

Designing Shape-Changing Interfaces for Atmospheric Mood Induction

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Contents

Abstract	ix
Überblick	xi
Acknowledgments	xiii
Conventions	xv
1 Introduction	1
1.1 Outline	4
2 Related Work	7
2.1 Shape-Changing Interfaces	7
2.1.1 Definitions and Taxonomies	7
2.1.2 Application Areas and Prototype Positioning	9
2.2 Soft Robotics for Shape-Changing Interfaces	11
2.3 Mood Induction and Target Affective States	13
2.4 Affective Expression through Shape Change	15

2.4.1	Shape-Changing Interfaces as Affective Displays	15
2.4.2	Crossmodal Associations with Shape, Touch, and Color	18
3	Prototype Design	25
3.1	Design Goals	25
3.2	Design Criteria for Affective Expression	26
3.3	Overall Form and Concept Development	29
3.4	Final Prototype Design	33
3.4.1	Appearance and Interaction	33
3.4.2	Shape-Change Mechanisms	34
3.4.3	Affective State Designs	37
4	Fabrication	41
4.1	Physical Construction	41
4.1.1	Prototype Body Structure	41
4.1.2	Texture Surface Fabrication	44
4.1.3	Tentacle Fabrication	50
4.1.4	Discarded Breathing Mechanism	53
4.2	Actuation and Electronic Components	54
4.2.1	Actuator Mounting	57
4.3	Software	60
5	Evaluation	63
5.1	Prototype Constraints	63

5.2	Exploratory Study	65
5.2.1	Study Method	65
	Participants	65
	Apparatus and Setting	66
	Procedure	66
	Data Collection and Analysis	67
5.2.2	Study Findings	68
	Interaction Behavior	68
	Initial Impressions	68
	Perceived Physical Qualities	69
5.2.3	Discussion of Findings	70
5.3	Revisiting the Research Questions	71
5.4	Limitations	72
6	Summary and Future Work	75
6.1	Summary and Contributions	75
6.2	Future Work	76
A	Prototype Setup and Operation	79
A.1	Required Components	79
A.2	Setup and Operation	80
A.2.1	Preparing and Uploading the Control Software	80
A.2.2	Operating the Prototype	81

A.2.3 Troubleshooting	81
A.2.4 Disconnecting the Prototype	81
Bibliography	83
Index	91

List of Figures and Tables

2.1	Taxonomy	8
2.2	Texture-changing silicone module	12
2.3	Circumplex model of affect	14
2.4	Shape-changing prototype for affective motion	17
2.5	Bending axes and example deformations	17
2.6	3D objects varying in angularity and complexity	19
2.7	Bouba/kiki shape-changing device	20
3.1	Design rationale for affective shape-change expressions	29
3.2	Paper prototype and measurement sketch	31
3.3	Final prototype	33
3.4	Tentacle orientation changes	36
3.5	Happiness/excitement prototype state	37
3.6	Anger prototype state	38
3.7	Calmness prototype state	38
3.8	Mapping of affective states to implemented prototype cues and visual states	39

4.1	3D model of the body parts	42
4.2	3D model of the top surface	42
4.3	3D model of the side walls	43
4.4	Modified two-part mold	44
4.5	Modified pneumatic channel layout	45
4.6	Placement of silicone tips in the base mold	46
4.7	Adjustable mold frame	48
4.8	Curing silicone blocks to the side walls	49
4.9	Tube routing through the side-wall blocks	49
4.10	Foam layers for the tentacle structure	51
4.11	Fishing-line guide component	52
4.12	Electronic component overview	54
4.13	Internal servo and LED placement	56
4.14	LED strip inside the prototype	57
4.15	3D model of the servo spool	58
4.16	Stepper motor and syringe mounting structure	59
5.1	Observed interaction patterns	67

Abstract

Shape-changing interfaces can communicate affect through physical transformations of form, texture, movement, and color. This thesis investigates how such interfaces can be designed as ambient stimuli for atmospheric mood induction by coordinating multiple affective cues within a single artifact. Based on a review of affective associations in the literature, design criteria were derived for three target affective states: happiness/excitement, anger, and calmness, representing distinct combinations of valence and arousal. The criteria were implemented in an abstract octopus-inspired prototype integrating pneumatic texture actuation, tendon-driven shape change, and optional color feedback. An exploratory qualitative study with eight participants was conducted to examine user perceptions of the prototype. The findings suggest that the artifact encouraged close bodily engagement and demonstrate the feasibility of combining multiple shape-changing mechanisms to convey affective qualities. At the same time, challenges regarding interaction legibility and material integration were identified. This thesis contributes an affective design framework for shape-changing interfaces, a prototype implementing coordinated affective cues, and initial insights into body-proximate affective interaction. The work provides a foundation for future controlled studies on affect communication and atmospheric mood induction through shape change.

Überblick

Shape-Changing Interfaces können Affekte durch physische Veränderungen von Form, Oberflächenstruktur, Bewegung und Farbe vermitteln. Diese Arbeit untersucht, wie solche Systeme als ambiente Reize zur atmosphärischen Stimmungsinduktion gestaltet werden können, indem mehrere affektive Hinweise in einem gemeinsamen Artefakt koordiniert werden. Auf Grundlage einer Literaturanalyse zu affektiven Assoziationen wurden Gestaltungskriterien für die drei Zielzustände Freude/Erregung, Ärger und Ruhe abgeleitet, die unterschiedliche Kombinationen von Valenz und Aktivierung repräsentieren. Die Kriterien wurden in einem abstrakten, von einem Oktopus inspirierten Prototyp umgesetzt, der pneumatisch erzeugte Oberflächenveränderungen, sehnengetriebene Formanpassungen und optionales farbliches Feedback kombiniert. Zur Untersuchung der Nutzerwahrnehmung wurde eine explorative qualitative Studie mit acht Teilnehmenden durchgeführt. Die Ergebnisse deuten darauf hin, dass der Prototyp körpernahe Interaktionen begünstigte, und zeigen das Potenzial der Kombination mehrerer Shape-Changing-Mechanismen zur Vermittlung affektiver Qualitäten. Gleichzeitig wurden Herausforderungen hinsichtlich der Verständlichkeit der Interaktion und der Integration der verwendeten Materialien identifiziert. Die Arbeit leistet einen Beitrag durch die Entwicklung eines affektiven Gestaltungsrahmens für Shape-Changing Interfaces, die Realisierung eines Prototyps mit koordinierten affektiven Ausdrucksmitteln sowie erste Erkenntnisse zu körpernaher affektiver Interaktion. Sie schafft damit eine Grundlage für zukünftige kontrollierte Untersuchungen zur Affektkommunikation und atmosphärischen Stimmungsinduktion durch physische Transformation.

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Conventions

Throughout this thesis we use the following conventions:

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

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Chapter 1

Introduction

Interactive systems increasingly move beyond conventional screen-based interaction through shape-changing interfaces that use physical form, movement, texture, light, and material change as part of interaction [Alexander et al., 2018; Rasmussen et al., 2012]. In affective interaction, such physical and spatial qualities are relevant because affect can be shaped not only by media content, but also by artifacts, environments, and atmospheres [Böhme, 2021; Fritsch, 2011]. This frames the atmosphere as a design space for interactive systems that aim to express or influence affect.

In entertainment and media contexts, affective qualities can be translated into accompanying visual, tactile, or physical forms. For example, emotion-based music visualization maps the emotional character of music to generated visualizations [Dharmapriya et al., 2023], tactile stimulation has been discussed as a way to enhance dynamic visual experiences such as films and games [Spence and Gao, 2025], and pneumatic haptic systems have been used to synchronize physical surface changes with affective movie scenes [Liu et al., 2024]. These examples show that affective augmentation is not limited to the media content itself. It can also shape the atmosphere in which an experience takes place.

Affective augmentation can extend from media content to the surrounding atmosphere.

Atmospheric mood induction uses designed objects as controlled affective stimuli.

This atmospheric perspective connects affective media augmentation to mood induction, where controlled stimuli are used to influence a user's affective state [Marcusson-Clavertz et al., 2019]. Established mood-induction procedures often rely on affective video or film clips, music, or self-referential statements [Marcusson-Clavertz et al., 2019]. However, affective interaction design and atmosphere theory suggest that affect is also shaped by interactive artifacts and designed environments [Böhme, 2021; Fritsch, 2011]. Ambient displays and actuating decorative artifacts further show how everyday spaces and objects can become interfaces through subtle changes in light, sound, movement, and physical actuation [Nabil et al., 2018; Wisneski et al., 1998; Zhong et al., 2023]. In this thesis, atmospheric mood induction is therefore treated as a design direction in which an object contributes to a surrounding affective atmosphere through controlled, perceivable changes.

Shape-changing interfaces can communicate affect through visible and tangible transformation.

Shape-changing interfaces are particularly suitable for this direction because they communicate through visible and tangible transformation. They use changes in physical shape or materiality as input or output and can convey information, meaning, or affect through computationally controlled movement and deformation [Alexander et al., 2018; Rasmussen et al., 2012]. Their expressive design space includes changes in form, volume, texture, orientation, movement, and material qualities, including elastic, inflatable, actuated, and hybrid forms of shape change [Qamar et al., 2018; Rasmussen et al., 2012; Sturdee and Alexander, 2018]. For affective design, this is promising because shape change can be both seen and felt, allowing affective cues to be expressed through visual, tactile, and dynamic properties [Dawson et al., 2013; Hu and Hoffman, 2019; Strohmeier et al., 2016; Tan et al., 2016]. Previous studies show associations between affective states and shape-changing properties such as curvature, angularity, speed, amplitude, frequency, stiffness, and texture [Feng et al., 2022; Lin et al., 2021; Liu et al., 2024; Steer et al., 2024; Strohmeier et al., 2016].

These associations show the affective potential of shape change at the level of individual physical properties. For atmospheric mood induction, however, the design problem is not only whether individual cues can express affective qualities, but how several cues can be coordinated as one coherent expression. Existing studies mainly examine isolated cues or affective expressions in individual prototypes [Hu and Hoffman, 2019; Lee et al., 2018; Lin et al., 2021; Liu et al., 2024; Neto et al., 2024; Steer et al., 2024; Strohmeier et al., 2016; Tan et al., 2016]. This leaves open a design challenge around coordinating multiple affective cues within one ambient shape-changing artifact. This thesis therefore focuses on how shape, motion, texture, and optional color feedback can be combined in one shape-changing artifact.

The open design challenge is to combine affective cues into one coherent ambient object.

The prototype focuses on three affective states: happiness/excitement, anger, and calmness. These states were selected because they differ in valence and arousal and therefore cover distinct regions of affective space [Russell, 1980; Strohmeier et al., 2016].

The thesis focuses on three affective states that differ in valence and arousal.

Based on this motivation, the thesis addresses the following research questions:

We formulated three research questions.

- Q1 Which shape, motion, texture, and color characteristics are associated in prior work with the target affective states selected for this thesis?
- Q2 How can these affective characteristics be translated into coordinated shape-changing behaviors?
- Q3 How can multiple shape-changing mechanisms be integrated into a single ambient prototype for atmospheric mood induction?

To investigate these questions through design and implementation, this thesis develops an atmospheric shape-changing prototype that expresses the selected affective states and provides an initial platform for future studies on mood induction effects. The prototype is an abstract octopus-inspired ambient object that combines a pneumatically actuated silicone surface, tendon-driven tentacle movement, and optional color feedback. An octopus-

A multi-mechanism prototype translates affective cues into implemented behavior.

inspired morphology was selected because the octopus's textured skin, rounded body, and flexible tentacles provide a natural basis for combining multiple forms of expressive shape change [Allen et al., 2014; Brocker et al., 2023; Hu and Hoffman, 2023; Jørgensen, 2017]. Its design translates affective cues into concrete prototype states [Hu and Hoffman, 2019; Liu et al., 2024; Neto et al., 2024; Strohmeier et al., 2016]:

- Fast goosebump movement and upward-curving tentacles for happiness/excitement
- Rapid spike movement and inward-bending tentacles for anger
- Slow rhythmic goosebump movement for calmness

The thesis contributes a design rationale, prototype implementation, and early qualitative insights.

Accordingly, the thesis focuses on the design and implementation of the prototype as a step toward understanding how physical shape change can contribute to atmospheric mood induction. The thesis contributes a literature-based affective design rationale, a concrete mapping from affective cues to coordinated shape-changing behaviors, an implemented multi-mechanism prototype, and early qualitative insights into how such an object is approached during first contact. This provides a foundation for future studies that can more directly evaluate affect recognition and mood-related effects in shape-changing ambient interfaces.

1.1 Outline

Chapter 2 reviews the theoretical and technical background, including shape-changing interfaces, soft-robotic actuation, mood induction, and affective expression through shape, movement, texture, touch, and color.

Chapter 3 presents the design of the prototype, from design goals and affective mappings to the final shape-changing concept.

Chapter 4 describes the fabrication and implementation of the prototype, including physical construction, actuation, electronics, and software.

Chapter 5 discusses implementation constraints and limitations and presents an exploratory study on participants' first impressions, interaction behavior, and perceived physical qualities of the prototype.

Chapter 6 summarizes the thesis, presents the main contributions, and outlines opportunities for future work.

Chapter 2

Related Work

This chapter reviews prior work that informs the design of an affective shape-changing prototype. It first introduces shape-changing interfaces, including definitions, taxonomies, and application areas, to clarify the interaction design space in which the prototype is situated. It then discusses soft-robotic fabrication and actuation approaches that are relevant for creating compliant and organic shape transformations. Finally, the chapter reviews mood induction, the selected target affective states, and prior studies on emotional expression through shape, motion, texture, touch, and color. Together, these areas provide the conceptual and technical basis for the design rationale developed in Chapter 3.

2.1 Shape-Changing Interfaces

2.1.1 Definitions and Taxonomies

According to Rasmussen et al. [2012], shape-changing interfaces (SCIs) are interfaces that use physical shape change as a form of input or output. Building on this definition, Alexander et al. [2018] provide a more specific description of shape-changing interfaces as interfaces that use physical changes in shape or materiality as input and/or output.

SCIs use physical changes to convey information, meaning, or affect.

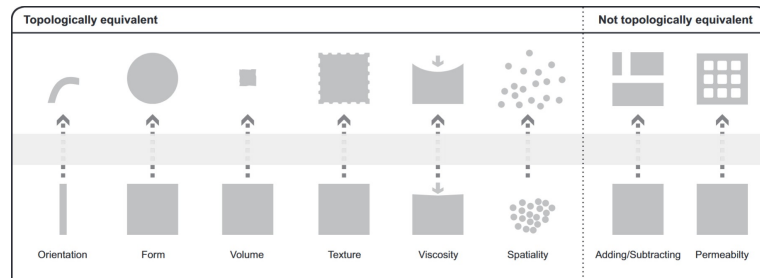


Figure 2.1: Taxonomy of different types of shape change. Reproduced from Rasmussen et al. [2012].

These interfaces are interactive and computationally controlled with the aim of conveying information, meaning, or affect. They can be self-actuated, user-actuated, or a combination of both forms of actuation.

Taxonomies classify SCIs by physical transformations and material or technical characteristics.

