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Foldlets: String-Actuated Shape Change for Disappearing Textile Interfaces

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Abstract

Textile interfaces allow to be integrated into everyday items like furniture, but permanently alter the object's aesthetic look and feel in the process. This thesis presents Foldlets: A novel approach to shape-changing textile interfaces using string-actuation to create folds in the fabric that can be hidden when not needed. Foldlets enable eyes-free interaction and can be actuated silently by making use of shape memory alloys. This thesis introduces consistent methods and guidelines for designing simple geometrical shapes, which can be combined to create individual icons and composed interfaces. We demonstrate the creation of segmented displays and pixel grids that enable the display of completely dynamic shapes. Additionally, we present the fabrication processes of Foldlets as well as accompanying structures that enable silent and automated actuation. Finally, five fully functional prototypes are created, representing different application scenarios of Foldlets in a smart home environment.

Überblick

Textile Benutzeroberflächen können in Alltagsgegenstände wie Möbelstücke integriert werden, ändern dadurch allerdings das ästethische Erscheinungsbild und das haptische Empfinden des Objektes. Diese Arbeit präsentiert Foldlets: Einen neuartigen Ansatz für formverändernde textile Benutzeroberflächen, welcher Fadenantrieb nutzt um Falten im Stoff zu erzeugen, die versteckt werden können, wenn sie nicht gebraucht werden. Foldlets ermöglichen eine blickfreie Interaktion und können geräuschlos durch die Nutzung von Shape Memory Alloys betätigt werden. Diese Arbeit beschreibt konsistente Methoden und Richtlinien, um simple geometrische Formen zu kreieren. Diese können kombiniert werden, um individuelle Symbole und zusammengesetzte Benutzeroberflächen zu erschaffen. Wir demonstrieren die Erstellung segmentierter Anzeigen und Pixelraster, welche die Darstellung völlig dynamischer Formen ermöglichen. Zusätzlich präsentieren wir die Herstellungsprozesse von Foldlets sowie die zugehörigen Strukturen, welche eine lautlose und automatisierte Aktivierung ermöglichen. Schließlich werden fünf voll funktionsfähige Prototypen hergestellt, die verschiedene Anwendungen von Foldlets in einer Smart-Home Umgebung repräsentieren.

Acknowledgments

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Finally, special thanks to my partner Jan Erik, for your constant love and support throughout this thesis and my university life, especially in stressful times. You constantly motivate me to achieve my best.

Conventions

Throughout this thesis we use the following conventions:

- The thesis is written in American English.
- The first person is written in plural form.
- Unidentified third persons are described in plural form.

Where appropriate, paragraphs are summarized by one or two sentences that are positioned at the margin of the page.

This is a summary of a paragraph.

Chapter 1

Introduction

In our everyday lives, we mostly interact with technology using touch screens, keyboards, buttons, or remote controllers that are made of glass, plastic, or metal. Those materials can seem rigid and cold, making them feel out of place in comfortable environments like our living rooms. Finding new and unique ways of interacting with technology is becoming more important as time passes.

Textile Interfaces offer a comfortable way to interact with technology.

The research field of Textile Interfaces aims to integrate electronic components into fabrics, creating unique user interfaces and new interaction techniques. Fabric allows for being touched, stroked, grabbed, and deformed, enabling vast new and unique interaction possibilities to be explored. The field has already produced a multitude of applications for different use cases. By creating clothing like sleeves that recognize arm gestures [Parzer et al., 2017] or smart pants pockets that sense their content [Wu et al., 2021], textile interfaces have been applied to the human body. They can also be put on furniture pieces [Brauner et al., 2017], or everyday items like cushions [Suzuki et al., 2020]. Interacting with textiles evokes feelings of comfort and warmth. Therefore, textile interfaces can create a more personal connection when interacting with technology.

Most textile interfaces are permanent and always visible.

But integrating textile interfaces into furniture creates a new challenge: The interface will change the object's aesthetic look and feel, as textile interfaces often utilize visual icons that are sewn, glued, or painted on to signify where an interaction should take place. These additions to the fabric are permanent. As a result, the interface is always present and cannot, like a screen on a phone display, be turned off and stored away when not needed. This is potentially problematic, since the interface appearance may clash with the furniture design and reduce the object's visual appeal. Additionally, applying changes to the interface after its fabrication is not possible. Ideally, textile interfaces could be activated when needed, seamlessly adapt to the current state of the device, and hide when interaction is not desired. This requires the interface to be able to change between states.

There are few approaches to dynamically changing textile interfaces or making them disappear.

Physically altering the form or surface of an object has already been explored for application in user interfaces. Research has produced shape-changing interfaces that dynamically transform in response to context [Alexander et al., 2018]. When shape-changing textile interfaces have been explored, it has been done for aesthetic purposes [Haynes and Steimle, 2024] or to create haptic feedback [Bau et al., 2009]. Dong [2019] presents a technique to activate and dismiss feedforwards on a textile interface. Their prototypes include LEDs glowing in a pattern underneath the fabric, as well as pulling parts of the fabric into the surface to display convex shapes. But to date, this appears to be the only research approach that has explored activating and hiding textile interfaces. Their method also remains relatively superficial, as they did not investigate the technique in depth, and have not been following up on it since.

Foldlets are string-actuated, silent, eyes-free textile interfaces that can be hidden when not needed.

To explore disappearing textile interfaces we present Foldlets: A novel approach to displaying and hiding textile interfaces using string-actuation. Foldlets dynamically create thin folds in a layer of fabric and make them disappear completely when not needed. We use shape memory alloys (SMAs) to actuate our prototypes completely silently, making them suitable for relaxed home environments. Additionally, Foldlet interfaces can be used eyes-free.

In this thesis, we introduce a consistent method to create textile icons with Foldlets. We present the design process of different geometric shapes and give design guidelines. Next, we demonstrate the fabrication of a Foldlet as well as its actuation technique using Shape Memory Alloys. Finally, we present five prototypes that demonstrate different application scenarios.

Chapter 2

Related Work

In this chapter, we provide an overview on the research fields of textile and shape-changing interfaces. We especially focus on the integration of textile interfaces in personal spaces like the home, and later discuss related work in shape-changing textile interfaces.

2.1 Textile Interfaces

Textile interface research has been an active field for nearly three decades, and continues to present a multitude of artifacts, guidelines, and sensing techniques. The two main research directions focus on interfaces positioned on the user's body, or on non-wearable items present in our everyday lives.

Wearable textile interfaces enable novel interaction methods like arm gestures or fabric deformation.

Multiple concepts for wearable textile interfaces have been explored, employing different kinds of textile sensors. As an example, Parzer et al. [2017] created a smart sleeve that integrates a textile sensor, allowing real-time recognition of touch gestures on the fabric surface as well as deformation gestures like twisting or folding. Similar approaches have been done by Schneegass and Voit [2016], who discussed touch input on a sleeve to be used as an alternative to smart watches. Xu et al. [2022] recognized arm gestures using a textile pressure sensor array. Wearable textile interfaces have received positive feedback in user studies [Zhao et al., 2024].

The second research direction focuses on applying textile interfaces to non-wearable everyday objects. As an example, a user study has found that textile interfaces in cars can reduce distractions while driving compared to a touch display [Khorsandi et al., 2023]. But the largest area concentrates on textile interfaces in personal spaces like the home environment. Research aims to replace common interfaces like remote controls by integrating sensors into furniture pieces that are already made from fabric. Suzuki et al. [2020] propose interaction with smart cushions as an alternative way to interact with smart home devices. Due to its softness, deformation gestures like pushing or squeezing can be used as input mechanisms. The authors recommend such interfaces as beneficial for the elderly, disabled, or children, focusing on safety and comfort during interaction. Other approaches include smart curtains [Heller et al., 2016] or larger furniture pieces like chairs [Brauner et al., 2017]. In the latter case, the authors created different textile sliders to control the reclining backrest of an armchair. Afterwards, a user study was conducted to investigate the acceptance of the interface in comparison to a conventional remote control. The participants showed interest in the different textile interfaces, and especially found the subtlety and seamless integration in textile furniture pieces attractive.

Textile Interfaces can be applied to everyday items in the home, replacing traditional remote controls.

When designing a textile interface, the interaction needs to be effectively communicated to the user. As a consequence, it is necessary to establish design guidelines. Research has put forth general guidelines that can be applied to all textile interfaces without depending on the context. As an example, visual and tactile signals like the direction of the fabric, the combination of different materials, or the size of icons can signify where and how an interaction with a textile is possible [Mlakar et al., 2021]. Knowing this kind of information is crucial. Similar guidelines have been established by Mlakar et al. [2025], presenting three categories of signifiers that can be utilized for indicating interactions. Additionally, more specific guidelines offer insights for designing the interface based on its application

To create intuitive interaction with textile interfaces, design guidelines give insights into textile signifiers.

purpose. In the context of smart home controls and furniture, the focus is especially applied to the creation of textile icons. Nowak et al. [2025] present haptic design guidelines for textile interfaces. After conducting user studies, they report their participants preferring larger sizes for textile icons. Other research has found that users prefer textile sliders with raised or recessed profiles compared to completely flat shapes [Nowak et al., 2022]. A similar result was reported for textile icons, where raised icons were preferred in a user study investigating recognizability of different haptic icons, as seen in Figure 2.1 [Schäfer et al., 2023]. It is important to know those guidelines when designing textile interfaces, as they allow users to interact with the icons eyes-free. Mlakar and Haller [2020] also investigate design guidelines for textile shapes. They name height differences as an easy method to identify textile elements, and concave shapes as being perceived as interactive.

Textile icons should be designed by using large, simple shapes and employing some kind of height difference, like foam or embroidery.

The interfaces described in those contributions are all created by sewing or embroidering the icons directly onto fabric. As a result, those interfaces are static and always visible. As a contrast, there have been approaches to textile interfaces that do not make any use of icons or other kinds of signifiers. Those interfaces are mostly created to recognize touch input on a flat surface. As an example, Lin et al. [2024] presented a textile interface enabling tracking touch gestures with high resolution. Similar approaches to textile touch sensors have been done by Wu et al. [2020], who developed a double-sided touch sensor for smart clothing, or Zühlke et al. [2024], who aim at improving textile sensor layout without disrupting the textile's look and feel. But in those cases, the system lacks visibility. The user has to know exactly how and where to interact, requiring the use of manuals or training. This can also slow down productivity and increase errors if the guidance is incomplete or unclear. In summary, textile interfaces remain static by either adding permanent icons to the interface or not making use of signifiers at all. However, a different research area in human-computer interaction focuses on creating dynamic interfaces.

Textile interfaces use permanent methods like embroidery and sewing to display icons, or do not use any signifiers at all.

Figure 2.1: Schäfer et al. [2023] investigate haptic recognition of textile icons in different shapes and fabrication variants. Their participants preferred raised icons.

2.2 Shape Changing Interfaces

Shape-changing interfaces employ physical changes in shape or materiality to create input and output in human-computer interaction. Types of shape change include change in form, volume, or texture, as described by Rasmussen et al. [2012]. Those techniques can be used to display or register data, but also to create aesthetics or evoke emotion in the user.

2.2.1 Shape Displays

Shape displays actuate individual pins on a 2D array, offering dynamic user input and output with a high resolution.

Shape Displays are user interfaces built from a 2-dimensional array of individually controllable pins. Thus, the surface of the interface can dynamically change to display output, or allows to be manipulated in order to receive input from a user. Poupyrev et al. [2004] present Lumen, a shape display that uses colored lighting as well as change in the interface surface to display information. The individual pins are controlled using shape memory alloys, which are attached to the pins using strings. Similar techniques have been presented by many authors, such as Follmer et al. [2013], whose shape display additionally allows for input by manipulating the individual pins. Their interface allows for high-resolution dynamic output shapes and enables new interaction techniques, as demonstrated in

Figure 2.2. Shape displays also allow turning off the interface by lowering all pins.

2.2.2 Shape Change in Textile Interfaces

Few approaches have been made to create textile shape displays, and they do not offer to dynamically display icons.

Shape displays can allow the incorporation of textiles. Leithinger and Ishii [2010] created a shape display that can be covered with fabric to display elevated landscapes. But this interface is used on a wooden table instead of furniture that is already made from fabric. The textile cover is also only used for shape output. A similar technique has been applied in BubbleWrap by Bau et al. [2009], who proposed a 2-dimensional matrix of actuators covered in fabric in order to create haptic feedback. They suggest their prototype be used for creating textile keyboards that can be retracted or hidden when not needed. This represents one of the few approaches to hiding textile interfaces. Still, their interface creates a relatively low resolution, where each pin represents a single key on a keyboard. It is not aimed at displaying shapes or icons on the interface, and markings would still be required for visualizing the purpose of the individual keys. Dong et al. [2023] approach to integrate shape-changing buttons into leather surfaces, aiming to create sensory feedback. While their design tries to seamlessly embed the buttons into the surrounding fabric, they do not focus on hiding the interface completely. Other shape-changing textile interfaces have been explored, like Jiang et al. [2024], who use machine embroidery to fabricate surfaces integrated in fabric that offer shape-changing abilities. But again, their interfaces are permanently embroidered into the fabric.

There has been an approach to a disappearing textile interface, but there has been no continuing research since.

