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KOOPA: A Kinetic Output Object for Physical Alerts

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Abstract

Ambient notification systems have shown promise for delivering information in less obtrusive ways. However, current systems often rely solely on visual or auditory cues, which can range from overly intrusive to easily overlooked. Shape-changing interfaces, an increasingly popular research area, offer more tangible and expressive interactions and present a promising avenue for expanding notification systems. We present KOOPA, a pillow designed as a protoype that uses both soft robotic and conventional robotic approaches to deliver notifications ranging from subtle to highly expressive, with a focus on incorporating emotional communication. We demonstrate the feasibility of string-controlled robotic limbs using air-inflated chambers as structural support and their application in shape-changing interfaces. We report on challenges and limitations encountered in the chosen modalities and the prototype's current implementation. Finally, we propose design directions for enhanced performance and expressivity, including the potential integration of textile-based input. This work contributes a technical prototype and shares our design insights for soft interactive interfaces, providing a roadmap for the development of similar shape-changing interfaces.

Überblick

Ambient-Notification-Systeme stellen ein vielversprechendes Forschungsfeld dar, um Informationen auf subtile und kontextsensensitive Weise zu vermitteln. Bestehende Ansätze basieren jedoch häufig hauptsächlich auf visuellen oder auditiven Signalen, die sowohl als störend aufdringlich wahrgenommen werden oder leicht übersehen werden können. Shape-Changing Interfaces sind ein zunehmend relevantes Forschungsgebiet in der Human-Computer-Interaction und ermöglichen greifbare sowie expressive Interaktionen, wodurch neue Möglichkeiten zur Verbesserung von Benachrichtigungssystemen eröffnet werden können. In dieser Arbeit stellen wir KOOPA vor, einen Prototyp eines Kissens, der soft-robotische und konventionelle robotische Ansätze kombiniert, um Benachrichtigungen in einem Spektrum von subtil bis expressiv zu übermitteln. Dabei wird auch die Einbindung emotionaler Zustände in der Kommunikation berücksichtigt. Wir demonstrieren die Durchführbarkeit schnurgesteuerter Roboterarme mit luftgefüllten Kammern als strukturelle Elemente und deren Anwendung in Shape-Changing Interfaces. Darüber hinaus analysieren wir die Herausforderungen und Limitationen der gewählten Modalitäten sowie der präsentierten Umsetzung. Abschließend werden Designanstöße vorgeschlagen, die die Ausdrucksstärke und Leistungsfähigkeit solcher Geräte verbessern können, einschließlich der potenziellen Integration textilbasierter Eingabemethoden. Diese Arbeit liefert sowohl einen technischen Prototypen als auch Erkenntnisse über den Designprozess interaktiver Shape-Changing Interfaces und bietet eine Grundlage für die Entwicklung zukünftiger verwandter Systeme.

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Finally, I am deeply thankful to my friends and family for their ongoing support.

Conventions

Throughout this thesis we use the following conventions:

- The thesis is written in American English.
- The first person is written in plural form.

Short excursuses are set off in colored boxes.

EXCURSUS:
Excursuses are set off in orange boxes.

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

Since its emergence, the field of human–computer interaction has consistently evolved, with the exploration of novel modalities of interaction becoming an increasingly popular theme. However, progress is often constrained by technical limitations, such as actuator size, speed, and reliability in shape-changing interfaces [Coelho and Zigelbaum, 2011], material constraints in soft robotics [Rus and Tolley, 2015], or limited sensing capabilities in ambient notification systems [Okoshi et al., 2016].

1.1 Shape-Changing Interfaces

Definition of shape-changing interfaces

Shape-changing interfaces (SCIs) can be understood as a natural extension of tangible user interfaces (TUIs) [Poupyrev et al., 2007]. Both paradigms use physical embodiments of digital information to enhance interaction.

Excursus: *Tangible User Interfaces*

TANGIBLE USER INTERFACES:
"Tangible Bits," as coined by Ishii and Ullmer [1997], refers to systems that couple digital information with graspable physical objects, which enable multi-sensory interaction. Building on this idea, the concept of tangible user interfaces was developed to describe user interfaces that incorporate such multi-sensory objects.

SCIs extend this concept by enabling the tangible representation to dynamically transform based on the requirements of the situation [Coelho and Zigelbaum, 2011]. Most definitions require such transformations to be self-actuated rather than passively induced, leading to an alternative classification as "actuated interfaces" [Poupyrev et al., 2007; Rasmussen et al., 2012]. The notion of “shape” in this concept is not limited to physical form alone. Rasmussen et al. [2012] identifies orientation, form, volume, texture, viscosity, spatiality, addition/subtraction, and permeability as dimensions of an artifact’s shape, and as such subject to change in SCIs. In shape-changing interfaces, dynamic physical transformations are used to convey information to the user. These are often used to augment output properties [Alexander et al., 2018], but common definitions of SCIs also include input devices that can modify their physical properties [Rasmussen et al., 2012] to support different input actions or to alter their affordances and signifiers, as described by Norman [2013].

Ultimate vision of SCIs is an "ultimate display"

Moving beyond traditional screens and static input devices, one promising direction is that of shape-changing interfaces, which seek to leverage dynamic changes in physical properties to more effectively convey information and support interaction [Alexander et al., 2018]. While this provides a basic definition, Sutherland et al. [1965] describe their long-term vision for SCIs as an "ultimate display," capable of transforming any of its properties to fit the required task.

Current state and challenges of SCIs

The research area of SCIs has grown and matured significantly in recent years [Alexander et al., 2018], but consumer-level devices rarely employ shape-changing properties and interest in SCIs among the general population remain relatively low [Coelho and Zigelbaum, 2011; Rasmussen et al., 2012]. This limited adoption can be attributed to several factors, including high production costs, technical challenges in reliable actuation and sensing [Coelho and Zigelbaum, 2011; Rasmussen et al., 2012], and difficulties in creating durable, responsive, and safe materials for everyday use [Ambaye et al., 2024]. Additionally, shape-changing interfaces are, also subject to accidental design shortcomings or malicious design patterns (e.g., dark patterns [Gray et al., 2018].), just like more conventional user interfaces [Alexander et al., 2018]. As demonstrated by Tang et al. [2025], haptic feedback can be used to manipulate the actions of users on mobile interfaces, highlighting the potential for manipulative designs in SCIs. These risks underscore the need for careful design and evaluation to ensure both usability and ethical interaction in shape-changing interfaces.

SCIs have the potential to enrich user interfaces significantly

Exploring the development of SCIs may provide a more intuitive and engaging form of interaction compared to traditional graphical or static physical interfaces. This could be achieved by leveraging changes in physical form to dynamically convey information simultaneously through multiple modalities [Coelho and Zigelbaum, 2011; Poupyrev et al., 2007]. Furthermore, SCIs build on the advantages of TUIs by embedding information into the physical environment while still enabling the dynamic display of information. [Jansen et al., 2015] describe this form of physical representation with the neologism physicalization. It enables richer ways of conveying information [Ishii and Ullmer, 1997] and can make abstract data more tangible and easier for users to interpret and interact with [Rasmussen et al., 2012; Alexander et al., 2018].

1.2 Ambient Notifications

Challenges in current notification formats

As the digital world becomes increasingly information-rich, and the volume of notifications carries the risk of overwhelming or annoying users [Okoshi et al., 2018], the idea of filtering notifications and providing adequately relevant representations has become increasingly prevalent in human-computer interaction. Disruptive notifications are a double-edged sword. While they aim to enhance users' awareness of secondary events or tasks by highlighting important information, they often negatively affect performance on the primary task. Czerwinski et al. [2004] found that interruptive notifications lead to frequent task switching among information workers, increasing cognitive load and causing time loss due to context switches. Similarly, Adamczyk and Bailey [2004] showed that interruptions during complex tasks raise error rates and prolong task completion times.

Wrongfully placed notifications are often viewed as annoying

Many notifications have been reported to cause annoyance, particularly when frequent alerts are judged as not being of imminent relevance to the user's current task [Sahami Shirazi et al., 2014]. This issue is compounded by the fact that many devices' notification frameworks do not adequately determine or differentiate between priority levels [Okoshi et al., 2018]. As a result, users often perceive such notifications as spam [Sahami Shirazi et al., 2014], underscoring the need for more effective notification management systems.

Possible mitigation strategies for notifications

Varying the modality of notifications and introducing novel visual representation styles can help mitigate the aforementioned negative effects associated with frequent alerts [Adamczyk and Bailey, 2004]. Similarly, choosing the modality of interruption based on the user's current allocation of cognitive resources can enhance effectiveness [Okoshi et al., 2016]. For example, auditory alerts may be more suitable for urgent events, forcibly distracting the user from their primary task [Lazaro et al., 2021], whereas peripheral or ambient visual cues can unobtrusively convey lower priority information without actively interrupting ongoing activities [McCrickard and Chewar, 2003; Jones et al., 2017]. Delaying the delivery of notifications until opportune moments, such as natural breaks in task performance, can reduce their disruptive impact on primary task performance [Bailey and Konstan, 2006; Czerwinski et al., 2000; Iqbal and Bailey, 2005, 2006].

Accurately predicting optimal notification timings is difficult

However, both approaches require an accurate foundational model of the task and the user's cognitive state. Consequently, while the theoretical concept appears straightforward, its practical implementation remains challenging and highly dependent on the individual user [Iqbal and Bailey, 2005, 2006; Okoshi et al., 2016].

Ambient prioritization of notifications

Different levels of notification priority can be addressed through correspondingly differentiated delivery mechanisms [Okoshi et al., 2016; Cho et al., 2025]. Ambient notifications aim to integrate such alerts into the surrounding environment, allowing low-priority notifications to fade into the background unless the user actively attends to them. This also enables prioritization to be expressed through variations in the intensity of movements or in positioning relative to the user's field of view. When placed in the periphery of vision, such notifications are more likely to be perceived during natural task breaks and ignored during task performance, thereby minimizing disruption to the user's workflow [Jones et al., 2017].

1.3 Soft Interfaces

Relationship of robotics and shape-changing interfaces

Bringing principles of shape-changing interfaces into the real world requires actuation mechanisms that can safely operate in close proximity to humans. Robotics is an obvious avenue to acquire accurate shape-change mechanisms. Soft robotics provides a natural fit for designing such novel interactive systems and interfaces in a human-safe way [Ambaye et al., 2024].

Excursus: *Soft Robotics*

SOFT ROBOTICS:
Soft robotics is a subfield of robotics that focuses on the design and construction of robots made from compliant, deformable materials, allowing them to safely adapt to unstructured environments and interact more safely with humans [Rus and Tolley, 2015; Kim et al., 2013]. Here, softness is determined by measures of material stiffness, such as Young's modulus or Shore hardness.

Cuddly User Interfaces

The concept of cuddly user interfaces [Sugiura et al., 2016] demonstrates that softness and a cuddly form can enhance both acceptance as well as emotional and physical engagement with interactive devices. Building on this insight, we chose the pillow form factor as an approachable medium for shape-changing interaction.

We will develop a compliant SCI for prioritized notifications in smart home environments

To stay within this soft realm, this thesis will apply a mixture of string-controlled soft robotic limbs and traditional stiff robotic parts with safety precautions to allow for compliant behavior and minimize the risk of human injury. In this thesis, we will design and build a prototype that enables a decorative pillow to deliver notifications with different priority levels. We envision that, in its final stages, this device could be integrated into a smart home environment to inform users about various events, such as the status of appliances or devices. The primary method of communication implemented will be shape-change, used to deliver output to the user. However, the device's functionality may naturally be extended to incorporate additional types of output, and potentially input as well (see Chapter 5). It is important to note that the focus of this thesis is solely on the implementation of the output device and its functions, and not on the underlying notification management system.

1.4 Outline

In Chapter 2, we will present some related research projects, focusing mostly on soft robotic concepts using similar mechanical principles and ambient notification systems that rely on similar communication methods.

In Chapter 3, we will present our design process, how we arrived at the features through interviews and literature, and how we realized those features in the prototype.

In Chapter 4, we evaluate the prototype's mechanical performance, examining the controllability of individual components and their interaction as a whole. We also identify limitations in the scope of this thesis and outline practical design directions for improving the system.

Chapter 5 revisits the main findings, reflects on the design's shortcomings, and highlights broader potential extensions and applications for future research.

Finally, Appendix A provides a step-by-step account of the prototype assembly process, while Appendix B details the supplementary materials, including the structure of our interviews and the CAD files.

Chapter 2

Related Work

In the following sections, we further present the fields introduced in Chapter 1 and narrow the scope to the subfields most relevant to this thesis. Furthermore, we present comparable prototypes and specific research that is directly relevant to this work, has served as inspiration for it, or both.