In prior research, several taxonomies have been proposed to describe the design space of shape change more systematically. Rasmussen et al. [2012] review existing research on shape-changing interfaces and propose a taxonomy, shown in Figure 2.1, that identifies and categorizes shape change into eight different types: *orientation*, *form*, *volume*, *texture*, *viscosity*, *spatiality*, *adding/subtracting*, and *permeability*. This taxonomy focuses on the physical transformation of an interface. For example, *orientation* refers to changes in direction or rotation while the interface maintains its overall form. *Volume* describes shape change in which the interface increases or decreases its physical size, while its overall form may remain recognizable. *Texture* refers to the change in the surface properties of an interface without changing its overall form, such as making it feel rough, smooth, bumpy, soft, or rigid. Another taxonomy, proposed by Sturdee and Alexander [2018], provides an overview of shape-changing prototype categories. While Rasmussen et al. [2012] focus on the types of physical transformation, Sturdee and Alexander [2018] classify shape-changing interfaces according to their material and technical characteristics. Their taxonomy includes categories such as *enhanced 2D*, *bendable*, *paper and cloth*, *elastic and inflatable*, *actuated*, *liquid*, *malleable*, and *hybrid* interfaces. Both taxonomies overlap in some areas. For example,

bendable interfaces can correspond to changes in *form* or *orientation* in Rasmussen et al. [2012]’s taxonomy. Similarly, *elastic and inflatable* interfaces are related to changes in *volume*. Together, these taxonomies offer useful frameworks for understanding how shape-changing interfaces can dynamically alter their form or material properties. Furthermore, they serve as a basis for contextualizing the rationale and development of the prototype presented in this thesis.

2.1.2 Application Areas and Prototype Positioning

In addition to taxonomies based on physical transformations and technical characteristics, shape-changing interfaces have also been discussed in terms of their application areas. Sturdee et al. [2015] conducted a public ideation study with 74 participants, collecting 336 application ideas for shape-changing technologies. These ideas were grouped into application areas, including *entertainment, augmented living, medical, tools and utensils, research, architecture, infrastructure, industry, wearables, education and training*, and *not relevant*. This categorization can be useful for situating shape-changing systems according to their intended context of use. Among these application areas, *entertainment* and *augmented living* are most relevant for this thesis.

In the study by Sturdee et al. [2015], *entertainment* was the most frequent application area, accounting for 16.36% of the ideas. It refers to shape-changing applications related to devices, toys, games, sports, events, and other recreational activities, including examples such as physical 3D television and sensory feedback for video games. Several works illustrate how shape-changing and deformable interfaces have been explored in entertainment contexts. In musical contexts, Troiano et al. [2015] investigated deformable interfaces for electronic music through workshops and a performance study, finding that musicians used deformation for sound manipulation, filtering, and expressive control rather than simple sound generation. In gaming, SHAPIO [Kajiyama et al., 2015] was presented as a shape-changing game controller whose three-dimensional form dynami-

Entertainment applications use shape change for expressive control, game interaction, and affective media augmentation.

cally represents game events and supports player interaction. Similarly, Lo and Girouard [2017] built an interactive flexible mobile gaming prototype based on bend gestures derived from gaming tasks in three interaction categories: navigation, action, and deformation. The prototype enabled players to control mobile games by bending the device and was used to evaluate how bend gestures could be mapped to in-game actions across different device sizes. Entertainment applications can also include the tactile augmentation of screen-based media. Spence and Gao [2025] reviewed how tactile feedback can augment both passive media experiences, such as watching films, and active experiences, such as gaming. In addition to enhancing presence or immersion, tactile stimulation may act as a non-diegetic mood cue that reinforces emotional engagement. In a closely related example, Liu et al. [2024] used synchronized pneumatic surface changes during movie clips to enhance affective experiences.

Augmented-living applications integrate subtle shape-changing artifacts into everyday environments.

The second most frequent area was *augmented living* with 12.79% of the ideas. It is defined as applications that improve everyday life through home improvements or smaller-scale aspects of interior architecture, such as form-sensing furniture, ventilation controls, and reactive aesthetics. For example, ambient displays have been proposed as a way of turning architectural space into an interface through subtle changes in light, sound, and movement [Wisneski et al., 1998]. Similarly, actuated decorative artifacts have been explored in everyday interior settings, showing how shape-changing objects can function as both interactive systems and decorative elements [Nabil et al., 2018]. Another shape-changing interface presented by Lee et al. [2023] supports the delivery of everyday notifications while showing how such systems can be interpreted as decorative, evocative, or uncanny. A long-term study of the shape-changing interface coMorphing Stool further suggests that subtle shape-changing artifacts can become accepted as part of the home over time [Zhong et al., 2023].

The shape-changing prototype for atmospheric mood induction presented in this thesis can therefore be positioned between entertainment and augmented living. It relates to entertainment through affective and expressive transformations that may contribute to immersive media experiences. At the same time, it relates to augmented living because it explores how subtle shape-changing artifacts could be integrated into everyday environments as ambient, affective objects.

The prototype is positioned between entertainment and augmented living.

2.2 Soft Robotics for Shape-Changing Interfaces

Soft robotics focuses on the design, fabrication, and control of robots made from compliant and deformable materials rather than exclusively from rigid links and joints [Kim et al., 2013; Rus and Tolley, 2015]. Because their bodies can deform under contact, soft robots can adapt to unstructured environments and support physical interaction in close proximity to humans. This compliance can reduce the risks associated with contact, although the safety of an interactive system still depends on its complete construction, including actuation forces and any rigid components. For shape-changing interfaces, soft robotics is relevant not only as an approach to actuation, but also as a way to create continuous and organic transformations. In an HCI context, Brocker et al. [2023] describe how flexible soft-robotic structures can produce natural and lifelike movements and investigate how users associate different soft-robotic shapes with familiar organisms and objects.

Soft robotics provides compliant, organic transformations for physical interaction.

One soft-robotic approach that is particularly relevant to this thesis is pneumatic actuation. By applying pressure to internal fluidic channels, a compliant silicone structure can transition between different surface states. Hu et al. [2018] presented a texture-changing skin for social robots based on two soft fluidic texture units: goosebumps and spikes. Goosebump units, shown in Figure 2.2 (b), deform outward into smooth bumps under positive pressure while spike units, shown in Figure 2.2 (c), use a two-chamber structure

Pneumatic actuation enables reversible surface-texture changes in silicone skins.

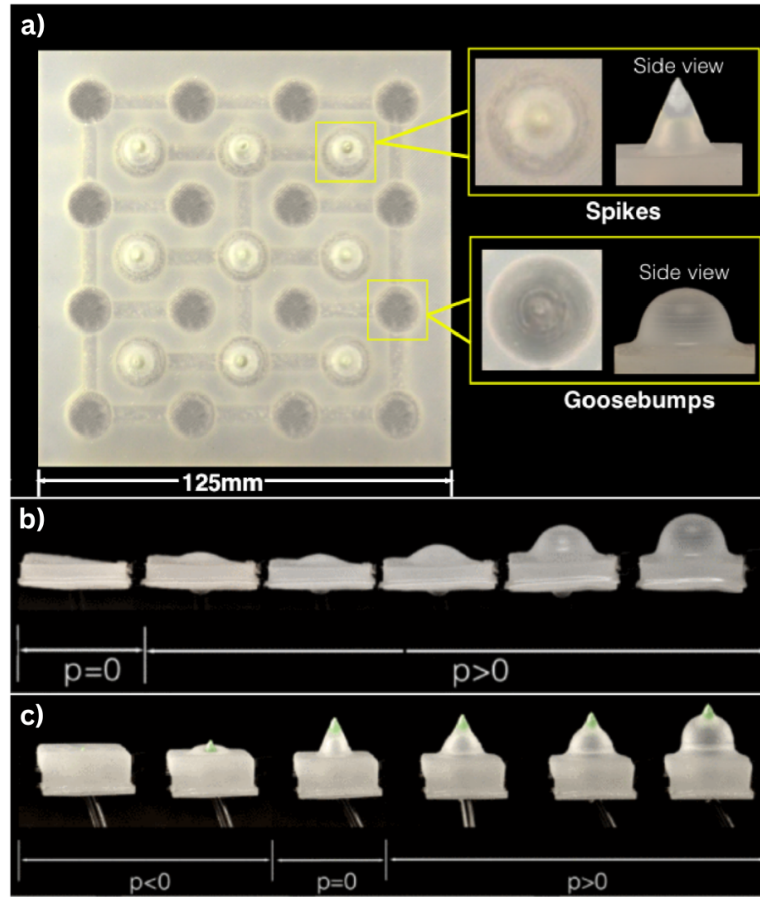


Figure 2.2: Texture-changing silicone module with interleaved spike and goosebump units: (a) module layout, (b) goosebump inflation under positive pressure, and (c) spike displacement under negative, neutral, and positive pressure. Reproduced from Hu et al. [2018].

with an embedded rigid tip that is recessed under negative pressure and protrudes outward under positive pressure. The units were arranged in an interleaved module with separate fluidic networks, allowing the two texture types to be actuated independently. A subsequent study by Hu and Hoffman [2019] examined users' emotional associations with such texture changes, as discussed in Section 2.4. This provides a direct technical precedent for the pneumatically actuated silicone surface used in the prototype presented in this thesis.

A second relevant approach is cable-driven actuation for flexible limbs. Wu et al. [2020] presented a silicone soft arm with embedded cables connected to servos. Retracting individual cables bends the arm into different configurations while the compliant body provides continuous deformation. Extending this principle, Wu et al. [2022] designed an octopus-inspired cable-driven soft arm that uses three servo-controlled cables to move flexibly in three-dimensional space. The design was also informed by the two-stage tentacle mechanism described by Vasquez, where each stage can bend in two orthogonal directions through cable tensioning, enabling organic-looking motion [By, 2016]. These systems differ from the prototype in their materials and intended applications, but they demonstrate how cable-driven actuation can create controllable tentacle-like movement in a deformable structure.

Cable-driven actuation enables controlled bending of flexible arms.

Together, these approaches provide a technical basis for the prototype fabrication described in Chapter 4. The prototype combines a pneumatically actuated silicone surface with cable-driven flexible tentacles. Rather than aiming to advance soft-robotic locomotion or manipulation, this thesis applies soft-robotic fabrication and actuation principles to an expressive shape-changing interface intended for close visual and tactile interaction.

The prototype applies soft-robotic actuation to expressive visual and tactile interaction.

2.3 Mood Induction and Target Affective States

Mood induction refers to the use of emotional stimuli to produce a shift in an individual's mood, for example, through films or imagined personal situations [Lempert and Phelps, 2014]. More formally, mood induction procedures can be understood as the use of controlled stimuli administered to temporarily alter affective states [Marcusson-Clavertz et al., 2019]. This concept is relevant for the present thesis because the prototype uses controlled visual and physical transformations as affective stimuli.

Mood induction uses controlled stimuli to shift affective states.

The target states span
mood-like and
emotion-like qualities.

At the same time, the target states examined in this thesis do not fit neatly into a single affective category. Emotions are described as relatively brief affective responses characterized by rapid onset, short duration, and coordinated physiological and expressive responses [Ekman, 1992]. Moods, by contrast, are more diffuse and longer-lasting affective states that are less strongly tied to a specific triggering event [Thayer, 1989]. Since the boundary between moods and emotions is not always clearly defined, as some affective terms may be used to describe both depending on context [Desmet et al., 2016], the selected target states span qualities that may be understood as either mood-like or emotion-like depending on context.

The circumplex model
frames the selected
states by valence and
arousal.

To provide a common conceptual basis for the selected target states, this thesis adopts the circumplex model [Russell, 1980] (see Figure 2.3). Within this framework, affective experience is described in terms of valence and arousal, allowing happiness/excitement, calmness, and anger to be treated as representative regions within affective space rather than as strictly bounded mood categories.

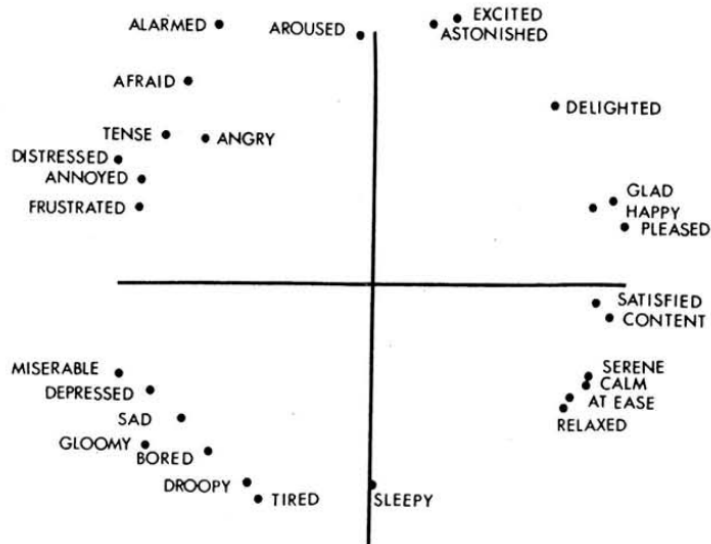


Figure 2.3: The circumplex model of affect, with valence represented on the x-axis and arousal on the y-axis. Reproduced from Russell [1980].

2.4 Affective Expression through Shape Change

Research on affective experience often uses dimensional models of emotion to examine how visual, tactile, and dynamic properties, such as shape, color, texture, and movement, are associated with affective responses.

Russell [1980] provided a foundational framework for many recent studies by introducing the circumplex model in which affective states are represented within a continuous two-dimensional space defined by valence and arousal. The first dimension, valence, reflects the negative or positive quality of an experience, also known as the pleasure-displeasure dimension. The second dimension, arousal, refers to the level of intensity of the affective state. For example, excitement is characterized by positive valence and high arousal, whereas distress is also high in arousal but negative in valence.

Valence and arousal describe affective quality and intensity.

2.4.1 Shape-Changing Interfaces as Affective Displays

The study by Dawson et al. [2013] is among the first works to apply Russell's circumplex model to examine affective gestural displays in shape-changing mobile devices. They designed a series of prototypes and conducted two user studies to explore how smartphones can communicate notifications and emotional meaning through lifelike shape-changing and visual-haptic gestural displays such as curling, crawling, breathing, ear-like movements, and vibration. In their first exploratory study, they found that participants naturally anthropomorphized these gestures and associated them with emotional and social meaning. Grounded in Russell's circumplex model, their second study used the DEVA prototype to evaluate five affective expressions: angry, depressed, neutral, excited, and relaxed. The results showed that users could distinguish levels of arousal, which were effectively conveyed through motion dynamics, especially the speed and intensity of

Shape-changing gestures communicate arousal more clearly than valence.

movement, whereas valence was conveyed only partially. In particular, excitement was perceived as positive, but the remaining expressions were not clearly separated along the valence dimension.

Flexible-surface studies
link static shape to
valence and motion to
arousal.

