It does not light up when DC or a low voltage AC (we identified < 14 V) is applied, or when one electrode is set to high impedance. Many sensing approaches fulfill these requirements, e.g. for sensing of touch [18, 19, 82], hover [19] or deformation [19], to give only a few examples.

By time-multiplexing between a display and a sensing cycle, the electrodes on one, or even on both layers, can be used for sensing. In case of DC sensing, the driver IC is turned off during the sensing cycle. The time for discharging depends on the charge of the internal capacitors. In our implementation, we measured a maximum discharging time of 1.7ms.

As an example instantiation, we implemented capacitive touch sensing using projected capacitance [82]. During the sensing cycle, we leave the high voltage AC signal on the lower electrode, set the higher electrode to high impedance and measure the transmitted signal. When touching the electrode, the signal amplitude drops (see Fig. 4.9). The amplitude of the signal is used for recognizing touch contact, as introduced in [82].

If display and sensing cycles alternate quickly and the display cycle is sufficiently long, there is no perceivable decrease in display quality. We identified the following cycle durations to not add flickering: a display cycle of 5ms is followed by a sensing cycle of 2ms. This results in a frame rate of 140 Hz. The sensing cycle decreases the luminance of the display by 24%, which however can be fully compensated for by increasing the AC voltage. If used in a passive matrix display, the frame rate is divided by the number of lines of the display.

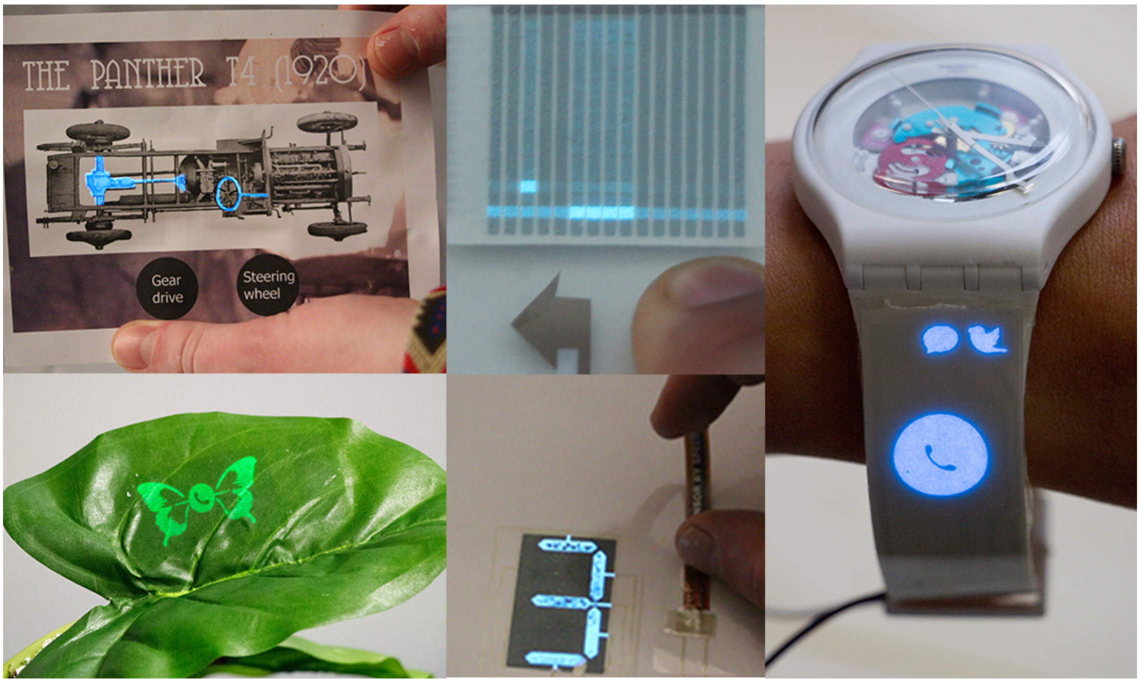


Figure 4.10: Application examples

The spatial resolution of sensing depends on the number, size and arrangement of display electrodes. If required, additional electrodes used exclusively for purposes of sensing can be printed in-between display segments. It is also possible to enlarge the top and lower electrodes of a display segment for sensing, without increasing the segment on the phosphor layer.

4.8 Application Examples

We present five application examples of custom-printed displays. They instantiate various dimensions of the design space and demonstrate the potential for applications in ubiquitous, mobile and wearable computing. The applications are illustrated in Fig. 4.10.

4.8.1 Interactive Paper Postcard

Interactive display segments can be integrated with static visual print. We printed a paper postcard that features on-demand visual information on a historical car. Two printed touch areas capture user input. The display segments are printed on the reverse side of the postcard. This application shows the high resolution of very custom-shaped segments and demonstrates the applicability for augmented paper and smart signage applications.

4.8.2 Interactive Watchstrap

PrintScreen enables customized wearable displays. In this application, a notification display is integrated in a watchstrap of a traditional wristwatch. It is printed on the backside of a thin white PET film, which is laminated onto the watchstrap. The display can be customized to fit the individual shape of the watchstrap. This smartwatch concept has the benefit to maintain the esthetics of a traditional watch.

4.8.3 Printed Pong

To demonstrate interaction with a printed matrix display and its responsiveness, we implemented an instantiation of the Pong game. The 16x16 matrix display features two capacitive touch buttons to control the paddle.

4.8.4 Awareness Flower

We augmented an artificial plant with displays on the backside of its flexible leafs, to provide awareness information. If an update (e.g. a new e-mail) arrives, the segment lights up. This application demonstrates how PrintScreen enables ubiquitous displays that seamlessly integrate with the underlying object and fade into the background when not needed.

4.8.5 Integration with Electronics

This application demonstrates that PrintScreen can be used for creating flexible circuit boards with integrated display elements. The bottom electrode layer contains additional printed circuitry for wiring of additional electronic components. A physical bend sensor allows the user to modify the number on a seven-segment display.

4.9 Technical Evaluation

4.9.1 Luminance

The light intensity of the display can be controlled by varying the AC voltage (amplitude and frequency). We analyzed the maximum light intensity of the displays. It depends on several factors: the substrate, the AC voltage and the strength of the inverter. When driven with the DC12V10M inverter at its maximum input voltage of 12V DC, the luminance of the display varies between 120 and 280 cd/m^2. On paper, PET, ceramics and leather, we measured a maximum luminance of approx.

170 cd/m^2. On very smooth materials (steel and marble), 280 and 250 cd/m^2 are reached. On wood, a quite porous material, we measured only 120 cd/m^2. In our experience, the strength of the inverter is the main limiting factor. In experiments with a stronger inverter, we measured intensities between 270 and 570 cd/m^2 at 18V DC. When using the mobile driver IC chip[2] with 7V DC, the displays are less bright, ranging between 15 and 35 cd/m^2. This is comparable to a super bright white LED.

4.9.2 Bending and Folding

To analyze how robust the display is when repeatedly bent or folded, we used an automated test setup. We used a display sample with a 6x1.5cm single segment, printed on office paper. A simple robotic apparatus bent or folded the display repeatedly, returning each time to a completely flattened state. A light sensor, placed 10 cm above the display surface when in flat state, automatically measured the luminosity after each deformation.

In a first test, the apparatus bent the display successively 10,000 times to a radius of 1.5 cm. After the test, the display was still functional and did not show any decrease in luminance. We tested this high number of repetitions to account for continuous deformations occurring when the display is used in wearable applications.

In a second test, the apparatus fully folded (with a sharp folding crease) and unfolded a different display sample a total of 3,411 times before parts of the segment ceased to emit light. During the test, the display did not show any decrease in luminance.

4.10 Discussion and Limitations

4.10.1 Ease of Fabrication

All display samples presented in this chapter were printed by two persons who both were not familiar with screen printing before joining this project. They used online tutorials and videos on the Web to learn the process. It took them between 3 to 5 hours to get familiar with the theory and another day to get practical experience. They did not encounter any real difficulties. One of the persons first had problems with homogeneously applying the UV-sensitive emulsion onto the mesh for UV lithography, but had learned doing it correctly after a few trials. Fine prints with

[2]http://www.rogerscorp.com/durel/producttypes/2/DUREL-EL-Driver-ICs.aspx

thin lines require a steady hand. Despite the imprecision of the manual process, our non-experts could robustly print conductive lines and lighting dots of 300 μm width and diameter. Printing of the displays for our example applications took between 2 and 4 hours. This demonstrates the practical feasibility of the approach.

4.10.2 Display Color

Our process requires for each segment or pixel to choose the color at design time. For our display samples, we used only one color. A full color display could be realized by printing three red, green and blue sub-pixels for each pixel [38]. Given the maximum pixel density in manual print, this is a viable approach only for displays that are looked at from some distance.

4.10.3 Safety

All substances used for fabrication of the displays are non-toxic.

- *Safety for production:* Users should read the health and safety guidelines in the material data sheets of the inks. It is recommended that the printing process take place in a well-aired room especially when curing the inks. Users should wear rubber gloves and goggles to protect eyes and hands. The display should be sealed properly.

- *Safety after production:* After the inks are cured, the display is safe to interact with. A current of max. 10mA is considered being physiologically safe [95]. For example, the EL driver IC can provide a maximum output current of 1.0 mA at 220 Vpp [86]. This driver IC can drive a segment area of 4 sq. inches. If we assume 10 driver ICs are connected in a parallel circuit (driving a surface of 40 sq. inch, a reasonable size for most mobile/wearable applications) the overall current is max. 10mA. If stronger inverters are used or if the display is exposed to mechanical stress or scratching, we recommend lamination with an insulating film.

4.10.4 Comparison with OLED Displays and Electronic Paper

In applications where a high-resolution matrix display or use of a full-color display is a prime requirement, off-the-shelf OLED or electrophoretic displays are still the solution of choice. However, if very strong bendability or even foldability is required for functional interface prototypes, our approach is without competitors, as to our knowledge such displays are neither commercially available nor can they be produced using a different approach. Likewise, PrintScreen is to our knowledge the only solution for designers, makers and HCI experts that allows direct integration of displays with various base substrates, very thin dual-sided and translucent displays and custom shapes.

4.11 Conclusions

PrintScreen is an enabling technology for digital fabrication of customized thin-film displays. We presented a systematic overview of graphical display primitives that act as buildings blocks for the digital design of the display. In order to instantiate the design, PrintScreen contributes two methods for rapid and inexpensive fabrication of the display, in a lab environment, print shop or even at home. The displays are deformable (even fully foldable and rollable) and can be highly customized by the user in several dimensions: their 2D and 3D shape, the material they are printed on, and the way contents are displayed. We further presented a framework that integrates sensing of user input (e.g. touch input) right into the display. Due to its versatility, PrintScreen opens up a wide space of new applications in ubiquitous, mobile and wearable computing.

In the next chapter, we extend the idea of digitally designing and physically instantiating custom-shaped interactive surfaces to 3D objects.

Chapter 5

Foldio: Digital Fabrication of Interactive and Shape-Changing Objects With Foldable Printed Electronics

PrintScreen showed a digital fabrication process for custom-shaped touch-sensitive 2D surfaces. In this chapter, we extend this concept to 3D objects by folding the interactive surface. We call the class of interactive folded objects "Foldio" (Foldable Interactive Objects). A Foldio is an interactive 3D object that is *folded of a thin sheet* of plastics, paper or cardboard. It can *sense user input and provide system output* through customized *printed electronic components* that are embedded within the foldable structure. Foldios are created by designers, makers and even end-users. The approach enables highly customized interactive 3D objects with embedded foldable touch and deformation sensing, display output and shape-changing output (see Figure 5.1).

Folding is routinely applied for 3D objects in a variety of domains, ranging from mundane packaging to sophisticated Origami or foldable structures in robotics. The high strength-to-weight ratio of folded objects enables thin, very lightweight, hollow and shape-changeable geometries [41]. Foldios also leverage the power of printed electronics, which makes it possible to realize sensors and output components that are very thin, deformable and cover large surfaces. The combination enables a novel and unique way to fabricate an interactive 3D object in a single printing-plus-folding pass (Figure 5.1a).

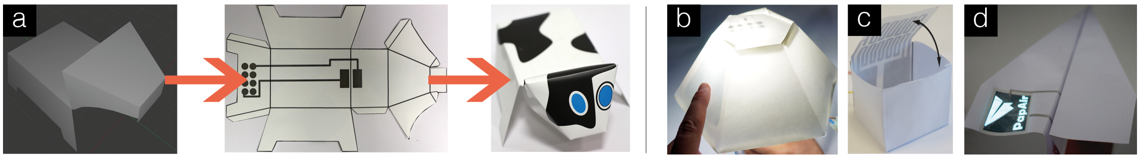


Figure 5.1: Foldios are designed in 3D. Print & fold layouts are automatically generated, including customized printable electronics for sensing and output. The technique enables quick, easy and inexpensive fabrication of a wide variety of folded interactive objects, including b) UbiComp devices, c) actuated shape-changing objects and d) lightweight paper crafts.

The design and fabrication of Foldios involves several challenges. For one, it should be possible to design the interactive object in 3D, rather than requiring the designer to create a non-intuitive and possibly complex 2D crease pattern. Moreover, the approach requires thin-film printable electronic components for embedding sensing and output into the folded structure. Instead of requiring the designer to specify low-level circuit designs for these components, it should be possible to add high-level interactive controls to the 3D model.

The first contribution of this chapter is a *design and fabrication technique for foldable interactive 3D objects*, which addresses these challenges. It significantly eases design and fabrication of such objects by a two-fold abstraction: it abstracts both from the 2D crease pattern and from low-level printed electronics. This enables the designer to design the object's geometry in 3D in a standard CAD software. Interactive behavior is added by assigning high-level user interface controls to the 3D model. We contribute a technical enabler for these abstractions: the first algorithmic pipeline which automatically generates from a given 3D model a custom 2D crease pattern with embedded parameterized designs of printable sensors, displays, and actuators. The pattern is then printed using conductive inkjet printing or screen printing and folded to become a 3D object. As a result, highly custom interactive objects can be realized quickly, easily and cheaply.

The second contribution of this chapter is a set of *printable controls for on-surface interaction on foldable objects*. They provide an inventory that allows the designer to realize interactive objects with a variety of input and output capabilities, taking into account the specific affordances of folded objects. We present novel controls for capacitive touch input on folded objects and for visual output using thin-film printed displays.