In another approach, Dong [2019] investigates feedforwards for textile interfaces to signify where the interaction should take place. Their techniques allow the visualizations being turned off and disappearing into the fabric surface when not needed. Three prototypes were created for visual and haptic feedforwards, as seen in Figure 2.3. Two of those prototypes utilize LEDs that shine through the fabric. In a third example, the fabric of the interface is pulled downwards into the furniture piece, creating a convex shape. This describes a first attempt at physically

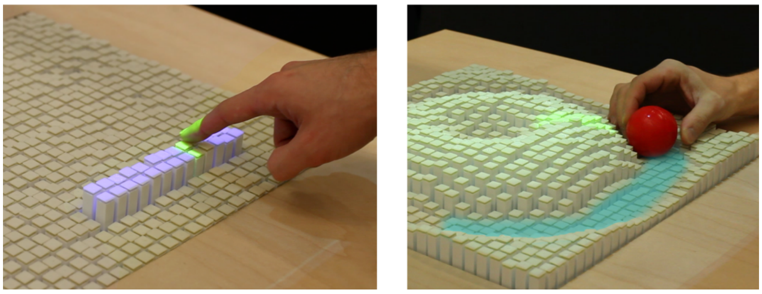


Figure 2.2: Follmer et al. [2013] created a shape display with a high number of pins, allowing for dynamic and high-resolution input and output.

changing the interface surface to switch between activated and deactivated interface signifiers. But, to this date, this appears to be the only approach to hiding textile interfaces. It also remains relatively superficial, as they did not investigate the technique in depth, and there has also been no continuing research since. Furthermore, the author chose to use a servo motor for pulling down on the fabric. This does not create a suitable activation method to be employed in the home, as the noise of a motor can quickly disrupt the comfortable environment.

Shape memory alloys allow lightweight integration into textile interfaces to actuate shape change in subtle ways.

There have been approaches to shape-changing textile interfaces that use different actuation mechanisms. A popular variant is to use shape memory alloys (SMAs). SMAs are metal wires that, after being deformed, will return to a pre-programmed shape when heated. Because of their small size and low weight, SMAs are favorable for wearable mechanisms. As an example, Muthukumarana et al. [2021] use SMAs in combination with custom 3D printed pieces. Their mechanism is used to actuate on-body textile interfaces that, for example, generate haptic feedback or convey information, such as text message notifications. Other approaches in this direction have been explored by Olberding et al. [2015], using SMAs for folding fabric into 3-dimensional bodies. Furthermore, Haynes and Steimle [2024] create shape-changing textile surfaces for aesthetic purposes by sewing SMAs into fabric and letting them selectively contract to create smocking patterns. In summary, shape memory alloys allow subtle and dy-

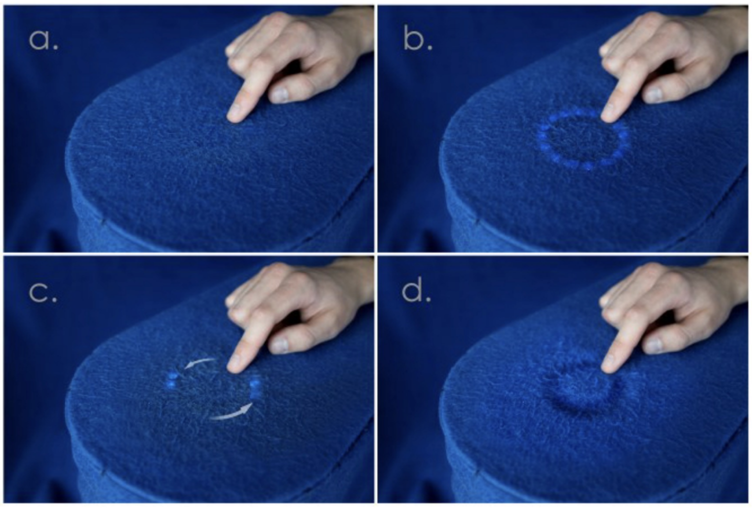


Figure 2.3: Dong [2019] presents approaches to disappearing textile interfaces. Two signifiers (b, c) are created by LEDs glowing through the surface fabric, and one prototype pulls down the fabric (d) in order to create a convex shape.

namic change in the shape of fabric surfaces, which has been employed, for example, to create aesthetic shapes and generate haptic feedback. Applications of SMAs in textile interfaces are motivated by their light weight and small size. For this reason, most of those approaches have been applied to wearable textiles. In this thesis, we make use of SMAs to actuate our textile interface icons silently.

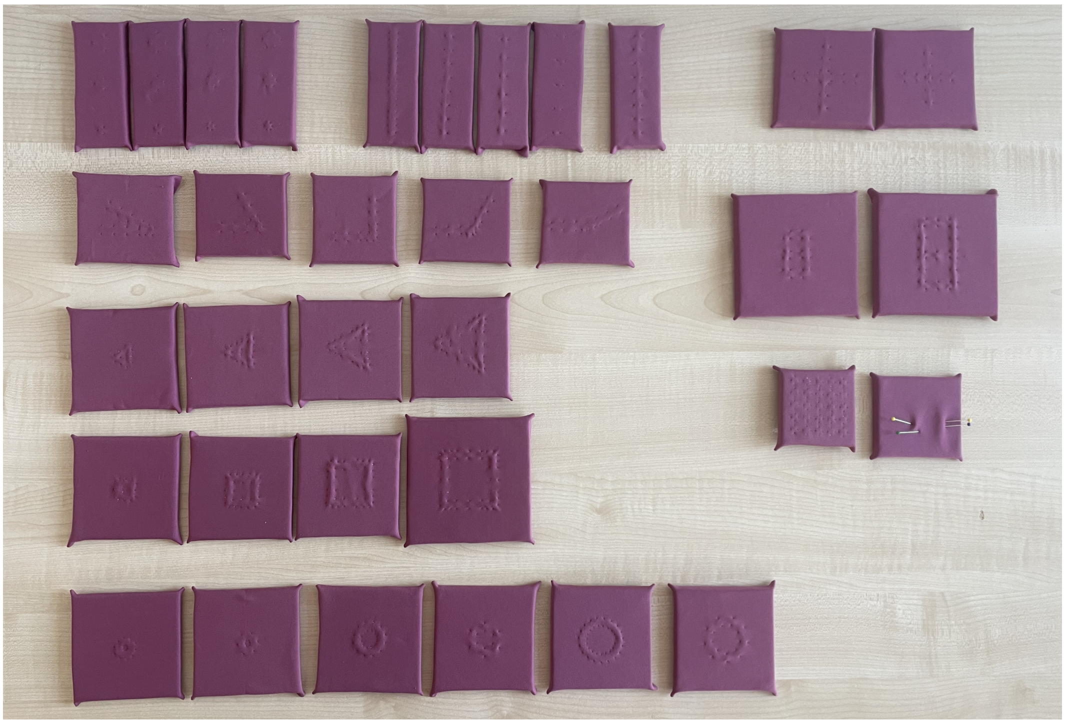


Figure 3.1: An overview of all Foldlets created in the scope of this thesis.

Chapter 3

Foldlets

We present Foldlets: string-actuated, eyes-free textile interfaces that create thin folds in the surface fabric, in order to display different kinds of shapes. The folds are created by loosely sewing a pattern of individual strands of sewing

Foldlets display shapes in fabric using string-actuation.

thread into the fabric. The extending parts of the threads are then bundled together underneath the Foldlet. When pulling down on those threads, the fabric selectively contracts, and the desired shape appears. By releasing the tension on the strings, the fabric relaxes, allowing the folds to disappear into the surface. To completely flatten the surface of the foldlet, it is necessary to gently stroke over the fabric a few times, depending on the number of stitches and the complexity of the shape.

A Foldlet is structured in three layers of materials, mimicking the surface of a couch armrest.

A Foldlet is a flat, handy mock-up of a textile interface icon, consisting of three parts. A surface layer of fabric is where the stitches are made, and which creates the interface the user interacts with. It is cushioned by a layer of foam below, and finally stabilized by a wooden bottom plate. The threads that form the fold are drawn through those layers and extend below the model. This construction allows creating a standalone draft showing one shape, which can be actuated by hand, as seen in Figure 3.2. Chapter 4 shows the fabrication of a Foldlet in detail. A Foldlet later can be integrated into the full prototype, including an automated actuation mechanism. Exemplary use-cases and prototypes are described in Chapter 5.

In the following sections of this chapter, we present a consistent method for creating Foldlets that display basic geometric shapes. For each shape, we name the design decisions behind the sewing patterns and give design guidelines.

3.1 Parameters

We define a set of design parameters used in Foldlet patterns.

In order to discuss the construction of different shapes, we define the following basic parameters used in each Foldlet template. A visual definition of the parameters can be found in Figure 3.3.

Definition: Anchor Thread

To shape a fold, single pieces of thread are stitched loosely into the fabric. We define one single stitch as an **anchor thread**. The stitch should be sewn as small as possible in

Figure 3.2: A Foldlet is a flat and handy model displaying a single shape. It can be actuated by pulling on the extending threads.

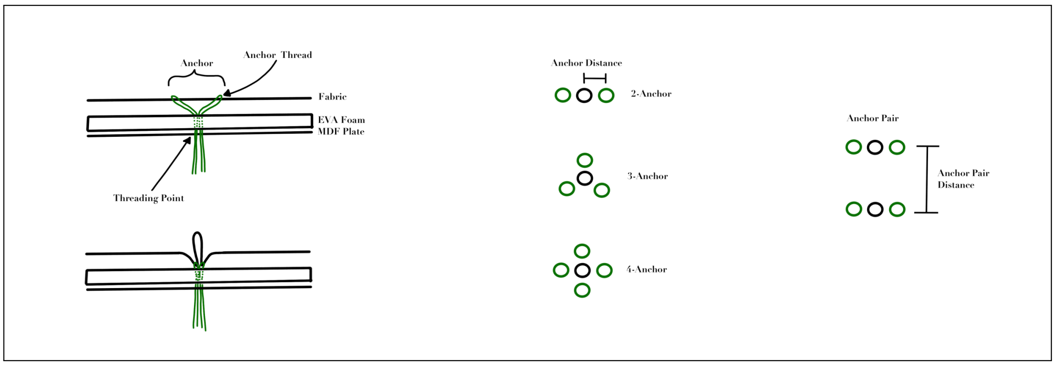


Figure 3.3: A visualization of all parameters relevant when designing a Foldlet pattern. Left: A 2-anchor creates a fold. Center: N-anchors and anchor distance. Right: Anchor pair and anchor pair distance.

order to leave the fabric surface flat and to hide the mechanism from the user.

Definition: (N-)Anchor

Multiple anchor threads need to be combined to shape a fold. A group of n such anchor threads is called an **n-anchor**. All threads of one n-anchor are bundled together and threaded through a single hole in the Foldlet layers. This point is called **threading point**. In most shapes, we use 2-anchors where the anchor threads are positioned at a distance, and their associated threading point is located in the center between them. One such 2-anchor creates a single straight fold between the anchor threads when force is applied to its strings, which we use to create straight lines. From now on, we will refer to these 2-anchors simply as **anchor**. Other instances of n-anchors will be specified when needed.

Definition: Anchor Distance

The anchor threads of a 2-anchor are positioned at a distance from the threading point, which we define as **anchor distance**. In most shapes, we chose an anchor distance of 3 millimeters, which then creates a fold in the fabric with that height. The distance between the anchor threads is 6 millimeters.

Definition: Anchor Pair and Anchor Pair Distance

To create continuous folds, we place multiple anchors next to each other. Two anchors that are neighboring we define as an **anchor pair**. The distance between those two anchors is calculated by the distance between their respective threading points. To describe this, we use the term **anchor pair distance**.

When creating Foldlet shapes, our goal is to find a configuration of anchors which creates the most aesthetically pleasing result while using as few stitches as possible. This is done to both reduce fabrication time as well as not disturb the aesthetic look and feel of the fabric. We explore different variants of the defined parameters in order to understand and compare their effects.

3.2 Points

The simplest geometric shape we aim to display is a singular point. To achieve that, we created 12 points using a range from 3-anchors to 6-anchors with anchor distances of 3, 5, or 7 millimeters, as presented in Figure 3.4.

Guideline: Small points are best created when using a 4-anchor and a small anchor distance.

For small points, we present 4-anchors with an anchor distance of 3 millimeters as the best possible result. Those points look visually pleasing and compact, and create a distinct and sharp tactile feel. 3-anchors do not offer enough stability in their shape, and using more than four anchors for a small point does not create a significantly better result, while larger anchor distances create unintended creases.

Guideline: Larger points should be avoided, since their integrity quickly fails.