Strohmeier et al. [2016] investigated how deformations of a 2D flexible surface can be used to convey emotional meaning. In their first study, participants shaped a smartphone-sized flexible surface to express twelve emotions, often relying on symbolic visual metaphors: positive emotions were represented with smile-like U-shaped bends, sadness with inverted U-shapes, love with heart-like folds, and anger with crumpled shapes. Their analysis showed that geometric shape parameters, especially curvature, were more closely associated with valence, whereas dynamic parameters such as speed, amplitude, and the moving area of the surface were more closely associated with arousal. In a second study, categorical recognition of the intended emotions was limited, with 33.8% correct responses, but responses were more meaningful when interpreted within the circumplex model rather than as discrete labels. The study therefore suggests that flexible surface deformation can support affective communication, particularly when shape and motion are understood as continuous cues for valence and arousal.

Motion parameters
influence perceived
valence, arousal, and
dominance.

Extending this line of work, Tan et al. [2016] examined whether biological motion theory could support a systematic approach to designing emotional expression through shape change. Using a shape-changing interface composed of a wooden box with a cylindrical bellows on top (see Figure 2.4), they conducted two experiments manipulating motion parameters: velocity, fluidity, direction, and orientation. In the first experiment, participants recognized four of six intended basic emotions. The second experiment demonstrated that velocity, direction, and orientation significantly affected perceived valence, arousal, and dominance. For instance, faster movements increased valence, arousal, and dominance. Upward movement corresponded to positive and dominant impressions, whereas downward movement was linked to negative and less dominant impressions. Overall, the study provides a preliminary foun-

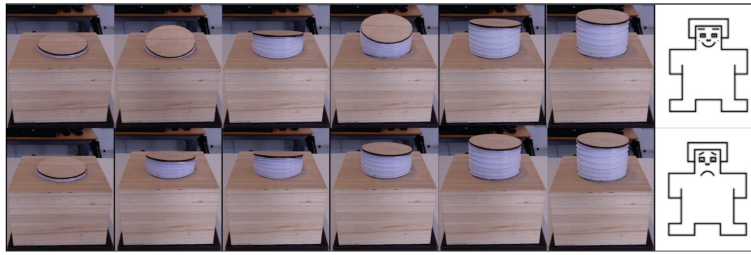
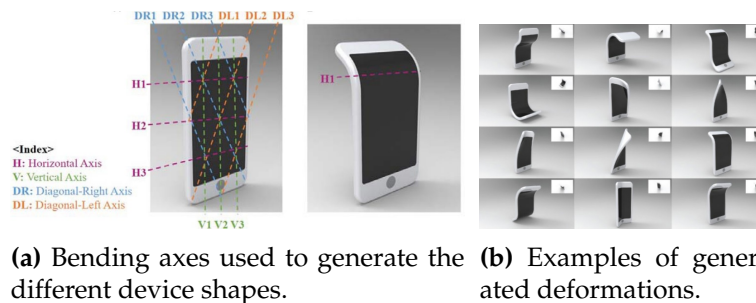


Figure 2.4: Shape-changing prototype used in the study by Tan et al. [2016], showing happy (top) and sad (bottom) behaviors. Reproduced from Tan et al. [2016].



(a) Bending axes used to generate the different device shapes. **(b)** Examples of generated deformations.

Figure 2.5: Bending axes and example deformations used to study emotional perception of anthropomorphic flexible-device shapes. Reproduced from Lee et al. [2018].

dation for systematically designing emotional expression in shape-changing interfaces through movement.

The work of Lee et al. [2018] extends research on how anthropomorphic deformation in a flexible display affects users' emotional perceptions. Lee et al. [2018] generated 101 flexible-device shapes by bending a device along horizontal, vertical, and diagonal axes, as shown in Figure 2.5. In an online survey, 281 participants rated how strongly each shape appeared to express happiness, sadness, fear, anger, and disgust. In their analysis, the authors grouped the results into three emotional categories due to correlations: happiness, sadness-fear, and anger-disgust. High-happiness shapes consistently involved horizontal-axis bending, mainly convex bending. High sadness-fear shapes also involved horizontal-axis bending, but primarily concave bending, especially around the middle, upper,

Bending axis and curvature shape emotions attributed to flexible displays.

or both horizontal axes. In contrast, high anger-disgust shapes were mainly associated with diagonal-axis bending and no horizontal-axis bending. This suggests that simple deformation parameters, such as bending axis and curvature direction, can shape users' emotional interpretations of an object. In relation to shape-changing interfaces, these findings can inform the design of movement or deformation along different axes, since such transformations may influence how users interpret an object's anthropomorphic or affective expression.

Texture type shapes
perceived valence,
while movement
frequency shapes
arousal.

Hu and Hoffman [2019] examined skin texture change as an emotional expressive modality for social robots. In their study, 139 participants experienced eight texture gestures through video, in-person observation, and touch, and labeled them with emotions from Russell's circumplex model. The results showed that texture type affected valence; for example, goosebumps conveyed a more positive valence than spikes, whereas movement frequency affected arousal. In addition, low-frequency goosebumps mapped to low-arousal emotions like calm and sleepy, while high-frequency goosebumps mapped to high-arousal positive emotions like happiness or excitement. High-frequency spikes were mapped to high-arousal negative emotions such as anger and fear. These results indicate that dynamic skin textures can provide an additional nonverbal channel for conveying affective states in social robots, especially for tactile interaction.

2.4.2 Crossmodal Associations with Shape, Touch, and Color

Crossmodal
correspondences
connect shape, color,
and touch as affective
design cues.

Together, these studies show that users can perceive affective meaning from shape-changing interfaces through features such as motion dynamics, geometry, curvature, and bending axis. This provides a basis for considering these features as design parameters for the prototype developed in this thesis. To further support this design approach, the following section turns to crossmodal correspondences, which describe systematic associations between features across different sensory modalities [Spence, 2011]. Such

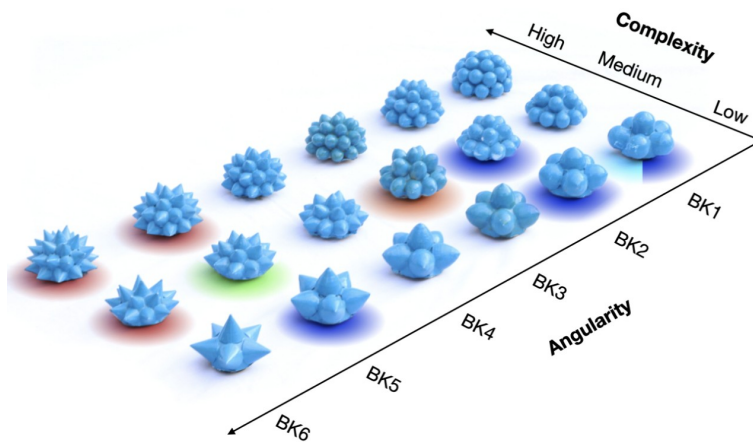


Figure 2.6: The 3D objects with varying levels of complexity and angularity used in the study by Lin et al. [2021]. Reproduced from Lin et al. [2021].

crossmodal correspondences provide a theoretical basis for why specific geometric, chromatic, and tactile features are well-suited for use in shape-changing interfaces to communicate affective states and potentially influence affective experience. A well-known example is the *bouba/kiki* effect, originally demonstrated by Köhler [1929] using the terms *takete* and *maluma*, and later presented by Ramachandran and Hubbard [2003], in which participants consistently associate rounded shapes with the word *bouba* and angular shapes with *kiki*.

Extending these effects, the work by Lin et al. [2021] investigated crossmodal correspondences among shape, color, and emotional responses using 3D-printed tangible objects. As shown in Figure 2.6, the shapes varied in angularity, from rounded to spikes, and in complexity. As a result, participants found objects with greater angularity and complexity to be less pleasant. They also perceived more angular and complex shapes as more exciting or arousing, while simpler shapes were associated with calmer feelings. Moreover, simpler objects with low angularity were more often associated with blue and higher brightness, while more complex, high-angularity objects were more often associated with red and lower brightness.

Angular and complex shapes are perceived as less pleasant and more arousing.

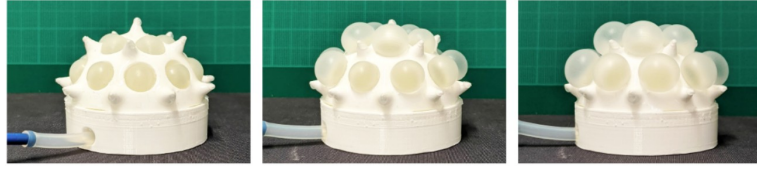


Figure 2.7: Bouba/kiki-inspired pneumatic device shown in three different forms and sizes. Reproduced from Feng et al. [2022].

Shape-change size
shapes valence, while
movement frequency
shapes arousal.

Building on previous work on touch-affect associations, Feng et al. [2022] investigated affective responses to dynamic shape-changing objects. Their studies used a tactile bouba/kiki-inspired shape-changing device, shown in Figure 2.7, which can transform between rounded and spiky forms, and participants reported their emotional responses using the valence and arousal dimensions of the circumplex model. The first study found that shape-change size strongly influenced valence; for example, larger, more bouba-like forms were associated with higher, more positive valence, whereas smaller, more kiki-like forms were associated with lower and more negative valence. For arousal, smaller, more kiki-like shapes were associated with higher arousal, especially in the static condition. In the second study, they investigated the frequency of the shape change and found that frequency significantly affected arousal. Moreover, low-frequency bouba-like shape changes induced low arousal, such as feelings of calmness. However, high-frequency shape changes evoked alertness regardless of shape.

Visual shape and color
cues can communicate
surface stiffness.

A similar study direction is presented by Steer et al. [2023], which investigates how people associate surface stiffness with visual features such as graphical shapes, physical shapes, and colors. Their findings link soft surfaces to lighter, brighter colors and stiffer surfaces to darker colors. Regarding the shapes, results showed that rounded, curved, and bouba-like shapes were associated with softer surfaces, whereas sharper, less curved, and more kiki-like shapes were associated with stiffer surfaces. Overall, the results suggest that designers can use visual cues, such as colors and shape angularity, to make deformable interfaces more intuitive.

A more advanced and closely related study was conducted by Steer et al. [2024], in which they examined crossmodal correspondences between deformable shapes, stiffness, colors, and emotions using stimuli that varied in angularity and stiffness in both visuo-tactile and tactile-only conditions. Their results show that both stiffness and angularity shaped these associations: soft, rounded forms were linked to pleasantness, rounder shapes to calmer impressions, and harder, spikier forms to unpleasantness and excitement. Color associations followed related patterns, with softer shapes tending toward cooler colors and harder shapes toward warmer colors, while brightness depended on the specific combination of shape and stiffness. Because these associations were similar across visible and tactile-only exploration, the study suggests that deformable shape and stiffness can inform both eyes-on and eyes-free interface design.

Angularity and stiffness jointly influence emotion and color associations.

To further contextualize the role of color, Meliksetyan [2025] reviewed the psychological meaning of color in design and showed that color can influence affective, cognitive, and behavioral responses. The review reports common associations of yellow with happiness and optimism, red with meanings such as danger and anger, and blue with calmness and trust. At the same time, colors often have dual meanings, such as red being associated with both passion and anger, or blue with calmness and sadness, so the associations and effects are highly context-dependent.

Color associations provide useful design cues but remain context-dependent.

Liu et al. [2024] confirmed earlier findings using a biomimetic pneumatic haptic system that frequency and volume significantly affected arousal, while surface texture contributed to differences in valence. Through their study, they also found that high-frequency goosebump movements increased the feeling of excitement, while low-frequency goosebump movements enhanced a calm, peaceful feeling. For negative high-arousal feelings such as anger, the study identified high-frequency spike movement as a relevant cue.

Frequency and volume affect arousal, while texture affects valence.

Dynamic tactile states
can elicit
distinguishable affective
experiences.

Similarly, Chen et al. [2025] presented a shape-memory alloy (SMA)-driven shape-changing haptic interface that transitions between four tactile states: soft only, stiffened, spike protrusion, and 3-DOF spike motion. In a preliminary user study, six of seven participants distinguished these haptic states on the forearm. The soft state elicited the highest ratings of pleasure and dominance and was often described as gentle, whereas spike protrusion and 3-DOF spike motion evoked higher arousal, with one participant describing the motion as scratching. The authors therefore suggest that continuous, dynamic shape-changing interfaces have the potential to induce diverse affective experiences.

Children share some
tactile-emotion
associations, while
others differ with visual
ability.

Furthermore, Neto et al. [2024] examined how children associate shape-changing tactile stimuli with emotions. The study involved 50 children, including 24 sighted and 26 visually impaired children, who were presented with 10 tactile stimuli in static and dynamic versions. Their key findings showed a clear association between dynamic spikes and the emotions of anger and fear across both groups. Children with visual impairment associated happiness with dynamic tentacle-like shapes, while sighted children mostly associated it with static tentacles. Finally, sighted children associated static wrinkles with calmness, while children with visual impairment associated them more with happiness.

Affective shape change
depends on combined
geometric, dynamic,
tactile, and chromatic
cues.

Taken together, these studies provide the basis for the design rationale presented in Chapter 3. Their findings suggest that affective shape-changing interfaces can be designed through a combination of geometric, dynamic, tactile, and chromatic parameters. Across the reviewed work, shape geometry, angularity, curvature, stiffness, and texture are mainly associated with emotional valence, while movement properties such as speed, rhythm, frequency, and intensity are more related to arousal. In addition, crossmodal correspondences among shape, color, and touch suggest that these parameters should not be considered independently but rather as mutually reinforcing design cues. This review also supports the selection of happiness/excitement, anger, and calmness as target affective states, as these states recur across the reviewed

studies and are associated with relatively distinct shape-changing cues [Hu and Hoffman, 2019; Liu et al., 2024; Neto et al., 2024; Strohmeier et al., 2016]. However, it remains unclear how multiple shape-changing parameters can be combined within a single interface to express and potentially influence specific affective states. This thesis investigates this gap by translating these findings into concrete shape-change design decisions aimed at expressing and potentially inducing happiness/excitement, anger, and calmness.

Chapter 3

Prototype Design

This chapter presents the design of the shape-changing prototype developed in this thesis. First, the design goals and affective design criteria are introduced, explaining how findings from the related work informed the prototype concept. The chapter then describes the overall form and concept development, followed by the final prototype design, including appearance, interaction, shape-change mechanisms, and affective state mappings.

3.1 Design Goals

As mentioned in Chapter 2, the prototype was designed to express three affective states: happiness/excitement, calmness, and anger. These states were selected because they differ in valence and arousal, covering distinct regions of the circumplex model. Specifically, happiness/excitement represents a positive-valence, high-arousal state; anger represents a negative-valence, high-arousal state; and calmness represents a positive-valence, low-arousal state [Russell, 1980]. This selection enables two comparisons: happiness/excitement and calmness differ primarily in arousal while retaining positive valence, whereas happiness/excitement and anger differ primarily in valence while retaining high arousal. The primary goal of the pro-

The prototype explores shape-changing expression for three states that differ in valence and arousal.

prototype is to explore how different types of shape change can be combined within a single interactive object to communicate affective states. However, beyond expressing the selected states, the prototype is intended to serve as an affective stimulus that may reinforce or induce corresponding affective responses in users.

Three design requirements follow from the affective-expression goal.

Based on this goal, the prototype should meet the following requirements:

1. **Affective expression:** Express and potentially induce distinct affective states through shape-changing behavior informed by prior research.
2. **Shape-changing variety:** Combine multiple types of shape change within a single prototype.
3. **Application context:** Function as an expressive object suitable for entertainment contexts and augmented-living environments, for example as a decorative or ambient object.