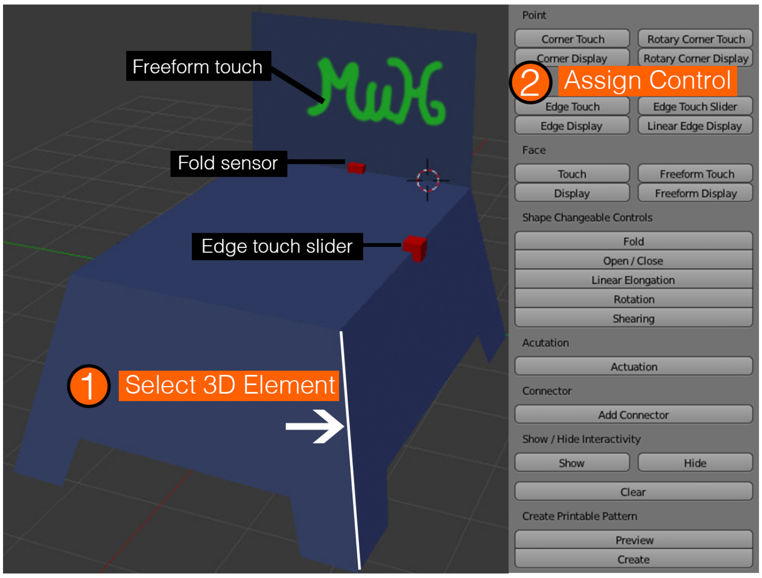


Figure 5.2: The designer models the object in 3D in Blender and adds interactive controls to the geometry.

The third contribution is a set of *printable controls for shape-changeable folded objects*. These controls capture shape-changing input and provide shape-changing output using thin-film actuators (shape-memory polymers). During design, each control can be easily assigned to the 3D model. In the fabrication step, each control is technically realized as an embedded thin-film component that leverages a unique combination of folded geometry and 2D printed thin-film electronics.

To validate the practical feasibility of the approach, a variety of application examples have been successfully realized with the framework. Areas include interactive paper craft and prototypes, interactive packaging, interactive furnishing, as well as custom-shaped input and output devices. Amongst others, we have realized an interactive lamp shade, a flying paper plane with display output, and an actuated shape-changing awareness display. The results demonstrate that a wide range of custom interactive objects can be designed and fabricated in less than one hour, while objects with more complex interactivity (such as light-emitting displays) can be realized in 2-3 hours.

5.1 The Foldio Design and Fabrication Pipeline

The design and fabrication pipeline of Foldio is illustrated in Figure 5.1. This section introduces the overall approach and presents a set of contributions, which technically

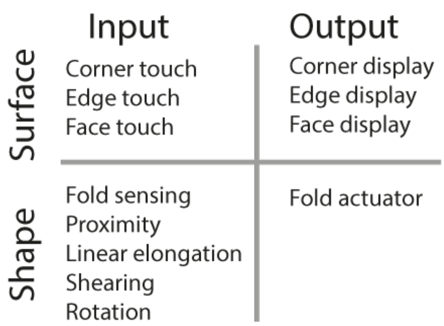


Figure 5.3: Design space of interactive controls for Foldios

enable the approach and make it usable for designers.

5.1.1 Step 1: Digital 3D Modeling of Geometry and Interactivity

The designer starts by creating a 3D model of the interactive object in a CAD modeling environment. The novelty of our approach is that it allows the designer to model the foldable object in 3D, like any standard 3D object, and to define interactive behavior with high-level user interface controls. Figure 5.2 illustrates the digital design environment. The user first selects a 3D element (e.g. an edge) that should become interactive. Then, he assigns the interactive behavior (e.g. a touch sensitive slider).

This chapter contributes a variety of printable UI controls. We contribute controls in four quadrants of a two-dimensional design space (see Fig. 5.3): controls for *making the outer surface of a 3D object interactive*, through capacitive sensing of touch input and through light-emitting display output; and controls for shape-change interactivity, through sensing of folding state and through shape-change output with thin-film actuators. A control can be assigned to a corner, edge or face of the 3D model with a single click (Fig. 5.2). We have implemented support for UI controls as a Python add-on for Blender, a free and widely used 3D modeling suite. As a result, the designer can use Blender's powerful built-in functionality for modeling the object.

5.1.2 Step 2: Automatic Design of a Custom Print-and-Fold Pattern

Next, the pipeline automatically generates a 2D print-and-fold layout for the foldable object (Figure 5.1a). This raises technical challenges of unfolding a 3D geometry with embedded printable electronics. We are not aware of any previous automatic approach. We contribute an automated approach to create a parameterized circuit design for printed electronics components, to match given geometric, sensing, and electronic constraints. A further challenge is on the interaction level: how does one provide the designer with real-time feedback on the complexity of the auto-generated fold, while she is modeling the object in 3D?

Unfolding and Parameterized Circuit Design

Unfolding arbitrary 3D shapes is known to be an NP-hard problem. However, for those shapes that can be considered to be practically foldable, the solution space for an unfolded shape is small enough such that heuristics [11, 56, 101, 110, 97] can find a good solution. We used an unfolding algorithm that is based on region growing and implemented in the freely available software "JavaView"[1]. To work correctly, the algorithm requires a 3D geometry, that has only planar faces. If the 3D model contains curved faces (e.g. a sphere), the designer can use Blender's built-in functionality to triangulate the mesh.

The result of the unfolding step is a 2D crease pattern with gluing flaps, which however does not yet contain the layout for printable electronics yet. We opted for an electronics-agnostic unfolding step to avoid having the complexity of the unfolded pattern be increased by additional constraints. This ensures the pattern is as easy to fold as possible.

In a subsequent step, our algorithm adds layouts for printable electronics to the 2D crease pattern. Interactive controls which the designer has added to the 3D model are stored as annotations of the 3D model, indicating the type of control and its parameters. The algorithm sequentially processes these annotations and accounts for several parameters: geometric constraints (location, size and shape of the control), the desired resolution of the component, and electronic constraints (min. and max. dimensions and distances between electrodes). If the faces are not large enough for the control to fit in, the user is notified.

[1] JavaView - Interactive 3D Geometry and Visualization. http://www.javaview.de

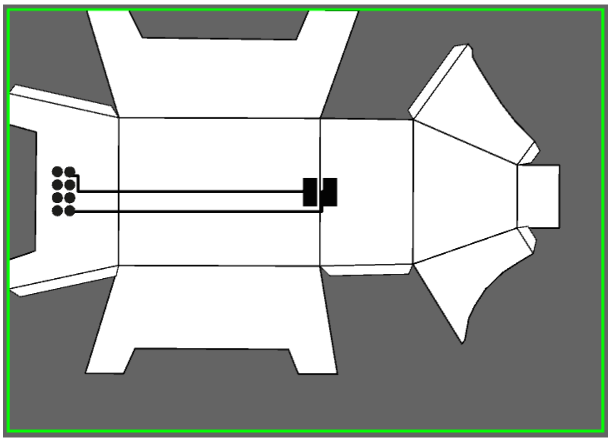


Figure 5.4: Instant Preview.

The unfolding process may require splitting up the mesh at an edge to flatten it. Each control, that is located on this edge or extends over it, is split into two separate parts. These are reconnected across the fold: the algorithm generates two gluing flaps, one on each slide, containing a conductive pin for each electrode. When the object is folded, a conductive connection between these pins is realized by using double-sided conductive adhesive tape (z-tape by 3M).

Lastly, the algorithm automatically creates conductive traces that connect each electrode with a connector area, where the microcontroller is connected. As folding introduces high mechanical stress at the crease, conductive traces are generated with 2mm width. We use the maze router algorithm [42], which is a powerful algorithm that is used in professional PCB layout tools.

Instant Preview During Digital Design

We have realized a separate application that displays an Instant Preview window (see Fig. 5.4). This window runs the unfolding algorithm and provides a live preview of the unfolded net while the designer is working on the 3D model in Blender. It visualizes the 2D unfolded shape including all layouts for printable electronics, conductive traces and auto-generated flaps. Each element and each group is color-coded. Panning and zooming allows for detailed inspection. Blender and the Instant Preview application communicate via a network socket connection.

The designer can use this information to check the complexity of the crease pattern. Beginners might prefer rather simple crease patterns, while origami experts can cope with highly sophisticated patterns. Independent of skill level, the complexity of the pattern greatly influences the time required for building the object. If desired, the designer can easily reduce the complexity of the crease pattern by using Blender's automatic mesh simplification function. This trades in geometric level of detail for ease of folding. In addition, the preview window allows the user to judge the quality of the auto-routed conductive traces. If not satisfied with the autorouting, the designer can generate an alternative routing with one click. Lastly, for a quick printability check, the preview window indicates whether the unfolded layout can be printed on a user-defined paper size.

5.1.3 Step 3: Printing

To fabricate the interactive object, the designer prints the automatically generated pattern (see Fig. 5.1). She can choose from two established and affordable printing methods for printed electronics. Conductive inkjet printing [33] is a fully automated and instant method, using an off-the-shelf inkjet printer. It is restricted to printing a single-layer conductor on thin substrates. It supports the touch sensing and shape sensing controls presented in this chapter. The second printing method is screen printing [70]. This is a more time-consuming manual process. It enables printing of light-emitting displays and actuators and supports a wider range of materials, including cardboard and PET sheets up to a size of A3. We recommend to first fold and unfold the substrate once before screen printing on it; this makes conductors more robust to folding. To ensure instant inkjet printouts are robust, we recommend patching conductive traces that go across folds with copper tape. Screen-printed conductors are more robust and need to be patched only if heavily used during continuous shape changing (see section 5.4.2).

Each Foldio consists of a multi-layer print file with at least two layers. These are printed on top of each other. The first layer defines the folding pattern and is printed using an off-the-shelf graphic printer. The second layer contains all conductive traces, touch controls and the connector. It can be printed with conductive inkjet printing or screen printing. The subsequent layers (dielectric material, phosphor and translucent conductor [70]) are optional and only required for visual output. In addition, we generate a layer containing the outline of the shape for optional laser cutting.

5.1.4 Step 4: Folding

The user manually folds the flat sheet to its 3D shape (Fig. 5.1). Many crease patterns require parts of the sheet to be cut off before folding. As an alternative to manual cutting, the sheet can be cut automatically with a laser cutter using the auto-generated outline graphic.

5.1.5 Step 5: Using a Foldio

Lastly, a hardware controller is connected to the printed connector area on the folded object. In our current implementation we used an external controlling unit (Arduino or Picoscope as detailed on below), which is connected via wires. Future implementations could use a dedicated FFC connector or embed the controller right onto the Foldio. During design time, the user can assign a connector area to any face of the model in the same way as the ”FaceTouch” control is added. The face must contain a minimum free area of $3.5x2cm$. When the print-and-fold pattern is generated, the pipeline also automatically generates high-level method stubs that allow application developers to easily interface with the controls in a high-level language. These allow the developer to easily read out sensor values, control displays, and control actuators in a Processing application. We use the Arduino CapSense Library for capacitive touch sensing. Emit-and-receive sensing was implemented on a Picotech oscilloscope. This functionality could also be implemented as a custom circuit, as demonstrated in [19]. Thin-film displays are realized as presented in [70]. A Processing application serves as the integrating hub: it controls these different HW components and reads out sensor data. In the following two sections, we will present the Foldio controls for on-surface and for shape-change interactivity.

5.2 Controls for On-Surface Input and Output

In this section, we introduce a set of printable UI controls for on-surface interaction with folded objects and present their technical realization. These controls take advantage of the affordances of folded objects. They adapt to their specific 3D geometry and follow subsequent modifications of the model.
Each control is defined by a unique combination of folded geometry and printed electronics. A control cuts across all process steps presented in the previous section. First, the designer adds digital controls to the 3D model; a parameterized print-and-fold layout is automatically generated for physical fabrication. The designer implements interactive behavior in Processing by using the automatically generated

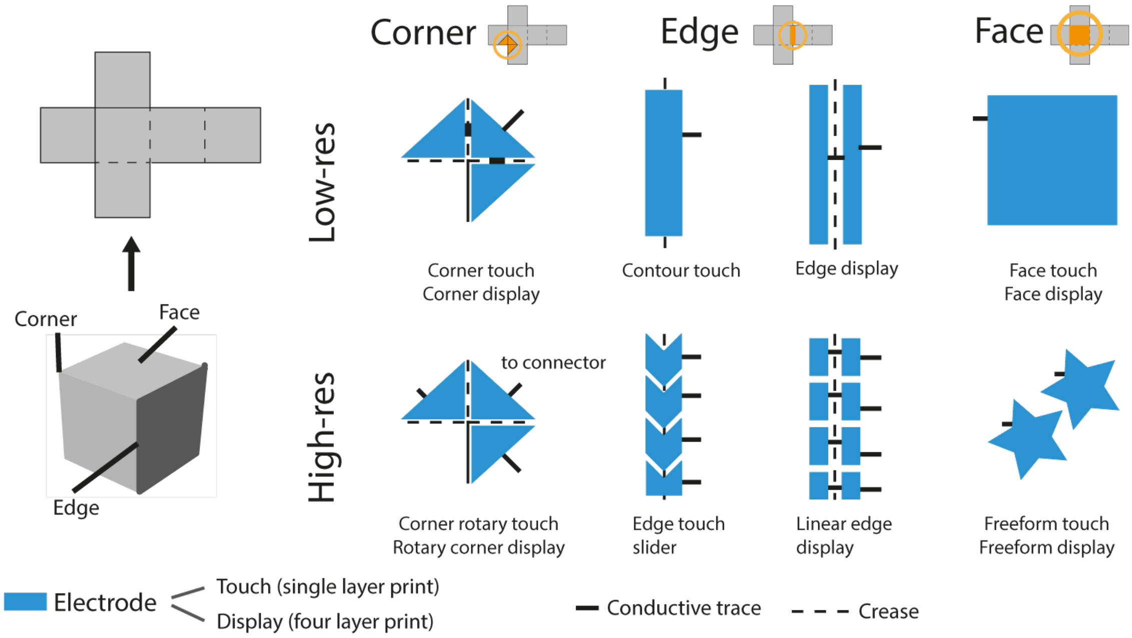


Figure 5.5: Controls for on-surface touch sensing and visual output

method stubs of the controls. This approach integrates the control seamlessly with the 3D modeling process and abstracts from its technical realization.

5.2.1 Controls for Touch Input

Foldable objects have unique affordances: Folds provide a natural way to be touched or slidden along. Faces between creases afford to be used as planar interactive surfaces. Corners created by the intersection of two or more folds have the affordance of a button or a rotary knob.

We contribute touch-sensitive controls for foldable objects: any corner, edge or face of the object can be made touch-sensitive by selecting it in the 3D model and assigning a touch sensor control. The resolution of sensing is defined by the designer. In low resolution, the control captures simple touch contact. In higher resolution, the control acts as a circular touch slider (corner), a linear touch slider (edge), or a free-form electrode (face). In addition, a free-form electrode can be defined either by directly drawing on the face using Blender's texture paint functionality or by placing a graphic onto the face (see Figure 5.2). Two or more controls of the same type can be grouped. This enables compound controls that span over a larger part of the 3D surface. For example, if multiple edges are selected and defined as a slider, they will behave as one continuous slider.