2.1 Soft Robotics

Advantages of soft robots

Traditionally, robotic systems are manufactured from rigid materials and incompliant mechanisms, with the purpose of granting maximal stability and force for predictable, repetitive tasks. However, this intended function also makes them potentially dangerous to operate in close proximity to humans [Rus and Tolley, 2015]. Soft robots, by contrast, offer significant advantages over traditional "hard" robots in adaptability and safety. Both advantages stem from the fact that softness allows the materials to absorb much of the energy from collisions [Ambaye et al., 2024]. This compliance is inherent to the materials themselves, rather than being introduced through compliance control or variable-stiffness actuators. A direct consequence is that collisions with objects or living beings are less likely to damage either the object or the robot. This property enables the robot to adapt more effectively to new, unpredictable

Figure 2.1: String-controlled octopus arm Wu et al. [2022].

environments and situations. It also allows soft robots to operate in a generally safer manner, including when interacting with humans [Kim et al., 2013; Rus and Tolley, 2015].

Typical actuation mechanisms for soft robotics

For the control of these soft components, many different mechanisms have been proposed and continue to be explored. The most common control strategies include pneumatic actuation through internal networks and variable-length connectors, such as dielectric elastomeric actuators (DEA) or shape-memory alloys (SMA), which mimic the function of muscles in animals [Kim et al., 2013; Ambaye et al., 2024].

Cable driven control of soft arms

A common design decision in general robotics is the use of strings or cables [Qian et al., 2018]. A similar approach can be adapted to soft robotics, as demonstrated by Wu et al. [2020, 2022]. They developed a silicone arm, inspired by octopus tentacles and mechanically actuated via servo-driven strings embedded in the silicone mold (see Figure 2.1). Deep Reinforcement Learning was then used to control the arm and achieve underwater bipedal loco-

Figure 2.2: Robot based on air-inflated trusses Usevitch et al. [2020]. Image taken from the video[1].

motion. In this thesis, we employ a comparable strategy by embedding strings within the soft limbs, with their lengths controlled by servo motors positioned outside the soft regions.

However, in contrast to Wu et al. [2020, 2022], we employ permanently inflated air chambers surrounded by a fabric layer, which provides shape and tensile strength while protecting against bursting, similar to the approaches of Usevitch et al. [2020] and Stuart et al. [2021]. They constructed robots that use inflatable trusses to generate structural integrity (see Figure 2.2). Rigid corner pieces were then employed to bend these trusses and move along them, allowing the robots to form different shapes, achieve locomotion, and even grasp objects.

Stiffness through air chambers

Engert et al. [2022] employed string control over illuminable spheres to create a spatial display interface. In addition, they released modular hardware and software systems that enabled rapid prototyping of different devices based on the same underlying building blocks and concepts. This modular, stackable control mechanism for string lengths and routing around motors served as inspiration for our work, although during the design process it was significantly adapted to meet the criteria of our prototype.

String controlled spatial display with modular control

2.2 Comparable Systems

String-controlled houseplant as a shape-changing interface

Many prior prototypes of SCIs have been developed to explore their ability to convey information through physical form. These systems vary widely in scale, actuation method, and application domain. Degraen et al. [2019] built a string-controlled arm, connecting the principles of SCIs with the robotics concepts discussed in Chapter 2.1 and covered it in an artificial houseplant to blend with the environment. The shape-changing ability was proposed to convey information about the home, such as subtly pointing toward a door to indicate it is unlocked, or expressing emotion in a manner analogous to a dog wagging its tail. The authors built a functional prototype and conducted a focus group to explore potential use cases, but did not pursue further development. Their prototype is capable of functions similar to those of our device, but it is larger, uses a different decorative niche to conceal the mechanism, does not utilize soft robotic components, and was not designed for as close proximity to the user as the pillow is.

Six-DoF robotic arm as an expressive shape-changing table lamp

Hu et al. [2025] employed a more complex six-degree-of-freedom robotic arm with a lamp head containing both a light and a projector, disguised as a decorative table lamp. Their focus was on expression-driven movements, using the arm not only for functional positioning but mainly to convey the robot's state and intent. This introduced emotional qualities and a sense of character to the object, which they found to enhance users' perception of the system. In this way, the arm functioned as a shape-changing interface, with its motion supporting communication through pointing and expression, while the light and projection served as the primary channels of information. They evaluated the device in various scenarios, including notification and reminder tasks. However, image projection played a central role in the interaction, and the arm itself was constructed using traditional rigid robotic mechanisms.

Shape-changing device for ambient notifications

Focusing on ambient notifications, Jones et al. [2017] developed a small shape-changing device capable of curling motions when supplied with an electric current. They evaluated its effectiveness at different positions relative to the

Figure 2.3: Two shape-changing interfaces mimicking plants for ambient notification of health goals Degraen et al. [2019].

user's field of view, finding that slow, peripheral shape-change can be used to notify users without causing significant distraction. This provides evidence for the viability of shape-change as a medium for ambient notification delivery.

3D-printed plants for ambient health notifications

Lee et al. [2023] built another shape-changing interface that superficially resembles a decorative household object and served to deliver notifications. They used 3D-printed house plants (see Figure 2.3) to notify users about health-related goals, employing movements and positional changes to convey information. They also investigated the emotional impact of these plant-like interfaces on users. While their work also focused on ambient notifications with differentiated priorities in home environments, our approach emphasizes soft robotic mechanisms embedded in a more intimate object.

Pillow-shaped SCI for menstrual data via shape-change

Ívansdóttir [2024], in a master's thesis, investigates how a pillow-shaped object can communicate menstrual data through shape-change of different inflatable regions on the pillow's surface. Although unpublished in peer-reviewed venues, this work is highly relevant, as it explores a similar form factor and employs shape-change as a communication channel. However, their approach emphasizes the physical representation of health data through codified deformations of varying intensity, rather than delivering notifications about appliances with different priorities.

2.3 Textile Interfaces

In our work, the textile surface primarily serves to conceal the robotic components, with the goal of allowing the device to blend seamlessly into a home environment. Prior research on textile-based interfaces could serve as potential extensions for our device (see Chapter 5), either by enabling input methods or providing additional output modalities.

Interactive and actuated textile interfaces

Textiles can also be actuated to support or extend the functionality of such devices. For example, Jiang et al. [2024] incorporated bistable actuation mechanisms into embroidered shapes, and Du et al. [2018] developed textiles that curl through thermally induced expansion.

Input functionality embedded in textile surfaces

In addition, integrating input capabilities directly into fabrics is a well-established research direction. One approach involves embedding touch-sensing functionality into the weave itself. Poupyrev et al. [2016] introduced a fabrication method that enables scalable production of textiles capable of detecting touch and gesture input with high fidelity. Based on such input methods, research has also explored the tangible design of textile interfaces, often achieved through embroidery or stuffing [Nowak et al., 2022; Schäfer et al., 2023]. Nack et al. [2007] integrated similar technologies into a pillow, creating an adaptive interface that incorporated a touchpad, LEDs, and vibration mechanisms, demonstrating the feasibility and user acceptance of embedding technical mechanisms within household textiles and even intimate objects like pillows. However, their work focused primarily on the technical implementation of connecting these pillows to a broader smart home communication system and did not significantly incorporate shape-change or the delivery of notifications.

In summary, the prior work reviewed here demonstrates the potential of SCIs as decorative objects in home environments. However, many of these systems rely on rigid mechanisms, while the soft robotic approaches included in this review have primarily been applied to domains such as locomotion or grasping rather than to SCIs. Building on this foundation, our work presents a soft robotic pillow designed to integrate into the home environment, emphasizing proximate interaction and allowing for future extensions toward bidirectional communication for prioritized notifications.

Chapter 3

Prototype Design

In this chapter, we first provide an overview of the methodology used in the design and development of the prototype. We then justify the prototype's design, starting with feature rationale followed by mechanical design explanations. By describing the steps taken, we aim to clarify the reasoning behind our design decisions.

3.1 Design Process

In this section we will quickly go over the methodology used in designing the prototype.

Literature review and feature sketching

After developing the fundamental concept of a pillow capable of pointing, we performed a brief literature review to identify similar devices, explore devices employing comparable modalities or mechanisms, and examine the general viability of such a device. Based on these findings, we developed a feature set, from which we created a series of feature sketches illustrating possible movements (see Figure 3.1) as well as potential mechanisms (see Figure 3.2).

Semi-structured interviews to gather design insights

Before proceeding further with the design process, we held a series of interviews to explore design possibilities, obtain first impressions, and validate both prior design de-

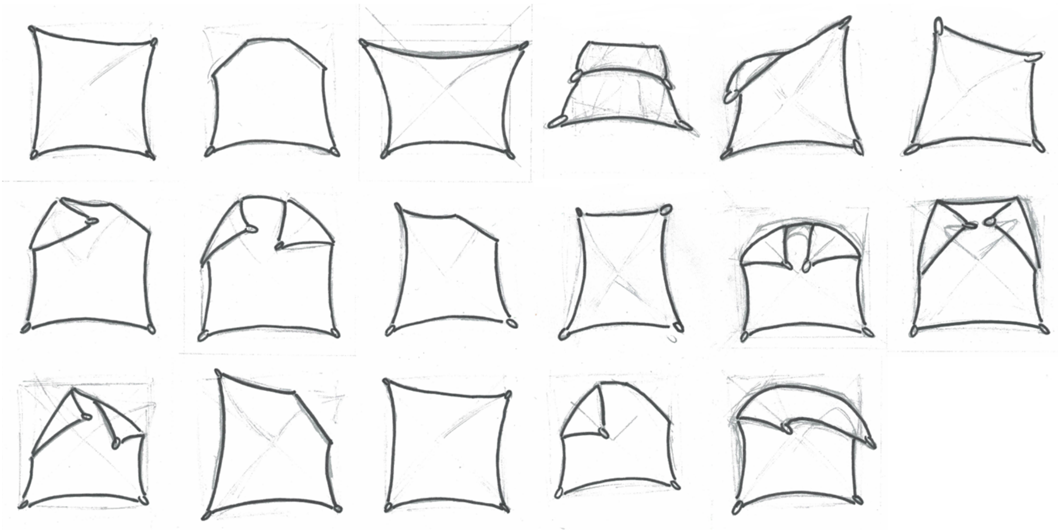

Figure 3.1: Our design sketches illustrating possible positions.

cisions and the overall design direction. We conducted five semi-structured interviews, each lasting between 45 and 90 minutes. The interviewees did not have a background in the specific topic, although all had technical backgrounds, and some even in HCI. An interview structure, presented in Appendix A, was followed roughly in all sessions. Depending on the flow of the conversation, some questions were skipped or reordered, and additional questions were included when they seemed relevant or served as follow-ups. During the interviews, we initially focused on general, open-ended questions about devices of this type to elicit participants' idealized systems. We then progressively narrowed the discussion, presenting our design ideas and gathering feedback on them. Additionally, we expanded the sketches of possible movements and discussed them with the participants to gather feedback on the particular possibilities of movement we imagined.

Interview insights and their influence on the design

Although interviews were conducted, their applicability is limited, and no dedicated report of their results will be produced. Nevertheless, we derived some insights for our design process from these interviews. In the following Sections 3.2- 3.3, we mention findings that influenced our design decisions or helped validate our initial ideas. Additionally, answers that contradict some properties of the fi-

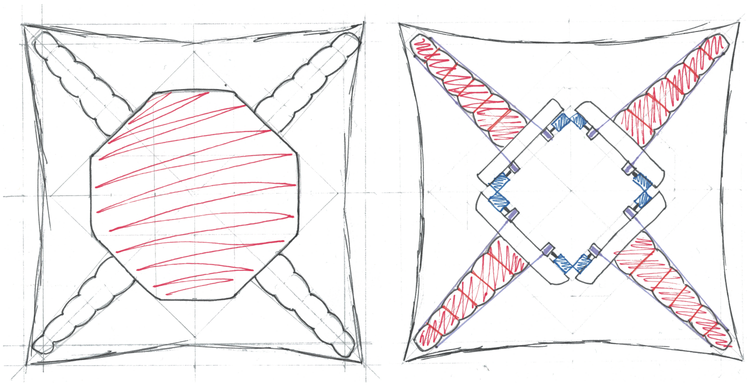

Figure 3.2: Our sketches for possible mechanisms.

nalized prototype will be discussed in Section 4.2. We will mention proposals that we consider particularly promising or that emerged as recurring themes across the interviews or ones we regard as interestingin Section 4.4.

After evaluating the interviews' results and engaging in further literature research, we proceeded with our iterative design and construction process.

3.2 Feature Design

In this section, we elaborate on the properties and features that were selected for the prototype and provide justification for these decisions.