These requirements guided the selection of the prototype's physical form, movement patterns, surface textures, and color mappings. The following sections describe how they were translated into design criteria and subsequently into the final prototype.

3.2 Design Criteria for Affective Expression

To address the first requirement defined in Section 3.1, this section draws on the findings presented in Chapter 2 to select the associations between shape, movement, texture, color, and affective states. These associations inform the design decisions presented in the following sections.

The primary affective expression of the prototype is created through shape change and motion dynamics. Color is used as a secondary expressive layer that reinforces the intended interpretation, but it is not treated as the primary mechanism of affective communication, as the focus of this thesis is on shape-changing expression.

Shape change is the primary expressive layer, while color reinforces interpretation.

In this thesis, happiness/excitement is treated as a combined positive, high-arousal expression. Within the circumplex model, happiness and excitement are both associated with positive valence but differ in their arousal levels. Excitement is characterized by high arousal, whereas happiness has similarly positive valence but lower arousal levels [Russell, 1980; Strohmeier et al., 2016]. The design accordingly incorporates cues related to positive valence alongside cues associated with energetic, high-arousal expression. Previous studies indicate that positive affect can be supported through curved forms, including U-shaped forms associated with happiness, delight, and contentment [Strohmeier et al., 2016], as well as horizontal bending associated with happiness [Lee et al., 2018]. Dynamic tentacle-like stimuli made from soft and flexible materials have also been associated with happiness [Neto et al., 2024]. To reinforce high arousal, fast movements and high-frequency surface changes were selected. Fast motion was used to express excitement in the study by Strohmeier et al. [2016], while high-frequency goosebump movements were associated with excitement [Hu and Hoffman, 2019; Liu et al., 2024]. Although spiky and angular shapes can also communicate high arousal, they may produce unpleasant associations [Lin et al., 2021; Steer et al., 2024]. Therefore, these features were reserved for anger, which is also a high-arousal state but differs in valence. Yellow was selected as a reinforcing color cue because it is associated with happiness, optimism, warmth, and energy [Meliksetyan, 2025].

Happiness/excitement combines curved, soft forms with fast surface motion and yellow.

Anger was represented as a negative-valence, high-arousal state [Russell, 1980; Strohmeier et al., 2016]. Prior work links anger and unpleasantness to angular, complex, irregular, and crumpled forms. Namely, participants frequently used crumpled shapes to express anger [Strohmeier et al., 2016]. Angry shapes have also been asso-

Anger uses angular, crumpled, and spiky cues with rapid motion and red.

ciated with diagonal bending rather than horizontal bending [Lee et al., 2018]. Moreover, tangible objects with high angularity and complexity have been linked to unpleasantness, high arousal, and a reduced sense of control [Lin et al., 2021]. To reinforce the high-arousal quality of anger, rapid and intense shape changes were selected. High-frequency spike movements have been associated with anger [Hu and Hoffman, 2019; Liu et al., 2024]. Dynamic spike-like shapes with fast inflation and deflation movements have also been linked to anger [Neto et al., 2024]. In addition, the spike-like texture can include firmer tips, as harder and spikier shapes tend to evoke more unpleasant associations [Neto et al., 2024; Steer et al., 2024]. Red was selected as a reinforcing color cue because it has been associated with spiky and angular forms [Lin et al., 2021], as well as with harder shapes [Steer et al., 2024]. Red is also commonly associated with anger, danger, aggression, and warning [Meliksetyan, 2025].

Calmness uses rounded, simple forms with slow rhythmic motion and blue.

Calmness was presented as a positive-valence, low-arousal state [Russell, 1980; Strohmeier et al., 2016]. Calm expressions can be communicated through rounded, simple, and low-angularity forms. Low-angularity and low-complexity tangible objects have been associated with calmness, pleasantness, and a sense of control [Lin et al., 2021]. Similarly, rounder shapes have been identified as suitable for calmer contexts [Steer et al., 2024]. To support the low-arousal character of calmness, slow and rhythmic movements were selected. Calm expressions have often been represented through slow, oscillating motion [Strohmeier et al., 2016], and slow inflation and deflation movements have also been linked to this state [Neto et al., 2024]. In addition, low-frequency goosebump movements have been linked to calm and peaceful feelings [Hu and Hoffman, 2019; Liu et al., 2024]. Blue was selected as a reinforcing color cue. Smooth and simple tangible objects have been associated with blue [Lin et al., 2021], while soft shapes have been found to correspond with cooler colors such as blue and green [Steer et al., 2024]. Blue is also commonly associated with calmness, trust, and stability [Meliksetyan, 2025]. Table 3.1 summarizes the characteristics selected for the prototype. The following section explains how these criteria were combined into a single shape-changing prototype.

Affective State	Shape and Texture	Movement	Color
Happiness/ excitement	Goosebumps, curved U-like shape, soft form	High-frequency, fast movement	Yellow
Anger	Spikes, angular, crum- pled, hard shape	High-frequency, rapid movement	Red
Calmness	Goosebumps, round, soft shape	Low-frequency, slow, rhythmic movement	Blue

Table 3.1: Design rationale for affective shape-change expressions

3.3 Overall Form and Concept Development

This section describes the selection of the prototype’s overall form and its refinement through an initial paper prototype and exploratory interviews. Based on the criteria derived from the literature review, the prototype was designed around three expressive layers: surface texture, tentacle deformation, and optional color feedback. Together, these layers address the requirements defined in Section 3.1: affective expression, shape-changing variety, and suitability for an ambient domestic or entertainment-related context.

An abstract octopus-inspired form was selected because it aligns with the design cues identified in Section 3.2, particularly organic curvature, rounded forms, and textured surface features. These qualities make the form a suitable candidate for integrating multiple types of shape change into a single coherent object. The design was not intended to reproduce an anatomically accurate octopus, but rather to use recognizable octopus-like features, such as a rounded body and tentacle-like extensions, as an expressive and familiar visual reference. The choice is informed by prior work on soft robotics and shape-changing interfaces, which suggests that soft, organic, and lifelike movements can support safer and more intuitive human-machine interaction by linking it to familiar real-world experiences [Brocker et al., 2023]. In Brocker et al. [2023]’s user study, participants frequently associated soft robotic shape changes

An abstract octopus-inspired form provides a familiar basis for organic shape change.

with marine life, animals, plants, and everyday objects, and the authors observed a preference for simple, rounded, and relatively abstract forms. Furthermore, the design is informed by research on everyday reconfigurable objects, which shows that familiar reconfigurable objects and deformation mechanisms can inspire the design of shape-changing interfaces [Kim et al., 2018]. These findings support the use of an abstract octopus-inspired form rather than a literal or highly detailed representation.

The prototype targets ambient domestic use and tactile media augmentation.

The prototype is intended to function as an ambient or decorative object in a domestic environment and to support entertainment contexts, addressing the third requirement defined in Section 3.1. In this context, the object could express affective states through movement, changes in surface texture, and optional color feedback without requiring continuous direct interaction. One possible use scenario is placing the object in the living room, for example, on the sofa, as this space is commonly occupied [Sood et al., 2026], making it a plausible location for an ambient interactive object. A second scenario is the tactile augmentation of screen-based entertainment. The living room is a central domestic setting for television viewing, second-screen use, and console gaming [D’heer et al., 2012; Vaida and Greenberg, 2009]. Research suggests that tactile feedback can complement both passive media, such as films, and active media, such as games, while potentially reinforcing mood and emotional engagement [Liu et al., 2024; Spence and Gao, 2025]. In this scenario, the prototype could rest beside the user or on the user’s lap, and synchronized shape changes could complement the media content and reinforce its affective tone [Liu et al., 2024; Spence and Gao, 2025].

The paper prototype tested the planned octopus-like body and dimensions.

To assess the intended overall shape and approximate dimensions of the prototype, a paper prototype was first constructed to represent the planned octopus-inspired body and approximate dimensions before fabrication of the final version. Figure 3.2 shows the outline sketch of the prototype’s main body, including its dimensions. The body measured 300 mm in length, approximately 306 mm in width, and 120 mm in overall height. The base and walls were constructed from 1.5 mm thick Finn board, while the 110 mm long tentacles were made from craft paper so that they

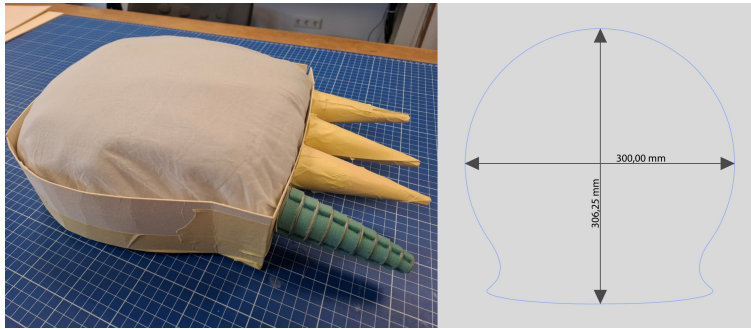


Figure 3.2: Constructed paper prototype and measurement sketch used to assess the initial body shape and dimensions.

could be shaped into cones. One tentacle was fabricated using the same method planned for the final prototype to indicate its intended flexibility to participants. The body's interior was filled with foam, which was covered with fabric to create the appearance of a closed shape.

After constructing the paper prototype, semi-structured interviews were conducted with twelve participants to evaluate its shape and size. The interviews were intended to refine the prototype design before fabrication. Participants were asked to hold and interact with the prototype and answer three questions:

- How would you interact with this object?
- What do you think about its shape?
- How do you perceive its size?

Exploratory interviews evaluated interaction, shape, and perceived size.

The most common placement was on the participants' laps, with their hands resting on the top surface or on the tentacles. The second most common placement was beside them, whereas some participants cuddled or hugged it like a pillow. Regarding the shape, seven of the twelve participants described it as "cute" and appreciated being able to recognize it as an octopus. Because participants could try multiple placements, these observations were not treated as mutually exclusive categories. One participant described

it as “funny-looking”, while others stated that the specific shape did not matter much and that another shape would have been acceptable. Regarding size, nine of the twelve participants preferred a smaller version, explaining that it would feel more “cuddly” and less “bulky”. The remaining participants considered the initial size appropriate.

These findings supported retaining the recognizable, octopus-inspired form while reducing the prototype’s dimensions. The observed lap placement and pillow-like interaction also reinforced the decision to design the prototype as a soft ambient object for domestic environments. Therefore, the final prototype was designed to be smaller and easier to hold or place on the lap while preserving the rounded body and tentacle-like features that made the object recognizable.

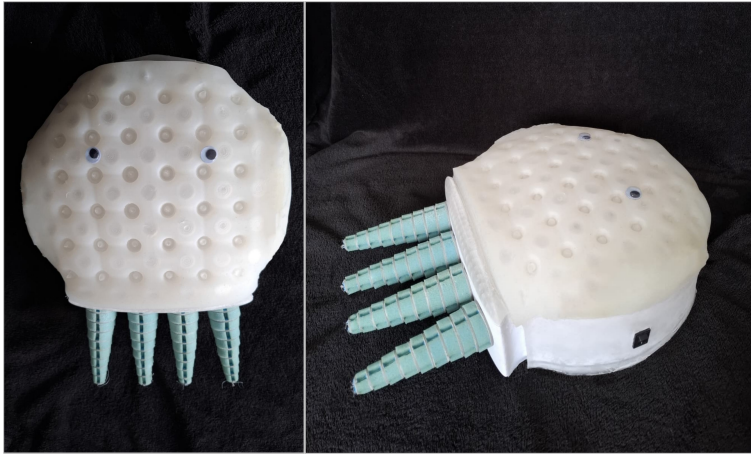


Figure 3.3: Final octopus-inspired prototype with a silicone-covered main body and four tentacle-like extensions.

3.4 Final Prototype Design

This section presents the final prototype and describes how the design criteria introduced in Section 3.2 were translated into physical form and shape-changing features.

3.4.1 Appearance and Interaction

The final prototype, shown in Figure 3.3, is an abstract octopus-inspired ambient object intended for use in a domestic environment, for example on a sofa or on the user's lap. It consists of a main body inspired by the form of an octopus, along with four tentacle-like extensions. Four tentacles were used instead of eight in order to preserve the octopus association while reducing mechanical complexity, actuator requirements, weight, and control difficulty. This choice also supports the abstract character of the prototype rather than aiming for anatomical accuracy.

Following the exploratory interviews, the dimensions of the prototype were reduced compared with the paper prototype. The main body is approximately 270 mm in length,

The final prototype abstracts an octopus form into a soft body with four tentacles.

260 mm in width, and 120 mm in overall height. The tentacle length was kept unchanged, with each tentacle extending approximately 110 mm from the main body. The smaller scale makes the object easier to hold, place beside the body, or rest on the lap. The final dimensions were also influenced by fabrication constraints: the prototype had to provide sufficient internal space for the mechanisms and electronic components while remaining small enough to be manufactured with the available 3D printer and covered with the silicone surface.

The top surface and side walls of the main body are covered with silicone, creating a soft and pillow-like appearance. In its neutral state, the top surface is smooth, but during affective expression the surface changes dynamically, while the side walls of the main body remain unchanged. The bottom plate is made from MDF to provide structural support and is covered with foam to improve comfort during lap-based use.

Users can observe motion, feel texture changes, and optionally see color cues.

The prototype is designed primarily as an expressive ambient object rather than as a device requiring continuous direct interaction. Therefore, users can observe its movements visually, while also experiencing its changes in texture and form through touch. The color mappings described in Section 3.2 were implemented through an optional LED system that can be enabled or disabled using a control switch.

3.4.2 Shape-Change Mechanisms

The prototype implements texture change, tentacle orientation, and optional color cues.

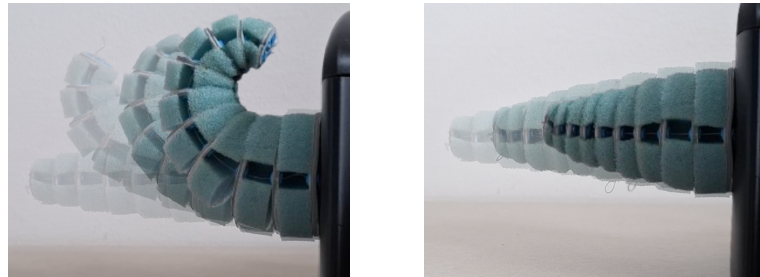
The final prototype implements two primary types of shape change: *texture change* on the silicone surface and *orientation change* of the tentacles. These transformations are complemented by optional color cues. This subsection explains the functional principles of the two mechanisms, while Chapter 4 describes how they were physically fabricated and assembled.

Texture change occurs on the upper silicone surface of the main body. The surface is based on a mixed pneumatic texture module adapted from Hu et al. [2018]. It contains two separate pneumatic channel networks: one network actuates rounded goosebump units, and the other actuates sharper spike units. In the unactuated state, the spike units remain physically present on the texture surface. To create a smoother texture, air is withdrawn from the spike network, reducing the protrusion of the spike units. When air is pushed into the spike network again, the sharper units protrude more strongly and create a more intense spiky texture. When air is pushed into the goosebump network, the rounded units inflate and create a soft, bumpy texture. The perceived movement is controlled through the timing of inflation and deflation. Fast repeated cycles produce high-arousal texture motion, while slower rhythmic cycles create a calmer surface behavior. Because the two pneumatic networks are separated, goosebumps and spikes can be selected independently for the different affective states.