Larger points, if needed, can be shaped by using a 5-anchor with an anchor distance of 5 millimeters. But we do not recommend using this technique too much, as with larger anchor distances the fabric begins to create creases outside of the desired shape, disturbing it's display. With an anchor distance of 7 millimeters, no matter the number of anchors

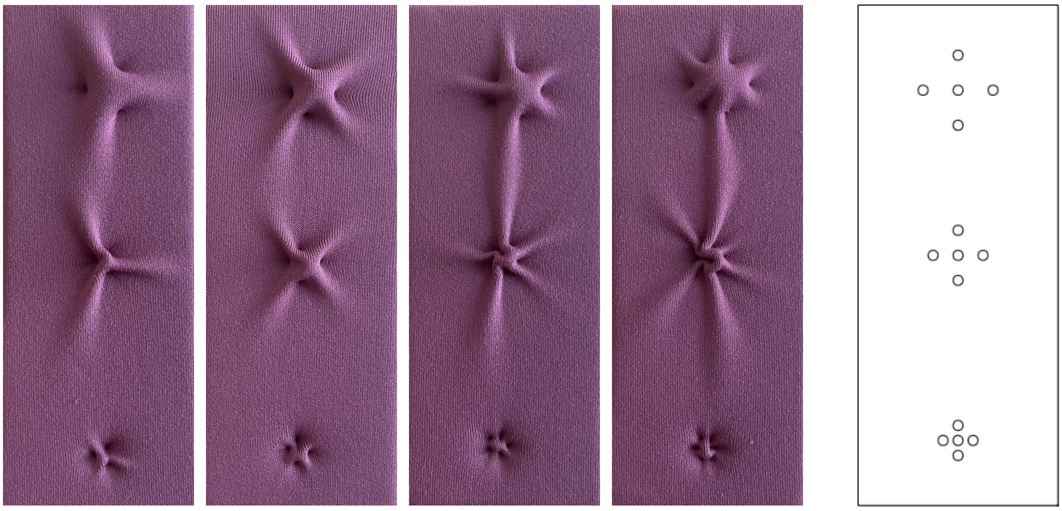


Figure 3.4: We explored displaying points using 3- to 6-anchor combinations (a) - (d) with anchor distances of 3 (bottom), 5, or 7 (top) millimeters. We conclude that 4-anchors create the most aesthetic points while using few anchor threads. Their sewing pattern is displayed in (e).

the integrity of the point begins to fail, as the fold that is created uses up a bigger surface area and therefore loses stability. If larger points are required to be displayed, we recommend making use of small circles instead. See Chapter 3.5.2 for those designs.

3.3 Lines

Lines can be created using 2-anchors with different anchor pair distances.

The only parameter that is relevant when creating lines is the anchor pair distance since we already established that an anchor distance of 3 millimeters suffices to create well-defined folds. We created multiple lines with an anchor pair distance of 5, 10, 15, and 20 millimeters each. As seen in figure 3.5, with a growing anchor pair distance the integrity of the fold begins to fade, while a smaller anchor pair distance creates a more consistent and aesthetic look. In contrast, folds that are built using larger anchor pair distances flatten more easily when tension on the strings is released. While the line that uses an anchor pair distance of

5 millimeters creates a more aesthetic look, the fabric takes longer to relax after actuation and requires more force when trying to flatten the fold by hand.

Guideline: Lines need to be created from at least two anchors.

The minimum size of a Foldlet line is the anchor pair distance itself, as it needs at least two anchors to create. For short lines, we recommend using multiple anchor pairs with smaller anchor pair distances to enhance stability of the fold. Longer lines can be represented with fewer anchors and larger anchor pair distance.

Guideline: Anchor pair distances of 10 millimeters balance aesthetic and fold stability.

From our created Foldlets, we conclude that a line with an anchor pair distance of 10 millimeters is the most efficient technique while balancing the amount of sewing and the stability and aesthetic look of the line. From this point on, we will use an anchor pair distance of 10 millimeters as a basis for all Foldlet prototypes that involve straight lines.

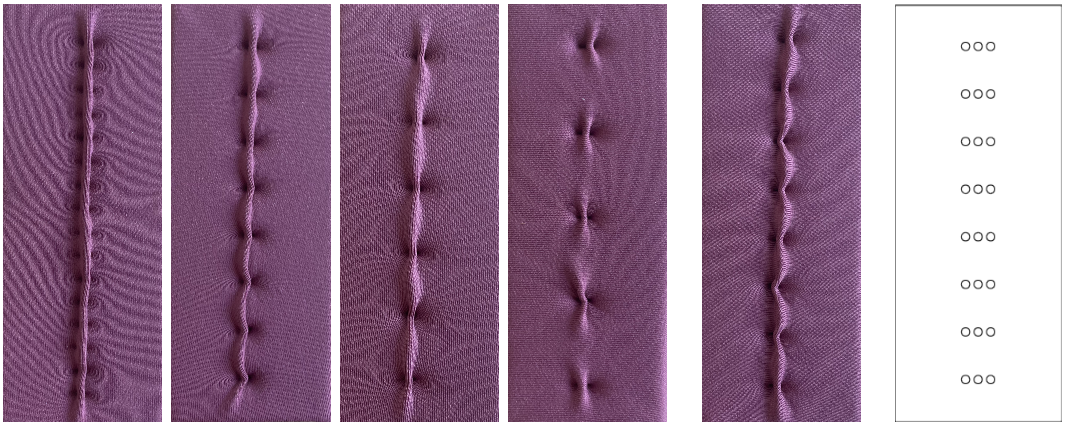
Guideline: Fabric grain can distort folds.

We want to note that when creating a line in a direction contrary to the fabric's grain, the folds can look slightly different than those sewn in parallel. An example of that can be found in Figure 3.5, where the folds in between two anchor pairs begin to deform slightly with the direction of the fabric. When creating Foldlets that display long lines, this fact has to be considered. For shorter lines or closed shapes that use multiple lines pointing in different directions, this is not considered important and can barely be noticed.

3.4 Corners

Creating sharp folds to display corners is challenging.

Creating corners where two straight lines meet is especially challenging, as we want the corner to be as clear as possible in visual optics and tactile feel. Therefore, we need precise stitches to create well-defined folds. When not considered carefully, the folds that create the corner can stretch out from the intended folding area and create creases into the surrounding fabric. This would disturb the recognizability of a Foldlet shape, especially eyes-free. In order to test both narrow and wide angles, we chose to create corners consisting of two lines of length 4 centimeters each. For demonstration, we created Foldlets covering sharp, right, and wide angles of 30, 60, 90, 120, and 150 degrees. The resulting Foldlets can be seen in Figure 3.6



(a) (b) (c) (d) (e) (f)

Figure 3.5: Variations of straight lines, using anchor pair distances of (a) 5mm, (b) 10mm, (c) 15mm, and (d) 20mm, with (b) balancing aesthetics and fold stability. When created contrary to the fabric's grain, a line can get slightly distorted (e). Figure (f) illustrates the sewing pattern of lines (b) and (e).

We developed a custom structure of anchors, which creates defined corners that are pleasant in look and feel. Our corner design consists of three parts, which are depicted in Figure 3.7: The corner itself is shaped by 5 anchor threads: A 3-anchor that creates the sharpness of the corner tip and a 2-anchor that is used for stabilization. Our method not only creates a defined corner in the fabric but also causes a localized tactile knob. This creates an additional haptic sensation that draws attention to the corner, improving eyes-free interaction. Two additional 2-anchors are required to enable a smooth transition from the corner pattern to the straight lines. For this connection, we use an anchor pair distance of 5 millimeters. Afterwards, the anchor pair distance used to shape the lines can be chosen at will. We also made sure to align the anchors of the corner pattern with the anchors of the two lines, both on the inside of the angle and the outside. This further creates a seamless transition from the corner tip to the lines. The resulting pattern is sketched in Figure 3.7.

A corner tip is created by 5 anchor threads, with an additional 2 anchors for stabilization.

This specific structure in the pattern of anchors is used for every corner Foldlet we created, and can also be adapted to work for all desired angle sizes in between. It has to be noted that extremely sharp or wide angles require slightly

The corner pattern needs to be slightly adjusted depending on the angle.

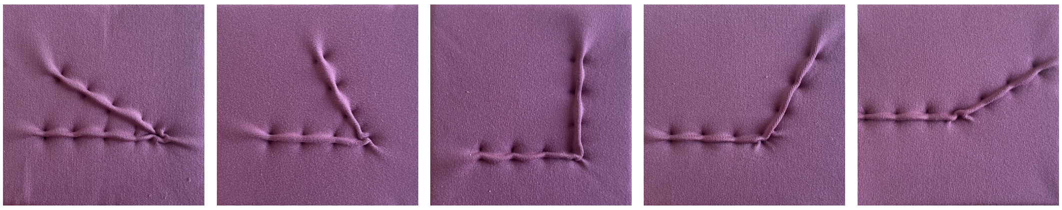


Figure 3.6: Foldlets displaying lines of 40mm length, meeting in corners of 30° (a) to 150° (e) in intervals of 30°. All patterns create clean and sharp corners, and can be adjusted to create all desired angles in between.

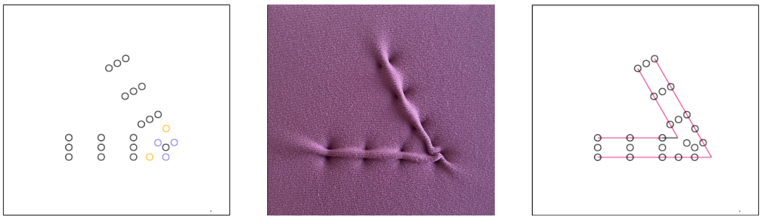


Figure 3.7: The sewing pattern of a 60° Foldlet corner. Left: The pattern of a corner tip, consisting of a 3-anchor (purple) and a 2-anchor (orange). Center: The resulting Foldlet shape. Right: Anchors are aligned to create seamless transitions.

different placements of the corner pattern's anchors and threading points.

3.5 Closed Shapes

The previously presented shapes can be combined to create polygons.

With the preceding techniques, we have covered all parts necessary to create polygons of different sizes and structures. To show this, we decided to create triangles and squares as the most basic but also common shapes in interface design. Additionally, we designed a technique to display curved lines. As a demonstration, we constructed circles of different sizes.

3.5.1 Triangles and Squares

We created Foldlets that display equilateral triangles and squares with side lengths of about 10, 20, 30, and 40 millimeters. Depending on the shape, we used our previously presented corner patterns of 60° and 90°, respectively. Corners are connected using lines with an anchor distance of 10 millimeters. The resulting shapes are displayed in Figure 3.8 and 3.9. To be able to display the smallest triangles and squares, only the corner patterns were used without any additional anchors.

We recommend avoiding shapes with sides shorter than 10 millimeters, since in those cases we have already overlapped their respective corner patterns. To go even smaller, a new method for folds and corner creation would be required, as our smallest triangles and squares only barely leave any surface inside.

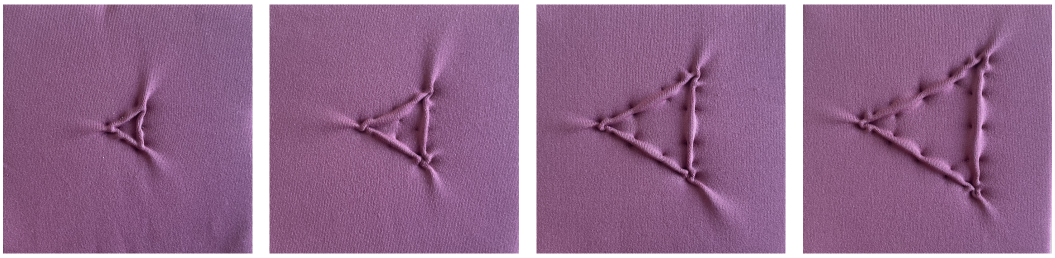
Guideline: Shapes smaller than 10mm are not possible to display.

Even though we only created equilateral triangles, this method can also be utilized when creating differently shaped triangles by applying a combination of different corner angles. We can recommend both shapes in all sizes to be used for textile interfaces.

3.5.2 Circles

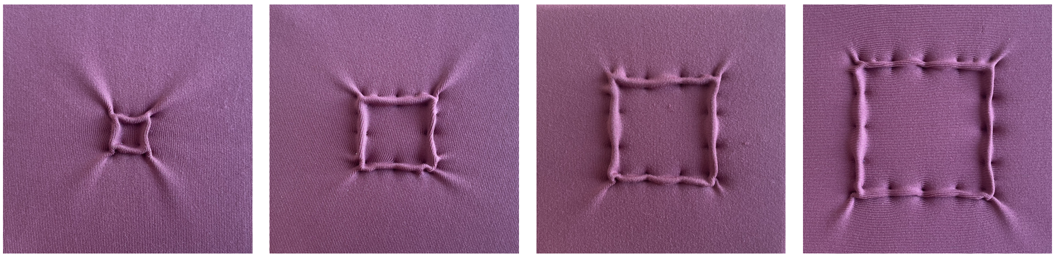
Curved lines are challenging shapes to display on a Foldlet. Fabric cannot easily be folded in a perfectly rounded line, which forces us to approximate the arches with a high number of straight lines. To achieve this, we decided to create circular polygons, where on each corner a 2-anchor is placed. A collection of six circle patterns have been created, which can be found in Figure 3.10. For polygons with a diameter of 20 millimeters or more, we tested anchor pair distances of 5 and 10 millimeters. We observed that circles with lower anchor pair distances, and therefore more anchors, create more continuous and aesthetically pleasing lines, whereas a larger anchor pair distance leads to the individual lines not appearing connected. Similar to the small triangles and squares we already presented, we wanted to create a small circle with a diameter of 10 mil-

Curved folds are challenging to display in fabrics.