Emotional and expressive communication through SCIs

As presented in Section 1.2, ambient notification systems can improve productivity and the emotional value of notifications [Adamczyk and Bailey, 2004]. Furthermore, Okoshi et al. [2016] and Cho et al. [2025] showed that varying the modality of notification delivery enhances both effectiveness and emotional connection. Wang et al. [2019] demonstrated that movement-based communication and tangible interfaces elicit greater emotional engagement from users compared to purely visual interfaces. Even abstract movements are often perceived as purposeful, expressive, and recognizable [Hu et al., 2025], and even simple shapes may be interpreted as having a personality when movement is applied [Kozlowski and Cutting, 1977]. In summary, these findings suggest that SCIs can communicate information in ways that are emotionally engaging and expressive.

Considerations for device placement in home environments

When considering possible locations for a shape-changing notification device in a typical home environment, our main priorities were to identify areas where people spend significant time and where the device could blend seamlessly into the surroundings. The living room is a promising candidate due to frequent leisure use [Sood et al., 2025]. The bedroom may feel too intimate for such a device, as indicated by [Brauner et al., 2017], which provides insights into the acceptance of textile interfaces in personal home environments, and as confirmed by our interviews. An office environment may limit the suitability for multiple devices or continuous interactions, but since ambient notifications can support work productivity [Adamczyk and Bailey, 2004; Okoshi et al., 2016], this location was also considered. Other areas, such as the kitchen, hallway, or bathroom, were excluded because they offer fewer opportunities for users to notice or attend to notifications, based on occupancy prediction models like [Sood et al., 2025] and feedback from our interviews.

Selection of pillow form factor

Based on these location considerations, we focused on the living room and sought a form factor that would integrate naturally, as suggested by Brauner et al. [2017], who argued that disguising an interface as a familiar textile household object can increase its likelihood of acceptance. The pillow emerged as a particularly suitable candidate, as it complements the couch and can be customized with different covers to match a variety of aesthetics seamlessly. The concept of cuddly user interfaces [Sugiura et al., 2016] further influenced our choice. As briefly mentioned in Chapter 1, Sugiura et al. [2016] demonstrate that softness and a cuddly form can enhance both acceptance and emotional or physical engagement with interactive devices. Furthermore, they showed that people are more likely to form emotional connections with pillows or other cuddly objects than with other inanimate objects. Our interviews supported this notion, as participants responded positively to the idea of a moving soft pillow, likening it to a "cute pet."

By selecting a familiar and emotionally approachable form, our design encourages proximate interaction while minimizing perceived foreignness. This positive emotional interpretation of the device can also reduce user annoyance toward the notifications it delivers.

Flexibility of placement

Although primarily designed for the living room, the pillow could also be placed in an office or bedroom, depending on the user's comfort with such technologies, personal preferences, and interior aesthetics. Overall, this form factor allows the device to blend unobtrusively into everyday environments while remaining approachable and flexible for different user contexts.

Pillow geometry and vision for shape-change

Our primary vision was for the pillow to change its overall shape in a smooth, continuous bending motion, preserving the visual softness and cuddliness that contribute to the positive effects identified by Sugiura et al. [2016]. We noted that a pillow's geometry is particularly well-suited for incorporating pointing gestures, as its corners are naturally shaped like arrows, which can effectively guide directional attention [Ristic and Kingstone, 2006]. This was further confirmed by several interviewees, who, when introduced to the concept of a shape-changing pillow, immediately recognized its potential for directional expression, even without prior exposure to our design plans.

Summary of pillow form factor rationale

In summary, we chose a pillow as the form factor for our shape-changing ambient notification device because it combines familiarity, emotional approachability, and sufficient flexibility in positioning. We envisioned shape-change emphasizing smooth, continuous bending and curling motions, which can convey directional cues while encouraging users to attribute expressive or emotional meaning to the movements.

Priority levels and motion cues

We aim to align with the findings of Cho et al. [2025] and support differentiation of priority levels through our device. This can be achieved by integrating multiple mechanisms and varying movement speed. Slower motions or subtle posture changes can effectively communicate emotions such as pleasure or relaxation [Klausen et al., 2022], or deliver notifications in a calm, non-intrusive

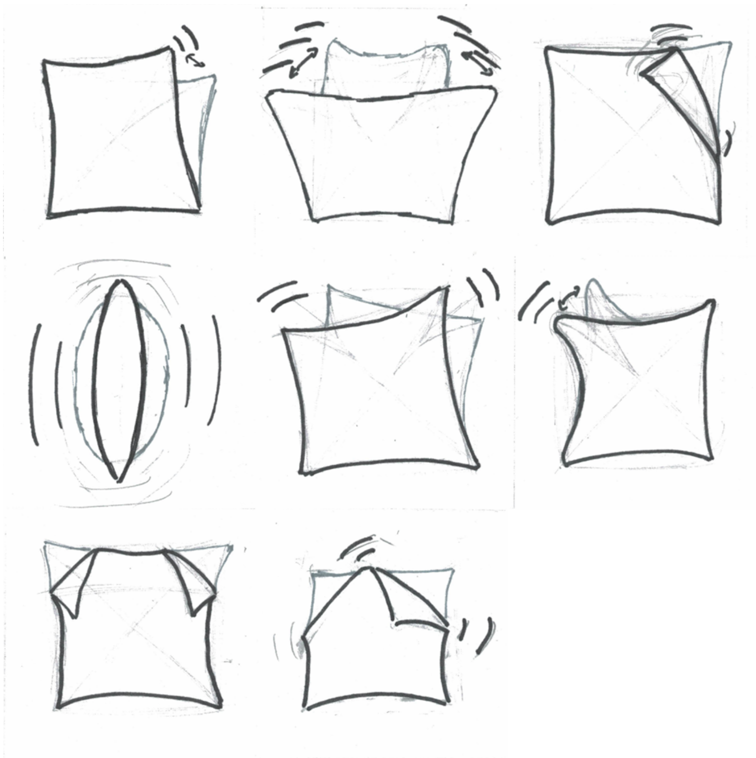

Figure 3.3: Movement sketches of the prototype pillow, illustrating proposed actuation patterns and expressive motions.

manner [Jones et al., 2017]. In contrast, faster, more abrupt movements are interpreted as urgent, signaling higher importance [Klausen et al., 2022; Lee et al., 2023].

Based on these design considerations, we identified two primary movement mechanisms to facilitate the aforementioned motions.

Curling mechanism and sketch exploration

The first mechanism was designed to allow curling of, and consequently pointing with, the corners, allowing for similar shape changes as in the designs by Degraen et al. [2019] or a simplified version of Hu et al. [2025]. To explore this, we created sketches (see Figure 3.1) illustrating the potential poses. The idea for these sketches was inspired by concept art presented in Hu et al. [2025] as well as the so-called "Disney flour sack" [Johnston and Thomas, 1995]. Although the Disney illustration is more whimsical in nature than our sketches, which were based on movements that our envisioned mechanisms would be capable of, it nevertheless inspired us by demonstrating that even a plain flour bag, or a similarly shaped pillow, can convey emotion through its movements and postures. We later expanded these sketches by adding additional poses and incorporating suggested movements (see Figure 3.3). They served both as a design guide and as material for interviews, in which participants were asked whether, and if so, which, of the postures they perceived as conveying emotion. Given the limited scope of our interview process, we do not provide a quantitative evaluation of the responses. Nevertheless, the interviews suggested that both the simple static deformations and the implied movements were already able to communicate emotion and information, which also aligns with the findings of Kozlowski and Cutting [1977] mentioned previously. Within the limited scope of our study, these impressions appeared consistent across participants and were even associated with human movements. We envision this modality being used to point at appliances in 3D, or to attract attention and convey emotion by imitating "arms in a bedsheet," a phrase from one of our interviews.

Volume-expansion mechanism imitating breathing

The second mechanism is intended to expand the volume of the entire pillow. Klausen et al. [2022] demonstrated that a "simple" breathing mechanism is sufficient to reliably convey levels of urgency and the corresponding level of pleasure of the robot to users. Faster breathing indicated a higher state of arousal, lower pleasure, and a high level of urgency, whereas slower breathing appeared to signal the opposite.

Literature and interview insights supporting volume expansion

We also identified additional related work exploring expanding and breathing SCIs [Kim et al., 2008; Liu et al., 2025], as well as a pillow design by Ívansdóttir [2024], already mentioned in Chapter 2, which uses local expansion as a means of communication (see Figure 3.4). Most of our interviewees also immediately suggested this as a design choice for the second mechanism. Taken together, these findings and the existing literature suggest that such behavior can be expressive [Kim et al., 2008; Klausen

Figure 3.4: Shape-changing pillow prototype capable of inflation [Ívansdóttir, 2024]

et al., 2022; Liu et al., 2025] and may serve as a natural form of expression for an animate pillow [Ívansdóttir, 2024; Nack et al., 2007; Sugiura et al., 2016].

Breathing, as a directionless modality

Participants further proposed using it as a directionally neutral notification modality, a recommendation we agree with. They noted that if the arms were employed for directional pointing to guide the user's attention, implementing a directionless notification with the same arms could be confusing. However, the exact details of which modality to use for specific notifications, or when pointing is most effective, warrant future investigation, for example through additional interviews or empirical studies (see Sections 4.4, 5.2). Our primary goal was to implement the mechanisms that we consider to represent the most relevant novel modalities in this context.

In summary, the two primary mechanisms we developed are corner curling for expressive pointing and whole-body expansion inspired by breathing, to support emotional communication and interaction in an animate pillow.

Summary of developed mechanisms

3.3 Technical Design

After these design stages, we implemented more concrete movement mechanisms to realize the intended features of our design. To support this, we reviewed existing literature on similar devices.

Bringing the principles of shape-changing interfaces into a real device requires actuation mechanisms that can safely operate in close proximity to humans. Given that the pillow is intended to operate near people, implementing compliant mechanisms was essential to minimize the risk of injury. Soft robotics (see Sections 1.3, 2.1) provides a natural framework for achieving compliance through the use of deformable materials, while also enabling expressive and controlled shape changes [Rus and Tolley, 2015; Ambaye et al., 2024]. In addition, we incorporated more conventional mechanical features, achieving compliance through careful mechanism design and component selection.

Compliance and soft robotics for safe actuation

The field of soft robotics was additionally beneficial, as a pillow is expected to be soft, and Sugiura et al. [2016] demonstrated that soft interfaces provide inherent advantages (see Chapter 3.2). Our goal was not to create the most comfortable pillow possible, but to ensure that using it as a pillow, specifically as a backrest on a couch, would remain feasible. A primary reason for the design choice of a pillow was to allow the device to blend seamlessly into its surroundings (see Chapter 3.2). Our interviews suggested that a design incorporating hard features would lead users to take precautions to prevent accidental use that might result in discomfort or even injury. Such precautions could single out the device and hinder its seamless integration into the environment.

Softness for comfort and seamless integration

When considering possible actuation mechanisms com-

Choice of actuation mechanism

mon in soft robotics, several options were evaluated. Both SMAs and DEAs (see Chapter 2.1) are widely used in soft robotics [Kim et al., 2013], but present notable safety concerns in our specific use case. Repeated activation of SMAs can generate surface temperatures hazardous to fabrics or skin [Mohd Jani et al., 2014], and the insulating materials, used to keep the pillow soft, restrict airflow and are often flammable, further exacerbating the risk of fire. DEAs operate at kilovolt-level voltages, raising the risk of dielectric breakdown or electrical arcing near flammable materials [Gupta et al., 2019]. Pneumatic networks, while also common in soft robotics [Kim et al., 2013], are either slow or require bulky pump setups [Jung et al., 2024], complicating their integration into a compact pillow design, particularly given the speed required to convey urgency and importance as suggested by [Klausen et al., 2022; Lee et al., 2023] (see Chapter 3.2). Given these constraints, we focused on motor-actuated strings as the primary actuation mechanism. Throughout the design, we used fishing line rated for 8 kg instead of more durable alternatives such as steel cables, to enhance safety and limit potential stress accumulation by incorporating a deliberate weak point.

Design of corner actuation mechanism ("arms")

To enable controlled movement of the pillow's corners, we designed a mechanism, referred to here as "arms" (see Figure 3.2), and constructed four identical versions. For these arms, we combined previously reported approaches of inflated air chambers for structural support [Usevitch et al., 2020; Stuart et al., 2021] and string-controlled soft arms [Degraen et al., 2019; Wu et al., 2020, 2022] (see Chapter 2).