Separate pneumatic networks control goosebumps and spikes at different rhythms.

Orientation change is generated by cable-driven movement of the tentacles. The tentacle mechanism follows the principle of cable-driven soft structures discussed in Section 2.2. Each tentacle uses four fishing-line routing positions arranged around the foam body. Pulling one line shortens the corresponding side of the tentacle relative to the opposite side, causing the tentacle to bend toward the pulled line. For the happiness/excitement posture, the upper line is tensioned so that the tentacles curve upward and form a U-like shape (see Figure 3.4a). For the anger posture, paired horizontal lines are tensioned so that the tentacles bend inward and create a compact, crumpled-looking form (see Figure 3.4b). For the calmness posture, the fishing lines remain relaxed and the tentacles stay close to their neutral configuration. Although each tentacle includes four fishing-line routing positions, only the lines required for the implemented affective postures are actively actuated. The upper lines create the U-like posture used for happiness/excitement, while paired horizontal lines create the inward movement used for anger. This reduces the number of required actuators while retaining the posture changes needed for the three implemented states.

Cable-driven tendons bend tentacles into the postures used for the affective states.



(a) Upward U-like tentacle posture.

(b) Inward crumpled tentacle posture.

Figure 3.4: Tentacle orientation changes used for the happiness/excitement and anger states.

A planned breathing-like volume change was replaced with low-frequency goosebumps.

Volume change was also considered during the design process. In particular, a breathing-like inflation and deflation movement was initially explored for calmness because it would have added a third shape-change type and could have reinforced the low-arousal character of this state based on prior research presented in Chapter 2 and Section 3.2. However, implementation tests showed that this mechanism could not be realized reliably within the technical constraints of the prototype, as described in Section 4.1.4. Calmness is therefore expressed through slow, low-frequency goosebump movements, based on prior findings that associate low-frequency surface movement with calm and peaceful affective states. Although this adaptation limits the addition of another shape-changing type, it allows the final prototype to communicate calmness through a technically more reliable mechanism that is already integrated into the prototype.

The shape-change mechanisms are complemented by optional color cues. Yellow is used for happiness/excitement, red for anger, and blue for calmness. These colors follow the mappings described in Section 3.2 and are used to reinforce the affective interpretation created through shape and movement.

3.4.3 Affective State Designs

Happiness/excitement: This state combines positive valence with high arousal. To express this state, the upper surface of the main body changes into a goosebump texture with fast, high-frequency movement. This creates a lively and energetic surface behavior while avoiding the unpleasant associations of sharper spikes. The tentacles bend upward to form a curved, U-like shape, reflecting the association between positive affect and curved forms. Yellow light is used as an additional cue to reinforce the energetic and positive character of the state.

Happiness/excitement uses fast goosebumps, upward tentacles, and yellow light.



Figure 3.5: Prototype state for happiness/excitement, showing goosebumps, upward-bent tentacles, and yellow light.

Anger: This state combines negative valence with high arousal. To communicate this affective state, the upper surface changes into a sharper, spiky texture with rapid, high-frequency movement. Compared with the happiness/excitement state, the texture is more angular and intense, emphasizing unpleasantness and agitation. The tentacles retract and bend inward to create a compact, irregular form reminiscent of a crumpled shape. Red light is used to reinforce the association with anger, warning, and high arousal.

Anger uses rapid spikes, inward-bent tentacles, and red light.

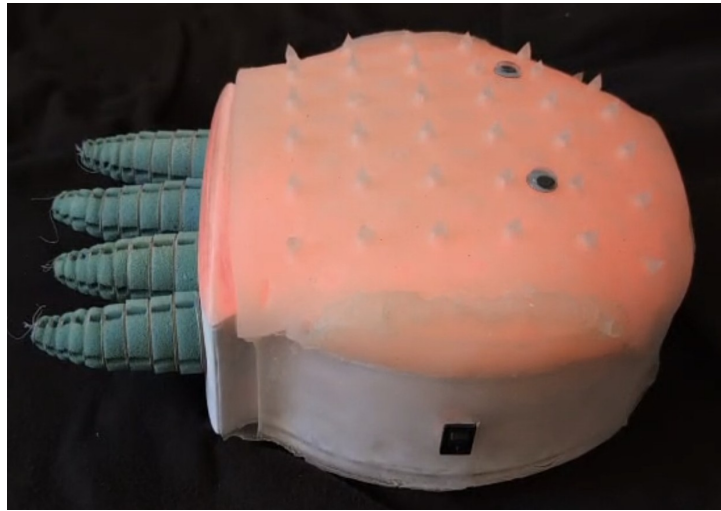


Figure 3.6: Prototype state for anger showing spikes, inward-bent tentacles, and red light.

Calmness uses slow
goosebumps, neutral
tentacles, and blue
light.

Calmness: This state combines positive valence with low arousal. The upper surface changes into a goosebump texture with slow, rhythmic, low-frequency movement, creating a less intense texture than in the happiness/excitement state. The tentacles remain stationary in their neutral configuration. Blue light is used as an additional cue because of its association with calmness, softness, and stability.

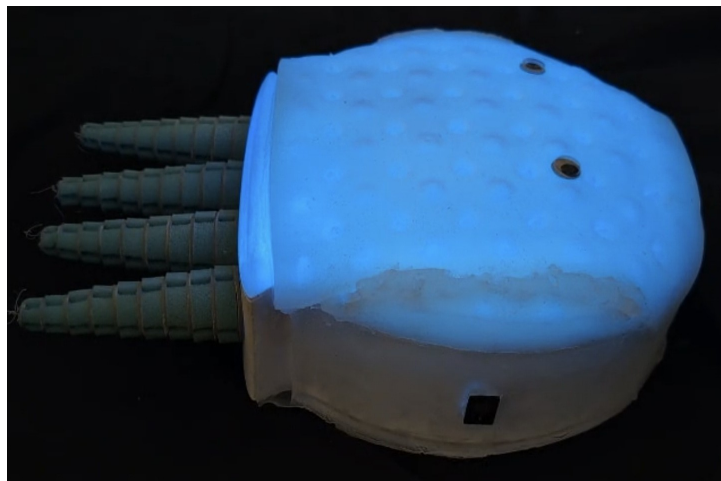


Figure 3.7: Prototype state for calmness, showing goosebumps, neutral tentacles, and blue light.

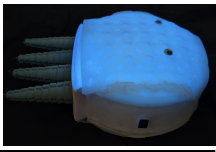
Affective state	Shape-change type	Texture and posture	Movement	Color cue	Prototype state
Happiness/ excitement	Texture and orientation	Goosebumps with upward-bent tentacles	Fast, high-frequency movement	Yellow	
Anger	Texture and orientation	Spikes with inward-bent tentacles	Fast, high-frequency movement	Red	
Calmness	Texture	Goosebumps with neutral tentacles	Slow, low-frequency movement	Blue	

Table 3.8: Mapping of affective states to implemented prototype cues and visual states

Table 3.8 summarizes how the selected affective criteria were translated into the implemented prototype states.

Overall, the final prototype addresses the three requirements defined in Section 3.1. Affective expression is addressed through the mapping of three affective states to specific combinations of texture, movement, posture, and color. Shape-changing variety is addressed through the combination of dynamic surface texture and tentacle orientation change. The application context is addressed through the prototype’s soft, compact, and ambient form, which makes it suitable for placement on a sofa, beside the user, or on the user’s lap in domestic and entertainment-related settings.

The final design addresses affective expression, shape-changing variety, and application context.

Chapter 4

Fabrication

This chapter describes the fabrication and implementation of the prototype introduced in Chapter 3. It focuses on the realization of the texture-changing surface and tentacle mechanisms introduced in Section 3.4.2. The chapter first explains the physical construction of the body, silicone surface, and tentacles, then presents the actuation system, electronic components, and control software. The source code and fabrication files are available in a GitLab repository¹. The repository contains separate folders for the ESP32 control software, the laser-cut files, and the 3D-printable parts used for the prototype.

4.1 Physical Construction

4.1.1 Prototype Body Structure

The prototype body was designed as an outer form inspired by the shape of an octopus. The body assembly consists of three main parts: the side walls, the top surface, and the bottom plate, as shown in Figure 4.1. The top surface has a slight curvature, giving the prototype a more organic

The body uses separate 3D-printed and laser-cut parts for form, access, and assembly.

¹ <https://git.rwth-aachen.de/i10/thesis/thesis-hana-masara-emotion-induction-sci>, accessed 22 June 2026.

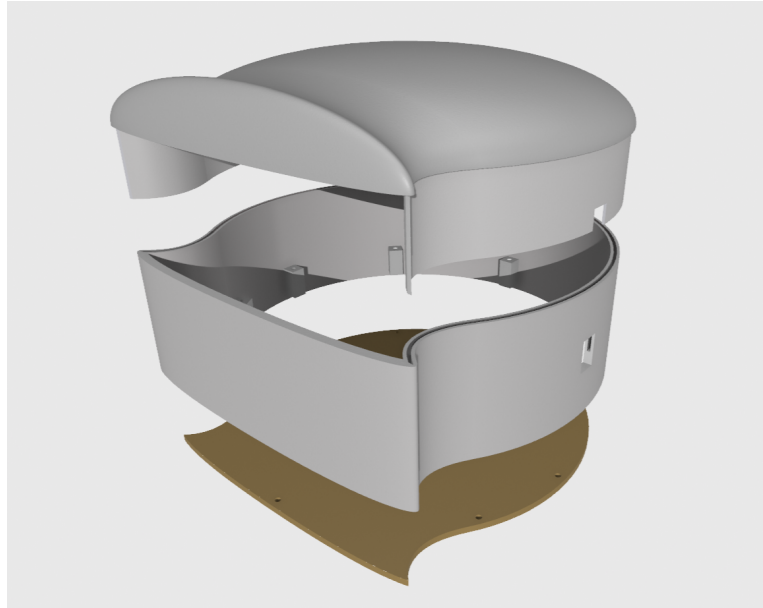


Figure 4.1: 3D model of the top surface, side walls, and bottom plate.

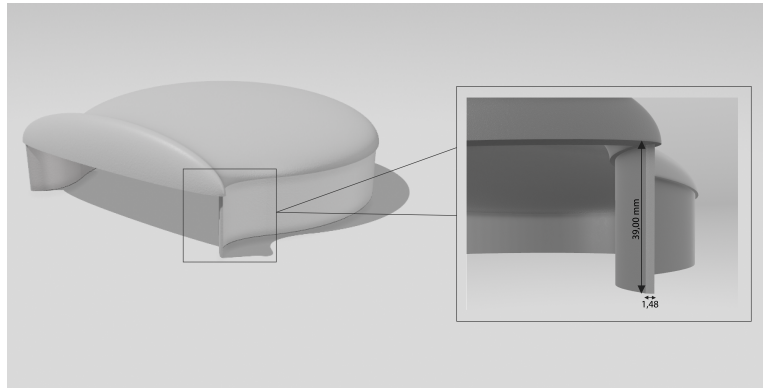


Figure 4.2: 3D model of the top surface showing the bottom extension that fits into the side-wall slot.

and less rigid appearance. On the underside of the top surface, a 39 mm long and 1.48 mm thick extension fits into the side-wall structure (see Figure 4.2). The front side does not include this extension, because the tentacles are mounted there and connected to the electronic actuation system inside the prototype.

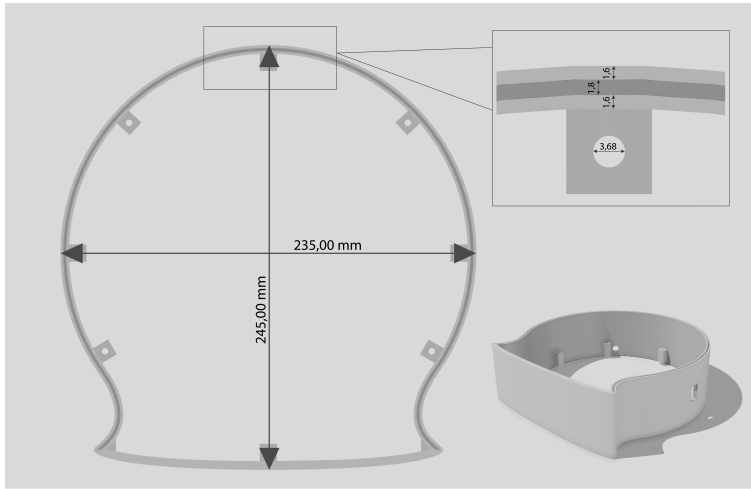


Figure 4.3: 3D model of the side-wall structure with the top-surface slot and mounting points.

The side walls have a height of 74 mm, allowing the electronic components to fit inside the prototype. As shown in Figure 4.3, the overall dimensions are 240 mm × 245 mm, with a wall thickness of 5 mm. Inside the walls, a 40 mm deep slot receives the extension from the top surface. This design improves alignment and stability when placing the top surface onto the walls, while avoiding the need for permanent gluing. It also allows the prototype to be opened from the top for modifications and supports access to the internal mechanisms. A mounting location for the control switch and a hole for routing wires were also added. Inside the walls, six 20 mm high mounting points allow the bottom plate to be screwed to the walls, making it possible to open the prototype from the bottom while securing the internal assembly. The top surface and walls were 3D-printed using polyethylene terephthalate glycol-modified (PETG) filament because of its comparatively high toughness and impact resistance. Transparent PETG was used for the top surface so that light from the LED system could pass through. The bottom plate was laser-cut from 4 mm MDF and included holes for the screws. The MDF bottom plate also served as the mounting base for the internal components. These included the tentacle actuation hardware, the LED system, wiring, and control electronics discussed in Section 4.2. This layout kept the mechanical and electronic

The side-wall and bottom-plate support stable assembly and later maintenance.

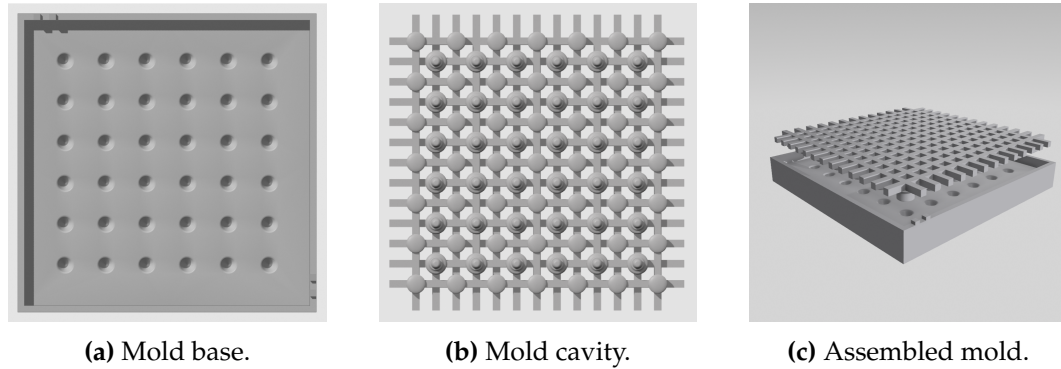


Figure 4.4: Modified two-part 3D-printed mold used to cast the silicone texture module.

components concealed while allowing the prototype to be opened from the bottom for maintenance and adjustments.