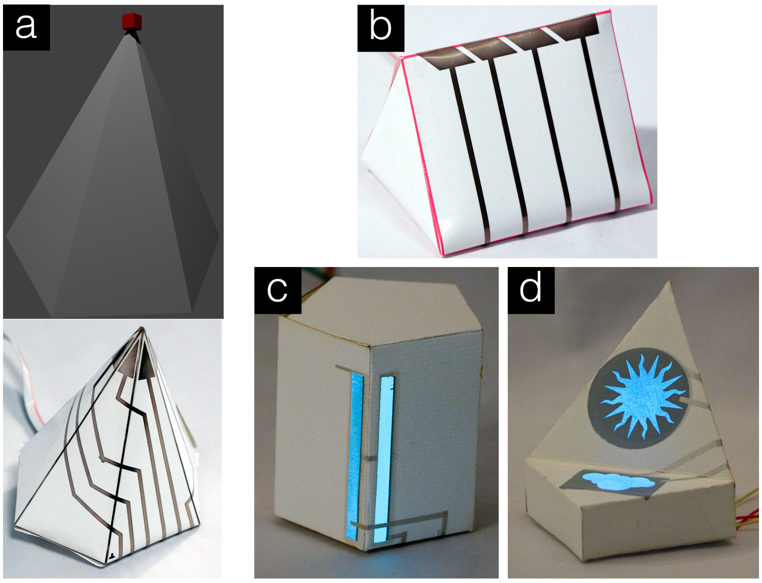


Figure 5.6: Touch and display controls (folded inside-out for better visibility of electrodes and traces)

Controls for on-surface input require only a single layer print and can be fabricated with conductive inkjet printing [19]. Figure 5.5 depicts the printable base patterns. The base pattern is automatically parameterized to fit the specific geometry and desired resolution.

A *corner control* is realized by automatically generating a triangle-shaped sensing electrode on each neighboring face. For high-resolution sensing, each electrode is separately read out; in contrast, for simple touch contact sensing, all these electrodes are interconnected. Touch sensing on an *edge control* is realized using a single electrode, which extends to both sides across the crease (designer-defined width $0.52cm$). For higher resolutions, the base pattern is divided into multiple juxtaposed electrodes, following a widely used pattern for capacitive touch sliders [5]. Lastly, a free-form touch sensing element is internally represented as a texture, which is mapped onto the unfolded model and printed as a conductive electrode.

Figures 5.6a and b depict printed examples of corner and edge sensors. Processing stubs are automatically generated for interfacing with the control in a high-level language. For example, a corner rotary touch control is instantiated by `RotaryCornerTouch t = Foldio.getControl("ctrname").`

5.2.2 Controls for Display Output

In addition to touch sensing, Foldio offers controls that provide visual output on corners, edges and faces of the folded object. Any *corner, edge or entire face* can be selected to become a light-emitting display segment. Alternatively, the designer can opt for the high-resolution variations of these controls, to display a *circular animation on a corner or a linear animation on an edge*. For instance, this allows to communicate a direction or convey progress. *Free-form display segments* can be added onto faces, similar to free-form touch sensors.

Display controls are technically realized through thin-film electroluminescent light-emitting displays. These are printed onto the foldable sheet using screen printing, as introduced in [70]. In contrast to touch sensing, which requires only one layer of conductor, display segments are printed with four layers. As demonstrated in [70], the brightness of each segment can be individually controlled at run-time and display output can be combined with touch sensing. It is also possible to realize segments in different colors, using different inks. To avoid capacitive interference between display elements and nearby controls, we suggest applying time multiplexing between both modes, as done in [70].

Figure 5.5 depicts the base patterns for these controls. They are the same as for touch sensing, except for the edge display: here, the pattern does not span over the edge. It is divided into two separate parts, which are interconnected by conductive bridges. This makes the displays more robust to strong notches and repeated folding. Figures 5.6c and d show printed examples of edge and free-form displays.

5.3 Controls for Shape-Changing Objects

Folding is very well-suited for realizing shape-changeable geometries [109]. We contribute a set of new embedded thin-film controls that capture the folded geometry in real-time and that provide actuated shape-changing output. The physical instantiation of the controls must fulfill several challenging requirements. First, mechanical components as shown in [29] are hard to integrate, since they increase the thickness of the substrate. Second, the control has to be parameterizable, to be compatible with custom geometries. Lastly, it needs to be easily printable. Ideally it requires only a single layer of conductor, to be inkjet-printable.

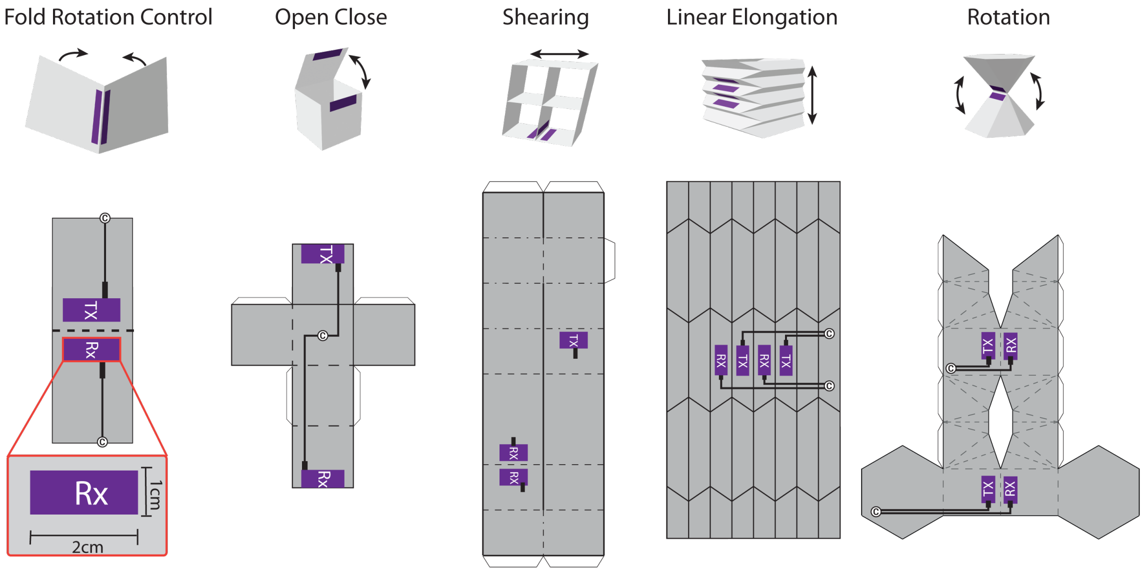


Figure 5.7: Foldable controls for real-time sensing of shape change

5.3.1 Controls for Sensing of Foldable Shape Change

We contribute controls to capture several basic primitives of foldable structures, including simple folding, elongation, shearing and rotations. Each control is a parametrically folded 3D geometry that is shape-changeable and senses its deformation. The overall sensing principle is based on the observation that shape change for folded objects is reflected as a change of the inner angle between two faces in the geometry. To ensure inkjet printability, we base our sensing solution on capacitive emit-and-receive sensing: one electrode emits an AC signal. This signal is received by a nearby electrode [19].

Fold Sensing Control

The most basic type of foldable shape change is the simple fold: the two adjacent faces can be rotated with respect to each other. The fold sensing control measures the rotary angle between adjacent faces of a fold. The designer can add the control to the 3D model by selecting the edge along which the rotary angle is to be captured.

The base layout of the printed sensor is depicted in Fig. 5.7. It consists of two electrodes (2x1cm), which are placed on opposite sides of the crease at a 3mm distance. An AC signal (10Khz, 10V) is applied on the transmitting electrode (Tx). The strength of the signal on the receiving electrode (Rx) allows the angle to be inferred. To allow the control to measure angles larger than 180°, another electrode pair can optionally be printed on the reverse side. In this case, electrode pairs are

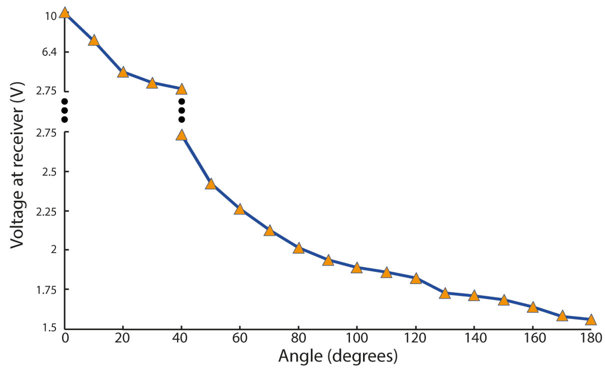


Figure 5.8: Raw values of the fold sensing control

horizontally displaced by 2cm to reduce capacitive crosstalk.

Figure. 5.8 shows a plot of the raw readings. The plot shows that even larger angles of up to 180 degrees can be inferred from the raw sensor readings. Yet, using signal strength as a continuous measure is sensitive to influences through capacitive noise. In our experience, the sensor works accurately if the user is not touching any of the electrodes nor interacting with hands or fingers in a 3 cm distance from the electrodes. The influence of capacitive noise can be decreased by printing multiple redundant emit-and-receive pairs at different locations. In addition, the sensor could actively identify if a finger is touching an electrode by time-multiplexing between a touch sensing cycle and an angle sensing cycle. If touch contact is detected, the value from angle sensing is then flagged as compromised.

While the capacitive approach is not ideal for applications that require highly accurate sensing, it provides reasonable accuracy for many practical applications in packaging, paper crafts and prototyping, as we will demonstrate below. These applications leverage on the simple printability of the sensor, its slim form factor and its mechanical robustness.

Proximity: Open/Close Control

Many applications in packaging include lids that can be opened and closed. The open/close control detects proximity between two faces, using the same principle as introduced above. In the 3D modeling environment, the designer selects two edges between which proximity is to be sensed. Open and close states are detected if the signal strength rises above or falls below a threshold. Figure 5.7 depicts the base pattern. Figure 5.9c shows a physical prototype.

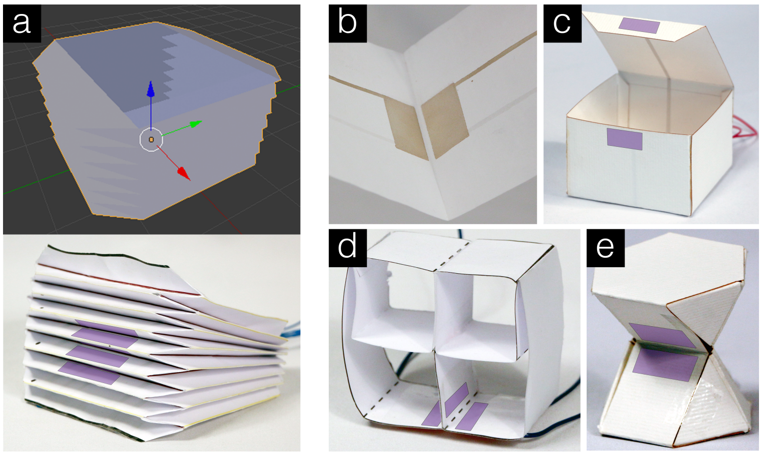


Figure 5.9: Shape Changeable Controls (internal sensor placement is highlighted)

Linear Elongation Control

A variety of crease patterns allow folded structures to be elongated [94]. The bellow fold is one of them. It is very versatile and easy to fold. The pattern was instrumented in previous work with manually placed sensors [125]. We improve on this by offering the user a digital control, that can be customized in size, and in addition we describe a fully printable implementation.

When adding the control to the 3D model, the designer can specify the maximum length of expansion. A customized fold layout is then automatically generated. Once generated, the shape can be scaled further in Blender.

A specific arrangement of capacitive electrodes on the bellow pattern (see Figure 5.7) allows the structure to sense its elongation. Each pair of emitting and receiving electrodes is measuring their respective angle, as introduced above. If the folded structure is elongated or compressed, the angle between the electrodes changes. This allows to infer the overall length of the folded structure. To reduce noise induced by the users' fingers and hands, the pattern contains multiple redundant emit-receive pairs. The sensor value is averaged over the raw values of all receivers. Figure 5.9a shows the digital design and a fabricated control.

Shearing Control

Shearing is a basic mechanism in shape-changeable structures [109]. We contribute a shape primitive that can be sheared and senses its state. For instance, the primitive can be used to laterally translate a component which is printed on its top. The

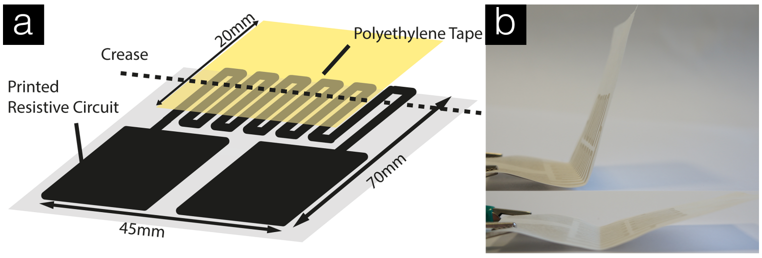


Figure 5.10: a) Base pattern of the fold actuator control b) Actuation of a 40g origami sheet (6.5 x 4cm)

structure is based on the crease pattern presented in [109]. Shearing is sensed by three electrodes on the folded structure (see Figure 5.7). Two receiving electrodes capture the signal, one for each direction. Figure 5.9d shows a fabricated control.

Rotation Control

The rotation control extends over a simple fold by providing a large movement range and structural stability. The crease pattern is based on [109]. The structure can be continuously moved to the left and to the right and senses its rotary angle. For sensing, the primitive contains two fold sensing controls on opposing sides of the folded geometry. Each fold sensing control measures the angle towards one side. Figure 5.9e shows a fabricated control.

5.3.2 Fold Actuator Control for Shape-Changing Output

Previous work in HCI has demonstrated applications for shape changing folded objects [78, 125, 76]. Actuation was realized with shape memory alloys, which needed to be knitted into the object, or using pneumatic pumps. Inspired by [12], we contribute a printable thin-film control that actuates a folded structure up to 90°. It makes use of a shape-memory polymer (SMP).

In the digital design environment, the designer selects the edge whose adjacent faces should be actuated. A parameterized printable layout is automatically generated. It consists of two layers (see Fig. 5.10a). The base layer contains a printed conductive trace, which functions as a resistor to heat the structure on demand (at 6 V, 0.6 A, 2 mm trace width with screen-printed silver ink [70], 40 g origami sheet). A patch of polyethylene tape is attached on top (3M #5421, 0.17 mm thick). Once the resistor heats up to 90°C, the polyethylene patch expands while the base layer retains its length. This results in an actuation of the compound material (see Fig. 5.10b).