String control mechanism for arms

Wu et al. [2020, 2022] implemented a design in which each motor controlled the length of a single string attached directly to the motor's horn. This string, in turn, actuated the arm, which imitates an octopus limb. Their string-mounting approach results in a sine-shaped relationship between the servo motor's rotation angle and the corresponding change in string length. Wu et al. [2020] used four string anchoring points to move the arm in two dimensions. By running two strings in parallel but attaching them at different lengths along the arm, they achieved finer control over the arm's shape compared to using only two

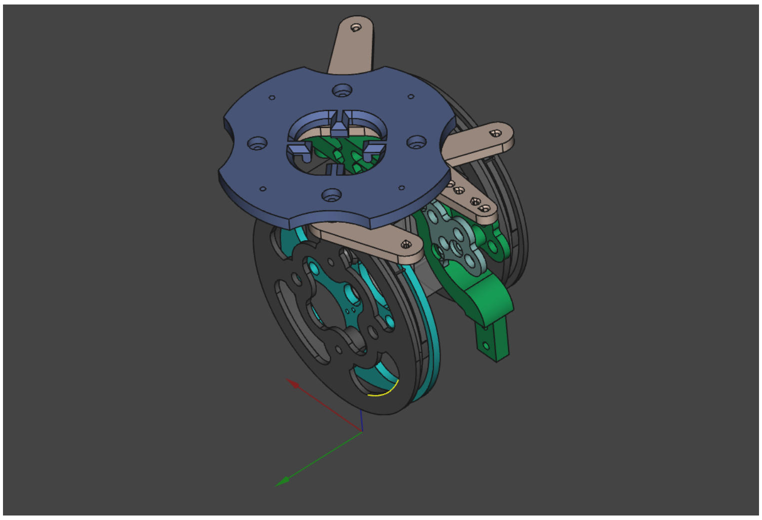

Figure 3.5: CAD file of the mechanism controlling the string position

strings. Later, Wu et al. [2022] employed three strings deployed at 120-degree offsets to enable 3D control, although this reduced some of the fine shape control used previously. We mounted the string onto spools, allowing it to wind as the motor turned. In contrast to the setup by Wu et al. [2020, 2022], this configuration produces a linear relationship between the motor's rotation angle and the corresponding change in string length, ensuring an equal distribution of torque throughout the movement, and increasing the achievable change in string length for a given spool radius, effectively improving the ratio between required space and string displacement. We further modified the design by reducing the degrees of freedom and the number of required motors. Owing to the axisymmetric production method of the arm (described below and in Appendix B), we used four strings arranged in two opposing pairs to simplify the control process, following an approach similar to that described by Degraen et al. [2019]. Beyond symmetry considerations, this configuration allowed a single spool to control the strings on opposing sides of the arm simultaneously by routing them over the spool in opposite directions. However, this approach necessitated a more complex routing system to guide the strings to their appropriate locations (see Figure 3.5). In addition, we used a second set of

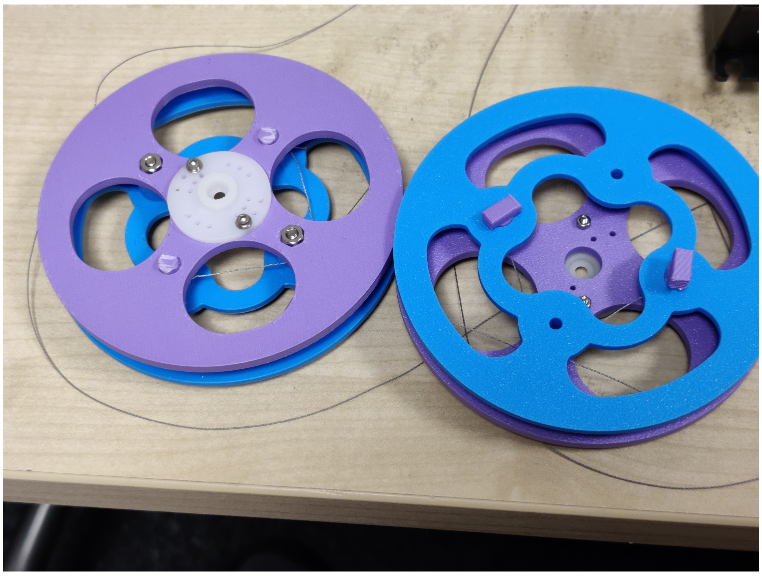

Figure 3.6: 3D Printed spool controlling the strings, with strings mounted to the tensioning mechanism

four strings running parallel to the primary ones, attached to the base element of the arm. These strings are not actuated and serve solely to anchor the base of the arm to the system.

String-tensioning mechanism inspired by guitar pegs

To simplify manufacturing and allow mechanical tuning of the strings controlling the arms, we adopted a design inspired by guitar pegs, which are commonly used to tune guitar strings and were also employed by Degraen et al. [2019] in their string-controlled arm. Guitar pegs In their design, the guitar pegs were larger and could be mounted on the opposite side of the motor. However, since we wanted that side of the arm to fit into the corner of the pillow, it needed to remain soft and could not accommodate the mounting of the pegs or a similar tightening mechanism. Therefore, we mounted the guitar pegs directly on the spools controlling the string lengths (see Figure 3.6).

Arm construction with inflatable air chambers

Rather than using a silicone mold, our arm was constructed from inflated air chambers. This approach is similar to that employed by Usevitch et al. [2020], although in their designs they integrated movable pinching points

Figure 3.7: Heat-sealed polyethylene chamber with integrated air valve

that permitted bending only in a single plane, whereas our design employed stationary circular constraining points allowing the beam to bend in multiple directions (see Figure 3.8). To create the airtight chambers, we used 150 μm thick polyethylene tubing films and a heat sealer, following a soft robotics toolkit guide[1] for creating pneumatic networks, along with ball valves to allow for the inflation of said chambers (see Figure 3.7, Appendix A). We then encased this polyethylene layer in a layer of stitched fabric. This increased tensile stiffness and was stitched to define the arms' geometry into three segments (see Figure 3.8), creating two weak points that allow the arms to bend more easily. We experimented with different numbers of segments, varying diameters at the weak points, and creating the weak points using external rings rather than the fabric itself. However, we settled on this design as the most reliable to produce while achieving equally good results in our prototype testing.

[1] `https://softroboticstoolkit.com/hpn-manipulator/fabrication/pneumatic-network`

Figure 3.8: Our arm design, using an external fabric layer to cause semgentation

Fabric layer as attachment point for strings

This fabric layer also serves as attachment points for the control strings, which were connected to the segment furthest from the motor. Additionally, strings were attached to the lowest segment and tightened to the frame itself, helping to stabilize the arm and secure its base. Initially, we attempted to shape the arms using only the heat sealer without a fabric layer. However, this method proved unreliable for maintaining airtightness when more than two layers of polyethylene tubing were used, allowed proper flexibility in only a single plane when just two layers were employed,

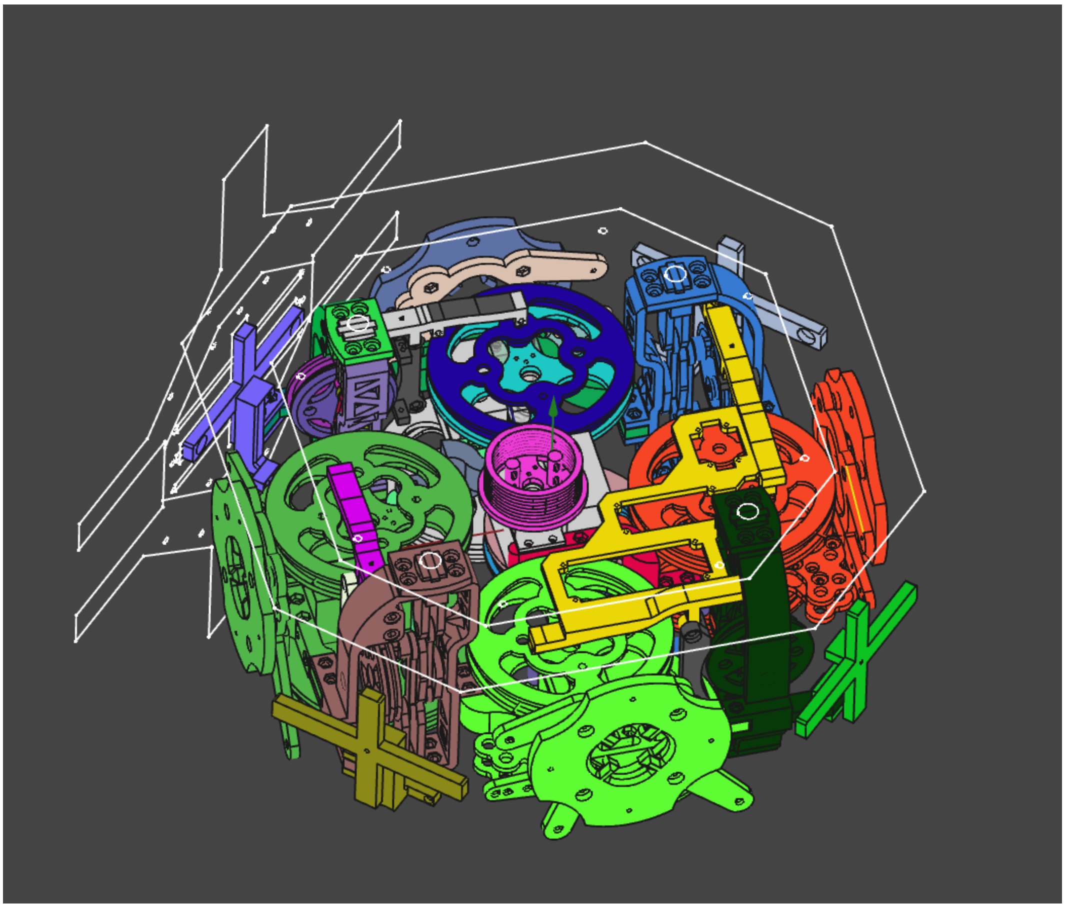

Figure 3.9: Render view of the CAD file containg all mechanisms.

and did not allow for as fine shape control as the sewing machine method.

The additional structures and mechanisms were designed in CAD software (see Figure 3.9) and subsequently fabricated using three-axis 3D printers. While this manufacturing method enables quick prototyping and iterative development, it also introduces robustness constraints and necessitates additional design considerations and limits on component size (see Section 4.2).

Design and 3D printing of additional structures

CAD overview

The motion imitating breathing is achieved using a mechanism that we, based on the visual similarity of our sketches

Breathing-like motion mechanism ("shell")

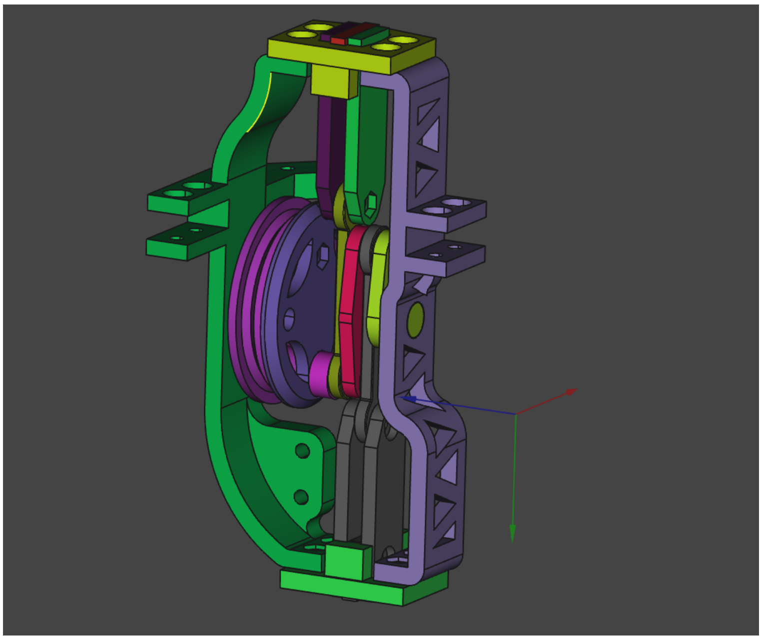

Figure 3.10: CAD model of the mechanism providing the breathing motion

to a turtle (see Figure 3.2, Figure 3.12), refer to as the "shell". The mechanism consists of a string-activated, piston-like crank-and-slider system, relying entirely on conventional mechanical components (see Figure 3.10). This approach was chosen over a pump-activated system to preserve a compact form factor while allowing rapid execution of the motion (see Section 3.2). For this, we employed four crank-and-slider mechanisms, distributed evenly across the front and back sides of the pillow (see Figure 3.12, Figure 3.11), with magnets encased in the top plates. All mechanisms are controlled by a single motor, with strings routed throughout the assembly. This design ensures mechanical synchronicity, maintaining alignment of the front and back plates during motion. In this mechanism, string length is also regulated using the previously described guitar-peg-inspired design. We then attached a laser-cut bookbinding board plate with affixed magnets, along with foam, to form the front and back faces of the pillow. The incorporation of magnets simplified assembly and also served as a safety feature. If a finger were to become caught behind the back