4.1.2 Texture Surface Fabrication

Texture-surface fabrication adapts the pneumatic mechanism to the larger prototype body.

The enlarged mold preserves texture-unit size while rerouting separate goosebump and spike channels.

The texture-changing surface forms the physical implementation of the pneumatic mechanism described in Section 3.4.2. This subsection therefore focuses on the mold modifications, material choices, casting process, and bonding steps used to integrate the silicone module into the prototype body.

To fabricate the texture module, the silicone was cast using a two-part 3D-printed mold (see Figure 4.4). The mold geometry obtained from the author consisted of two STL files: one for the base mold and one for the cavity-forming mold part, which is placed on top of the base mold, as shown in Figure 4.4c. The original mold produced a texture module with nine spike units and sixteen goosebump units. For this prototype, both STL files were modified in Blender to fit the body dimensions and the available fabrication setup. Although the original module is reported as 125 mm×125 mm in the work by Hu et al. [2018], casting silicone using the received mold geometry produced a module measuring 126.5 mm × 126.5 mm. The mold layout was therefore enlarged to fit the prototype body by extending the texture pattern and adding additional goosebump and

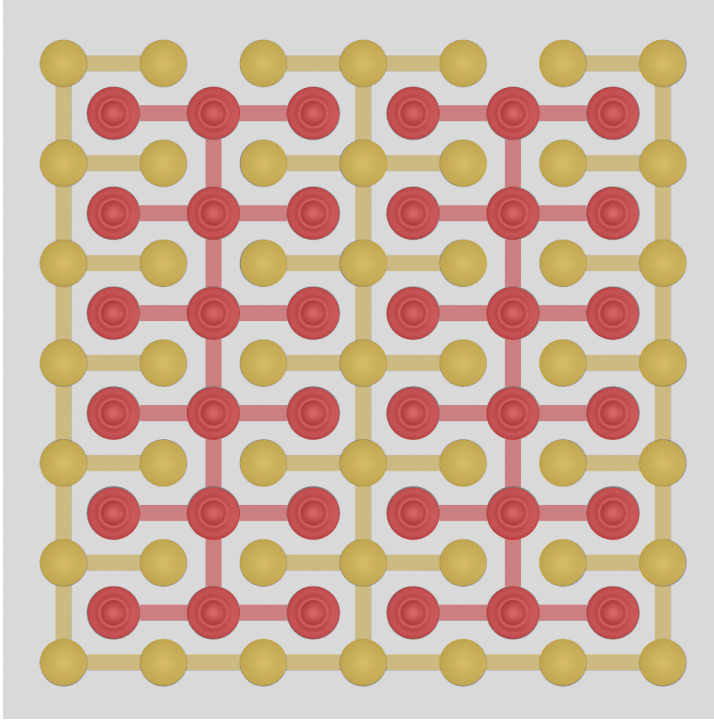


Figure 4.5: Modified pneumatic channel layout in the cavity mold. The yellow channels indicate the goosebump network, and the red channels indicate the spike network.

spike units, rather than uniformly scaling the individual texture units. This resulted in a final module size of approximately 221 mm × 221 mm while keeping the texture units close to their original dimensions. Compared with the original module, the enlarged design contained an increased number of texture units, with 40 goosebump units and 36 spike units. Because the number and spatial arrangement of texture units changed, the original pneumatic channel layout could not be transferred directly to the modified geometry. The internal connections were therefore rerouted to match the new unit distribution while preserving the functional separation between the two texture types. As shown in Figure 4.5, the yellow channels indicate the pneumatic network for the goosebump units, whereas the red channels indicate the network for the spike units. This adaptation allows air pressure to be distributed across all units of each texture type while maintaining independent actuation of the goosebump and spike structures.

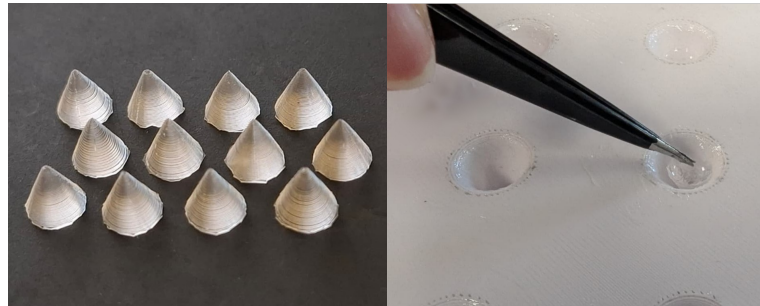


Figure 4.6: Finished silicone tips and their placement in the base mold before casting the texture module.

The texture module combines Shore 00–30 silicone with separately fabricated spike tips.

Silicone spike tips replaced PLA tips to improve bonding and durability.

After modifying the mold files, the molds were 3D-printed from PETG filament. Following the fabrication approach described by Hu et al. [2018], the texture module was based on a soft silicone elastomer with additional tip elements for the spike units. The original implementation used an extensible elastomer, specifically Smooth-On Ecoflex 00–30, and rigid tip elements made from polylactic acid (PLA). For this project, two-component silicone rubber with Shore 00–30² was used as an available material with a comparable hardness class.

Initial fabrication tests showed that PLA tips did not bond reliably to the silicone used in this prototype and detached under light rubbing. The PLA tips were therefore replaced with a second silicone material, two-component silicone rubber type 19³. This material bonded more reliably with the Shore 00–30 silicone and exhibited improved resistance to friction while still providing a sharp, clearly distinguishable haptic sensation. To cast the spike tips, a separate 3D-printed mold with 5 mm high tip cavities was designed and printed from PETG.

² <https://trollfactory.de/Produkte/Silikon-Kautschuk/Haertegrad-Shore/weich-Shore-A25/TFC4412/TFC-HIGH-FLEX-Silikon-Kautschuk-00-30-1-1-Groesse-2kg-2x1kg>, accessed 17 June 2026.

³ <https://trollfactory.de/Produkte/Silikon-Kautschuk/Haertegrad-Shore/weich-Shore-A25/TFC4191/TFC-Silikon-Kautschuk-Typ-19-transparent-Shore-1-1-Special-Effect-Groesse-1kg-2x500g>, accessed 17 June 2026.

Before casting, the silicone was prepared according to the manufacturer's instructions. The base and curing agent were mixed in a 1 : 1 ratio by weight using a precision scale. After mixing, the silicone was degassed in a vacuum chamber for one minute until visible air bubbles were removed. The material was then handled carefully to avoid reintroducing air pockets that could weaken the cured structure. After the tips had been cast and cured, they were placed into the base mold (see Figure 4.6), and approximately 400 g of silicone was poured into the mold. The cavity-forming mold part was then placed on top of the base mold to define the internal pneumatic cavities and connecting channels.

The texture surface was cast by degassing silicone, placing the tips, and closing the cavity mold.

For the bottom layer, Hu et al. [2018] cast a thin elastomer layer with an inextensible film embedded inside it in order to seal the fluidic cavities. The film constrains downward deformation, causing the surface to bulge upward when the cavities are pressurized rather than expanding toward the bottom layer. In this prototype, the bottom layer was cast from two-component silicone rubber type 19 after several fabrication tests. This material provided sufficient surface deformation during pressurization while also allowing light transmission through the surface. This material choice was important because the LED system is located inside the 3D-printed outer form; an opaque or semi-opaque film would have blocked the light from passing through the silicone surface.

A transparent silicone bottom layer seals the cavities without blocking LED light.

To cast the transparent bottom layer, a mold frame was 3D-printed based on the principle of an adjustable aluminum casting frame⁴. The frame consists of four angle plates that can be adjusted to the desired size and secured with clips. An acrylic plate was placed underneath the frame to provide a flat casting surface, as shown in Figure 4.7. To prevent leakage, hot glue was applied along the lower edges of the frame, ensuring adhesion between the frame and the acrylic plate and preventing the silicone from seeping underneath. After adjusting the mold to match the size of the texture surface, the silicone was mixed, poured into the frame to create a transparent bottom layer with a height

The bottom layer was cast and bonded to seal the fluidic cavities.

⁴ <https://trollfactory.de/Produkte/Zubehoer/Werkzeuge/TFZ1051/TFZ-Formenrahmen-SET-ALU-Formbaurahmen-Giesskasten-Rahmen-Formenbau-100mm>, accessed 17 June 2026.

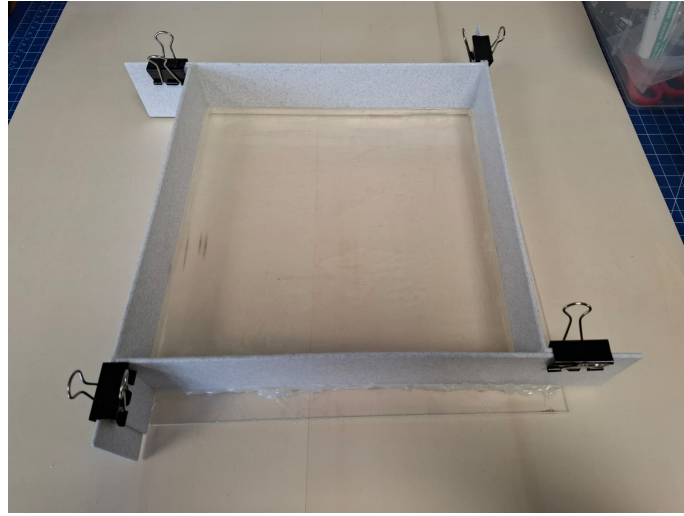


Figure 4.7: Adjustable mold frame on an acrylic plate for casting the transparent silicone bottom layer.

of approximately 5 mm, and allowed to cure fully. Once both the surface and bottom layers had cured, a thin layer of Shore 00–30 silicone was applied to the bottom layer as an adhesive interface. The two layers were then carefully aligned and bonded together to seal the fluidic cavities.

Fabric enabled bonding
between the silicone
blocks and printed side
walls.

Using the same mold frame, silicone blocks with a thickness equal to the silicone surface and a height matching the side walls were cast from two-component silicone rubber type 19. Because the silicone surface has a square geometry, the goal was to attach the silicone blocks to the side walls and to the main silicone surface in order to create a continuous, seamless surface around the perimeter. However, silicone does not adhere well to PETG or PLA. To overcome this limitation, several bonding approaches were tested. These tests showed that silicone adheres well to fabric, while fabric can be reliably bonded to PETG using cyanoacrylate adhesive. Based on this observation, a sandwich-like bonding concept was developed. First, a piece of fabric was glued to the side walls using cyanoacrylate adhesive. Then, a layer of two-component silicone rubber type 19 was applied to the fabric and to the silicone blocks. The blocks were then clamped against the side walls and left to cure, as shown in Figure 4.8, resulting in a bonded fabric-silicone interface.

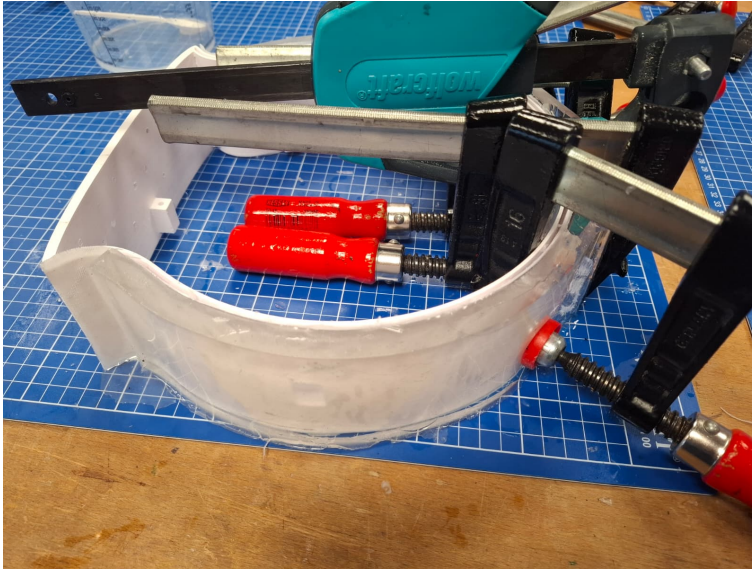


Figure 4.8: Silicone blocks clamped to the side walls during curing using the fabric-silicone bonding interface.

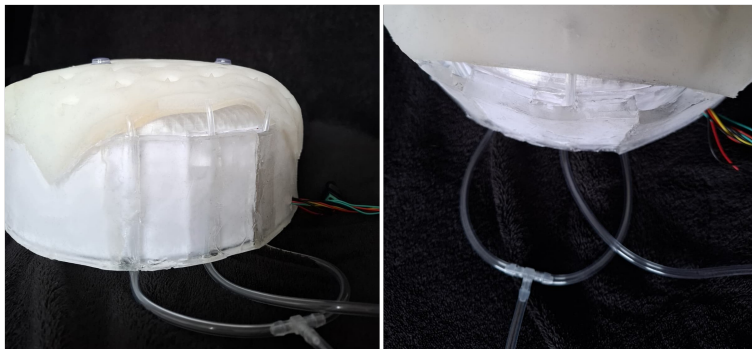


Figure 4.9: Carved side-wall blocks with routed pneumatic tubes and tube connections.

After the silicone side-wall blocks had cured, longitudinal channels were carved into the blocks to route the pneumatic tubes through the body. These channels held the tubes in place during interaction. After the surrounding silicone had been trimmed and the electronic components described in Section 4.2 had been added, the top surface was placed onto the side walls and bonded with silicone. The texture module was then placed on top and bonded to

Tube channels and separate pneumatic connections completed the texture module integration.

the side-wall blocks, creating a continuous connection between the texture surface and the outer body. The pneumatic connections were routed separately for the two texture systems. For the goosebump network, one tube was inserted directly into the texture module and connected to the continuous goosebump channel. For the spike network, two tubes were joined using a three-port tube connector⁵ and connected to the corresponding pneumatic channels. Figure 4.9 shows the carved blocks, tube routing, and resulting tube connections. This was necessary because the spike network consisted of two separate channels, as shown in Figure 4.5, whereas the goosebump network used one continuous channel.

4.1.3 Tentacle Fabrication

Alternating PU and EVA foam layers create lightweight, repeatable tentacle bending.

Each soft tentacle was constructed using foam as the main compliant body. Unlike the reference designs discussed in Section 2.2, which commonly rely on a central spine or silicone-based structure, this prototype used two types of foam with different thicknesses to achieve a balance between flexibility and controlled deformation. The variation in foam stiffness allowed the tentacle to bend smoothly while maintaining enough structural support to return toward its neutral shape after actuation. After several rounds of tests and design refinement, two foam materials were selected: 10 mm polyurethane (PU) foam and 2 mm ethylene-vinyl acetate (EVA) foam. Both foam layers were laser cut into the required shapes, as shown in Figure 4.10. The widest foam layer measured 41 mm, and each subsequent layer decreased in width by 3 mm, creating a tapered profile for the tentacle. The assembled tentacle had a length of 110 mm and consisted of 10 EVA foam layers and 9 PU foam layers arranged alternately. These dimensions were selected so that all four tentacles could fit within the available mounting area of the prototype body while preserving the intended proportions. The PU foam was used as the main flexible layer, allowing the tentacle to bend smoothly during actuation, while the EVA foam was added as a structural support layer. The combination of these two materials

⁵ <https://www.adafruit.com/product/4662>, accessed 17 June 2026.