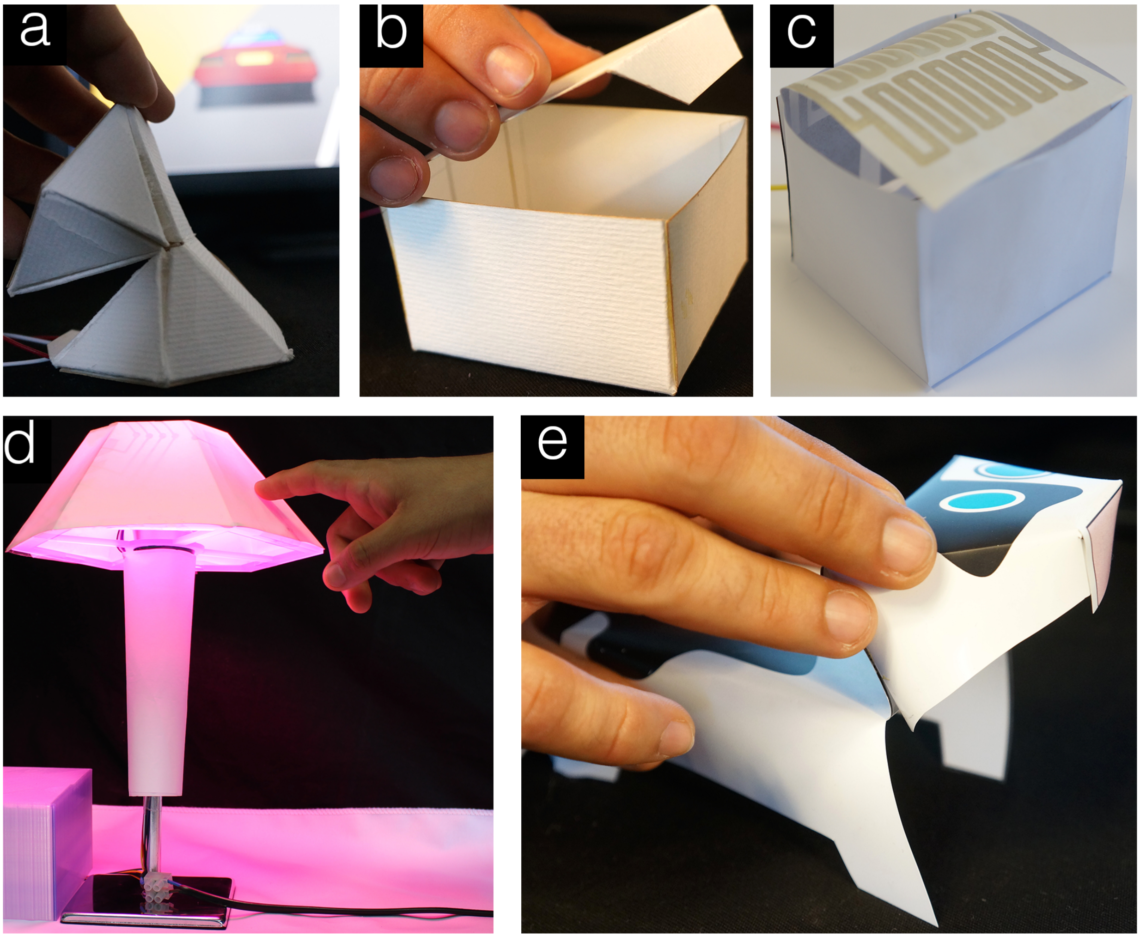


Figure 5.11: Application cases of Foldios

We have conducted a series of experiments to characterize the actuator. The transition from the fully unfolded state to a 30, 60, or 90 degree angle took 33s, 67s, and 122s, respectively. It took around 3 min. to retract to a flat state after heating was switched off. While this is too slow for shape change at interactive rates, it is well-suited for ambient output and for slowly moving structures.

5.4 Validation

To validate the Foldio technique, we have realized eight application examples. In this section, we will present the results and discuss lessons learned.

5.4.1 Practical Application Examples

Interactive Paper Craft & Paper Prototyping

Due to its quick fabrication process, Foldio enables the user to quickly explore the combination of shape and interactivity for objects. We demonstrate this with an interactive paper cow (see Fig. 5.11e). The cow features a fold sensing control. When the head is lifted up, a "moo" sound is played back on an external speaker. Printed electronics are folded to the inside to provide a more visually appealing outer surface. It took approximately 15 minutes to design the 3D model and 25 minutes to fabricate the prototype with conductive inkjet printing.

To demonstrate that Foldios can be very lightweight, we fabricated a paper plane that features a light-emitting display segment on its wing (see Fig. 5.1d). The device weighs 22 grams including the simple controller electronics and battery. This is lightweight enough for it to fly while lit up.

Interactive Packaging

The high stiffness-to-weight ratio of folded objects enables the fabrication of hollow objects. This makes Foldio well-suited for smart packaging. We have created an interactive box, made of cardboard (see Fig. 5.11b). It senses when its lid is opened or closed using the open/close control. The digital design took 10 min. Fabrication with screen printing took about 2h. Printing the same example using inkjet printing takes only around 20 min. to fabricate.

Interactive Furnishing

To demonstrate use of Foldios for interactive furnishings, we have created an interactive lamp shade (Fig. 5.1b, Fig. 5.11d). The user can touch the lamp shade to switch a digitally controlled light bulb inside the lamp on and off. Sliding along a crease dims the lamp. We fabricated the lamp shade by screen printing the layout with translucent conductive ink on an A3-sized translucent PET sheet of 0.5 mm thickness. The digital design took about 30 minutes, followed by around 3h for fabrication.

Custom-Shaped Input Devices

Foldio enables quick and easy fabrication of custom-shaped devices that act as specific controllers or provide computer output. As one example, we have realized a game controller that makes use of the rotation control (see Fig. 5.11a). It offers a direct control of an online car racing game. Design and fabrication on cardboard with screen printing took approximately 2h. Another example is an ambient weather display, which features several display segments for visual output (Fig. 5.6d). It took 40 min. to design the object and 3 hours to fabricate it with screen printing.

Shape-Changing Display

Lastly, we have realized a shape-changing display (see Fig. 5.1c in open state, Fig. 5.11c in closed state). Upon incoming messages, the display folds up to notify the user. It is realized with the fold actuation control. Design of the object took 15 minutes and fabrication with screen printing took 2 hours.

5.4.2 Lessons Learned

By designing and fabricating the application examples, the author, three researchers in computer science who were familiar with the work and three additional persons (an interaction designer, a computer graphics expert and a maker experienced in 3D printing) have used the Foldio framework intensely over the course of several weeks. Here we summarize their practical insights and lessons learned.

Fabrication Time

All interactive objects could be designed and fabricated quickly. Design of an object took a maximum of 40 min; many could even be designed in just 15 min. The physical fabrication of the object took less time with inkjet printing (20-25 min.) than with manual screen printing (2-3 hours).

3D Design

It turned out that the 2D view of the unfolded geometry was an essential tool, that was used during 3D modeling alongside the 3D model view. A typical approach to designing an interactive object was to start by downloading a 3D model from the internet, for instance a lamp shade for the application example, and to add some first interactive controls. Then the unfolded layout was inspected to judge the sizes of the unfolded model and its creases, as well as its complexity. If the crease pattern was found to be too complex, the 3D mesh was reduced with Blender's functionality. This was frequently followed by a phase in which design options for shape and interactivity were more deeply explored in several iterations and cross-checked in the 2D view, before the designer opted for a final layout.

Foldable Geometries

Foldios cannot contain curved surfaces. However, a curved surface can be approximated by subdividing it into folded tessels. We experienced that in practical applications, the unfolding algorithm was not a limiting factor for the set of foldable geometries. For instance, the algorithm was able to unfold a reduced mesh of the Stanford bunny with over 2000 creases in less than a minute. Rather, the set of foldable geometries is limited by the users' skill level in folding and by the time available for folding the object. In our experience, the approach supports very well all those geometries that are mostly comprised of planar surfaces; it is particularly well-suited for lightweight, hollow and shape-changeable structures. Foldios can also be combined with 3D prints (such as inlay, wrap or attached part) to combine the benefits of printed interactivity with curved geometry.

Scalability

The maximum size of the inkjet printer or screen printing frame defines the upper limit of an object's size. We have printed crease patterns on sheets of up to A3 size. Larger objects can be realized by splitting the crease pattern into multiple individual pieces. The maximum number of interactive controls is defined by the number of I/O pins on the microcontroller.

The minimum size of objects is essentially defined by the minimum size of printed electrodes, which need to fit entirely onto a given face. The minimum size of a face with touch sensing or visual output is 5x5 mm. The minimum size for fold or shape sensing is 20x10 mm. The minimum size for actuation is 40x20 mm. The size of the connector area (8 pins) can be further decreased to 1.5 x 1cm by using a standard FFC connector (SFW10S-2STE9LF).

Interface Complexity

Interactive areas and traces share the same space. Too many controls on a small surface can therefore leave too little space for routing the traces. This problem can be addressed by resorting to multi-layer routing, by extending the routing algorithm such that it can route traces over gluing flaps, and by highlighting in the design tool any interactive elements that are too large, such that the designer can reposition or resize them.

Materials

We have successfully printed and folded objects made of thin origami paper ($40g/m^2$), office paper ($80g/m^2$), inkjet-printable photo paper ($200g/m^2$), thin cardboard ($250g/m^2$), PET sheets ($120g/m^2$), and thicker cardboard ($200g/m^2$). Conductors printed on materials of up to $250g/m^2$ could be folded. In contrast, thick cardboard was problematic because the material broke at the outer creases when folded, damaging the conductor. We recommend printing conductors on such thick cardboard only on the inner side (along valley folds) or to patch them with copper tape. We have also tried to realize objects made of wood (0.5mm foldable microwood paper). We could successfully screen print silver conductors onto the substrate, but the material broke when folded if it was more than 2cm wide. Hence, small objects can very likely be realized with this material.

Repetitive Folding

Repetitive folding for continuous shape change can result in material fatigue at the creases, which can break the traces. We found that inkjet-printed conductors can be slightly folded once for building a 3D object of static shape; however, they do not withstand to very sharp notches (created by sliding with the fingernail across the crease). In contrast screen-printed silver or translucent conductors can be slightly folded and unfolded at least several hundred times. We measured the resistance of a translucent conductor printed on office paper across a fold while we repeatedly folded and unfolded the sample 200 times. We took a data point for every tenth fold. The resistance increased fairly linearly and had increased by 13.5% after 200 folds. With silver ink, a very sharp notch (fingernail) can be folded 5 to 10 times. Generally, conductors across valley folds are more robust to folding than those across mountain folds. In any case, a conductor can be patched with copper tape to be more robust. In addition, the material PET-G is especially resistant to folding and unfolding. Changes in the resistance can require a recalibration of the sensor.

5.5 Conclusions

In this chapter, we have contributed a new approach to fabrication of interactive 3D-shaped and shape-changing objects. It is based on a combination of printed electronics and folding. We have demonstrated that a two-fold abstraction enables the designer to design the foldable object in 3D, rather than manually designing non-intuitive 2D crease patterns, and to add high-level interactive controls, rather than manually designing low-level circuitry for printed electronic components. Moreover, we have presented two sets of printable controls for folded objects, which leverage unique combinations of foldable geometries and printed electronics to enable on-surface input and output as well as shape sensing and actuated shape-change.

Chapter 6

A Cuttable Multi-touch Sensor

In both Foldio and PrintScreen, a digital fabrication approach is applied. They require a digital model of the physical object, which is then physically instantiated. While this has the advantage that the digital model can be digitally shared, and since there are no material constraints or requirements for the expertise of a craftsman, the model can be flexibly modified. But it also carries the disadvantage that they require a fabricator and the skill to create digital models. This can be problematic when the shape of the interactive surface should be created in an ad-hoc fashion, e.g. at the place where it is to be used.

People have traditionally cut materials to tailor them to their specific needs. At home, people wrap packages with various materials that are cut to shape; they cut protective films to cover books and devices of various sizes; and they create artistic shapes in paper craft. In the workplace, tailors cut textiles to fit the size of the customer, carpenters cut wood to build furniture, and designers or engineers cut cardboard and plywood to create physical prototypes.

In this chapter, we present a multi-touch sensor that can be cut to a large variety of shapes while remaining functional (see Fig. 6.1). More generally, we propose cutting as a novel paradigm for ad-hoc customization of printed electronic components. This form of very direct manipulation enables people to quickly and easily create custom shapes and objects; in addition, the direct manual interaction with the material encourages thinking by doing [22]. As a first instantiation, we contribute a printed capacitive multi-touch sensor, which can be cut by the end-user to modify its size and shape. This very direct manipulation allows the end-user to easily make real-world objects and surfaces touch-interactive, to augment physical prototypes and to enhance paper craft.

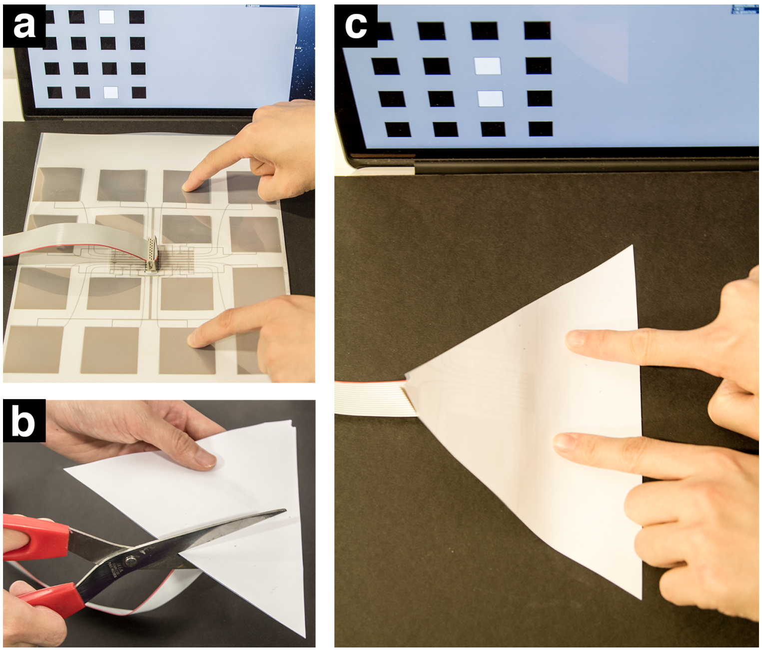


Figure 6.1: We contribute technical principles and an implementation of cut-robust printed multi-touch sensor sheets. a) The multi-touch sensor features a novel wiring scheme. b) This allows the sensor to be cut very much like a conventional material while (c) remaining touch-sensitive.

We contribute a set of technical principles for the design of printable circuitry that makes the sensor more robust against cuts, damages and removed areas. This includes novel physical topologies and printed forward error correction. A technical evaluation compares different topologies and shows that the sensor remains functional when cut to a different shape. We validate our technical contributions by a detailed *simulation*, an evaluation of the *electronic sensing properties*, and a proof-of-concept implementation of several letter-sized cuttable sensor sheets.