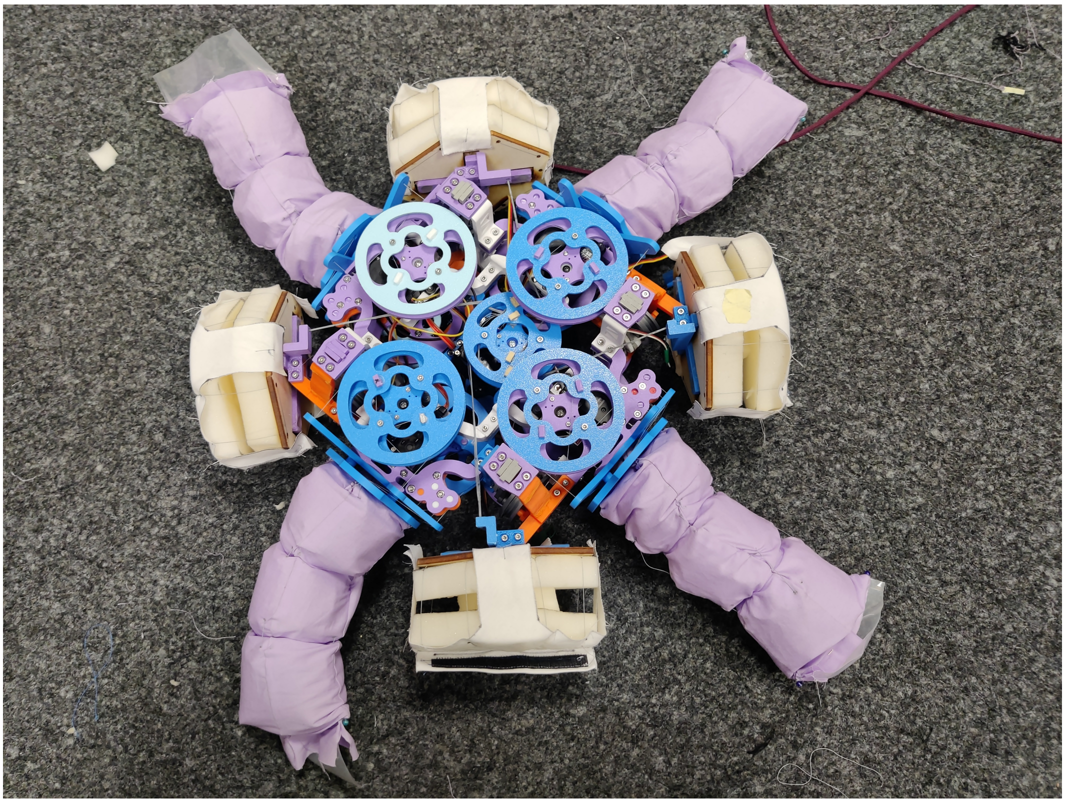

Figure 3.11: Finalized Protoype with the top of the shell removed to provide view of the insides

plate while it was extended, retracting the plate would not crush the finger, as the magnets are relatively weak and would simply detach the back plate.

Additional technical features for comfort and usability

The following section presents additional technical features incorporated into the pillow's design to support the primary functional goals.

Foam enclosure of internal components

Firstly, to ensure that the pillow remains soft and cuddly [Sugiura et al., 2016], all rigid internal components are encased in soft foam padding, including the areas between the arms (see Figure 3.11). While this padding enhances comfort, it also reduces the range of motion and expressivity of the arms. To address this limitation, we integrated a mechanism that can compress the foam between the arms, thereby freeing them to move more effectively. This mechanism operates via a motorized spool that pulls a string at-

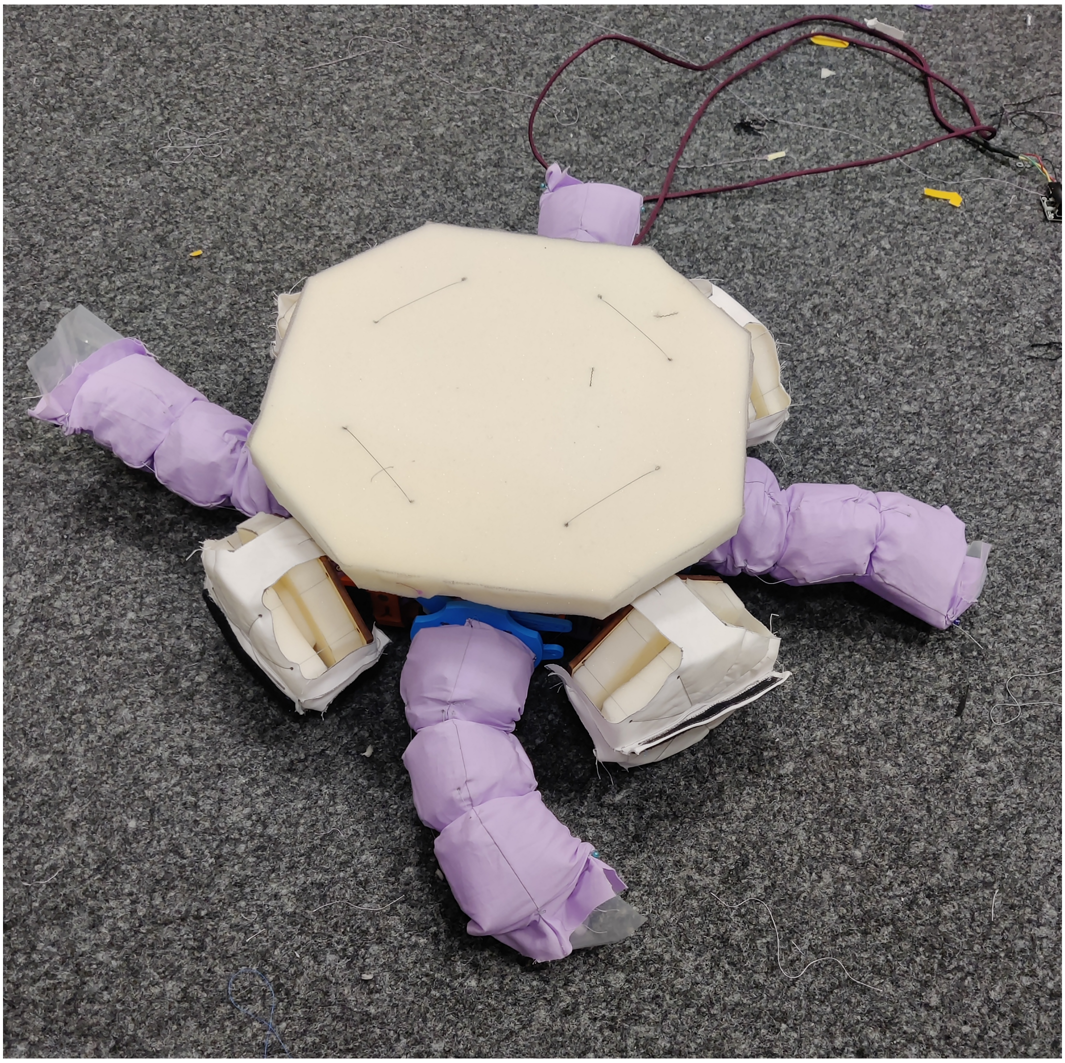

Figure 3.12: Finalized Protoype with no cover.

tached to the top of the foam. When the string is tensioned, the foam is compressed, and when released, the foam returns to its original shape, restoring the pillow's softness.

Additionally, the pillow's cover is secured to the mechanism using a hook-and-loop fastener, which not only keeps the mechanism in place and enhances the visual prominence of the arms when engaged, but also fixes the position of the device relative to its cover while allowing for easy maintenance. The foam stacks are attached to the device's core using magnets embedded in the foam's back-

Figure 3.13: Finalized prototype encased in the heavier fabric cover, placed on a couch next to real pillows

plate. Similar to the use of magnets in the shell component, this simplifies the production process and decreases the likelihood of mechanical failure.

Dimensions of the pillow

The pillow was designed to have a size of 50 × 50 cm. These dimensions were selected based on a combination of interview feedback, typical commercial pillow sizes, and technical considerations related to the mechanisms incorporated within the pillow, ensuring both usability and manufacturability. However, the cover must be slightly oversized to ensure that the movements of the arms and shell are not constrained by a tight fit.

Material choice for covers

We designed two covers with different properties. The first cover was made from monochromatic cotton popeline, that was also used for the construction of the arms. It is a relatively smooth, thin, and light fabric. Nonitchy and pleasant-to-the-touch fabrics were highlighted as highly important by both interview participants and prior research on soft interactive interfaces [Sugiura et al., 2016]. This material clearly shows the movements of the pillow, but does not obscure the technical shape very well (see Chapter 4.1). The second cover was made from a thick woven fabric with a heavy texture 3.13, as [Sugiura et al., 2016] suggested that materials with "interesting" surfaces are more likely to be interacted with. Additionally, the thickness of this material helped obscure the shape of the mechanism, allowing the pillow to blend in better (see Figure 3.13). However, this also obscured the arm movements (see Chapter 4). The cover material remains highly customizable, as it can easily be removed, and even a standard pillow cover could be used with the simple addition of a hook-and-loop fastener or by omitting the constricting feature.

3.4 Electronic Components and Control

In addition to the mechanical design, the pillow required electronic components and sensing capabilities to appropriately control its features.

Choice of servo motors for string control

To control the length of the strings for the movement of the arms, we employed HiTec HS-311 servo motors. These motors were selected because their rated strength of 30 Ncm at 4.8 V was sufficient to move the arms in our prototype testing, while meeting size constraints, speed requirements, safety considerations by not exceeding the necessary force, and availability. Although the mechanisms were designed to fit this motor model, similarly sized motors with comparable or higher strength could also be used. For controlling the mechanism imitating breathing and the mechanism compressing the foam between the arms (see Figure 3.11), we used Bluebird BMS-630MG motors. These have a similar size and speed profile but provide higher torque (130 Ncm at 4.8 V), which was necessary for these mechanisms during testing. The breathing mechanism lifts the pillow's body if it is lying down, and due to its weight (see Section 4.2), the weaker HS-311 motors could not perform this action. Similarly, the foam-compressing mechanism requires additional force to compress the padding material effectively. The HS-311 motors operate at a maximum speed of 0.19 seconds per 60 degrees, while the BMS-630MG motors operate at 0.17 seconds per 60 degrees at 4.8 V (our prototype runs at 5 V), both with a range of motion of 180 degrees. This provides sufficient responsiveness for our application, as Klausen et al. [2022] demonstrated that 40 cycles per minute are adequate to convey high-arousal states in a breathing-like motion, while also supporting slower movements to communicate calmer states. Additionally, the design of our breathing motion allows for an arbitrary reduction in range of motion, trading in amplitude of the motion for a higher frequency, pushing even higher frequencies, if deemed neccessary or benefitial. Additionally, our mechanism enables the breathing motion to be adjusted by trading amplitude for frequency, supporting higher motion speeds if deemed necessary or beneficial.

Electronics for orientation and control

A central requirement for enabling the intended interactions and avoiding undesired behavior was the system's ability to recognize its own orientation and position. Firstly, accurately pointing at objects inherently requires knowledge of orientation and position. Secondly, awareness of its own orientation allows the system to handle practical constraints, such as avoiding the use of downward-facing arms that could cause the pillow to tip over or produce gestures that are unclear or unrecognizable to the user. The control logic is handled by an Arduino Nano as the central controller, with motor actuation managed by a PCA9685, a 16-channel PWM servo driver board. For simplicity and reliability during prototyping, the system was powered through a wired 5V power supply using a barrel jack. In our prototype, the IMU was used to measure absolute orientation, allowing the pillow to account for its rotation. Additionally, the IMU could be used to estimate relative changes in position from acceleration data and, if combined with a calibration procedure and regular grounding, provide absolute localization, as using only the acceleration data is prone to drift [Farahan et al., 2022]. All of these components are mounted inside the device and protected from direct outside contact (see Figure 3.14).