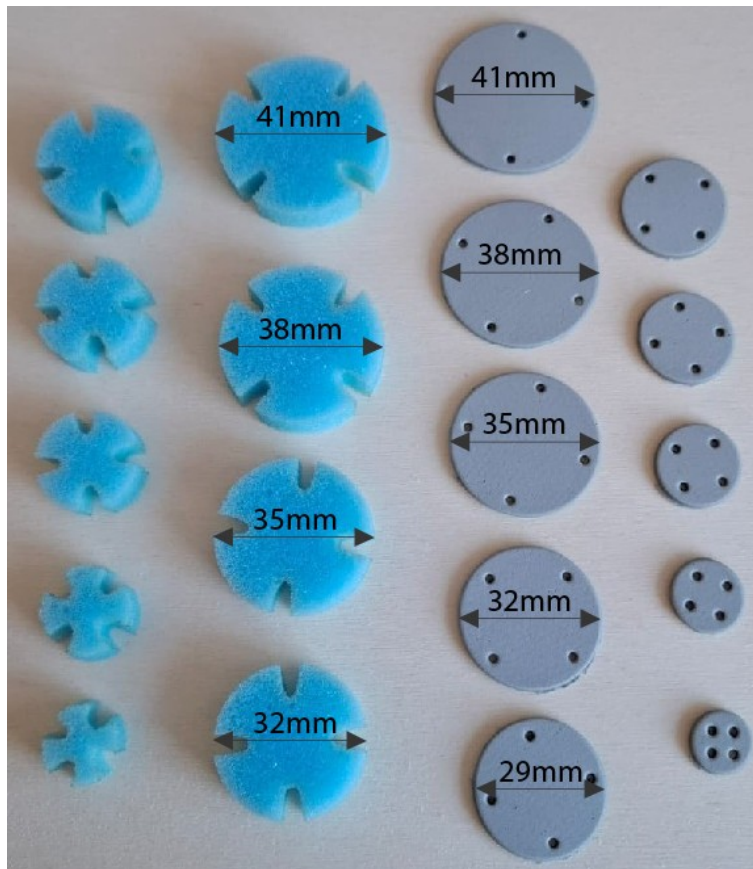


Figure 4.10: Foam layers used for the tentacle structure. The left design shows the PU foam layer, and the right design shows the EVA foam layer.

allowed the tentacle to remain lightweight and compliant while still providing sufficient stiffness for repeatable motion.

For each tentacle, four fishing lines were routed along predefined positions around the foam body. Braided fishing line⁶ was selected because it combines high tensile strength with a small diameter and sufficient flexibility. This made it suitable for repeated servo-driven pulling while reducing the risk of tearing or adding excessive stiffness to the tentacle. An elastic thread was inserted through the cen-

Fishing-line and guide parts enabled durable tentacle actuation.

⁶ <https://www.bauhaus.info/schnuere/westline-angelschnur-4-x-braided-line/p/30150504>, accessed 17 June 2026.

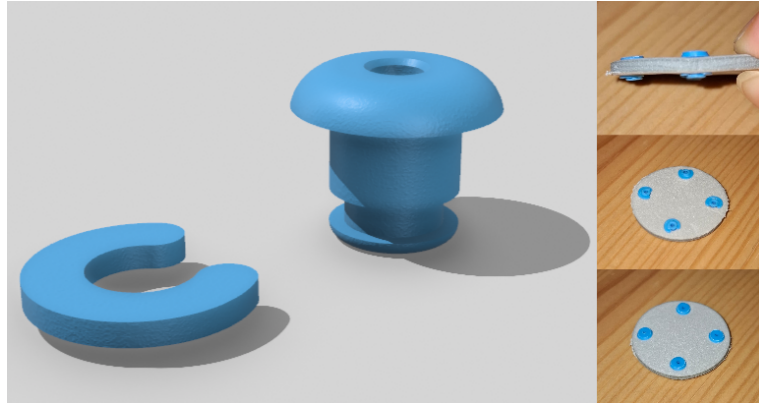


Figure 4.11: Guide component used to reduce friction between the fishing line and the foam.

ter of the structure to keep the foam layers aligned without significantly restricting the bending motion. To improve durability, small 3D-printed guide components were inserted into the holes in the EVA foam at the points where the fishing lines come into contact with the foam, as shown in Figure 4.11. These components reduced direct friction between the fishing lines and the foam during repeated actuation, helping to prevent tearing, wear, and deformation of the foam. To mount the tentacles onto the main body, the placement of each tentacle was first determined according to the visual arrangement. For each tentacle, four holes were drilled through the body to allow the fishing lines to pass from the tentacle into the internal actuation space. The fishing lines were then routed to the servo motors located inside the body. After checking that the lines could move freely, the tentacles were fixed to the body using cyanoacrylate adhesive. This attachment method provided a firm connection between the foam structure and the body while allowing the fishing lines to move freely during actuation.

4.1.4 Discarded Breathing Mechanism

During the design process, a dedicated breathing-like volume change was explored as an additional shape-change mechanism for the calmness state. Two approaches were tested, but neither could be implemented reliably because of the limited available space, material constraints, and mechanical strength limits of the prototype. The first approach was inspired by a blooming lotus automata⁷ mechanism, in which a 3D-printed structure opens and closes like a flower to create the impression of breathing. A test model was fabricated, but the thick silicone layer required more force to stretch than the 3D-printed components could withstand, causing the printed parts to deform and break during expansion. In addition, the inextensible bottom layer of the silicone texture module constrained global expansion, making this approach unsuitable for the prototype. The second approach involved placing a scissor-jack mechanism inside the body to lift the 3D-printed top surface by approximately 3 cm, using thoracic expansion during breathing as a reference [Farrall et al., 2023; Padasdao et al., 2013]. An added extension to the top-surface model, shown in Figure 4.1, allowed vertical movement in principle. However, the available internal space was insufficient to integrate the mechanism reliably, and the printed parts lacked the mechanical strength required to push the top surface and silicone layer upward. For these reasons, a dedicated breathing mechanism was not included in the final prototype. Instead, calmness was implemented through slow, low-frequency goosebump movement using the pneumatic surface mechanism.

Breathing-like volume change was tested but excluded from the final prototype.

⁷ <https://www.instructables.com/Print-and-Build-a-Lotus-Blossom-Automata>, accessed 17 June 2026.

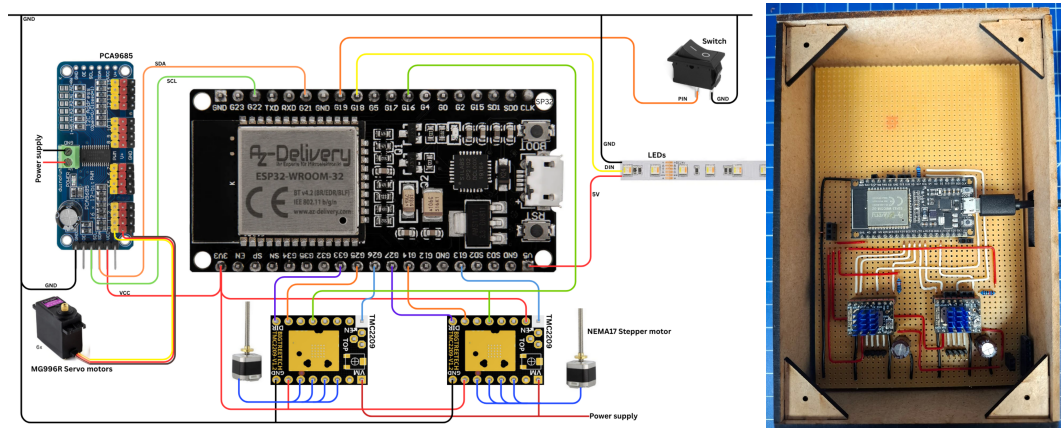


Figure 4.12: Overview of the electronic components and their connections.

4.2 Actuation and Electronic Components

The ESP32 coordinates texture actuation, tentacle movement, and optional LED output.

The prototype used an ESP32 development board⁸ as the central controller for the actuated texture surface, the tentacle movement, and the optional LED cues. An overview of the electronic components and their connections is shown in Figure 4.12. During operation, the ESP32 was connected to a laptop via USB, which provided the serial interface used to select the affective state. The actuators were not powered directly from the microcontroller. Instead, the stepper drivers, servo driver board, and LEDs used separate power connections appropriate to their current requirements.

Two stepper-driven syringes provide independent pneumatic actuation for goosebumps and spikes.

The dynamic texture surface was actuated using a syringe-based pneumatic system with two independent channels. A 60 ml syringe was used for the goosebump units, and a 100 ml syringe was used for the spike units. The larger syringe was used for the spike channel because this pneumatic chamber network required a larger displaced air volume to reach the intended deformation. Each syringe was driven by a NEMA-17 stepper motor. The rotary motion of the motor was converted into linear motion by the sy-

⁸ https://cdn.shopify.com/s/files/1/1509/1638/files/ESP_-_32_NodeMCU_Developmentboard_Datenblatt_AZ-Delivery_Vertriebs_GmbH_10f68f6c-a9bb-49c6-a825-07979441739f.pdf?v=1598356497, accessed 17 June 2026.

ringe mount described in Section 4.2.1, allowing the syringe plunger to push air into or withdraw air from the corresponding pneumatic chamber network. The stepper motors were controlled through Bigtreetech TMC2209 V1.3 stepper motor drivers⁹. The motor drivers were powered by a 12.5 V power supply. The mechanical mounting of the pneumatic actuation system is described in Section 4.2.1.

The tentacle movement was actuated using servo motors connected to the fishing-line tendon mechanism described in Section 3.4.2. Initially, continuous-rotation servos, specifically the Adafruit FS5103R¹⁰, were considered. However, these servos control rotational speed rather than an absolute angular position. If the prototype stopped during a movement, for example because of a power interruption, the controller would not know the actual position of the line spool after restarting. Because the servos are mounted inside the prototype body, manually resetting their position would require opening the prototype or adding a more complex homing procedure in software. Therefore, MG996R 180-degree servo motors¹¹ were used instead. These servos can be commanded to defined angular positions, which made it easier to return the tentacles to known states after startup or after completing a movement. The MG996R servos were selected because their torque was sufficient to tension the fishing-line tendons in prototype tests while remaining compact enough to fit inside the prototype body. Because the rotation range is limited to 180°, the spool diameter was selected so that the available angular movement produced the required pulling distance for the intended tentacle postures.

Position-controlled servos enabled reliable tentacle actuation within the body.

For the U-like posture, the upper fishing line of each tentacle was connected to a dedicated servo motor. For the compact crumpled posture, one shared servo was placed between each pair of neighboring tentacles and connected to their horizontal fishing lines. This arrangement allowed paired tentacles to move inward with similar timing while

The servo layout reduced space while enabling coordinated tentacle movement.

⁹ <https://www.roboter-bausatz.de/p/5x-bigtreetech-tmc2209-v1.3-schrittmotortreiber-uart>, accessed 17 June 2026.

¹⁰ <https://www.adafruit.com/product/154>, accessed 17 June 2026.

¹¹ <https://eckstein-shop.de/WaveShare-MG996R-Servo-Metal-Gear-Motor-High-Torque-180Grad>, accessed 17 June 2026.

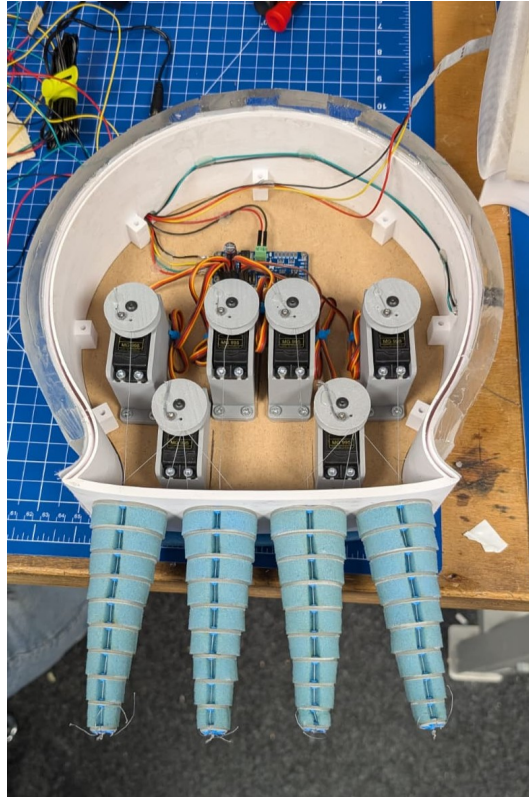


Figure 4.13: Internal placement of the servo motors and LED strip inside the prototype.

reducing the number of required servo motors and saving space inside the body. In total, six servo motors were used for tentacle actuation. Their placement inside the prototype is shown in Figure 4.13. Because multiple servos had to be controlled simultaneously, a PCA9685¹² 16-channel PWM servo driver board was used. The driver receives control commands from the microcontroller via an I²C connection and generates the PWM signals for the servo motors. The servo system was powered through a separate wired 5 V power supply using a barrel jack, because the current required by several simultaneously moving servos exceeds what can be supplied safely by the microcontroller.

¹² <https://www.mouser.de/ProductDetail/Adafruit/815?qs=GURawfaeGuCGKbWyy9179Q%3D%3D>, accessed 17 June 2026.

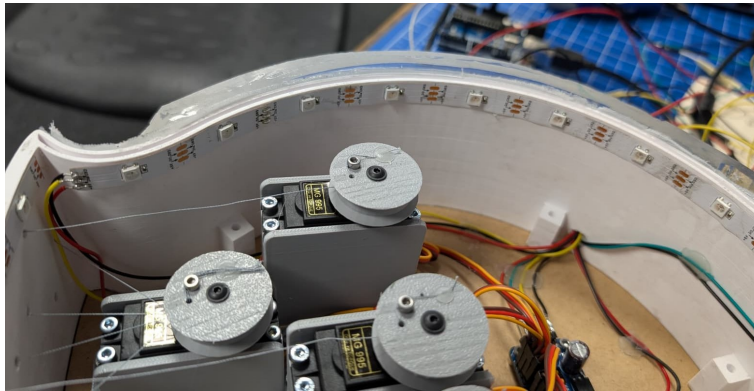


Figure 4.14: Addressable LED strip mounted along the inner side walls of the prototype.

In addition to the mechanical texture and tentacle movements, the prototype includes a visual color output channel. For this purpose, addressable 5 V LEDs were installed inside the body. The LED strip was glued along the inner side walls of the prototype, as shown in Figure 4.14, so that the light could diffuse through the translucent outer material. The LEDs were connected to a switch and can therefore be turned on and off manually. This allowed the visual color cue to be used as an optional secondary output channel rather than as a mandatory part of the shape-changing expression.

Addressable LEDs provide optional secondary color cues through the translucent body.