6.1 Towards Cuttable Materials with Embedded Multi-Touch Sensing

Our vision is that printed sensors will be so inexpensive that multi-touch sensing capability will become an inherent part of the material. For instance, manufacturers of protective foils will offer a product line that features multi-touch sensing. Paper manufacturers will offer paper, cardboard or adhesive labels, which will have the printed multi-touch sensor embedded. Woodworking suppliers will offer boards that feature the sensor. The user buys the material in one of several standard sizes

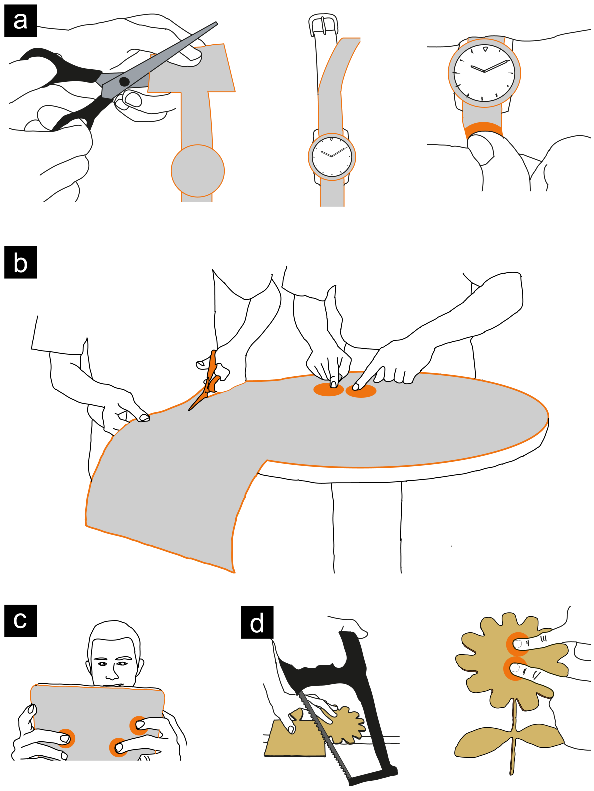


Figure 6.2: a-c) Easily touch-enable objects with a cuttable multi-touch foil. d) Build interactive objects, prototypes or paper crafts out of raw materials with embedded sensing.

and then cuts it to the desired size and shape, using tools such as scissors, razors, saws, or laser cutters. This very direct physical manipulation seamlessly integrates with existing practices for customization, prototyping and crafting. It stands in contrast with existing solutions, which require either an additional step of designing the sensor at a computer [93], or an expert to design a customized sensing solution.

Cuttable multi-touch sensor foils, sheets and boards will be a ubiquitous resource, enabling a wide range of applications. For ubiquitous computing, people can easily add multi-touch input on pretty much any physical object or surface, by using an *adhesive multi-touch foil* that is cut to match the desired size and shape. As illustrated in Fig. 6.2a-c, this enables people to easily touch-augment physical objects and devices. In prototyping and crafting, *touch-enabled paper, cardboard or plywood* empowers people to make models, prototypes and artwork interactive (Fig. 6.2d).

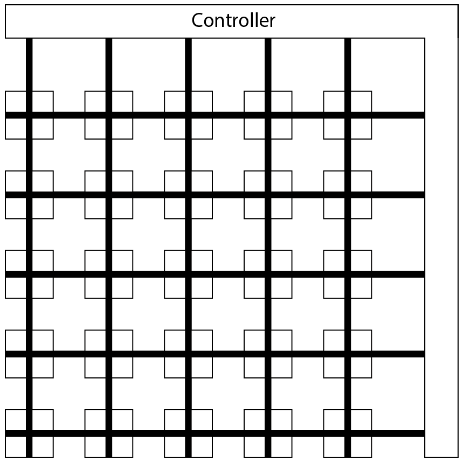


Figure 6.3: Concept of a traditional multi-touch pad

6.2 Background of Traditional Multi-touch Sensors

The commonly used principle for the construction of a multi-touch sensor [82, 98, 116, 88, 50, 9, 83] is illustrated in Fig. 6.3. A set of electrodes is arranged on a regular two-dimensional grid. Each electrode senses one touch point. The electrodes are connected to a controller with a set of horizontal and vertical wires; each electrode is situated at the intersection of one horizontal and one vertical wire. Therefore it can be uniquely addressed by the appropriate combination of two wires. The elegance of this approach is in requiring only a minimal number of wires. However, this grid topology is not designed for shape adaptation. It is not robust to cuts and removed parts. Since each wire addresses many electrodes, damage to a wire results in a burst effect: many electrodes become unusable and possibly large areas of the sensor stop working. Moreover, the controller connects to the sensor by its outer edges; in consequence these edges cannot be removed, meaning round shapes are not possible.

6.3 Requirements

Multi-touch sensors must fulfill a set of technical requirements, such as a specific spatial and temporal resolution, dynamic range and number of touch points. Shape-adaptable multi-touch sensors extend this set with several additional requirements that are specific to cutting. We identify four desirable properties that a cuttable sensor sheet ideally should fulfill. Taken together, they define what is intuitively understood by "robustness" of the sensor to cutting.

Besides these intrinsic properties of the shape, extrinsic characteristics are affected by where and how the shape is placed on the sensor sheet:

- **Set of supported shapes:** The sensor should support a large set of cut-out shapes, including convex and non-convex shapes. This means that all electrodes on the cut-out shape remain functional.
- **Scale and aspect ratio invariance:** The cut-out shape can be of any size and aspect ratio, as long as it fits on the sheet.
- **Rotation invariance:** A specific shape should be supported regardless of its orientation on the sensor sheet.
- **Location invariance of the connector:** The sensor sheet has a connector to tether it to the controller. It should be possible to locate this connector at several locations or even any location on the cut-out shape, to integrate well with the specific requirements of the application.

While a working solution does not have to support all of these requirements, supporting more of them increases its usability, as the user can cut a wider variety of shapes and place them more freely on the sensor sheet.

6.4 Mathematical Problem Definition

The problem can be defined mathematically. The problem definition is illustrated in Fig. 6.4. Consider P to be a simple polygonal plane with $P \subset \mathbb{R}^2$. Let $E \subset P$ be a set of touch-sensitive electrodes e. Let $c \in P$ be a connector. P can be cut into simple polygons P' which contain c. The set of all these polygons is called P^*. Let L_c^e be the set of all wiring layouts on how c is connected to an individual electrode e with $L_c^e = \{f \in \mathscr{C}([0, \frac{3\pi}{2}]), f(0) = c \wedge f(\frac{3\pi}{2}) = e\}$, in which $\mathscr{C}([0, \frac{3\pi}{2}])$ is the set of all continuous functions from $[0, \frac{3\pi}{2}] \to \mathbb{R}$.

For a given set of electrodes $E \subset P$ and a fixed connector $c \in P$, we define the set of all possible wiring layouts as $L_C^E = \{f \in L_c^e, \forall e \in E\}$.

Furthermore, we have practical constraints:

1. There is at least one wire per electrode:
   $\exists f \in L_c^e \, \forall e \in E \, \forall c \in P$
2. Wires on the same layer are not allowed to cross:
   $\forall e \in E \, \forall e' \in E : e' \neq e \, \exists f \in L_c^e, f' \in L_c^{e'} : f(x) \neq f'(x) \, \forall x \in [0, \frac{3\pi}{2}]$

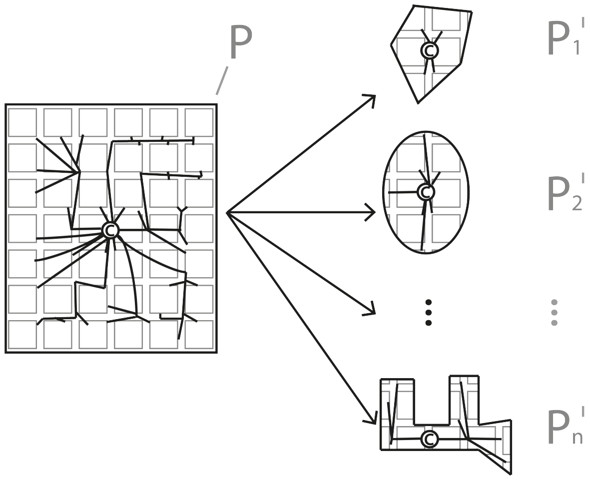


Figure 6.4: We want to find a geometric wiring layout that allows a given polygon P (left) to be cut into a set of polygons P^* (right) so that P^* is as big as possible and the remaining sensitive area on each cutout P'_n is as big as possible.

3. The amount of layers is finite.

We define the layout properties rotation, location and scale invariance as follows: Independently of how P is rotated, positioned or scaled before a cut is applied, there is at least one wire in L_C^E such that every electrode $e \in E$ on the cutout is connected to c.

In the following sections, we contribute layouts to create more robust multi-touch sensors.

6.5 Topologies for Cuttable Multi-touch Sensors

Multi-touch sensors are typically based on a matrix topology. As we have discussed in the related work section, this topology is not robust to cuts and removed areas and does not support a variety of cut-out shapes. Ideally, there is an alternative wiring layout that can be cut into any simple polygon. We are going to show that this is not the case. Since there is no general wiring layout, we contribute solutions that can support geometric subclasses of simple polygons.

These layouts are the result of combining two perspectives: a *wiring* perspective, which focuses on the internal organization of the sensor, and a *geometrical* perspective, which focuses on the shapes that can be cut out.

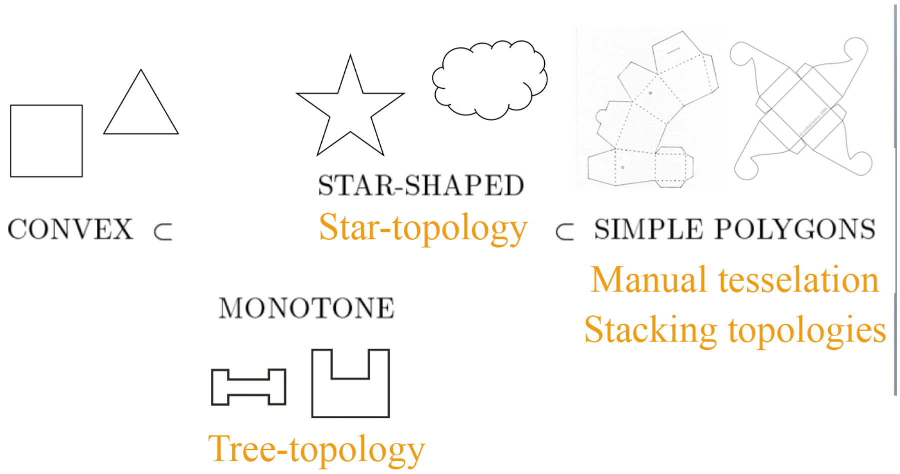


Figure 6.5: We contribute layouts for important subclasses of simple polygons. This includes layouts for convex, monotone and star-shaped polygons. The sensor topologies that support specific subclasses of polygons are indicated in orange.

Taking the *wiring* perspective, radial and tree structures are very common organizational principles in biological systems, e.g. in blood and nerve systems, in the physical structure of plants and in fungal structures [52]. This ensures not only effective transmission, but also protects vitally important parts in an inner area of the system. Also in computer networks, star and tree structures are among the most central topologies [112]. Meshes are a further promising structure, often applied in computer networks, which however require active routing components.

From the *geometrical* perspective, we can find subclasses for shapes of simple polygons that are also useful in the context of custom shaped sensors. We found these are convex, star-like and monotone polygons (see Fig. 6.5). Convex polygons are useful for basic shapes, such as triangles, rectangles or circles. Star-like and monotone polygons extend this set, such that shapes with concavity are also supported. This is important for e.g. cutting out shapes that act as connecting elements.

Figure 6.5 shows that both perspectives can be combined. We will show radial wiring structures that support convex and star-like polygons and tree structures that support monotone polygons.

Similarly to the conventional matrix topology, the proposed wiring topologies place the electrodes on a regular grid. This ensures a consistent spatial resolution across all areas of the sensor. In contrast to the standard matrix topology, they use point-to-

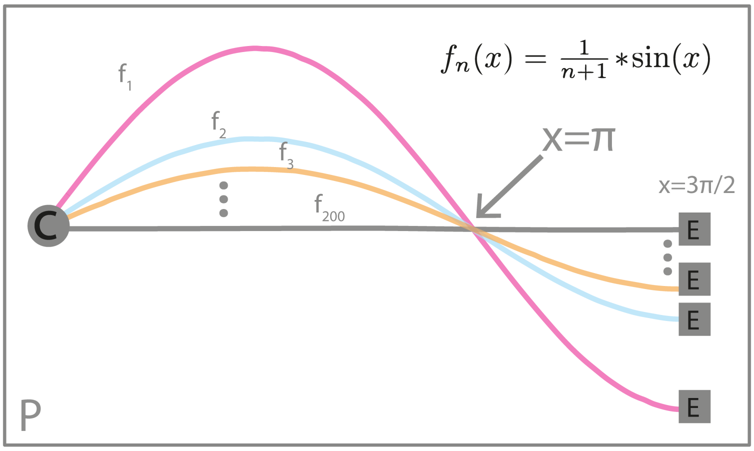


Figure 6.6: Modeling a cutout as a function. All wires cross at the same point. This results in an individual layer for the wiring layout for every cutout. Since there are infinitely many shapes, it results in an infinite number of layers.

point connections between connector and electrodes to avoid burst effects, in which loss of a single wire would result in irreversibly damaging multiple electrodes.

6.5.1 No Optimal Layout

Suppose that there exists an optimal layout for all polygons $P \subset \mathbb{R}^2$ and for all $c \in P$ with conditions (1)-(3) fulfilled. Now set $P = [0, 2\pi] \times [-1, 1], c = (0, 0), P_n' = \{(x, \frac{1}{n+1} * \sin(x)) \mid x \in [0, \frac{3\pi}{2}]\} \forall n \in \mathbb{N}$. Since every P_n' needs a wire layout to connect c and e_n, the corresponding wiring layout has to be exactly the function $f : [0, \frac{3\pi}{2}] \to [-1, 1] \quad f^n(x) = \frac{1}{n+1} * \sin(x)$. Since $f_n(\pi) = 0 \forall n \in \mathbb{N}$, condition (2) implies that the optimal layout needs one layer for every $n \in \mathbb{N}$ in order to connect c and e_n for all cutouts P_n'. This conflicts with condition (3). Figure 6.6 illustrates the preceding argumentation.

6.6 Star Topology

The first layout follows the geometry of a star (Figure 6.7a). The connector, which is used to tether the sensor sheet to a controller, is placed in the center. Wires extend radially to the electrodes. This topology can be realized with two layers (wires are routed underneath the electrodes with proper shielding) or as a single layer (wires are routed around the electrodes).