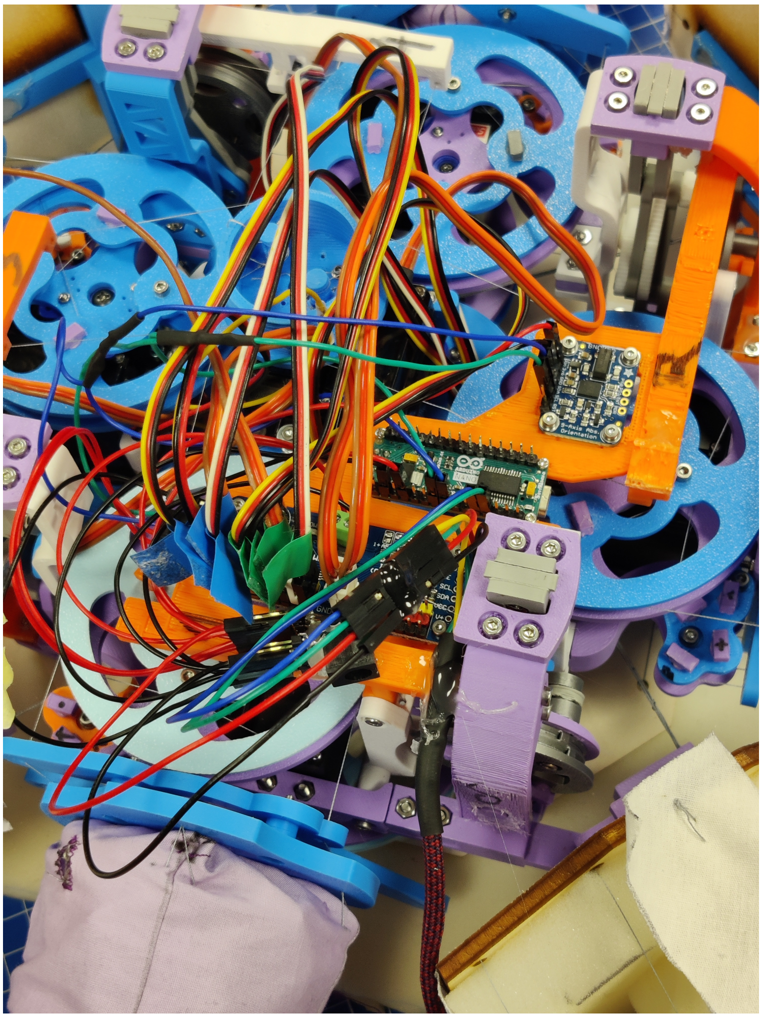

Figure 3.14: View of the cables and electronics mounting

Internal and external communication

The communication inside the device between the microcontroller, IMU, and servo driver is implemented using an I^2C bus, reducing cable clutter and simplifying communication implementation. In addition to the power supply, the current prototype requires a second cable for data transfer, consisting of four lines connected to the Arduino's RX and TX pins, as well as ground and 5V. This connection enables communication with an external microcontroller using UART serial communication. This setup increases modularity and separates motor control from higher-level processing, effectively relegating the device to an output-only role while externalizing the decision making, and also reducing cable clutter.

Demonstration functionality

In our demonstration implementation, the internal Arduino Nano controller is responsible solely for executing motor commands and incorporating rotation data from the IMU. An external Arduino Nano transmits commands via the aforementioned UART connection, either specifying the absolute pointing direction or commanding the execution of a predefined gesture or posture. For demonstration purposes, the external microcontroller calculates its instructions based on input from a joystick and buttons. In a fully integrated system, however, control would be managed by a unified notification management framework (see Chapter 2) and sent through the same communication channel.

Chapter 4

Discussion

This chapter critically reflects on the findings presented in the preceding chapters, highlighting both the shortcomings of the constructed prototype and the limitations of the presented process and results. Following this discussion, Section 4.4 outlines potential improvements, focusing on the identified shortcomings and also presenting recommendations for expanding the functionality of the prototype, drawing on insights from related work and providing concrete guidance for future development.

4.1 Prototype Performance

In this section, we report our predominantly qualitative description of the prototype's performance.

Performance of the arms mechanism

The constructed arms performed roughly as expected, exhibiting a range of motion similar to the previously mentioned string-controlled arms (see Section 2.1).With an arm pressure of around 20 kPa, we achieved a maximum bend of slightly over 90 degrees relative to the root of the arm. This was the highest value reached in our experiments with string tension and air pressure. The bending mapped accurately to the motor's position, with a range of motion of 180 degrees for both the arm and the motor, allowing for precise and consistent control, with in an almost one-to-one relationship between motor angle and arm orientation. However, variance between arms, stemming from imprecise production methods (see Appendix A) and the lack of an integrated external validation method for the string-tensioning mechanism, required that each string be adjusted separately and manually via quick trial and error.

Performance of the breathing mechanism

Even in the worst-case scenario, where the pillow had to lift itself using the breathing motion, it reached a maximum speed at full amplitude of roughly 34 bpm. This falls slightly short of the maximum of 40 cycles per minute described by Klausen et al. [2022], but remains within the range sufficient to communicate clear urgency. Placing significant additional weight on the pillow (e.g., resting an arm) slows the motion considerably or even stops it completely, reflecting the deliberate strength limitations implemented for safety, as the breathing mechanism relies on conventional mechanical components. However, these limitations also constrain its potential use cases and situational flexibility.

Performance of the compression mechanism

The compression mechanism successfully moves the foam out of the way of the arms and provides a stable base for the pillow when placed upright. Without it, the arms simply buckle and split apart. However, its movement is barely noticeable as an independent modality, since the range of motion is only 3 cm on each side. The motor is unable to complete a full rotation because the force required to compress all four foam pads and overcome friction, combined with the lever effect caused by the spool size, exceeds its capacity.

4.2 Prototype Shortcomings

The constructed prototype exhibits several shortcomings that influenced its practicality and overall expected performance.

Prototype weight and motor noise

First, the device is relatively heavy, primarily due to the motors, which reduces its believability as a pillow and limits both the speed and load-bearing capacity of the breathing mechanism. Secondly, the motors produce a noticeable level of noise during operation, which we suspect may reduce applicability for ambient notifications [Jones et al., 2017], as it reintroduces continuous sound. This is unsuitable for the full range of notification priorities which is one of the primary motivations for introducing shape-changing modalities into notification frameworks [Lazaro et al., 2021; Okoshi et al., 2016] (see Section 1.2).

Limited expressivity of complete device and conver choice

However, in the final device, with all components installed and the cover in place, the breathing mechanism dominates the overall shape and obscures the arm movements. This issue is compounded by the usage of the cover made from the heavier, thicker material. We suspect that this significantly limits the perceived range of motion, as the interpreted curvature appears to be drawn not from the base to the tip of the arm, but from the shell to the tip, with the shell protruding considerably beyond the arm's base, although this claim should be verified with actual users. Whereas the thinner cover allows the arms to be seen more clearly, it also exposes the underlying structure, potentially marking the pillow as a foreign object in the home environment.

Cable tether of prototype

Like mentioned in Section 3.4 Data transfer was implemented through a wired connection and joystick input. While sufficient for demonstration purposes, this approach tethers the device and limits natural integration into a home environment. A wireless solution using a suitable receiver module may be more appropriate. As the microcontroller controlling the motors currently just articulates the motors in the way it is told through the serial interface, expansion to include a wireless receiver could be done fairly easily by exchanging the joystick currently controlling the motion by through a wireless module feeding the information through the UART connection. Alternitively a wireless transmission module could be connected to the i2c bus, removing the need for a second microcontroller, althoug that would require changes in the code running on the microcontroller inside the device as well. Power delivery was constrained by reliance on a wall-connected supply. A common smartphone battery of 5000 mAh could theoretically sustain the peak load of the power supply used for approximately 50 minutes. The actual power draw, however, was not measured, as no broader system integration was available to support realistic testing. Based on motor specifications, continuous operation of all ten motors would correspond to a runtime of over three hours. In practice, however, continuous operation is not expected, and our implementation uses no more than six motors simultaneously, further reducing expected overall power draw. These factors suggest that real-world energy demands would be considerably lower and battery life correspondingly longer.

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Physical size constraints and productin method limitations

Finally, the physical size of the device is quite large and partly constrained by the strength and quality of the 3D-printed components. While most structural elements could potentially be scaled down, the spools cannot be reduced in size without negatively affecting the arm's range of motion or requiring a corresponding reduction in overall arm size. The guitar-peg-inspired components used to control string tension remain essential in our design. However, during construction, these parts were often inconsistent in strength, frequently breaking and requiring experimentation with 3D printer settings and printing orientation. Further reduction in their size is therefore not recommended unless the production method is modified. Similarly, the production of the air chambers described in Section 3.3, although fast and uncomplicated, was not as reliable as desired and does not lend itself to high-accuracy production.

4.3 Limitations

Lack of user-based design validation

The conducted interviews were exploratory in nature and intended to provide insights into the field. Consequently, their results are not representative. The design choices presented in this thesis were not validated through systematic user-centered testing. Moreover, the integration of the constructed mechanisms into coordinated full-body postures and movements lay beyond the scope of this work and was neither implemented nor examined through user studies that could have identified promising candidates.

Prototype not integrated into a notification system

The prototype was not connected to a functioning notification system, and no communication channel with a potential system was implemented. Instead, it was controlled via a joystick-based mechanism directly wired to the microcontroller, serving primarily as a proof-of-concept device to demonstrate and enable the implementation of different modalities in future work.

Laboratory-only evaluation of technical performance

Finally, the technical performance reported in Section 4.1 were evaluated exclusively under laboratory conditions with the prototype fixed in place and not based on users' interpretation. These constraints limit the generalizability and transferability of the findings and apply only to the technical performance.

4.4 Design Directions

The shortcomings of weight, noise, and power supply could potentially be addressed by using more efficient, quieter, and lighter motors, or by exploring alternative actuation methods that meet these requirements, if available.

Incorporate user tests into movement implementation

In our view, the next step in developing this prototype is to integrate it into realistic use cases and evaluate it with test users. While some of our interview questions explored possible postures and movements, these were not implemented in the prototype. We suggest investigating movements in parallel with an additional round of user interviews. Graphical animations could be employed to explore interaction scenarios without being constrained by the current prototype's physical capabilities.

Improvements to prototype expressiveness

For a more accurate evaluation of the prototype, in addition to integrating it into realistic scenarios, we recommend enhancing the expressivity of the arms (see Section 4.2). One relatively simple approach would be to separate the breathing mechanism from the arm mechanism, thereby slimming the pillow's form factor. However, this would reduce the number of simultaneously available output modalities. A longer-term strategy adapting the current design could involve redesigning the shell mechanism in a smaller form factor, trading some amplitude of the breathing motion for compactness. Alternatively, a design rework could explore other expansion mechanisms capable of greater compression, such as air inflation (see Section 2.2). Conversely, increasing the size of the arms could also improve expressivity, but this would enlarge the pillow and potentially necessitate modifications to the control system.

Possibility of integrated input

Our interviews also indicated the potential for an input modality. This avenue warrants further investigation, as previous work has demonstrated the viability of a pillow as an interactive interface [Nack et al., 2007]. Similarly, Sugiura et al. [2016] illustrates the potential benefits of such soft devices for input.

Using pressure sensor readings on air chambers

One approach could involve integrating pressure sensors into the arms or replacing the foam with pressure chambers, either controlled by pumps or permanently inflated. These could augment or replace the breathing modality and provide an additional input channel. Related work in

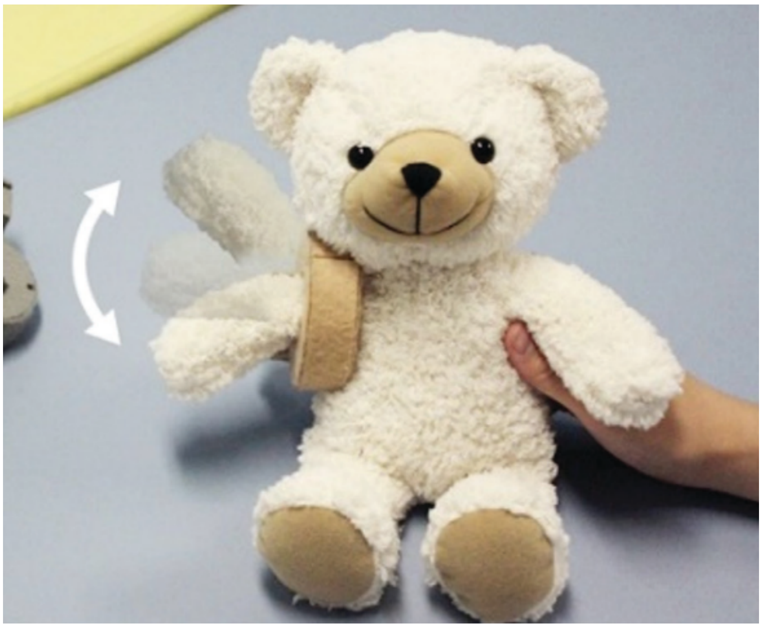


Figure 4.1: Self-actuating teddy bear arm by Sugiura et al. [2016]

shape-changing interfaces has explored similar concepts involving the interplay of inflation and pressure-sensing input [Liu et al., 2025]. Instead of large chambers, the design could also be divided into smaller, individually controlled air chambers, allowing for more complex deformations, as demonstrated by [Ívansdóttir, 2024].

Textile interfaces for input or additional output

Additional avenues for input could leverage the textile surface of the prototype. Similar methods in previous work include textile touchscreens [Poupyrev et al., 2007] or haptic textile interfaces [Schäfer et al., 2023; Nowak et al., 2022]. Extensions to output modalities were also desired in our interviews and are supported by previous research. Leveraging the textile surfaces could further include integrated thermal shape-changing fabric elements [Du et al., 2018] or bistable embroidery [Jiang et al., 2024].