(a) (b) (c) (d)

Figure 3.8: Exploring different sizes of triangles, using side lengths of 10mm (a), 20mm (b), 30mm (c), and 40mm (d). Lines are created with an anchor distance of 10mm. All patterns result in stable and aesthetic shapes.



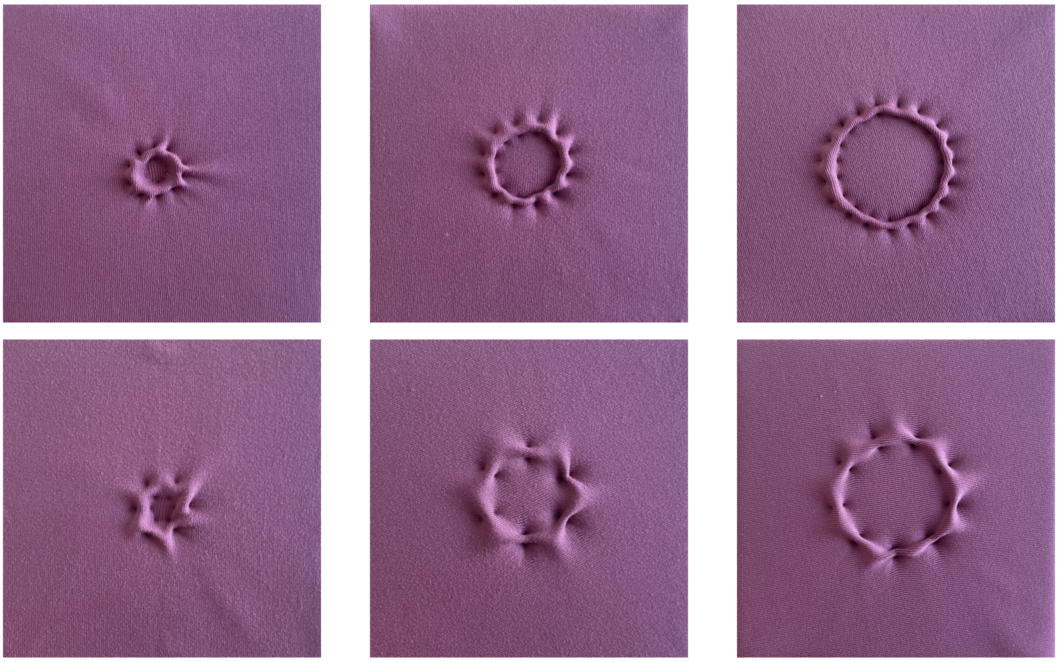
(a) (b) (c) (d)

Figure 3.9: Exploring different sizes of squares, using side lengths of 10mm (a), 20mm (b), 30mm (c), 40mm (d). Lines use an anchor pair distance of 10mm. All patterns result in stable and aesthetic shapes.

limeters. But even with an anchor pair distance of 5 millimeters, the individual lines created by the anchors did not appear connected, resulting in an edged and distorted shape that slightly resembles a star. For this reason, we chose an even smaller anchor pair distance of 3 millimeters in our next trial. As a result, a more continuous circle was created, but it still did not appear as clean as the larger circles.

Guideline: A high number of anchors and small anchor pair distances create defined curves.

When designing Foldlets that display circles or curved lines, small anchor pair distances and a high number of anchors should be chosen. Especially small circles or lines of great curvature need more anchors to form a defined shape. We recommend creating circles with a diameter of at least 20 millimeters to avoid its shape appearing distorted.



(a) (b) (c)

Figure 3.10: Exploring Foldlet circles using different parameters: (a) shows small circles of diameter 10mm with an anchor pair distance of 3mm (top) and 5mm (bottom). (b) and (c) display larger circles of diameters 20mm and 30mm, using anchor pair distances of 5mm (top) and 10mm (bottom).

3.6 Overlapping Shapes

So far, we have defined shapes that can be displayed individually on Foldlets and disappear at will, but are not dynamic in themselves. To address that, we have found two ways of going forward that enable changing between shapes that are displayed in the same area on the interface.

3.6.1 Alternating Shapes

We created Foldlets that alternate between displaying two distinct shapes.

Two patterns of individual shapes can be sewn onto the same space of the fabric. When pulling on the anchor threads of only one of those shapes, it creates the designated folds and displays this shape, while the threads belonging to the other shape stay loose. As a result, we can switch between displaying two distinct shapes. This can be used to save space on the interface surface, or if two interface controls are never active at the same time anyway. More on applications alternating shapes is described in Chapter 5.4. To demonstrate this technique, we designed a Foldlet that switches between displaying a triangle and two parallel lines, imitating the play and pause buttons on a conventional remote control.

Stitches of one shape can disturb the creation of the alternate shape's folds.

While developing this Foldlet, we noticed some limitations created by this technique. Even when one of the shapes is not activated and its stitches are lying loosely in the fabric, their presence interferes when displaying the second shape. This increases drastically when multiple anchors are placed in the same spot for each shape. Figure 3.11 shows our first design of the play and pause template. As the line of the pause button is lying directly adjacent to one side of the triangle, many anchors overlap. Initially, we wanted to use this fact to our advantage, as the template used to mark the anchor threads and threading points becomes clearer when markings can be shared between desired shapes. But in reality, this distorts the folds of both shapes. In our second attempt, as seen in Figure 3.12, we changed our design of the Foldlet. To avoid too many anchor threads interfering with each other, we moved the second line of the pause shape to the center of the triangle. Therefore, the shapes overlap less, resulting in both shapes being displayed more clearly than before. It is still observable that the anchors of one shape influence the folds of the other, but that is far less noticeable.

Guideline: Avoid overlapping too many anchors when alternating between shapes.

To summarize, alternating shapes should be designed in a way that the stitches of the individual shapes overlap as little as possible. This forbids the stitches from interacting with each other, resulting in clearer shapes when displayed independently. But this also defeats the purpose of displaying two shapes on top of each other. It remains to be investigated how this problem could be solved differently, for example, by changing the number of anchors in both shapes or strategically altering the Foldlet design.

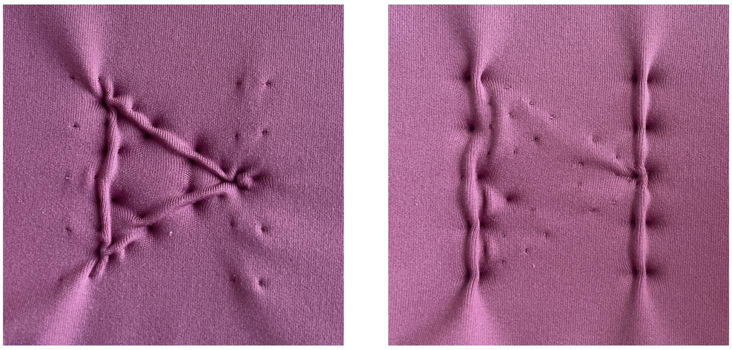


Figure 3.11: Our first attempt at creating an overlapping shape, displaying a play (left) and pause (right) icon. Since the left side of the triangle and the first pause line overlap, their anchors disturb each other's fold creation.

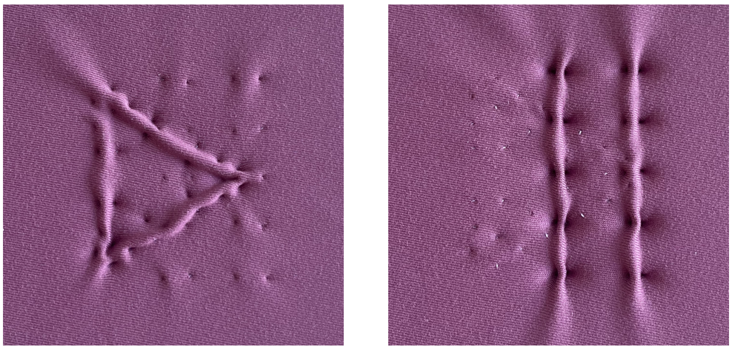


Figure 3.12: Our second attempt at creating an overlapping shape. We moved the first line of the pause icon to the center of the triangle, resulting in no disturbances because of fewer overlapping anchors.

3.6.2 Additive Shapes

As an alternative solution to this problem, we present the technique of additive shapes. Since the construction of a foldlet allows us to pull on the threads belonging to one anchor independently, this also allows us to only pull on some threads of a shape at a time. Subsequently, when aiming to display multiple shapes on the same spot on the interface, we can use the already existing stitches of one shape and also integrate them into the second shape. As an exam-

By sharing anchors, we aim to eliminate disturbances of overlapping shapes.

ple of that technique, we created a design where two lines are drawn perpendicular to each other, mimicking a cross shape or plus sign. It is possible to only pull on the threads that form the horizontal fold, consequently displaying a minus sign. Pulling on all threads, on the other hand, displays a plus sign. Since both shapes share the horizontal anchors, no threads can interfere with each other here.

An intersection of two lines can be designed in different ways, enabling new visual and tactile feedback.

To handle the creation of folds where the two lines meet, we designed two different anchor configurations. For the approach presented in Figure 3.13, we did not place any anchors in the intersection of the lines, in order to observe the natural formation of the fabric. As a result, a lager, point-like shape is created in the space between the four lines, marking their meeting point. With another technique, as seen in Figure 3.14, we deliberately placed two 2-anchors in the intersection. When both lines are actuated, these 2-anchors blend together and create the 4-anchor structure that we already used to create small points. This also results in an emphasis on the meeting point, both visually and tactile. To conclude, both designs offer well-formed shapes with different visual and tactile qualities. We can recommend both techniques, depending on the designer's vision and aesthetic.

Guideline: When possible, use additive shapes to combine folds.

Additive shapes, in contrast to alternating shapes, should be designed to overlap in as many positions as possible. If the application purpose allows, both shapes should have many stitches in common. This decreases fabrication time and also enables clear shapes to be displayed in both states.

3.7 Grids and Segmented Displays

With overlapping shapes, we introduced a Foldlet that is able to dynamically change the displayed shape based on the application context. Going one step further, we want to create a technique that allows switching between multiple different shapes on one Foldlet, without having to manually design many overlapping shapes. Segmented displays already offer those possibilities on digital displays, which is why we want to bring that concept to textile interfaces.

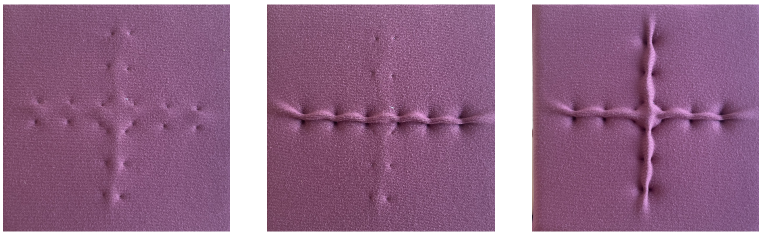


Figure 3.13: An additive Foldlet in stages: No actuation (left), minus icon (center), and plus icon (right). This attempt does not use anchors at the intersection, resulting in a larger, round fold.

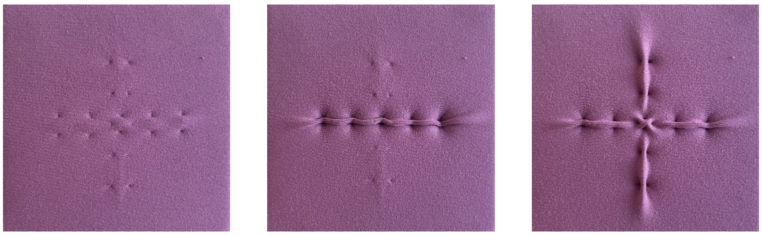


Figure 3.14: An additive Foldlet in stages: No actuation (left), minus icon (center), and plus icon (right). This attempt uses anchors that form a point where the lines intersect.

3.7.1 25 Point Grid

A matrix grid of individual points allows displaying a large number of shapes dynamically.