The star topology has a number of desirable properties. Due to the circular scheme,

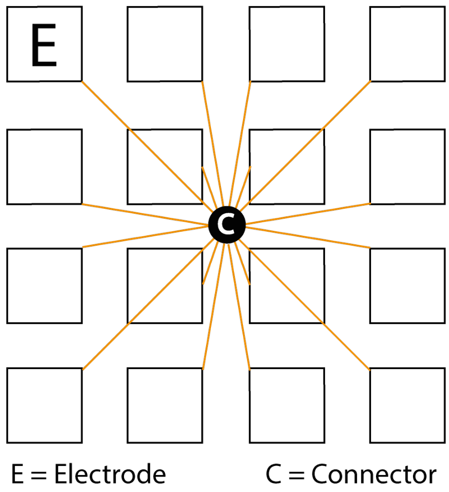


Figure 6.7: The star topology wires the connector radially with each electrode.

all wires run towards the center of the sheet on the shortest path between the electrode and the connector. This reduces the likelihood of a wire getting cut while the corresponding electrode remains on the sensor.

As outlined above, a shortcoming of the classical matrix topology is that an electrode can be affected by a cut at the far opposite end of the sensor. In the star topology, the electrode and its corresponding wire are always located within the same pie slice. Cuts in the remaining pie slices will never affect the electrode. Another benefit is that the topology is point-symmetric. A shape is supported no matter how it is rotated around the controller.

6.6.1 Deriving the Layout Mathematically

We will derive the star topology in two steps: first by showing that it can support any convex polygon and then by showing that is optimal for star-like polygons.

We call a set of points $K \subset P$ the kernel of T if all points of P are visible from every point in the kernel. Then a polygon P is convex if $K = P$.

If P is cut into a set of convex shapes P_c^* then there is a minimum intersection area, since every cutout includes c. Following the definition of convex shapes, all electrodes are visible via a line of sight from c and $c \in P' \; \forall \; convex \; P' \in P_c^*$. This directly translates into a point-symmetric, radial layout L_{star} in which all electrodes are connected via a straight line with c (see Fig. 6.8): $L_{star} = \{f_i \in linear \; function, \; with \; f_i(0) =$

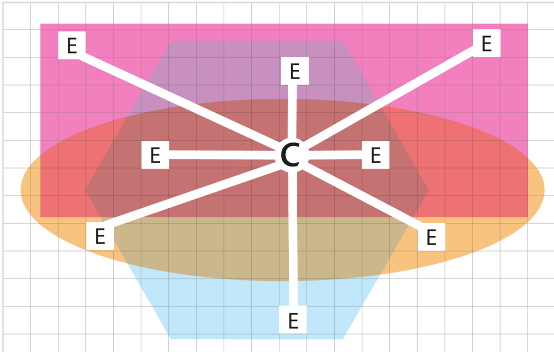


Figure 6.8: Three shapes are cut out of P. Since all shapes are convex, every electrode can be reached via a line of sight, resulting in a radial wiring layout.

$c, f_i(1) = e; \forall i \in \mathbb{N}\ \forall e_i \in E(i \in \mathbb{N})\}$.

L_{star} is rotation-, scale- and translation-invariant, since all scaled, rotated and translated variations of a specific cutout are also included in P_c^*.

Now every possible convex cutout $P_c^{'} \in P_c^*$ includes c. Since $P_c^{'}$ is convex, $P_c^{'} = K$ and therefore all $e \in P_c^{'}$ are by definition visible via line of sight from c, and therefore still connected with c via the star topology. If there exist $e^{'}, e^{''} \in P_c^{'}$ with $e^{'}$ and $e^{''}$ being on one line of sight from c, then we propose two alternative wiring layouts in order to solve this: (1) Move $e^{''}$ to a separate layer. (2) Reposition the connector c such that there are no two electrodes on one line of sight from c. Practically, the electrodes have a minimal physical size (e.g. 5×5 mm). We could position the wires in such a manner that they are not crossing at all just by connecting the wires not to the center of the electrodes (see Figure 6.7).

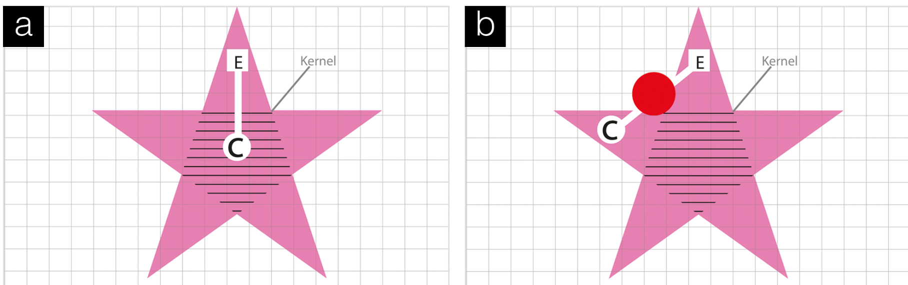


Figure 6.9: a) As long as the c is inside the kernel, the shape is supported. (b) As soon as c is outside, some electrodes cannot be connected anymore.

Extending upon the definition of convex polygons, a polygon is star-shaped, if $K \neq \emptyset$. This implies that L_{star} is not location-invariant for star-shaped polygons, since c has to be inside the kernel (see Fig. 6.9).

6.6.2 Implications for Applications and Interactions

This topology supports a large variety of shapes, including triangles, convex rectangles and ellipses (see Fig. 6.10a). These shapes can be located anywhere on the sheet as long as the connector is inside the shape (realizing location invariance). Moreover, the shapes can have arbitrary scale and aspect ratio. The star topology also supports some non-convex shapes, such as “heart-like”, “cloud-like” or “star-like” shapes, provided they are properly placed on the sheet (see Fig. 6.10b). However, it only partially supports more complex shapes, such as the ones depicted in Figure 6.14.

6.6.3 Implementation

We implemented a prototype sensor sheet in letter size, which is based on the star topology and has 36 electrodes (Fig. 6.11). We printed fine radial lines on the front side to communicate the wiring layout to the user. As a rule of thumb, the shape will be supported if each line is cut no more than once.

6.7 Tree Topology

In the tree topology, all electrodes are orthogonally connected to one stream of wires, which is then connected to the controller (Fig. 6.11a).

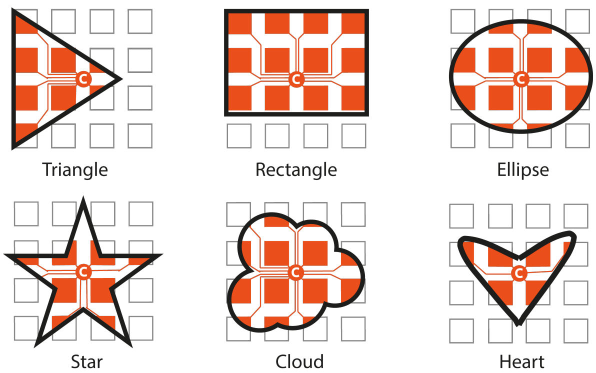


Figure 6.10: a) The star topology supports a large variety of convex shapes including triangles, rectangles and ellipses. b) It also supports shapes that introduce concavity, provided they are properly placed.

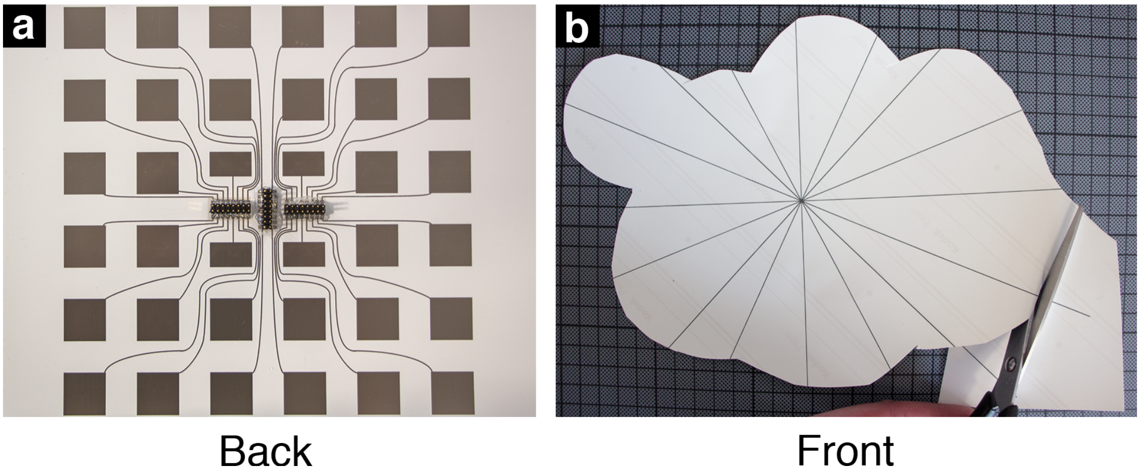


Figure 6.11: a) Back of the fabricated multi-touch sensor featuring a grid of 6x6 electrodes. b) To guide the user, the front side features fine printed lines.

6.7.1 Deriving the Layout Mathematically

A polygon P in the plane is called monotone with respect to a straight line G, if every line orthogonal to G intersects the outline of P at most twice. Given that, we can find a novel layout L_{tree}. We thereby insert a wire *stem* and connect each electrode first with *stem* and then indirectly via the stem G to c (see Fig. 6.13a). Given a set of monotone shaped cutouts P_c^*, for every concrete cutout, there will be a line L which connects the electrode e to the stem G.

When two electrodes lay on the same line of sight from G, we proceed similarly to the star layout, either by moving one of the electrodes to a separate layer, or by juxtaposing the wires (see Figure 6.12).

As shown in Fig. 6.13b, the position and orientation of G might differ between

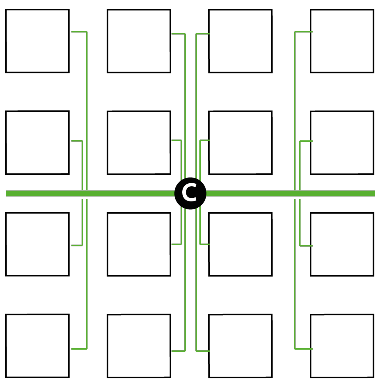


Figure 6.12: In the tree topology, all wires are routed to a central stem.

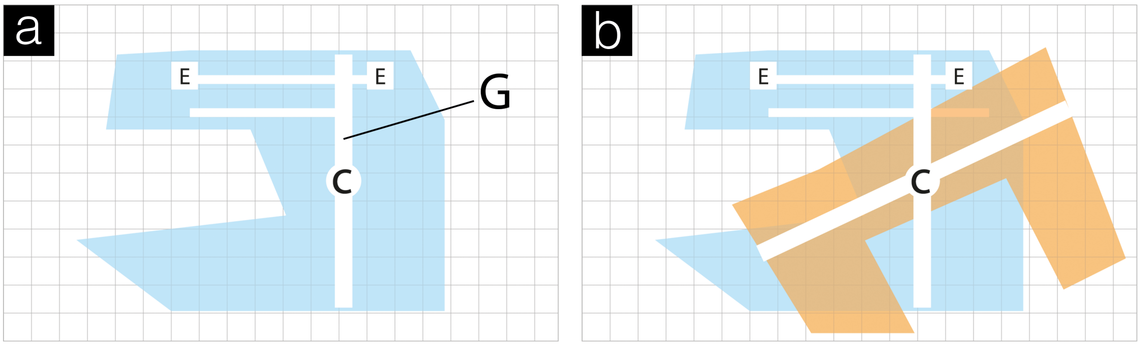


Figure 6.13: (a) To support monotone polygons, every electrode is orthogonally connected to the stem, which then connects to the connector. (b) The tree-shaped layout is not rotation- and position-invariant. The user has to carefully place the cutout on P.

cutouts.

6.7.2 Implications for Applications and Interactions

Through the indirection in how electrodes are wired with the connector, the tree topology supports shapes that are not supported by the star (and vice versa). This specifically includes shapes that introduce concavity, as depicted in Figure 6.14a, b. Carve-outs are only partially supported (see Fig. 6.14c,d).

The tree has the limitation that it is not rotation-invariant, but it supports different sizes and aspect ratios of the cut-out shape.

6.7.3 Implementation

We implemented a first instantiation of a letter-sized sensor sheet, depicted in Fig. 6.15. We printed fine lines on the paper to provide guidance about which cuts are supported.

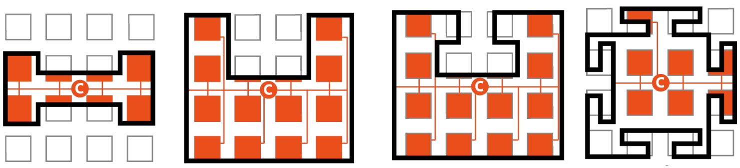


Figure 6.14: The tree supports carve-outs at the border of a shape (a,b). Puzzle-shaped connection pieces are partially supported (c,d).

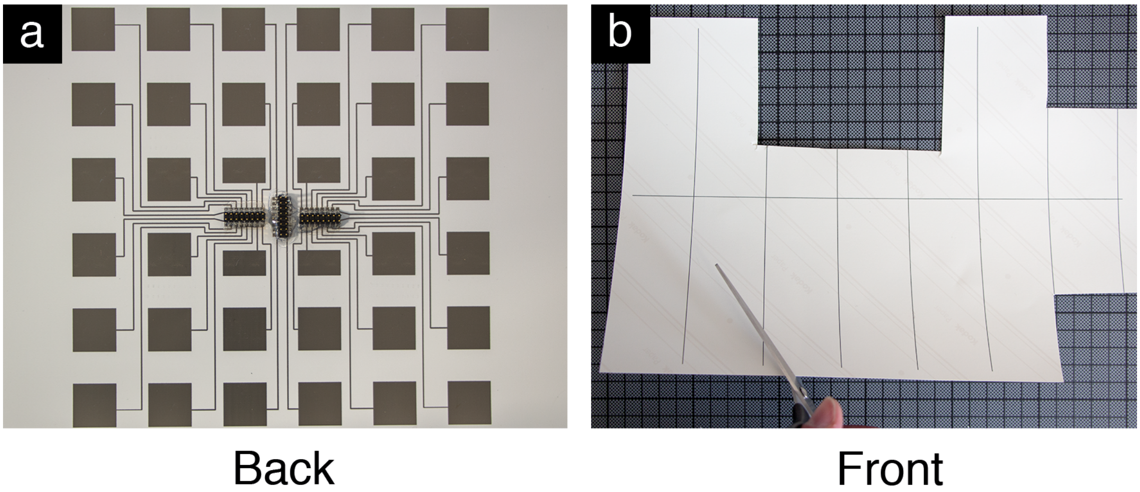


Figure 6.15: a) Prototype of a multi-touch sensor that implements the tree topology. b) As long as the user does not cut a line twice, the shape is supported.

6.8 Towards Supporting Simple Polygons

In this section, we show two strategies for supporting simple polygons. The first is to manually tessellate the desired shape into star- and tree-shaped tiles. By connecting the individual tiles together, the user can form a sensor sheet of the desired shape. The second is to stack individual layouts to make the multi-layer sensor sheet more robust against cuts.

6.8.1 Manual Tessellation

We propose a technique that allows users to create sensor sheets for arbitrary simple polygons. From computational geometry it is known that each shape can be tessellated into multiple convex [72] or monotone polygons [72]. Manual tessellation is done in two easy steps:

1. The user manually tessellates the desired shape into a set of convex, star-shaped and monotone polygons (see Fig. 6.16).