Other output modalities

Other ambient notification strategies, such as light or color changes [Tentori, 2020; Wiehr et al., 2016; Umaña et al., 2024], could provide subtle cues and improve the visibility of the pillow's movements in dark environments, as suggested by our interviews. Sound could also be incorporated, similar to smart home assistants, to enhance the expressive potential of the pillow and provide additional interaction modalities.

Usage and expandability of our arm design

This prototype also demonstrates the viability of combining string-based arm actuation with air-pressurized stiffness components, an approach that could be applied in other partially soft robotic contexts. For instance, Sugiura et al. [2016] explored a teddy bear with controllable soft arms (see Figure 4.1), and we believe our design could enhance the expressivity of similar such a device. Additionally, further refinement of the arm mechanism could explore parameters such as multiple string attachment points along the same axis for finer control [Wu et al., 2020], varying segment counts, variable-radius spools, mechanically decoupled control of opposing strings, and dynamic pressure control of the arm. The use of stepper motors or unrestricted servo motors alongside such variable pressure control could enable the system to dynamically extend or contract the arm, similar to vine robots [Blumenschein et al., 2020].

Chapter 5

Summary and Future Work

In this final chapter, we summarize the content and contributions of this thesis and outline potential directions for future work.

5.1 Summary and Contributions

This thesis was motivated by the challenge of designing interactive, shape-changing devices that can deliver notifications using novel modalities while blending seamlessly into the home environment.

Potential of shape-changing interfaces

Shape-changing interfaces are a promising avenue for creating more expressive and tangible user interfaces, pushing human-computer interaction into new and unexplored domains. At the same time, current notification systems often face challenges related to intrusiveness and distraction. Ambient notification systems aim to improve efficiency by optimizing both the timing and modality of notifications. However, this requires the availability of devices capable of delivering notifications across multiple modalities, which is where this thesis contributes a prototype solution.

Prototype overview

We present a prototype that combines the soft robotic principles of string-controlled arms with inflatable air chambers, integrated expansion mechanisms, and orientation tracking electronics to create a shape-changing interface capable of expressive communication, including the conveyance of emotional states. This prototype demonstrates the feasibility of constructing air-inflated, string-controlled soft robotic limbs and employing them in shape-changing interfaces for tangible and expressive output, while also illustrating the potential to embed such devices inside pillows for seamless integration into a home environment.

Design limitations and trade-offs

During the design and construction process, we identified several limitations and trade-offs. The expressiveness of the prototype is constrained by the competition between the arms and breathing mechanisms. Movements are partially hidden by the cover material, and the noise produced by the motors significantly reduces the effectiveness of shape-change as a subtle communication modality. Additionally, the prototype was neither integrated into a complete notification system nor tested with end users, leaving the assessment of interaction effectiveness and user experience as a task for future work.

5.2 Future Work

The work presented in this thesis also highlights multiple promising avenues for future research and development:

Enhancing arm visibility and expressiveness

A primary next step is to improve the visibility and clarity of the arms' movements within the cover, thereby enhancing their expressivity. We recommend following this with user studies to evaluate the perceptibility, effectiveness, and emotional responses elicited by these shape-changing modalities. Such evaluations would deliver invaluable insights into optimizing the design for user experience.

Integration into a Notification System

Incorporating the prototype into an existing notification framework is a natural progression. This could involve both technical integration, potentially coordinating multiple novel devices, and implementation of supporting software. Such integration would allow the assessment of practical utility in real-world contexts and facilitate more ecologically valid user evaluations.

Expanding interaction modalities

Further exploration of output modalities, as well as the addition of input capabilities, could greatly enrich interaction possibilities. Particularly promising are textile-based interfaces or actuated covers, which could provide additional feedback and input channels while maintaining the soft and unobtrusive qualities of the prototype.

Refining the arm mechanism

A quite different design direction could be focused on optimizing the arms and their actuation mechanisms, enhancing functionality and potentially shifting the focus more towards soft robotic performance. A distinct design direction could focus on optimizing the arms and their actuation mechanisms. Enhancements in this area could improve precision, responsiveness, and expressive range, while potentially shifting the design emphasis towards soft robotic performance.

Appendix A

Build Documentation

This appendix provides a brief walkthrough of the steps involved in assembling the prototype, with a focus on supporting reconstruction and offering transparency into the development process. While it reflects our construction process, the content is organized by individual components and tasks rather than following the chronological order of assembly. Additionally parts are refered to as their file names, for definite identification, although we are aware it hinders readability.

A.1 3D Printing

All models listed in the folder *3DPrinter* (see Section B.4) were printed in the quantities specified in the file names. For the *x44_guitar_peg.3mf*-parts, the printing orientation was chosen as shown in Figure A.1, alternatively, a stronger material could be used, as these parts were prone to breaking under stress when printed in other orientations.

Apart from this, standard ABS material and orientations minimizing support structures were suitable for our prototype.

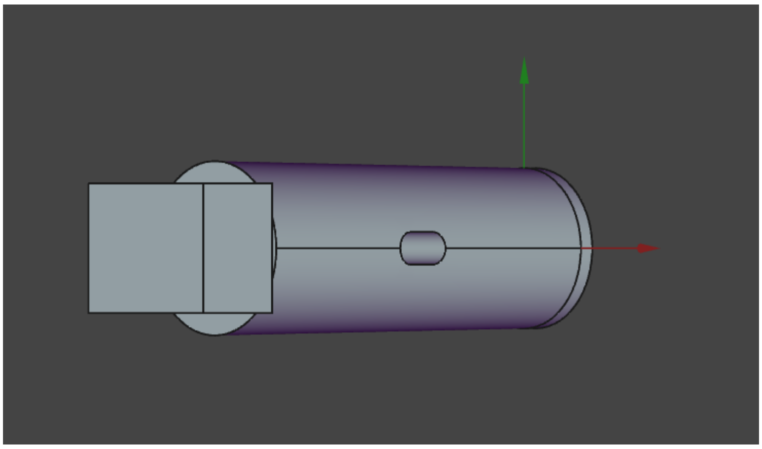


Figure A.1: CAD model of the *x44_guitar_peg.3mf*-parts shown in the orientation used for printing.

A.2 Lasercutter

All shapes listed in the folder *Lasercutter* (see Section B.3) were cut in the specified quantities. The lasercutter was tuned such that vector graphics cut through the material, while filled graphics only engraved it.

The cutout from the file *x4_pincher_plate.svg* required special attention. The colored layers were split into two separate cuts, with the material rotated in between. The light blue cross shape was singled out for the second cut and engraved on the backside (see Figure A.2). 5 mm thick wood was used for this cut. All other cuts were performed single-sided on 2 mm bookbinding board.

A.3 Screws

Aside from the servo motor horns, all components were assembled using M2.5 screws and nuts with lengths of 8 mm, 12 mm, and 20 mm. Most screw holes included nut pockets to facilitate assembly. Nuts were glued into these pockets after printing to simplify construction.

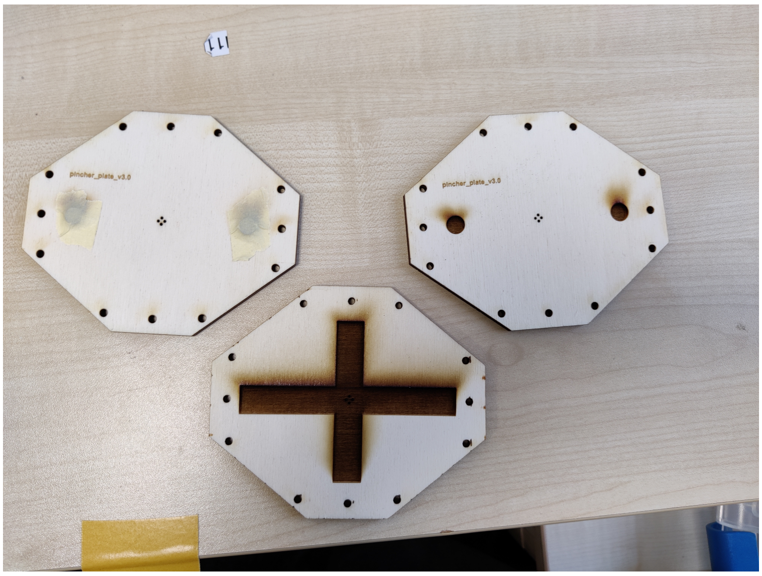


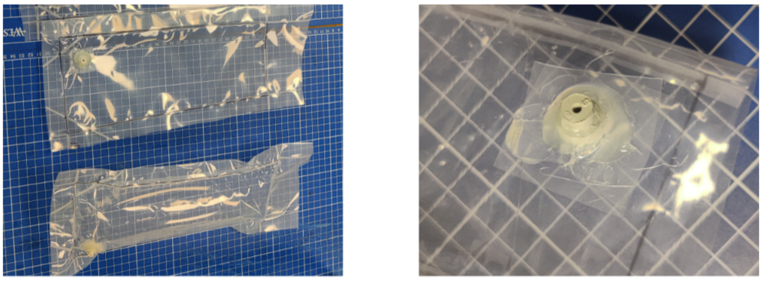
Figure A.2: Lasercut of the *x4_pincher_plate.svg* file, showing both front and back sides being cut.

A.4 Air Chambers and Arms

The production of a single arm is described here This process was repeated four times for the prototype.

The laser-cut cutout from the file *x1_stencil_arm_polyethylene_double_95-85.svg* was used to mark and heat-seal two pieces of 150 μm polyethylene tubing along the outside of the stencil (see Figure A.3 (a)). A ball valve was installed in the circular cutout by adding extra pieces of polyethylene tubing on both sides of the valve and fusing them with hot glue to create an airtight seal (see Figure A.3 (b)).

Next, the cutout from *x1_stencil_arm_fabric_rounded_95-85.svg* was used to cut four fabric pieces (see Figure A.4 (a)). Reinforced holes were created using the sewing machine's buttonhole setting for attachment to the 3D-printed hooks. One fabric piece included an additional buttonhole for access to the ball valve (see Figure A.4 (c)).



(a) Polyethylene chambers **(b)** Valve

Figure A.3: (a) Heat-sealed polyethylene chambers (b) Valve close-up

(a) Stencil outline **(b)** Fabric tube **(c)** Buttonholes

Figure A.4: (a) Stencil outline and fabric markings (b) Fabric tube, turned inside out (c) Close-up of Buttonholes and string ends

The fabric pieces were sewn together along the long edge, leaving the top and bottom open to form a tube (see Figure A.4 (b)). Four pieces of fishing line were inserted along each sewing edge using the cutout holes as guides, and fixed at the top of the inner marking. Another four pieces were inserted at the bottom round cutout and attached to the corresponding squared markings. All lines were left with sufficient length for subsequent construction steps (see Figure A.4 (c)).

After completing the fabric and tubing layers, the fabric was turned right side out (see Figure A.4 (b)) and the

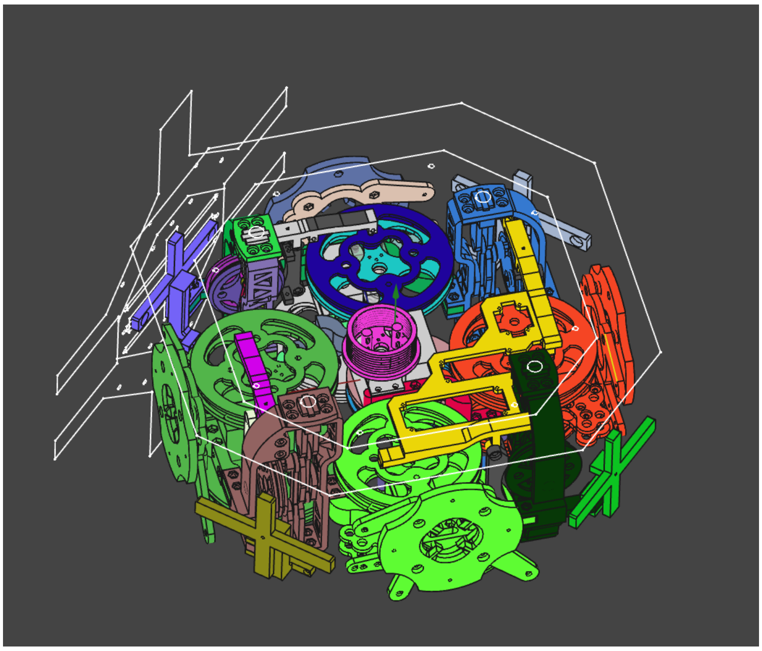


Figure A.5: Preview of the *ASSEMBLY.FCStd* CAD file, showing the arrangement of all components.

polyethylene tubing was inserted and the layers were then secured with a stitched line across the top.

This process produced four fully constructed and functional arms for the prototype.