We created a 5x5 grid of 4-anchor points, spaced 10 millimeters from each other both horizontally and vertically. This creates a pixel-like matrix that allows each point to be activated individually. As this Foldlet only holds 25 points, the resolution of any shape we can display on this piece is limited. Still, it allows to displaying basic shapes like lines and rectangles. We were additionally able to display an arrow and attempted to create a circle. Those designs can be observed in Figure 3.15. As an unexpected side effect, neighboring points create straight and connecting creases in the fabric when activated simultaneously. This additionally emphasizes the created pattern and enables creating clean lines and angles. The only position where this fails is for diagonally spaced points that are activated together,

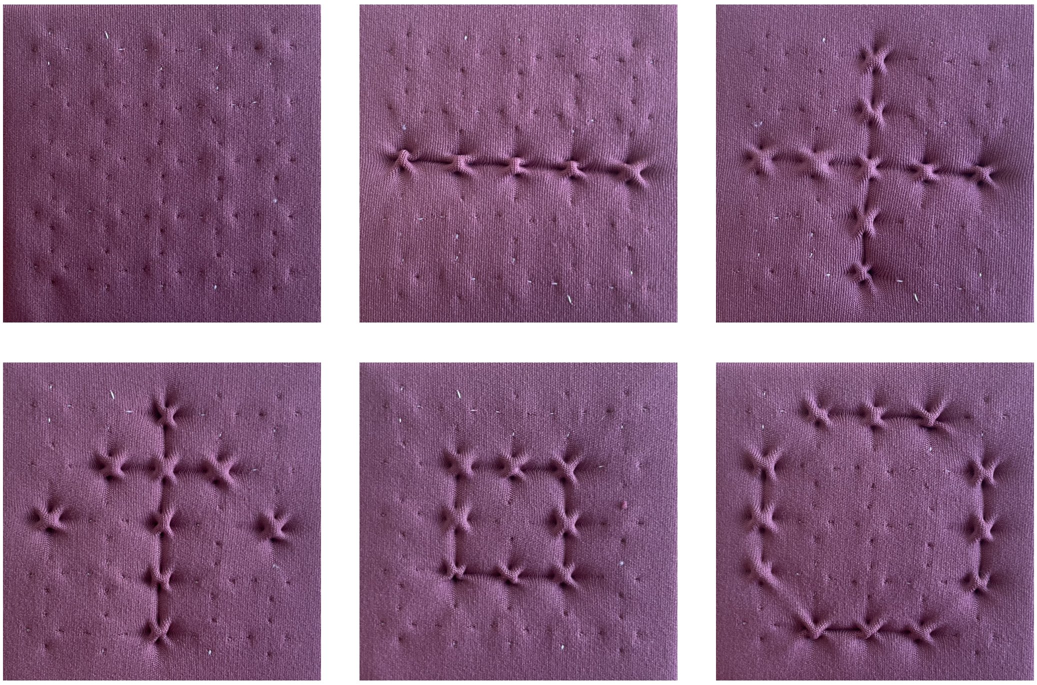


Figure 3.15: Show our point grid and multiple shapes

resulting in a well-defined line for the base line of the arrow, but not for the arrowhead wings. But this does not degrade the qualities of the shape.

We believe that when spacing the points together even more and increasing the number of points, a higher resolution can be achieved. But as each point requires sewing four anchor threads larger grids would require even more time for fabrication. Depending on the context and what kinds of shapes are ultimately needed to be displayed on a Foldlet, it might suffice to choose overlapping shapes or consider different kinds of segmented displays.

3.7.2 Seven Segment Display

We created a textile seven-segment display using independently activated lines.

A limited but more specific use of a grid-like structure can be a seven-segment display, which allows the presentation of the numbers 0 to 9 as well as a selection of letters. Each segment consists of one line, which can vary in length and

number of anchors. In Chapter 5.5, we go into detail discussing the advantages and applications of a textile seven-segment display.
We have recommended creating lines using an anchor pair distance of 10 millimeters, as this creates clearly visible and tangible lines, but reduces the amount of fabrication work necessary. For this reason, we first created a seven-segment display with that anchor pair distance and a line length of 20 millimeters. Additionally, we wanted to compare whether a smaller seven-segment display would suffice, so we built a second Foldlet with a line length of 10 millimeters using only two anchors each. The resulting Foldlets are shown in Figure 3.16.

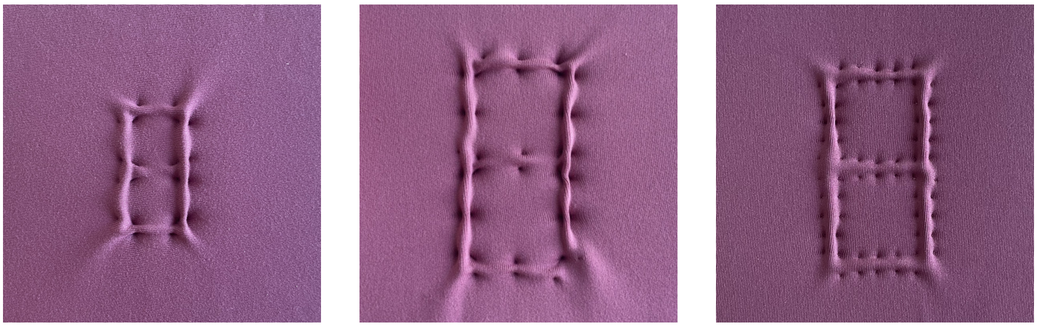
With both Foldlets, we noticed that the horizontal lines do not create the folds as defined as the vertical ones, especially when more or all segments are actively shown. This is most observable in the center segment of the display. We suspect that when all segments are active, the vertical lines are longer and therefore more stable, and as a result, create more tension than the horizontal lines. This results in the vertical lines pulling away the fabric from the middle of the shape, leaving too little fabric to be pulled together for the horizontal segments. This is especially true for the center segment, since it is surrounded by four other, vertical segments.

The longer vertical lines create a stronger tension on the fabric, preventing the horizontal folds from appearing correctly.

But it also has to be noted that when creating this first trial, we did not take into account the grain of the fabric. As we already mentioned in Chapter 3.3, the direction the fabric is woven in can have an influence on the shape of Foldlets that display straight lines. We initially concluded that for longer and individually standing lines, it is not an issue. But in this case, we use shorter lines for our horizontal segments, which creates less stability in the folds. Additionally, since we use a combination of horizontal and vertical lines, the effects of the fabric direction can be directly observed and compared.

The grain of the fabric can influence horizontal and vertical folds in this design.

To solve this issue, we created another iteration of the seven-segment display using more anchor threads and a smaller anchor pair distance of 5 millimeters. This resulted in cleaner and more aesthetic segments, which are dis-



(a) (b) (c)

Figure 3.16: We created three approaches to displaying seven-segment displays: (a) A small segmented display with lines of 10mm length, and (b) a larger approach using a line length of 20mm, both with anchor pair distances of 10mm. Lastly, in (c), we use an anchor pair distance of 5mm, which enables equally strong folds horizontally and vertically.

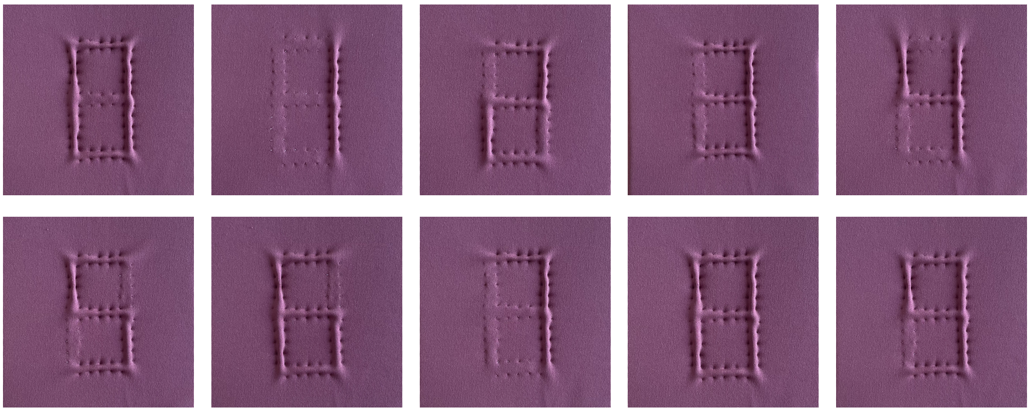


Figure 3.17: Using our final seven segment display with an anchor pair distance of 5mm, we are able to display the numbers from 0 to 9.

played in Figure 3.17. We also observe less differences between the horizontal and vertical segments in this Foldlet. Still, the horizontal segments are activated slightly more relaxed than the vertical lines when activated. But this is barely noticeable, and the displayed numbers are of good quality.

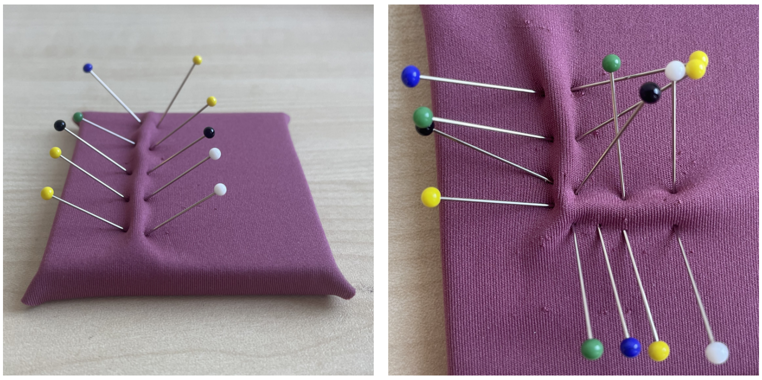


Figure 3.18: Exemplary use of our rapid prototyping model by using sewing pins. Using this, mock-ups of Foldlet designs can be tested with little effort, shortening the prototyping iterations.

3.8 Rapid Prototyping

Each Foldlet requires to be designed and fabricated by hand. Creating a design for a new shape or trying to solve a problem with an existing Foldlet can require multiple iterations of designing and testing until the best mechanism has been found. To shorten the duration of those iterations and reduce the amount of work when testing, we developed a technique to prototype Foldlet patterns without any sewing necessary. By building a Foldlet model with no anchor threads sewn in the fabric, regular sewing pins can be inserted into the Foldlet to mimic the effect of anchor threads. It has to be noted that the threading points of an anchor need to be considered when using this technique. Since a threading point is positioned between two or more anchor threads, the sewing pins need to be injected at an angle, mimicking the thread being pulled towards the position of the threading point. An example can be seen in Figure 3.18. This technique has been used to design the pattern of the corners we presented previously. Since different angles require slight repositioning of the five anchors that shape the corner tip, using this rapid prototyping allowed us to successfully test different anchor placements before committing to fabricate a complete Foldlet.

A rapid prototyping model allows for testing Foldlet designs without much effort.

Chapter 4

Fabrication

So far, we have presented how to design the shapes that are displayed on a Foldlet, but its activation has only been possible by hand. To actuate a Foldlet mechanically, we need a new way to exercise tension on the threads. We want this mechanism to be carried out without taking up much space or generating noise, as we ultimately aim to integrate this interface into furniture pieces in a home environment. Additionally, we need a mechanism that, depending on the Foldlet type, can actuate single parts of the interface independently of each other. This would allow for changing between alternating shapes or controlling fully segmented displays.

4.1 The Actuation Mechanism

Shape Memory Alloys allow silently pulling on the strings of a Foldlet.

For our actuation mechanism, we make use of **shape memory alloys** (SMAs). SMAs are metal wires that can be programmed to a specific shape by applying extreme heat. Even after being deformed, the wire will then return to its shape when heated again. As a result, SMAs programmed in the form of a spring can generate high tension. To heat the SMAs momentarily for actuation, we run current through the spring until it contracts long enough to pull on the Foldlet's strings. In order to do that, we need a construction that holds the SMAs in place, connects them to the Foldlet threads, and controls the power input.

The actuation stand is the structure where the Foldlet is fastened and connected to the SMA.

This is realized by what we call the **actuation stand**. There are different types of actuation stands, as seen in Figure 4.1, depending on the characteristics of the shape. We will discuss these different structures in the following sections of this chapter. Each actuation stand is built on top of a bottom layer where the SMA is attached and wired. To hold the Foldlet on top of the structure, we place it on wooden poles, allowing the threads to loosely extend downwards. To connect the Foldlet threads to the SMA, we have to differentiate between the different types of Foldlets we want to actuate, as well as their size.

Actuating small shapes can be done by a single SMA.

Small Foldlet shapes with a width and height below 20 millimeters allow for actuation by only one SMA. The extending threads of the Foldlet can be knotted together and attached to the SMA at one singular point. That point, and therefore the SMA, needs to be positioned in the center of the shape, in order to pull down on all threads with the same force. This actuation mechanism is the easiest to fabricate and smallest in size. An example of this stand can be found in Figure 4.1.

Actuating larger shapes requires the use of a stabilization plate, which allows equal pulling on all threads at once.

Shapes that are bigger than 20 millimeters in width or height can only be actuated by multiple SMAs, since one spring alone does not generate enough force to pull down the higher number of strings. Additionally, for bigger shapes, we need some kind of stabilization while pulling. The bigger the shape, the more threads are spread out over a wider area. Pulling in only one spot would therefore imbalance the forces across the distributed strings. In our trials, this resulted in the Foldlet not being activated at all, or only some folds appearing on the surface while the others remained flat. To solve that problem, we created a **stabilization layer**, as seen in Figure 4.1, that sits parallel to the Foldlet and allows attaching all threads perpendicularly. Now the SMAs are fastened to this stabilization layer in a symmetrical pattern, pulling it downwards evenly. The wooden poles that we use to hold the Foldlet in place also function as railings that guide the plate vertically.