2. Each of the tessels is then cut out and then all individual sheets are connected together.

6.8.2 Stacking Layouts

In this section we show how to further increase the robustness of the sensor and to support more shapes by combining two or more topologies in one sensor sheet. Since

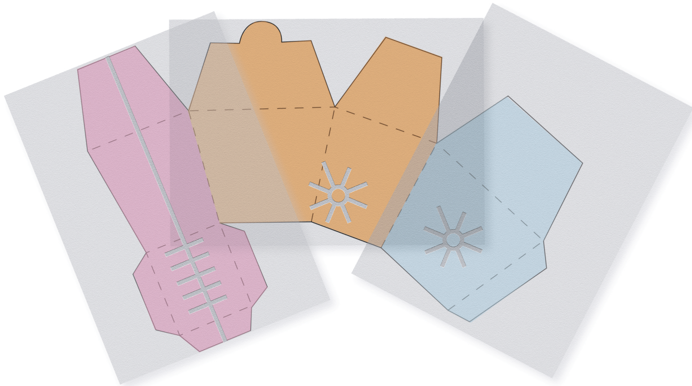


Figure 6.16: The user tessellates the desired shape into star-shaped and monotone polygons. The shape is then covered by connecting multiple individual sensor sheets.

different topologies each have their unique strengths and drawbacks, combining them adds valuable redundancy and geometric robustness. Each electrode is connected to the connector via two or more potentially very different paths. Note that this does not increase the number of pins required at the hardware controller, since all wires from all layers that are connected to the same electrode are combined at the connector.

Conceptually, we distinguish between two cases, namely overlaying (1) distinct topologies and/or (2) the same topology:

1. Overlaying distinct topologies can combine their advantages. For instance, consider overlaying a star topology with a tree topology. This would support all shapes of Fig. 6.10 and Fig. 6.14a, b.

2. Overlaying the same topology can overcome some limitations inherent to the specific topology by repeating it in a rotated or displaced manner. For instance,

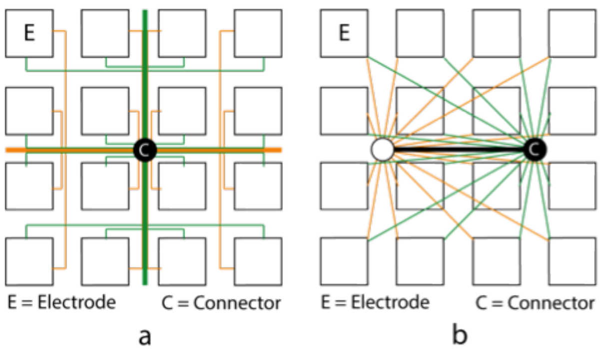


Figure 6.17: Overlaying two tree topologies improves rotation invariance. b) Overlaying two star topologies allows for a wider range of supported shapes.

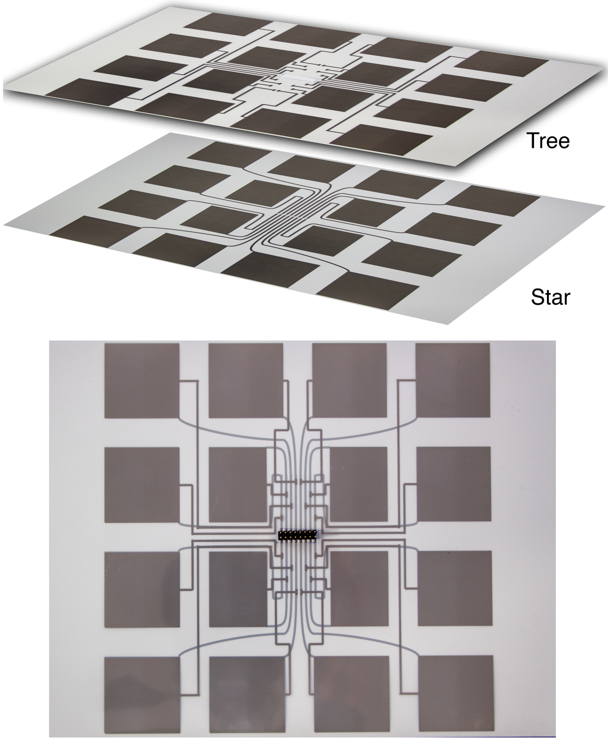


Figure 6.18: Prototype of a dual-layer sensor with overlaid tree and star topologies for a 4 x 4 sensor sheet. The tree topology is printed on a transparent PET film. Both layers are connected using 3M conductive z-Tape.

consider overlaying two tree layouts rotated by 90 degrees around the center point (see Fig. 6.17a). This makes the layout invariant to 90 degree rotations. Overlaying two star layouts in a displaced manner (see Fig. 6.17b) allows for supporting shapes with certain concave elements, which otherwise would be supported only by the tree (see Fig. 6.14a,b).

Mathematically, the outline of the shape can be divided in segments. As long as each segment can be represented by a valid function in at least one of the overlaid topologies, the shape is supported.

We implemented a first prototype of a sensor with two overlaid topologies, an overlay of a tree and a star. Figure 6.18a shows how the tree and star are overlaid; Figure 6.18b shows the compound sensor.

6.9 Increasing Robustness Within a Topology

In this section, we contribute methods for encoding redundancy within a topology.

6.9.1 Basic Redundant Wiring

Figure 6.19 (a1) shows an example of an electrode that is cut in two pieces. While a considerable part of the electrode remains on the sensor sheet, it cannot be read, since the wire is cut off. Connecting each electrode with two redundant wires from its opposite sides makes the sensor robust to such situations (see Fig. 6.19 a2)). Moreover, this adds robustness to cases where one of the wires is damaged (see Fig. 6.19b). This rather simplistic form of redundancy requires double the amount of wires.

6.9.2 Printed Forward Error Correction

A more advanced solution adds redundancy with fewer wires. It is inspired by coding theory. Forward error correction (FEC) provides mechanisms to encode data in a redundant way to cope with errors in data transmitted via an unreliable channel [58]. Examples are the parity bit (error detection) or the Hamming code (error correction). The underlying idea is to calculate a redundant symbol as a function of several payload symbols.

Based on this principle, we contribute a solution to encode an FEC mechanism right on the printout; it involves a specific wiring scheme and a modified electrode design. Our approach is depicted in Fig. 6.20a. Both electrodes are read independently via direct wires a and b. In addition, a redundant wire c connects to both electrodes. In contrast to the above example of the parity bit, the sensor readings are not binary. Each electrode captures a dynamic range, so it gives a continuous value. Nevertheless, a combined reading of two or more electrodes can be designed, since the capacitance of two capacitors adds up if they are connected in a parallel circuit. Therefore, wire c connects to both electrodes in a parallel circuit; it adds

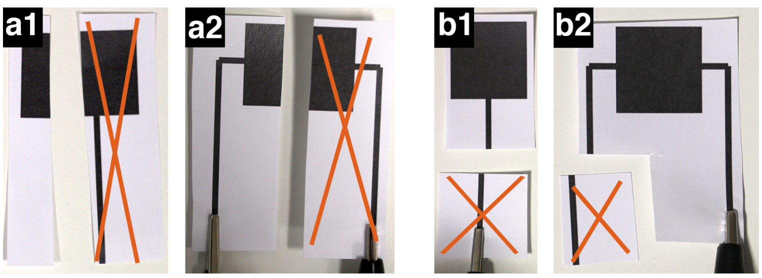


Figure 6.19: Basic form of redundant wiring: a cut on the electrode (a1) or a cut on the wire (b1) can be compensated for by adding a redundant wire (a2 and b2).

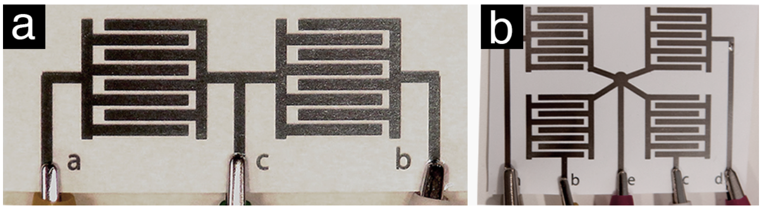


Figure 6.20: Printed forward error correction (FEC) for reconstructing sensor readings from a missing wire: a) 2+1 redundancy, b) 4+1 redundancy.

up their respective capacitance. To prevent wire c from generating a short-circuit between both electrodes, we split each electrode into two interdigitated parts which are mutually insulated. This ensures independent reading of a, b and c.

Redundancy: As long as any two wires of the block remain functional, the controller can reconstruct the value of the non-functional third wire, since $c = a + b$. If at any time the readings do not sum up (within a defined threshold) and one of the values is close to zero, it can be safely assumed this wire is not functional. Compared to the basic solution, this FEC approach reduces the number of redundant wires by 50%. However, only one of three wires can be removed instead of one of two wires.

This approach allows varying the proportion of redundancy in the encoding. Figure 6.20b shows how a block of 4 electrodes can be wired with one additional redundant wire. In this case, the number of wires added through redundancy is only 25% of the number of payload wires. All electrode readings can be reconstructed as long as no more than one wire is broken, using the formula $e = a + b + c + d$. One sensor sheet may contain blocks of different redundancy levels; for instance outer areas, which are prone to cuts, could have more redundancy than inner areas. Theoretically, more electrodes can be connected with one redundant wire. In practice, the limit is defined by the sensing resolution of the controller. Beyond some point, imprecise readings, which add up, result in an imprecise reconstruction of a missing value.

6.9.3 Graceful Degradation

The FEC encoding has one important beneficial side-effect. If two or more wires in a block are damaged, it is not possible to fully reconstruct the original sensor readings. However, due to the redundant wire, the sensing resolution gracefully degrades. If the redundant wire remains on the sensor sheet, it tells whether touch interaction is occurring somewhere in the block. Hence, the sensor is still providing data, albeit with a reduced resolution in that area.

6.10 Implementation

We implemented our proof-of-concept prototypes with conductive inkjet printing. In contrast to larger-scale roll-to-roll processing, this allows us to easily experiment with different topologies and does not require a complex setup. The principles and technical solutions introduced in this chapter transfer to other printing technologies that are capable of printing passive conductive traces. We are using silver ink to print conductive traces and electrodes on photo paper using an off-the-shelf inkjet printer [10]. The method requires no post-process sintering and is functional within minutes after printing. The sheet resistance is $0.21\Omega/\square$, with a thickness of 0.5mm and a length of 50mm.

For ease of implementation, we picked an electrode size of 20x20mm with an offset of 15mm. However, the approach supports smaller sizes; the maximum number of electrodes is defined by the microcontroller. Our wires have a minimum width of 0.5mm, which is defined by the printing process that we use. Industrial printing solutions allow for a much smaller width, down to 40nm[1].

We realized the multi-layer sensor by printing each layer on a separate substrate and combining them with Z-Axis Electrically Conductive Tape from 3M[2]. This is an adhesive transfer tape with anisotropic electrical conductivity only on the z-axis, designed for interconnecting flexible circuits. The tape has the very important property that it can be easily cut. Our proof-of-concept implementation has two layers. We use regular Scotch tape to insulate both layers from each other. In industrial-scale production, several conductive and insulating layers would be printed on top of each other, on the same substrate.

The implementation uses time-multiplexed loading mode capacitive sensing for detecting touch input. Processing of sensor readings is performed on an ATmega2560 microcontroller, which runs the Arduino CapSense Library[3] with a 10 $M\Omega$ resistor per electrode. The controller features up to 48 input pins. To support a higher

[1] http://www.semi.org/en/node/44156
[2] 3M Electrically Conductive Adhesive Transfer Tape 9703
[3] http://playground.arduino.cc//Main/CapacitiveSensor

number of electrodes, multiple controllers can be connected. We picked a fairly large size for ease of experimenting with different topologies. An industrial solution would support a much higher number of input pins per microcontroller. The connector is attached to the sensor sheet using 3M Z-Tape.

We normalize the raw data from partially cut electrodes. We used a simple calibration step. After cutting the sensor to a new shape, the user moves her flat hand once over the entire sensor, ensuring that the entire surface is covered. During this calibration step, the processor updates a calibration matrix, which holds one entry per electrode. Each entry stores the maximum capacitive value that is registered at this electrode during calibration. This maximum reading is proportional to the size of the remaining electrode.

6.11 Evaluation

To validate the technical principles contributed in this chapter, we performed two evaluations: (1) A mathematical simulation demonstrates that the proposed topologies support a variety of cut-out shapes. The results provide guidance in choosing a suitable topology. (2) A series of technical experiments demonstrate the technical feasibility of the principles.

6.11.1 Mathematical Simulation

We implemented a simulation framework, which takes any sensor topology and any set of 2D shapes as input, modeled in SVG files. To account for the requirements listed above, the framework automatically scales, moves and rotates these shapes to simulate a large variety of cut-out shapes over the entire sensor sheet. As a performance index, it calculates the average proportion of the area on the cut-out that remains touch-interactive.

We simulate a *sensor sheet* of 266 x 266 mm, covered with a rectangular array of 26 x 26 electrodes, each sized 10 x 10 mm and spaced 0.25 mm apart.

We simulate the following *topologies:* grid as the baseline (G), star (S), tree (T), overlaid star and tree (ST), overlaid tree and tree rotated by 90° around the center point (TT), as well as overlaid star, tree and rotated tree (STT).

In addition to the simulation of a multi-touch sheet that can be manufactured with industrial machinery, we also simulated the prototypes that we have built, using the dimensions and topologies introduced earlier in this chapter.

We simulate the following *cut-out shapes:* triangle, rectangle, ellipse, star (Fig. 6.11), carve-out (Fig. 6.14b) and puzzle-shaped connector (Fig. 6.14d). The triangle, rectangle and ellipse are very basic shapes that are commonly used in a wide variety of tasks. The star, carve-out and connector represent more complex shapes that are used in crafting and prototyping.

The minimum size of the shape has a bounding box of 150 x 150 mm, which is the width of an A5 sheet. A minimum of 16 non-uniform scales are randomly generated, with a maximum step size of 1.0; a minimum of 358 random locations are generated, with a maximum step size of 12.5 mm; and a minimum of 8 random rotation angles are generated, with a maximum step size of 22.5 degrees.

The simulation algorithm calculates the performance index for each combination of $location_{(x,y)} * scale_{(x,y)} * rotation\ of\ the\ shape$ as follows:

$$SensingCoverage = \frac{A_{shape,el}}{A_{shape}} * \frac{A_{sheet}}{A_{sheet,el}}$$

with A_{shape} being the overall area of the cut-out shape, $A_{shape,el}$ being the area on the cut-out shape covered with sensor electrodes, A_{sheet} being the overall area of the entire sensor sheet, and $A_{sheet,el}$ being the area on the entire sensor covered with sensor electrodes. The second fraction normalizes a more or less dense electrode arrangement on the sensor sheet. A partially cut electrode is considered functional if the remainder is still tethered to the connector and has at least 1/3 of the original electrode size. In this case, the readings are still clearly distinguishable from touching the wire. This is a conservative estimate.