A.5 Assembly of Arms

For each arm, printed parts from the folder *3DPrinter/ARMS* (see Section B.4) were assembled with two HiTec HS-311 motors into the bases for the arm, according to the layout in the ASSEMBLY file (see Section B.2.1, Figure A.8). The two spools (*x8_base_wirespool.3mf*-parts and *x8_lid_wirespool.3mf*-parts) were left split in half, and the *x4_connector_beam_plate.3mf*-part was left detached. Two *x44_guitar_peg.3mf*-parts were inserted into each *x8_lid_wirespool.3mf*-part, and four into the *x4_connector_beam_plate.3mf*-part.

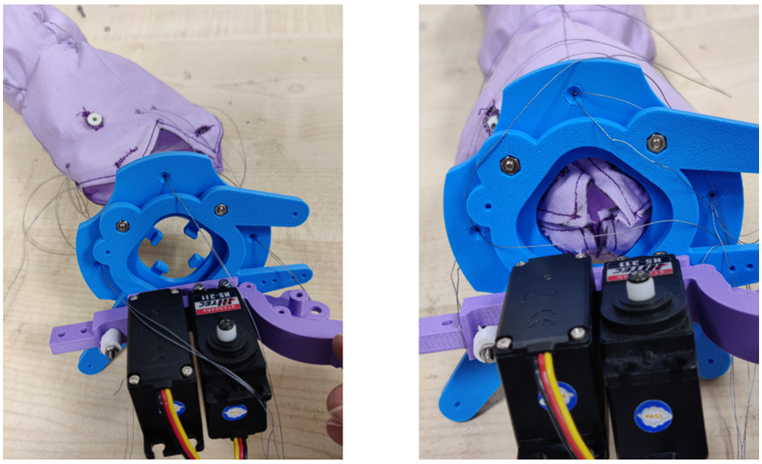


Figure A.6: Fabric layer attached to the hooks, with strings being fed through the first layer of routing holes.

The arm's fabric and polyethylene tubing was placed on the arm's base, with the buttonholes attached to the hooks on *x4_mountingplate.3mf*-part (see Figure A.6). Strings were routed through the holes in the *x4_mountingplate.3mf*-part and *x4_arm_string_routing*-part (see Figures A.6,) such that the strings attached to the lower square markings of the armswere funneled toward the space for the *x4_connector_beam_plate.3mf*-part, while the longer strings attached to the top of the arm were funneled toward the spools. The string holes are slightly tear-drop shaped and oriented in the direction from which the string should pass (see Figure A.7).

Loose ends were attached to *x44_guitar_peg.3mf*-parts, passed through the spools and beam plate, which were then mounted according to the ASSEMBLY file (see Section B.2.1). The air chambers were inflated and the strings tightened with the guitar pegs, completing four seperate functional arms.

(a) Tear-drop holes **(b)** Routing spool

Figure A.7: (a) Strings routed through tear-drop guiding holes. (b) Strings routed along spools and attached to guitar pegs.

A.6 Assembly of Breathing System

Parts from the folder *3DPrinter/PISTONS* (see Section B.4) were assembled into four identical components, according to the layout of *PISTONS* in the ASSEMBLY file (see Section B.2.1). Strings with excess length were attached to two *x44_guitar_peg.3mf*-parts inserted into the *x4_piston_lid_wirespool.3mf*-part. Cylindrical neodymium magnets (3.2 mm diameter, 4.1 mm height) were inserted into the slits of *x8_piston_head_tip.3mf*-parts (see Figure A.8).

A.7 Combination of Constructed Parts

The *x2_beams_outer.3mf*-parts, *x1_beams_innerA.3mf*-part, and *x1_beams_innerB.3mf*-part were assembled with the two Bluebird BMS-630MG motors attached to the centre, and with the outsided attatched to the motors of the completed arms (see ASSEMBLY file, Section B.2.1). The com-

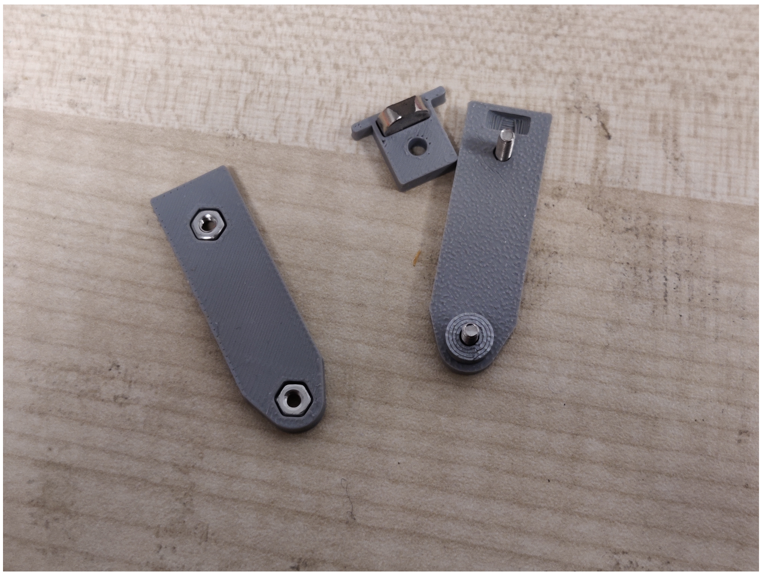


Figure A.8: Image of the piston head components with an inserted magnet.

pleted piston components were inserted into their corresponding slots according to the ASSEMBLY file, finalizing the basic construction.

A.8 Construction of Padding Parts

The outer line of the *x4_pincher_plate.svg*-cutout was used to cut two foam pieces with central holes, plus a small round piece with a central hole. The *x1_stencil_pincher_fabric.svg*-cutout was used to cut a fabric piece, which was then folded along the central lines and outfitted with with hook-and-loop fasteners attached to both sides (see Figure A.9 (a). Magnets were placed in the circular recesses (see Figure A.2) of the *x4_pincher_plate.svg*-cutout. The foam pieces were then placed on the *x4_pincher_plate.svg*-cutout, with the small piece in the center (see Figure A.9 (b)). Fishing lines were funneled through the central holes in the *x1_stencil_pincher_fabric.svg*-cutout and foam pieces. They then exited the fabric through the top, before looping back dowars the holes on the outside of the diagonal faces of the

(a) Fabric piece

(b) Foam layers

Figure A.9: (a) Fabric with attached hook-and-loop fasteners. (b) Foam layers and strings fastening the fabric layer.

x1_stencil_pincher_fabric.svg-cutout. The string was then fed back the same way, only through the hole on the other side of the diagonal face (see Figure A.9 (b)). Finally the cross-like extensions of the fabric cutouts were fastened to the remaining holes in the *x1_stencil_pincher_fabric.svg*-cutout (see Figure A.9 (b)). This process was repeated four times.

The shell padding was constructed using the *x1_shell_base_top.svg*- and *x1_shell_base_bottom.svg*-cutouts as the base, and two foam pieces cut based on the *x1_stencil_shell_foam.svg*-cutout. Magnets were placed in the small circular recesses, and the foam pieces were secured with strings through the cutout markings.

A.9 Final Construction Steps

The *x1_piston_central_wirespool.3mf*-part was mounted in its location (see ASSEMBLY file, Section B.2.1). Parts *x4_breathing_string_bracer.3mf*, *x1_breathing_string_routingA.3mf*, *x1_breathing_string_routingB.3mf*, and *x1_breathing_string_routingCD_and_electronics_mount.3mf* were placed in position and the strings routed to

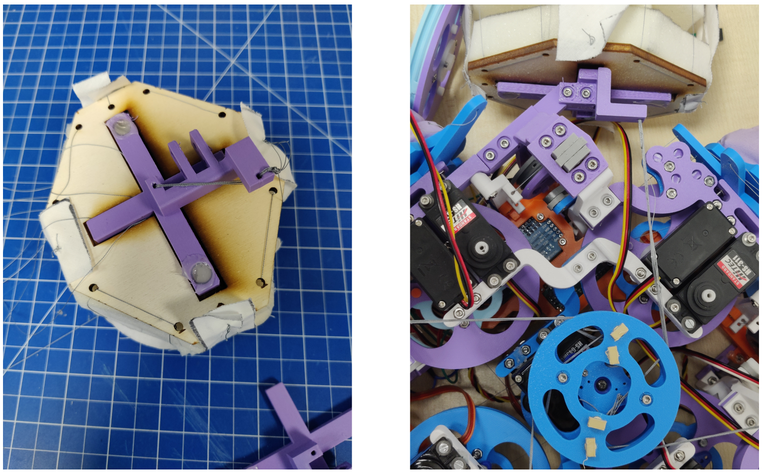


Figure A.10: Foam padding with a magnet-attached mounting mechanism, with strings routed to the spool and mounted to the guitar pegs.

A.10 Final Construction Steps

The *x1_piston_central_wirespool.3mf*-part was mounted in its designated location (see ASSEMBLY file, Section B.2.1). The *x4_breathing_string_bracer.3mf*-, *x1_breathing_string_routingA.3mf*-, *x1_breathing_string_routingB.3mf*-, and *x1_breathing_string_routingCD_and_electronics_mount.3mf*-parts were also placed in their corresponding positions. The strings from the piston mechanism were routed through the corresponding holes of the *x1_breathing_string_routingA.3mf*-, *x1_breathing_string_routingB.3mf*-, and *x1_breathing_string_routingCD_and_electronics_mount.3mf*-parts towards the *x1_piston_central_wirespool.3mf*-part and mounted there. This configuration was done such that the *x1_piston_central_wirespool.3mf*-part can synchronously extend and retract the pistons when turned. These strings were then tightened using the guitar pegs mounted inside the *x4_piston_lid_wirespool.3mf*-parts.

Magnets were inserted into the circular recesses of the *x1_pincher_string_routingA.3mf*-

, *x1_pincher_string_routingB.3mf*-
,*x1_pincher_string_routingC.3mf*-
,*x1_pincher_string_routingD.3mf*-parts through, in an orientation, that allows for the wooden side of the completed *x4_pincher_plate.svg*-cutout parts to attach to the outside (as defined in the ASSEMBLY file, Section B.2.1). The cross recesses on the wooden plate were aligned with the corresponding 3D-printed parts (see Figure A.10). All eight string ends emerging from the center of the *x4_pincher_plate.svg*-cutout were funneled through the two holes of the *x1_pincher_string_routingA.3mf*-, *x1_pincher_string_routingB.3mf*-, *x1_pincher_string_routingC.3mf*-,*x1_pincher_string_routingD.3mf*-parts as shown in Figure A.10.

These assemblies were then screwed into the appropriate locations on the *x4_connector_beam.3mf*-parts (see ASSEMBLY file, Section B.2.1). The string bundles were attached to guitar pegs, inserted into the *x1_pincher_lid_wirespool.3mf*-part, which, together with the *x1_pincher_base_wirespool.3mf*-part, were mounted to the remaining central motor (see ASSEMBLY file, Section B.2.1) and subsequently tightened.

Appendix B

List of supplementary materials

This appendix is organized according to the structure of the folders in the supplementary materials and briefly outlines the purpose and contents of each file or subfolder.

B.1 Interviews

The *Interviews* folder contains the basic layout we followed during our interviews (see Section 3.1), in Microsoft Word format along with its exported PDF version. Relevant findings and insights are referenced throughout the main sections. The folder structure is subdivided based on whether the files needed to be printed once per interview, once in total, or multiple times per interview.

B.2 CAD Files

This folder contains the CAD files representing all designs used in the final prototype. They were created in FreeCAD and use its native file format.

QQ12 Ist diese Art der Benennung ok, sind jetzt 1 zu 1 wie in der ordnerstruktur

B.2.1 Assembly

The *ASSEMBLY.FCStd* file contains almost all of the designed parts (see Section B.2.2), positioned in their correct spatial relationships as in the final build, as well as some of the sketches used to generate the lasercutter files.

B.2.2 Guitar Pegs

The *guitar_pegs.FCStd* file contains the guitar pegs used to tension the strings. It was separated into its own file due to extensive fine-tuning and experimentation with this component.

B.2.3 Cutout Sketches

The *arm_cutouts.FCStd* file contains sketches used to generate the lasercutter files that served as stencils for the arms.

B.3 Lasercutter Files

The *Lasercutter* folder contains all files that needed to be produced using the lasercutter, with the required quantity indicated in each filename. The files are provided in SVG format, but were converted to PDF as required by our lasercutter. They were derived from the sketches in the CAD files, with color coding added to separate layers in the lasercutter software, and including a wordmark to distinguish different iterations.

B.4 3D Print Files

The *3DPrint* folder contains all files that needed to be 3D printed, with the required quantity indicated in each filename. The files are provided in .3mf format, a standard export and 3D model exchange format. It is organized into subfolders to facilitate the modularization of the construction process.

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