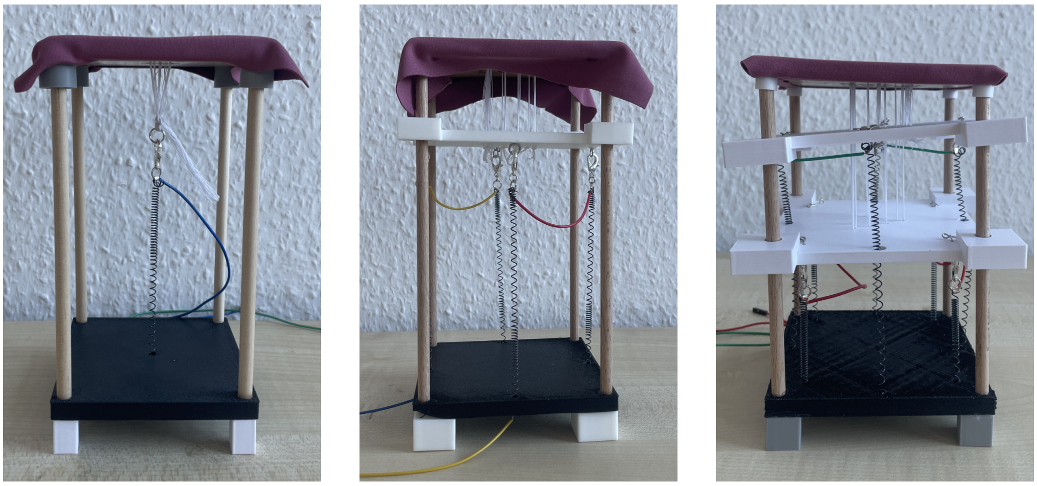


Figure 4.1: Different actuation mechanisms are required depending on the Foldlet shape. Left: A single SMA activating a small shape. Center: Large shapes require a stabilization plate pulled by four SMAs. Right: Independent shapes can be actuated using two stabilization plates and eight SMAs.

In order to activate overlapping shapes independently from each other, we need independent mechanisms for both shapes pulling on the respective strings. As a result, we need two stabilization plates, as demonstrated in Figure 4.1. The upper stabilization plate fastens all threads of the first shape, and makes space to extend the threads of the second shape downwards to the second plate, where the remaining threads are secured.

Actuating overlapping shapes can be done by vertically stacking stabilization plates.

In the following sections, we will break down each part of a Foldlet actuation stand, describe their different integrations in our prototypes, and present the fabrication processes required.

4.2 Layer 1: The Foldlet

When actuated Foldlets are applied in furniture pieces, the user only directly interacts with the Foldlet surface, while the rest of the stand is hidden away inside the object. An important application for Foldlet interfaces is on armrests or supporting surfaces of couches or living room chairs.

Therefore, a Foldlet is constructed to create a comfortable interaction experience by mimicking a soft and padded surface. Its anchor threads are sewn into a piece of thin and elastic fabric. We use an especially stretchy fabric here, which enables the Foldlet surface to retain tension and be completely flat when not actuated. At the same time, this allows the folds to form easily when force is applied to the threads. A layer of EVA foam is positioned underneath the fabric to provide padding. We specifically use a low-density foam that is soft and shape-retaining. Even after multiple actuations, the foam returns to its original shape, preserving a flat surface. At the bottom, an MDF plate is used for stabilization.

Templates of basic Foldlet shapes can be joined together to create complex interfaces.

To create a consistent way to fabricate Foldlets, we created templates in Autodesk Fusion for all shapes we described in Chapter 3. When creating a new Foldlet, the individual templates can be used as they are, or combined to create closed shapes like triangles and squares, or more complex polygons. A collection of all Fusion Templates for Foldlets as well as other fabrication parts can be found in our RWTH GitLab Repository [1].

A Foldlet is fabricated by sewing individual threads in fabric, and drawing them through its layers.

A timeline of assembling a Foldlet can be found in Figure 4.2. For transferring the template onto the materials, we use the MDF plate as a stencil to mark the anchor threads on the fabric, and draw the threading points on the EVA foam slice. For stabilization, the EVA foam should be glued to the MDF plate.
Each anchor thread is one individual string of thread that is stitched loosely into the fabric. The stitch should be sewn as small as possible, hiding the thread on the interface and creating localized tension when pulling on it. All anchor threads of one anchor need to be drawn through the foam layer and into the respective threading point in the MDF plate. To fix the fabric in place, its seams are glued to the bottom of the Foldlet. This should be done firmly without creating creases in the fabric surface, but it should be noted to not completely stretch the fabric, as too much tension would hinder the formation of the folds on the surface. For now, the threads are hanging loosely from the foldlets.

[1] `https://git.rwth-aachen.de/i10/thesis/thesis-jennifer-drew-foldlets`

Figure 4.2: Fabricating the Foldlet: Sewing the anchor threads into the fabric, then drawing the strings of one anchor through the respective threading point in the Foam and MDF plate. Finally, glueing the excess fabric in place.

When pulled on by hand, the foldlet creates the designed folds that form a shape.

4.3 Layer 2: Connecting The Foldlet And SMAs For Actuation

After a Foldlet is placed on top of the actuation stand, its threads need to be connected to the actuation mechanism. As already described, this can be done by tying the threads to the SMA directly or by using a stabilization plate. In the both cases, we want the threads to be fastened securely, but also enable an easy exchange of the Foldlet. Additionally, we need to wire the SMAs in a circuit for actuation. The surface of the SMA does not allow soldering, so we use crimping beads instead. After attaching the wire to the bead, it can be clamped in place on the SMA spring, as shown in Figure 4.3. On the top end of the SMA, we additionally attach a small metal hoop. When adding a carabiner to it, we can modularly attach and remove the Foldlet from the SMA. Both fastening methods are depicted in Figure 4.3.

Attaching and wiring an SMA requires the use of crimping beads.

Each stabilization layer needs to be custom-made for a specific Foldlet and its actuation stand. For that, we re-use and adapt the sewing template of the Foldlet, in order to perfectly align the plate with the threading points of the

The stabilization plate fastens all threads of a Foldlet and is pulled down by four SMAs.

Figure 4.3: Left: Wiring the SMA underneath the actuation stand. Right: Wiring and connecting an SMA to the stabilization plate. We use carabiners to allow easily exchanging between Foldlets.

Foldlet. An example template and stabilization plate is shown in Figure 4.4.

During fabrication, fastening mechanisms for the required SMAs need to be added. One stabilization plate is pulled down by four SMAs which are attached at each side of the actuation stand. As seen in Figure 4.5, we create loops made of metal wire on the underside of the plate. This is where the carabiners that we already connected to the SMA can be attached. Next, we need to fasten the anchor threads to the plate. Our templates offer holes to fasten all anchor threads of one anchor individually. We use spacers to set up the stabilization plate at a fixed distance on top of the Foldlet for fabrication. The threads are then drawn through the holes in the stabilization plate and fastened using small beads. To securely tighten the strings we recommend gluing the beads to the stabilization plate. All threads should be tightened securely before glueing. This allows the threads to all be in a similar state of tension and thus to create all folds equally strong when actuated.

When the Foldlet shape gets larger, the number of anchor threads might become too high for four SMAs to actuate. Then more SMAs would be needed, or multiple actuation stands which each using an independent plate.

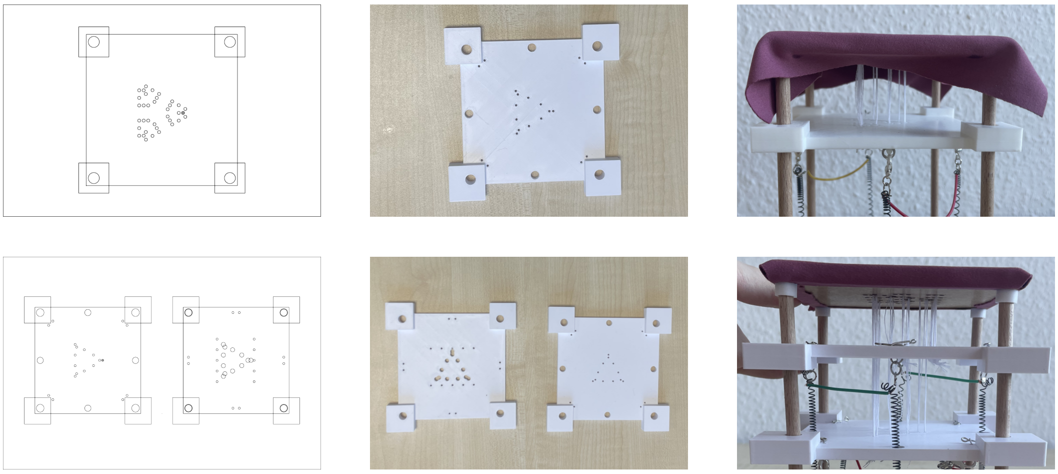
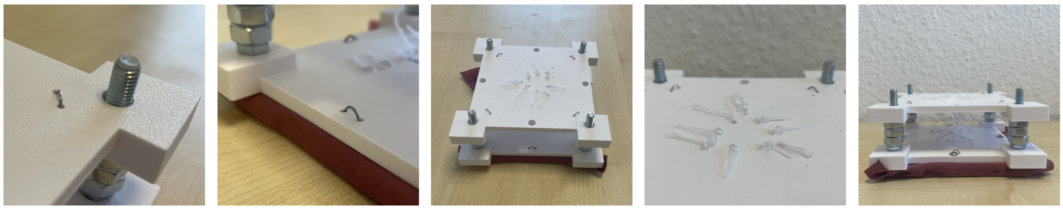


Figure 4.4: The two applications of stabilization plates: A singular plate for actuating large Foldlets, or two paired plates enabling alternating between overlapping shapes. Patterns of the plates (Left), 3D printed pieces (Center), integrated into the actuation stand (Right).

When creating a prototype that displays an overlapping shape, two stabilization plates are required. This design presents itself as the most challenging, since the plates must be carefully designed to align perfectly with each other as well as the Foldlet, but avoid friction to not get tangled up. Each plate fastens the threads of one of the overlapping shapes. Therefore, the upper stabilization plate must include all fastening mechanisms for that shape, as well as leave space for the remaining threads hanging downwards. The lower plate has to integrate holes for the SMAs to reach through, pulling down on the upper plate. Examples of templates and stabilization plates are shown in Figure 4.4.

Multiple stabilization plates can be connected vertically to display different shapes.

When using two stabilization plates, it is necessary to create enough space both to the Foldlet, as well as between the plates. This allows both plates to move up and down independently along the railing without interfering with each other.



(a) (b) (c) (d) (e)

Figure 4.5: When putting together the stabilization layer, the following techniques have to be executed: (a) and (b): Creating attachment points for the SMAs. (c): Using spacers to stack the stabilization plate onto the Foldlet. (d): Fastening the threads using beads and glue. The resulting stabilization plate is shown in (e).

4.4 Layer 3: The Actuation Stand

The actuation stand is built from the same concept for each application purpose.

The Actuation stand is the structure that holds everything together. Each actuation stand consists of the same base design. An exemple and the required materials are depicted in Figure 4.7. The bottom of the stand forms a 3D printed plate created with nylon filament. This plate needs to be heat-resistant, as we want to draw the SMAs through it and fasten them underneath. Since the SMAs heat up during actuation, we want to avoid this damaging the material of the plate. Wooden rails are used to hold the Foldlet in place and let the stabilization plates slide vertically.

4.5 Making the Interface Disappear

With the current design, the user needs to stroke over the fabric in order to completely flatten the folds.

The SMA springs heat up and therefore contract when current is run through them. When no current is running, the SMAs slowly cool down to room temperature and expand, loosening the pressure on the strings. In that process, the fabric on top of the Foldlet also relaxes, but is not under enough tension to completely return to a fully flat and untouched state. As of now, the user needs to stroke across the relaxed fabric a few times to fully make the folds disappear. Figure 4.6 depicts the strength of folds durinc actuation, after the SMAs have cooled down, and after relaxing the fabric by hand.

Figure 4.6: Stroking over the fabric is required to completely flatten the surface of a Foldlet, even after the SMAs have completely cooled down. Left: An activated Foldlet using SMAs. Center: State of the folds when the SMAs have cooled down. Right: Completely flat surface after manually stroking across it.

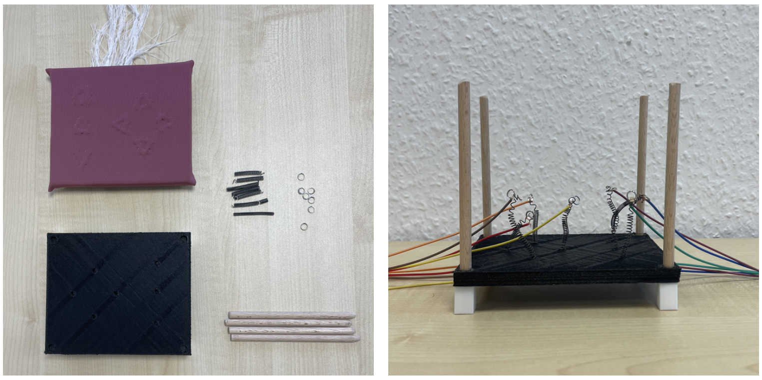


Figure 4.7: Materials required (Left) to build the actuation stand (Right).

Using a metal spring as an opposing force for the SMA reduces the Foldlet quality.