The result is calculated as the average of the more than 30,000 simulated variations of each shape. Variations that do not entirely fit on the sensor sheet or do not contain the connector are not considered.

Results

As discussed above, the conventional grid topology, our baseline, supports only a few very specific shapes (most notably rectangles, and a few carefully selected polygons).

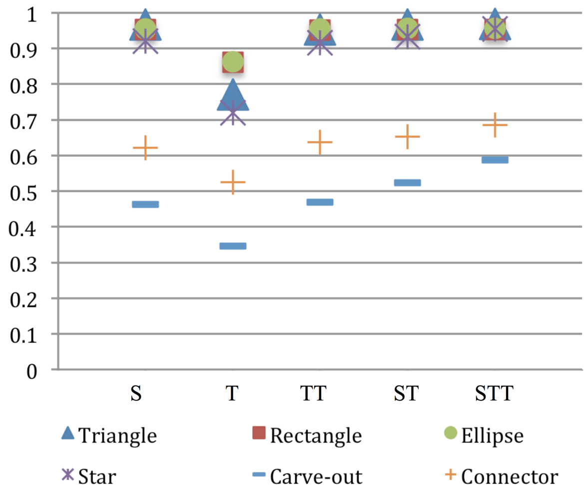


Figure 6.21: Sensing coverage of different shapes using various topologies. Shapes are freely rotated, translated and scaled on the sensor sheet.

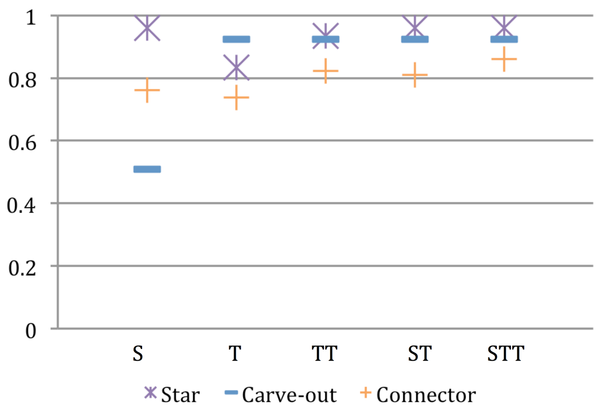


Figure 6.22: Sensing coverage of complex shapes when placed at one location without rotating, but with scaling.

In all cases, two sides of the shape must be straight lines that are laid out in a 90 degree angle. Moreover, these shapes have to be placed at one specific location on the sensor and must not be rotated.

Figure 6.21 shows the simulation results for the new topologies that extend considerably over the baseline. A large set of common shapes (triangles, rectangles, ellipses) can be placed at arbitrary locations and with any rotation on the sensor, yielding an average coverage of around 96%. The fabricated prototype has an average coverage of 86%. The tree topology performs less well, but still offers coverage above 83% (80% for the prototype).

Combinations of several topologies do not considerably increase the coverage for these simple shapes. In contrast, the coverage for complex shapes (star, carve-out, connector) is increased by using overlaid topologies. Particularly the combinations of star and tree improve the results. However, even with overlaid topologies, an average of roughly one third of the surface of the carve-out and connector shapes remain uncovered. This is because we simulate arbitrary placement and rotation on the sensor sheet.

For these complex shapes, we performed a second simulation in which we did not require location invariance and rotation invariance, but maintained scale invariance. From a practical perspective this means the user has to adjust the shape at a specific location and rotary angle. The results (Fig. 6.22) show that in this case even complex shapes are well supported. Even the most complex connector shape yields an average coverage of more than 85% (SD=1.6%).

Furthermore, we performed all simulations for topologies with redundant wiring added. This increased the results from 3% to 15%, with the most improvement for the tree topology.

6.11.2 Technical Experiments

We conducted a series of technical experiments to demonstrate the technical feasibility of the principles. Since our implementation is based on a standard method for capacitive sensing, we did not evaluate basic touch sensing in detail, but rather focused on the critical technical aspects that are added by our contributions: we evaluated whether electrodes which fully or partially remain on the cut-out sensor are functional, whether dual-layer sensing is possible and whether the forward error correction can be realized.

Figure 6.23 shows a letter-sized sensor sheet that uses the star topology. It is cut into a user-defined shape (left part within the image). The sensor readings (right part) show that electrodes that remain on the cut-out are functional and capable of detecting touch input.

To evaluate the feasibility of cutting in more detail, we tested what minimum size of a partially cut electrode allows it to remain functional with a variety of materials the sensor is sandwiched into (paper, 3mm thick cardboard, 3mm acrylic, 3mm plywood). If the electrode gets too small, it is not possible to reliably distinguish

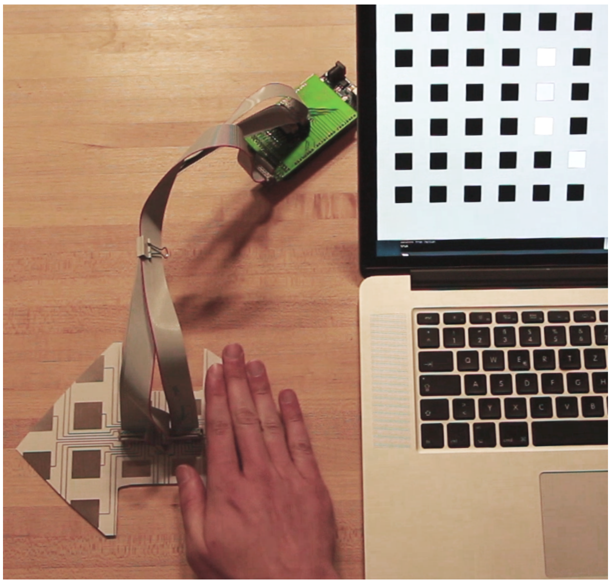


Figure 6.23: Normalized sensor readings of a partially cut sensor sheet

whether the user is touching the electrode or touching its wire. Table 6.1 shows data from electrodes of 2x2cm size, according to the dimensions used in the simulation. The data shows that if only 1/3 of the electrode remains, touch input can still be reliably analyzed.

In a third experiment, we studied whether a multi-layer sensor can be cut without creating a short circuit between the two layers. As expected, we were able to validate that the sensor remains functional and both layers independently connect the electrodes with the connector.

Last, we tested the forward error correction principle. Figure 6.24 shows the data plot for the setup illustrated in Fig. 6.20a. The data shows that the capacitive measurements of both electrodes roughly add up in the redundant FEC wire. The data demonstrates the feasibility of FEC, but shows that a proper selection of the threshold for sum detection is required, ideally set individually for each electrode. This could be done in the calibration step proposed above.

Material / Electrode Size	**Wire**	**1/3**	**2/3**	**Full**
Paper	0.34	1.90	5.30	8.12
Cardboard	0.06	0.13	0.26	0.34
Acrylic	0.07	0.12	0.28	0.37
Plywood	0.06	0.10	0.22	0.32

Table 6.1: Capacitive sensor readings in pF of partially cut electrodes

6.12 Benefits and Limitations

Results from the evaluation show that the contributed sensor topologies support a variety of standard and more complex shapes. Those with a convex shape can be effectively supported by using just one layer with the star topology. They are rotation-, location- and scale-invariant, providing a free-form cutting experience which comes close to cutting conventional, touch-insensitive materials. Overlaid topologies provide improved support for more complex shapes. Due to the infinite number of possible shapes, our validation can only provide some representative examples to shed light on the space of supported shapes.

Our implementation of a cuttable Letter-sized sensor sheet has a lower number and density of electrodes than used in the simulation and is restricted to two layers. These restrictions are due to our prototypical manufacturing method. However, the dimensions were sufficient to test and validate the electronic properties of the sensor. The simulation results show what can be achieved with higher-density and multi-layer industrial fabrication.

The 1-pin-per-electrode design requires more wires than the traditional grid, which raises questions of scalability. This is an inherent trade-off of the design space: either requiring fewer wires, which comes at the cost of robustness, or making it robust to cuts using additional wires. In order to alleviate this issue we propose the following strategies: (1) While current print technologies can already realize wire widths down to 40nm[4], which allows for a large number of wires on a single

[4]http://www.semi.org/en/node/44156

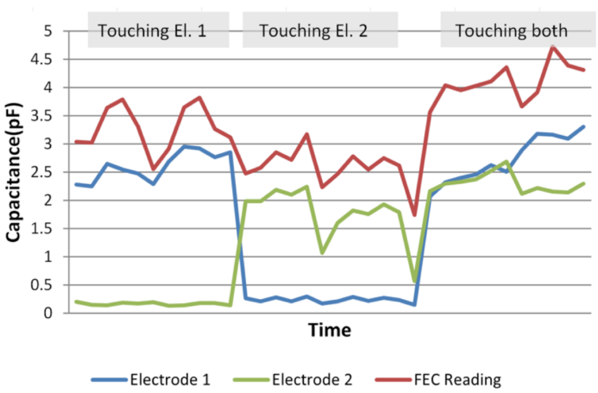


Figure 6.24: Capacitive sensor readings of a 2+1 redundant forward error correction block (depicted in Fig. 6.20a).

layer, wires can also be outsourced to one or more additional layers, using multi-layer printing. (2) Attaching multiplexers at the connector allows the number of input pins to be reduced significantly. (3) From a longer-term perspective, printing flexible multiplexers directly on the sensor sheet allows the bundling of adjacent wires. Future work should also explore sensors with mixed topologies. These could comprise many smaller areas that are internally wired with the efficient grid design and connected with the controller using our more robust topologies.

Our implementation requires the connector to be located at one specific location on the sheet. Hence, only one shape can be cut out of a sheet. With larger sheets, this possibly wastes large portions of the material. Several spatially distributed access points on the same sheet could be realized by printing multiple layers with displaced topologies. This enables several shapes to be cut out of one sheet.

The approach presented in this chapter is compatible with a wide variety of non-conductive materials. As first examples, we discussed paper, cardboard, acrylic and plywood. For use with transparent materials, the sensor grid could be made transparent using indium tin oxide (ITO).

6.13 Conclusions

In this chapter, we contributed principles for a printed multi-touch sensor that is robust against cuts and removed areas. The sensor can be embedded within conventional materials and touch-enable them, while maintaining the very direct customization possibilities of the material. The principles are inspired by topology and coding theory. We introduced novel topologies for the circuitry layout of multi-touch sensors that support a variety of cut-out shapes. Furthermore, we showed how to increase the set of supported shapes by combining several topologies and by printing a redundancy scheme that realizes a form of forward error correction. We evaluated strengths and limitations of the topologies in a mathematical simulation and presented a first proof-of-concept prototype to demonstrate the possibilities for crafting and prototyping.

Chapter 7

Conclusions

In this work, we presented novel user interfaces and fabrication processes for thin-film interactive surfaces with a custom shape. These are designed and fabricated by the end-user, which allows for highly personal solutions. Within a preceding analysis, we determined a series of requirements for these interfaces (Chapter 2): (1) fabrication of custom-shaped interactive displays; (2) highly interactive 3D objects on the basis of 2D surfaces; and (3) definition of shape and function at use time or at design time. Orthogonally to these requirements, it should be possible to embed interactive surfaces into the different materials to better integrate them into the environment.

Based on these requirements, we developed three solutions: With PrintScreen, we presented a novel approach that enables non-experts to produce custom touch-displays (Chapter 4). As the displays are represented as polygons during digital design, they can be created in a standard vector graphic environment. We structured and extended the design space of possible display types, by offering a set of display primitives that the user can refer to during the creation process. In order to physically instantiate the digital design, we presented printing processes that can be executed by the non-expert. These make it possible to print displays within a short time as well as to print displays that have particular properties (e.g. translucence or integration with a traditional print). We also show that one can print directly onto various substrates. Lastly, a technical solution was presented to combine touch with the displays.

On this basis, we presented *Foldio*, a design and fabrication approach for highly interactive folded 3D objects (Chapter 5). We thereby built on the philosophy of the first contribution by digitally defining shape and functionality, and physically instantiating these subsequently. The digital design environment allows the user to annotate the 3D model with interactive elements. These encompass touch input and display output on the outer surface, along with sensing of shape change and actuation. Thus, input and output interaction with the surface as well as interactions with the physical structure of the folded object can be realized. Based on the annotated 3D model, we automatically generate folding and printing patterns as well as method stubs for the interactive elements.

The last contribution focused on physically forming the shape at the time of use. We presented a novel cuttable multi-touch sensor foil, which remains functional after being cut (Chapter 6). Thus, the same tools that would normally be used for cutting the material can still be used here (e.g. scissors). Based on observations of biological systems as well as computational geometry, we present novel internal wiring layouts, which make the sensor resistant to damages induced by cuts. The robustness can be further increased by compositing these layouts and by applying printed forward error correction within an individual layout.

We demonstrated the rich ways in which custom thin-film interactive surfaces can be applied with a variety of example applications that cover the areas of ubiquitous, mobile and wearable computing, prototyping, crafting and interactive packaging.

7.1 Directions for Future Work

Based on the work presented, we identified promising directions for future research. These are as follows:

Feedback Loop Between Physical and Digital Shape Customization: The work that was presented in this thesis allows the user to either specify the shape digitally and then to physically instantiate it, or to directly customize it physically. Future work should explore a feedback loop between the digital specification and the physical shape. Applied in rapid prototyping, the digital shape of the multi-touch sensor (see Chapter 6) would stay in sync with the shape that has been cut physically. The sensor layout could be automatically optimized and then fabricated for the next iteration of the prototype, removing the need for an additional digital modeling step.

Creating Digital Interactive Models: Foldio (Chapter 5) enabled the user to combine the affordances of the folded object (e.g. a corner) with interactive controls. Future work should extend this approach to objects with a higher geometric resolution (e.g. a sphere). This would require novel user interfaces that automatically analyze the affordances of the 3D geometry and propose geometrically adapted digital controls that fit to that particular shape. It would also require novel fabrication processes for interactive 3D models with a high geometric resolution.

Automatic and Integrated Fabrication of Personal Interactive Surfaces: Both PrintScreen (Chapter 4) and Foldio (Chapter 5) require manual fabrication steps. Future work should further automatize the fabrication of interactive objects, so that the surface or object is created without the involvement of the user. Approaches for self-folding machines that are applied in robotics [12] are a very promising direction.

7.2 Concluding Remarks

The way objects and surfaces are fabricated is changing. Novel printing technologies allow individuals to create custom solutions, exactly matching their specifications, in low quantity. However, these are lacking interactivity. The concepts presented in this work enable the non-expert to design and fabricate custom interactive surfaces and objects. We envision this to be the beginning of a new class of objects and surfaces, whose interactivity and shape correspond exactly to the needs of users.

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