In an attempt to automate the relaxation of the fabric, we tried utilizing metal springs as an opposing force to the SMA. The spring is attached to the bottom layer of the Foldlet and the upper end of the SMA, where the threads are fastened. When the SMA contracts, it also pulls on the metal spring, which expands as a result. We hoped that when the current stops running and the SMA cools down, the spring could pull the Foldlet threads back up quicker than before. This could potentially let the fabric snap back into its flattened state. But in practice, that effect was not given, and we could not notice a difference in the relaxation of the fabric. As an additional disadvantage, the SMA now needs to put additional tension on the metal spring. As a

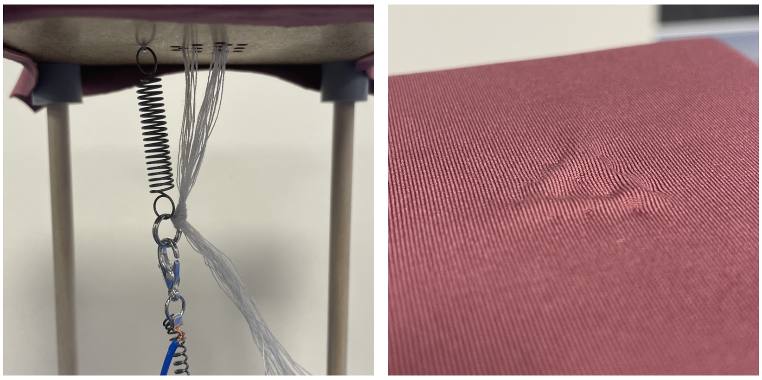


Figure 4.8: We tried using a metal spring as an opposing force to the SMA, with the goal to automate making the fold disappear. The SMA was not strong enough to pull down both the spring and threads, resulting in a barely activated Foldlet.

result, it is not able to activate the Foldlet as strongly as before, resulting in the folds being barely activated. The setup and resulting Foldlet can be seen in Figure 4.8. A more promising approach could be to somehow manipulate the fabric of the interface itself in order to relax the tension. Such a mechanism would need to pull or stretch the complete surface of the interface in order to fully remove any folds, but this would heavily alter the surface integrity. Since the goal of Foldlets is to make as little changes to the furniture piece as a whole in order to preserve aesthetics, creating such a mechanism poses a challenge for future research.

4.6 Controlling the Actuation

Based on the number of SMAs and their wiring, different power demands are being made to the structure.

To control the actuation process, we need to regulate the current flowing through the SMAs. For Foldlets that only activate a single shape, we can directly wire all required SMAs in series and apply current. To independently control single SMAs or groups of SMAs, these circuits must be connected in parallel. It has to be noted that, depending on how many SMAs are controlled and how the circuit is designed, the power demands can change drastically. Depending on which device or furniture piece a Foldlet should be integrated in, the power demands might pose a limitation to the application.

Our actuation stands are controlled by an Arduino Uno. Using relay modules, current can be switched from an external power supply to the individual circuits of SMAs. Based on the application, this can either be done for all SMAs at once, for example when pulling on a stabilization plate of a bigger shape, or individual circuits that need to be activated manually. This is necessary when controlling activation of overlapping shapes, or individual parts of an assembled interface.

We use an Arduino Uno to control the flow of the current.

Chapter 5

Application Scenarios

Since Foldlets require an actuation by pulling on their threads perpendicularly to the surface, including a stabilization mechanism, they are not suited for integration into soft items like blankets or into the thin layers of smart clothing. Instead, we imagine Foldlets built into larger furniture pieces, such as chairs, beds, or couches, but also lamp stands and shades. The resulting interface can either be used to interact with the furniture piece directly or just be placed there to control independent devices across a room. Additionally, Foldlets are suitable for displaying output. They can be used to display the state of a device, notifications, or external factors such as the time or temperature. Foldlets can be designed simply for aesthetic purposes as well, showing art or movement without transporting information.

Foldlets can be built into larger furniture pieces, but not thin blankets or clothing.

When used as an input device, Foldlets offer a variety of techniques to be controlled. Closed Foldlet shapes can be used to signify possible touch interaction, acting as textile buttons. In that case, both the inner flat part of the shape as well as the folds themselves could be used to register touch or force input. As an alternative option, we envision stroking across a fold, pinching the fabric, or pulling on it as feasible interaction approaches. Moreover, Foldlet shapes do not have to be activated to enable interaction. The fold could be used to supply haptic and visual feedback during or after the input action on flat fabric. To demonstrate

There are different approaches to interacting with a Foldlet.

different input mechanisms as well as usage scenarios for Foldlets, we created five actuated prototypes. For each, we illustrate specific application examples and explain their advantages.

5.1 Prototype 1: Small Triangle

Small Foldlets can be used as buttons.

Our first prototype, as demonstrated in Figure 5.1, displays the smallest triangle we were able to create, with a side length of 10 millimeters. As this is roughly the size of a fingertip, the small shape can be made out by touch easily and allows to be used as small buttons to be pressed or tapped. This design guideline for textile interfaces has been established by Mlakar et al. [2021].

Small Foldlets allow integration into limited spaces.

Because of its small surface area and the low number of anchor threads needed, we were able to actuate this shape by using only one SMA without any stabilization technique. This also holds for the other small shapes we created, like the square, circle, or short lines. As a result, their actuation mechanism requires little space. In future approaches, the actuation stand could be scaled down further to allow integration into smaller objects. Therefore, small Foldlet shapes are well-suited for use in limited spaces or on compact objects that do not offer much display space. As an example, many chairs are made from or covered in fabric, but are often designed slim for aesthetic purposes. A Foldlet of this size could be integrated into a chair's slim arm or backrest, as illustrated in Figure 5.2. In this context, the interface can be used to control devices across a room without needing to leave the seat.

Devices with few modes can be controlled by single buttons.

Individual small shapes can be used if the controlled device only allows restricted functionality or a few modes to choose from. Lamps, for example, mostly need one button to be turned on or off. This is typically controlled by a plastic switch placed directly on the lamp or hanging down from it on a cord. Using a small Foldlet icon on either the lamp's fabric stand or lamp shade, the interface could be seamlessly embedded, hiding away the electronic components.

Small Foldlets offer clean aesthetics.

Additionally, small Foldlet shapes require few stitches and

Figure 5.1: Our first prototype uses an actuation stand including a single SMA to activate a small triangle.

therefore do not disrupt the look and feel of fabric textures as much as bigger shapes might do. Therefore, employing smaller shapes allows to create a clean and minimal aesthetic, and preserves the object's original appearance.

5.2 Prototype 2: TV Remote Mockup

If more surface area is available, individual Foldlets can be composed into complete interfaces. Small Foldlets are especially suitable here to keep the interface compact. Such an interface enables control without having to reach too far away from the center. Additionally, this enables one-handed interaction.

Multiple small Foldlet shapes can be combined to create complex interfaces.

As demonstrated in Figure 5.3, we created a mock-up of a TV remote consisting of seven small Foldlet shapes. The bottom half of the interface displays four triangles that form a directional pad for navigating GUIs. Placing an additional icon in the center could be done as well. On the upper part of the interface, a row of three icons is located. We use a triangle and a square shape to act as play and stop controls, as well as a 60° angle representing an interface typical "go back" button. Since all icons are small, they can

As an exemplary application scenario, we created a TV remote interface mock-up.

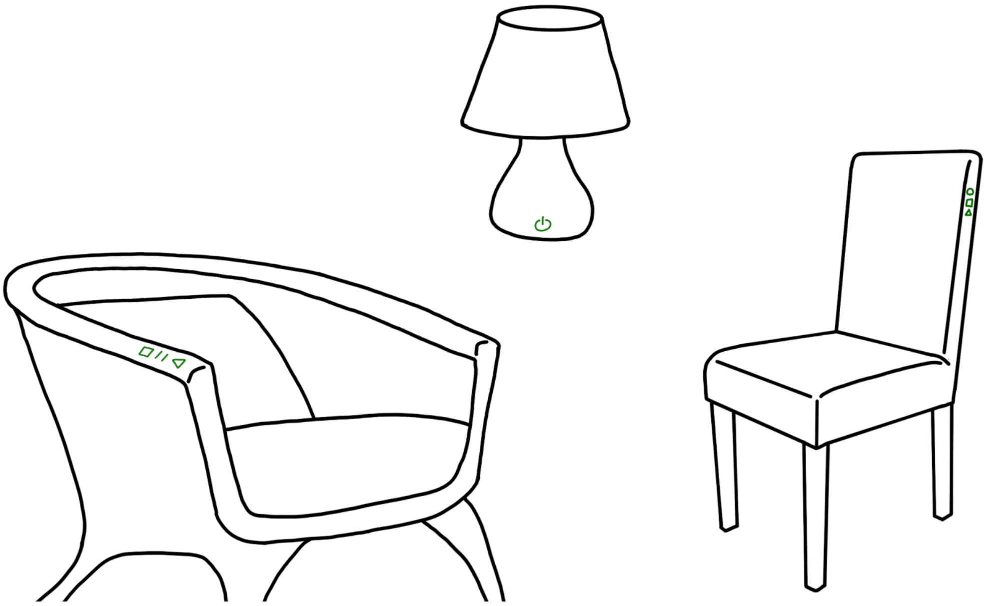


Figure 5.2: Small Foldlet shapes can be applied on furniture pieces that offer little surface space, like chair arm- and backrests, or devices with few states, for example, lamps.

be actuated by an individual SMA spring each. This additionally enables the icons to be activated independently of each other. While all icons can be displayed a the same time if needed, it can be beneficial to dynamically hide or activate individual controls. As an example, the interface could alternate between activating the play and stop icons when watching a movie, depending on the state of the current playback. Additionally, the icons could only be made available in situations when the user might need them. The play and pause icons could be hidden when the user navigates a menu, but then be activated once video playback starts. Similarly, when navigating horizontal scrollable menus, the up and down buttons of the directional pad are not needed and can be hidden.

One such interface can also be used to control different devices spread across the room, for example, turning on lights, the TV, or activating smart shutter blinds. We imagine this kind of interface to be located on top of a couch or chair armrest, to easily reach and control the icons when sitting down. An additional application can be the bedroom

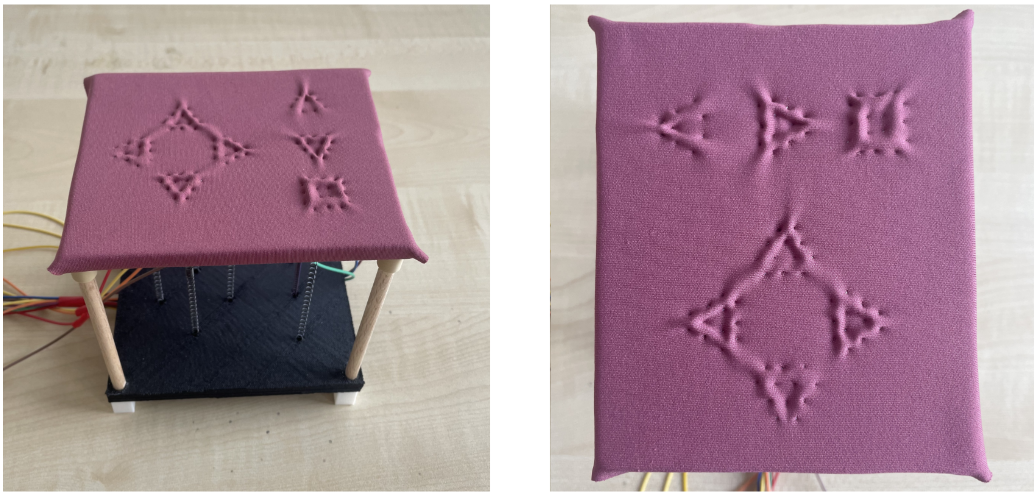


Figure 5.3: This prototype displays a mock-up of a TV Remote.

in order to control height adjustable beds. Those scenarios are sketched in Figure 5.4.

5.3 Prototype 3: Large Triangle

To give an example of a larger shape, our next prototype displays a triangle with side lengths of 30 millimeters. We used an actuation stand with four SMAs that integrates a stabilization plate. The prototype and its actuated shape can be seen in Figure 5.5.

Larger Foldlet shapes enhance visibility and can create contrast.

Small Foldlet icons are limited in their display resolution. We were able to display simple geometric shapes like a triangle, a square, and short lines, but reached the limits when designing a small circle. Additionally, complex shapes with a higher number of corners and edges get more challenging to design. In those cases, increasing the size of a Foldlet shape can help to create cleaner interfaces. Some users prefer to interact with larger shapes, as Nowak et al. [2025] have found. As an additional factor, larger icons enhance visibility and can create contrast when displaying multiple icons for a larger interface. This can be used, for example, by designing the important buttons or inputs using larger icons. An interface that controls music playback

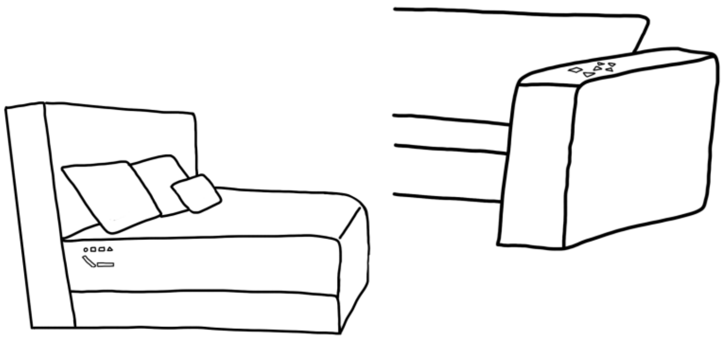


Figure 5.4: We imagine a Foldlet interface to be integrated into larger surfaces on furniture. Left: An interface on beds with adjustable back rests. Right: Application on a couch armrest for controlling the TV or other smart home products.

could magnify the size of its play and pause buttons, as those might be the ones used regularly.

Sliders can be designed by long rectangles or lines.

As another example of larger Foldlet shapes, we imagine textile sliders. A slider could be created by using a wide rectangle where the interaction is done in its inner area, or single Foldlet lines that are stroked across directly. Moreover, creating longer folds makes it possible to utilize different parameters like anchor distances. This can not only change the quality of a fold, but also its aesthetic or tactile feedback during interaction. Differences in anchor distances could be used to signify different states or usecases. Additionally, large shapes are especially well-suited for displaying output, as their increased size enhances visibility and draws the viewer's attention. This could be done both for aesthetic reasons, like displaying art, or when communicating information like the state of a device, the weather, or the temperature. Furthermore, combining different kinds of folds on a wider surface area allows for easier display of more complex shapes, enabling the creation of intricate and detailed images.

Output can be displayed more clearly using large shapes.

Figure 5.5: This prototype makes use of a stabilization plate to display a single larger triangle.

5.4 Prototype 4: Alternating Shapes

Alternating shapes can be employed for saving space or simplifying the interface.

When there is not enough surface area available, multiple larger icons can be displayed alternating instead. This approach not only saves space but also creates a clearer interface structure by reducing the number of icons that are displayed at a time. It supports context-dependent information, ensuring that users see only what is necessary at any given moment. In turn, focusing the attention on the most relevant actions is possible, which avoids overwhelming the user with possible inputs.
With this prototype, we present a dynamic Foldlet that can alternate between displaying a triangle and two lines, representing the combination of a pause and play button. Figure 5.6 shows the complete actuation stand as well as the displayed shapes. Because a play and pause button never need to be interacted with at the same time, it is justified to combine them in this manner. The interface could again be used for controlling a TV, but also for music, radio, or any kind of playback.

In chapter 3.6.2, we presented additive shapes as another option to alternating shapes. Additive shapes, like the plus and minus icons we presented in Figures 3.13 and 3.14, al-

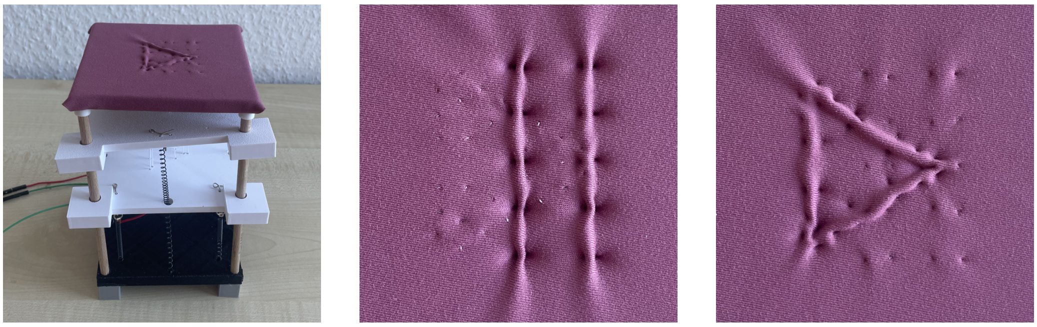


Figure 5.6: This prototype uses two stabilization layers (Left) in order to switch between displaying a pause icon (Center) or a play icon (Right).

Additive shapes serve the same purpose as alternating shapes, but are more complicated to display.

low the combination of anchors requiring less fabrication and avoiding the anchor threads unintentionally interacting with each other. But in contrast, the actuation stand for such a Foldlet would require a different structure than what we presented in this thesis. Because of the size of the Foldlet shapes, we would still require stabilization plates to activate all folds evenly. But when two shapes share common anchor threads there has to be a mechanism that pulls on those threads independently from both shapes' remaining threads. Depending on the complexity of the shapes, it might be necessary to use three or more stabilization plates, complicating the fabrication of the actuation stand greatly, which is why we did not attempt it in this thesis. But using a combination of the fabrication techniques we presented in Chapter 4, such an interface is certainly possible to create. Depending on the application context, it still can suffice to use another actuation technique instead.

5.5 Prototype 5: Seven Segment Display

Seven-segment displays allow displaying a high number of different shapes dynamically.

So far, we have seen Foldlet interfaces that change their displayed shape used for saving space and only displaying relevant information. In order to customize the displayed interface even more, we have created approaches to build completely dynamic and segmented interfaces. In Chapter 3.7, we presented a point matrix as well as a seven-segment display. Since small parts of the interface can be controlled individually, it allows for displaying a much larger vari-

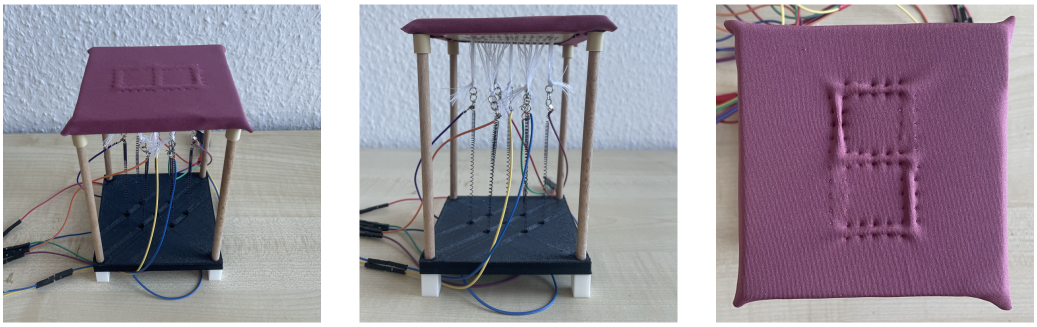


Figure 5.7: Left and Center: In order to actuate a seven-segment display, we attach the threads of one segment to one SMA, which then can be activated independently. Right: An exemplary display of the number 5.

ety of shapes. This construction additionally allows for the display of multiple shapes that share anchors without having to complicate the fabrication process. To demonstrate that concept, we created a prototype actuating a seven-segment display, where each segment is created by a line of 20 millimeters, with an anchor pair distance or 5 millimeters. The actuation stand and resulting interface are depicted in Figure 5.7. Similar to the TV remote mock-up in Chapter 5.3, each segment is actuated by a single SMA without requiring additional stabilization. Our prototype allows displaying the numbers 0 to 9, as well as a limited selection of letters.

Combining segmented displays allows for displaying the time, temperature, or similar numerical values.

Being able to display numerical values, several new application purposes in textile interfaces are possible. As an addition to our TV remote interface, a seven-segment display can be used to display channel numbers or the current speaker volume. A textile clock could be created as a standalone furniture piece or be integrated into existing textile surfaces. Similarly, numerical information like the time or temperature could be displayed. Also, setting a timer or an alarm in the bedroom can be integrated seamlessly without requiring an external device. When expanding the concept of this segmented display and creating a larger grid from short horizontal and vertical lines, many more and also larger shapes could be activated dynamically as well.

A seven-segment Foldlet can be used for inputting numbers.

So far, we have only named output applications for a segmented display. This Foldlet can additionally be used to register actions from a user by stroking over the individual segment folds to input a number. The entered number can then be activated after the interaction, acting as feedback.

Chapter 6

Limitations and Future Work

In this thesis, we presented a novel approach to creating disappearing textile interfaces. Since our work represents the first in-depth exploration of this technique, we recognize that certain shortcomings and limitations need to be considered.

Techniques for reducing interferences in overlapping shapes are needed.

While a majority of our shape designs resulted in the creation of clean and aesthetic folds, we were limited in how alternating shapes were designed. Even though the anchor threads are sewn into the fabric loosely and using small stitches, their presence disturbed the creation of the second shape's fold. We observed this process especially when multiple anchors of both alternating shapes were placed in proximity, restricting the design of shapes in that use case. Depending on the shapes we intended to display, it is possible to position them in a way such that only a few anchors overlap. We were able to achieve this with our second iteration of the play-pause combination, which we demonstrated in Figure 3.12. But this will not be possible for all shape combinations. In such cases we recommend using additive shapes or segmented grids and displays instead. Those approaches resulted in the dynamic display of more stable and clean shapes. Alternatively, it would be an interesting approach to create alternating shapes that use more anchors as well as smaller anchor pair distances. While this would seem to be counterintuitive, shapes that use smaller anchor pair distances did create more stable folds in our prototypes. As a result, this could limit the interaction of the not-activated anchor threads, leading to fewer interferences.

Actuation stands should be adapted in order to reduce its volume.

When actuating larger Foldlets, one or more stabilization plates are required for each shape. Thus, our prototype structures take up a considerate amount of space. Integrating Foldlets into larger and rigid furniture pieces like chairs or couches can be possible, but for thinner objects like blankets or soft cushions, this is not currently possible. Applying a Foldlet always requires a certain robust part to accomodate the actuation mechanism. Depending on the application of a Foldlet, we can imagine this structure to be hidden inside larger parts of the respective objects. Since our primary application aims were targeted at surfaces on couches, beds, or chairs, this does not pose drastic limitations. Still, future research should investigate whether an adapted version of our actuation stands could be created to save space and offer more flexibility.

Energy costs and sustainability pose a challenge to our actuation technique.

Another limitation of our actuation design is posed by its energy consumption. The power demands of actuating multiple SMAs at once quickly exceed typical electronic household devices. While actuating a small Foldlet shape with a single SMA only requires about 5 watts, using four SMAs to actuate a single larger shape already needs 10 to 15 watts to function. This scales even more when multiple shapes are used to assemble an interface, especially if each shape must be independently able to activate. Depending on the complexity of a Foldlet interface, this can be difficult to integrate into the typical household. Additionally, environmental aspects need to be considered. Since smart home devices are a popular demand, our homes already collect many electrical devices. Sustainability is an established challenge of shape-changing interfaces. Future work with Foldlets, therefore, should consider this and ultimately aim to reduce the current power demands.

Foldlet fabrication techniques can be improved to reduce efforts in fabrication.

As presented in Chapter 4, fabrication of Foldlets and their actuation mechanism is currently done completely by hand. Static textile interfaces often employ embroidery to display icons onto fabric, which can be automated by an embroidery machine. But since Foldlets require the integration of small and loose stitches, this poses a challenge when creating them en masse. Additionally, the stabilization plates that are required for some shapes take much time to assemble and precise work in order to evenly distribute the force pulling down on the strings. Continuing research could find novel ways of integrating SMAs into the actuation process while simplifying the fabrication process.

It is necessary to find techniques that flatten the fabric completely after activation.

Flattening the fabric on the Foldlet surface after actuation currently needs to be done by stroking over the folds after the SMAs release the tension on the strings. While this is feasible for now, it requires additional action by the user and can disrupt the flow and ease of seamless interaction. In Chapter 4.5, we tried to counteract the pulling force of the SMA by applying a metal spring in the other direction. This did not work out as intended, as the spring was not able to hide the folds and even limited the display of the Foldlet shape on the fabric. Thus, other approaches to solve this problem need to be developed. One approach could be to use different kinds of fabric for the Foldlet surface. The fabric would need to be flexible enough to create folds using our technique, but rigid in a way that it stretches out by itself when not actuated. In a similar manner, different kinds of threads, for example, elastic thread, might make a difference. Other strategies could aim for mechanically pulling on the surface fabric itself and stretching it out to remove the folds. Attention should be paid to not complicate the actuation structure any further, as the mechanism would still need to be integrated into furniture pieces seamlessly.

Foldlets have to be evaluated with users.

Lastly, this thesis focused on the design of Foldlets and the presentation of their fabrication and actuation. As a result, we did not conduct any user studies to evaluate our interfaces. Future research needs to investigate how users accept this new type of textile interface, and whether its qualities appeal to them. Furthermore, we have discussed some ideas for interacting with the folds, like touching the shapes themselves and the fabric in between, or pinching and pulling on the folds. Therefore, we recommend investigating users' first impressions and intentions on how to interact with foldlets. Results could additionally further shape the design process of new shapes and fold creation techniques.

Chapter 7

Conclusion

This thesis presents Foldlets: A novel approach to silent and eyes-free textile interfaces that dynamically adapt to the application context and disappear when not needed. Foldlets use string-actuation to create folds in fabric, displaying shapes in the process which can be hidden from sight. We establish consistent design methods and give guidelines for creating basic shapes like points, lines, and angles. Using those building blocks, it is possible to assemble closed or complex shapes and custom interfaces. Furthermore, we present fabrication techniques for all parts of the interface as well as its actuation mechanism. Lastly, we demonstrate different application scenarios and interaction techniques by building five prototypes.

Our technique for designing and displaying shapes is simple and versatile, allowing for the creation of any required shape in fabric. Our completely dynamic interfaces can display a multitude of shapes, change them at any time based on the application context, and make them disappear when not needed. Foldlets can be integrated into many furniture pieces in the home, creating a comforting way of interaction while preserving the aesthetic look and feel of the object. We are excited to present this toolkit, enabling designers and researchers to use our concepts for improving interaction experiences in the home.

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