4.2.1 Actuator Mounting

The servo motors for the tentacle actuation were mounted inside the main body on the MDF bottom plate. Their positions were chosen to keep the fishing-line paths as short and direct as possible between the tentacles and the servo arms. They were fixed using 3D-printed servo mounts¹³. Two different mount heights were used. The two servos responsible for the crumpled posture used the original mount geometry, while the four servos responsible for the U-like posture were raised. This height difference aligned

Servo mount heights align spools with tendon paths to reduce friction.

¹³ <https://www.thingiverse.com/thing:4483512>, accessed 17 June 2026.

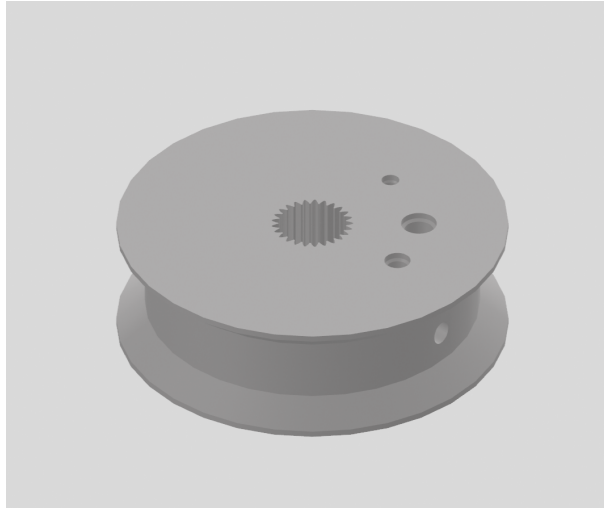


Figure 4.15: 3D model of the custom servo spool used to convert servo rotation into tendon displacement.

each servo spool with the corresponding fishing-line routing point. By keeping the spool and fishing line at approximately the same height, the tendon could be pulled more directly, reducing friction and minimizing the force required to actuate the tentacle.

Custom spools
translate the limited
servo rotation into the
required tendon pull.

Because the tentacle system used position-controlled 180° servos, as described in Section 4.2, custom spools were designed and 3D-printed for the servo horns. The spool radius was selected so that the available angular range produced the required tendon displacement. Figure 4.15 shows the designed spool with a diameter of 26.5 mm. With this diameter, the 180° rotation of the servo corresponds to a theoretical tendon displacement of approximately 41.6 mm. Two spool heights were used. The four servos actuating the U-like posture used spools with a height of 4 mm. The two servos actuating the crumpled posture used spools with a height of 5 mm, because each of these servos had to wind four fishing lines simultaneously. The additional height provided enough space for the fishing lines to sit on the spool without interfering with each other.

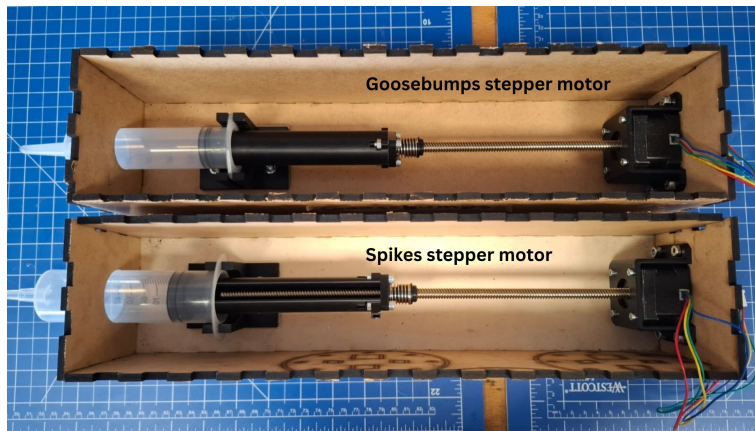


Figure 4.16: External mounting structure for the stepper motors, syringes, and plunger-drive mechanisms.

In contrast, the stepper motors for the pneumatic texture actuation were mounted outside the prototype body. They were fixed to an external mounting structure that held the stepper motors, syringes, and plunger-drive mechanisms in alignment. This external arrangement was necessary because the syringe-drive mechanism required more space than was available inside the body and needed to remain accessible for adjustment during testing. The pneumatic tubes were routed from the external actuator unit into the silicone texture module. The external structure was built from a laser-cut MDF box, which could be closed to reduce the motor noise during operation. The 3D-printed NEMA-17 stepper motor mounts¹⁴ were positioned at the ends of the box. The syringes were held by cutouts in the MDF structure and an additional 3D-printed syringe-edge mount inspired by the syringe pump design by Dr. D-Flo¹⁵. The original syringe plungers were replaced with 3D-printed plunger connectors based on an existing open-source model¹⁶. These connectors attached the syringe plungers to the lead-screw drive of the stepper motors.

The pneumatic syringe actuators were mounted outside the prototype body.

¹⁴ <https://makerworld.com/de/models/1984864-nema-17-43-34-stepper-motor-vertical-mount>, accessed 17 June 2026.

¹⁵ <https://www.drdflo.com/pages/Projects/Syringe-Pump.html>, accessed 17 June 2026.

¹⁶ https://github.com/FelixKasteel/digital-appendix-thesis/blob/main/Soft_Robot_Fabrication_Actuation/controller/3D%20models/Syringe%20Connector.stl, accessed 17 June 2026.

As the stepper motor rotated the lead screw, the plunger moved linearly, pushing air into or withdrawing air from the pneumatic texture channels. The final mounting structure is shown in Figure 4.16.

4.3 Software

Serial commands select the three affective states.

The control software runs on the ESP32 development board and coordinates the pneumatic texture actuation, tentacle servo actuation, and optional LED output. It was uploaded to the microcontroller using PlatformIO in Visual Studio Code. After upload, the prototype can be controlled through the serial monitor. The software listens for one-character commands that select the implemented affective states: E for happiness/excitement, A for anger, and C for calmness.

Each state command coordinates texture, tentacle posture, and color.

Each command activates a predefined combination of texture behavior, tentacle posture, and color cue. For happiness/excitement, the software actuates the goosebump syringe with faster repeated inflation and deflation, withdraws air from the spike channel so that the spikes remain retracted, moves the tentacles into the upward U-like posture, and sets the LED cue to yellow if the LED system is enabled. For anger, it actuates the spike syringe with rapid inflation and deflation while the goosebump channel remains unactuated, moves the tentacles inward into a compact posture, and sets the LED cue to red. For calmness, it actuates the goosebump syringe with slower rhythmic inflation and deflation, keeps the spike channel retracted, keeps the tentacles close to their neutral posture, and sets the LED cue to blue.

Position control and driver boards enable repeatable actuation.

Because the selected servos are position-controlled, the software can command defined angular positions so that the tentacles return to known configurations. This is important because the tentacle mechanism depends on tendon tension and should not require manual resetting after interruptions. The PCA9685 servo driver receives commands from the ESP32 through an I²C connection and generates the PWM signals for the six servos. The stepper mo-

tor drivers receive control signals from the ESP32 and drive the two NEMA-17 motors that move the syringe plungers. Detailed setup and operating instructions are provided in Appendix A.

Chapter 5

Evaluation

This chapter evaluates how the prototype designed in Chapter 3 and fabricated in Chapter 4 functions as an implemented affective shape-changing prototype. The evaluation is aligned with the three design requirements introduced in Section 3.1: affective expression, shape-changing variety, and suitability as an ambient object for domestic and entertainment-related contexts. It does not claim to validate atmospheric mood induction. Instead, it combines a reflection on implementation constraints with an exploratory qualitative study of first-contact interaction. Together, these perspectives examine whether the built object supports proximate tactile engagement and which aspects of the implementation would need to be refined before controlled evaluations of affect recognition or mood-related effects.

5.1 Prototype Constraints

The final prototype was sufficient to demonstrate the intended combination of pneumatically actuated surface texture, tendon-driven tentacle orientation, and optional color feedback. However, several implementation-related constraints influenced how convincingly these expressive layers could be experienced. These constraints are relevant be-

cause the prototype was designed as a soft ambient object positioned between entertainment and augmented-living contexts, rather than as a visibly technical device. They are therefore discussed not as isolated engineering issues, but as factors that shaped the object's believability, legibility, and affective quality.

Size, weight, and motor noise affected the ambient character.

Although the final dimensions were reduced following the paper-prototype interviews, the constructed object was still heavier and bulkier than intended. This was mainly caused by the silicone body, the MDF base, and the internal placement of the servo motors and electronics. At approximately 2.3 kg, the prototype could still be placed on a sofa and interacted with directly. However, it was less lightweight and less easy to handle than originally envisioned. This affected the pillow-like and ambient character of the object, as users could perceive it as bulkier and more technically constrained. In addition, the servo motors and pneumatic actuation system produced noticeable mechanical noise during movement. While this was acceptable for a demonstrator, the noise drew attention to the underlying mechanism and reduced the impression of calm, natural, or organic affective expression.

The missing breathing mechanism limited low-arousal expression.

Another constraint was the absence of the breathing mechanism described in Section 3.4. This mechanism was originally intended to add a slow, body-like volume change to the prototype. Its absence is important because the related work distinguishes volume change from texture change and orientation change as a separate type of shape-changing behavior. In the final implementation, calmness therefore had to rely on slow, low-frequency goosebump movement and optional blue light instead of a dedicated breathing-like volume transformation. Including this mechanism would likely have enhanced the low-arousal expression and strengthened the prototype's shape-changing variety.

External actuation and wired control reduced technical integration.

Finally, the prototype was not fully self-contained. The pneumatic syringe-drive unit was mounted outside the main body, the texture surface was connected through pneumatic tubes, and the implemented states were selected through serial commands from a connected laptop. The ac-

tuator systems also required separate wired power connections. While this architecture was suitable for prototyping, testing, and adjustment, it increased setup complexity and made the object feel less integrated than required for a domestic ambient scenario. A more compact power, actuation, and control architecture would better support more natural interaction in a living-room or entertainment setting.

5.2 Exploratory Study

After implementing the three affective states, an exploratory study was conducted to examine how participants initially perceived and interacted with the prototype. Rather than measuring affective outcomes or testing recognition of the individual states, the study focused on first impressions, natural interaction behavior, and perceived physical qualities. At this stage, the priority was to examine whether the prototype was approachable enough to support the intended body-proximate interaction. The study should therefore be understood as an early design evaluation that investigates whether the object invites tactile engagement and which qualities may affect later evaluations of its affective expressions.

5.2.1 Study Method

Participants

The study was conducted with eight participants aged between 25 and 32 years. Four participants were female and four were male. Six participants were university students and two were employed. All participants reported that they had no prior experience with shape-changing interfaces. Due to the small sample size and exploratory format, the participant group is not treated as representative of a broader population.

Eight participants took part in the exploratory study.

Apparatus and Setting

The study took place in a domestic sofa setting.

The study used the final prototype designed in Chapter 3 and fabricated in Chapter 4. The study was conducted in a home environment in order to approximate the intended domestic context of use. Participants sat on a sofa, and the prototype was initially placed on the sofa like a pillow. During the study, the prototype remained connected to the external components required for operation: the stepper-driven syringe unit for pneumatic texture actuation, the wired power supplies, the ESP32 controller, and a laptop used for state selection through the serial interface. These external components were placed on a side table next to the sofa, with pneumatic tubes and cables routed to the prototype. This setting was chosen because the prototype was designed as an ambient object that could be placed near the body during relaxed media consumption or everyday interaction.

Procedure

Participants freely explored the prototype and described their impressions.

The study followed a qualitative, semi-structured format. Participants were invited to engage with the prototype freely while it displayed the implemented affective states. They were given a brief general explanation of shape-changing interfaces, but were not told in advance which movements or affective states the prototype would display. They were also not asked to assign predefined emotion labels to the states. This choice kept the focus on spontaneous interpretation and avoided turning the session into a recognition test. This open-ended interaction was used to observe whether the object invited touching, holding, cuddling, lap placement, or more distant observation. During the interaction, participants were asked to verbalize their thoughts and impressions. The conversation was kept flexible so that participants could comment on aspects they noticed themselves, while still covering the main themes of first impression, tactile experience, and physical qualities.

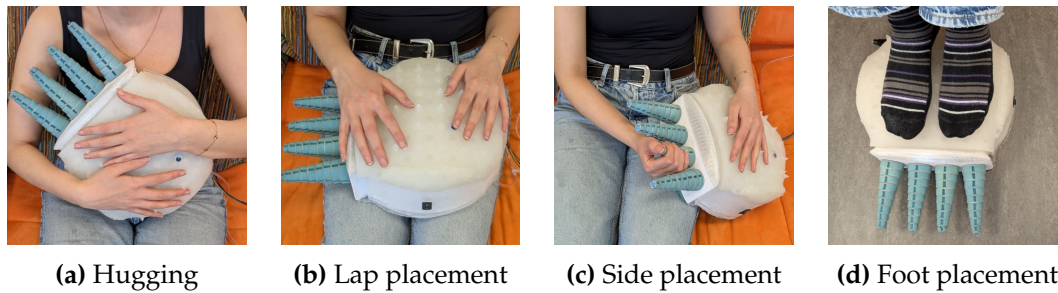


Figure 5.1: Illustrative reconstructions of observed interaction patterns during the exploratory study.

The study was guided by the following three questions:

- How did participants describe the prototype during initial contact?
- How did participants interact with it when no specific interaction technique was prescribed?
- Which positive and critical qualities did participants identify during direct interaction?

Data Collection and Analysis

The evaluation relied on qualitative observations and participants' verbal feedback during the sessions. Comments, observations, and handling behavior were grouped into recurring themes related to interaction behavior, initial impressions, physical qualities, and practical limitations. Because the study was designed as exploratory design feedback, the findings are reported as qualitative patterns rather than as statistical frequencies. Comments about affective meaning were treated as descriptive feedback rather than as evidence of recognition accuracy. The analysis focused on whether the prototype invited proximate tactile engagement and how its physical form, movement, and material qualities shaped participants' first impressions.

The analysis focused on recurring qualitative themes.

Because participants did not want to be photographed, the observed interaction patterns were recreated for documentation in Figure 5.1. These images should therefore be understood as illustrative reconstructions rather than as direct photographic records of the study sessions.

5.2.2 Study Findings

Interaction Behavior

Participants approached the prototype through close bodily contact.

During free exploration, participants interacted with the prototype in several body-proximate ways. The most common interaction pattern was to treat the prototype as a soft pillow-like object by hugging or cuddling it (see Figure 5.1a). Several participants placed it close to their body, for example on their lap or beside them on the sofa (see Figures 5.1b and 5.1c). These behaviors indicate that participants often approached the object through close bodily contact rather than distant observation. This supports the design goal of creating an affective ambient object that users accept as touchable and body-proximate. One unexpected interaction was observed when a participant placed the prototype under their feet and used it like a footrest (see Figure 5.1d). This behavior indicates that the object also invited forms of contact beyond the initially envisioned hand-based or lap-based interaction.

Initial Impressions

The form was approachable, but the interaction possibilities were not immediately clear.

Participants' first impressions included both positive and critical responses. Positive responses often centered on descriptions of the prototype as "cute", particularly because of the added eyes and the recognizable octopus-like appearance. The object was also described as "unique" and "creative", which suggests that participants perceived it as unfamiliar compared with everyday interactive objects. Participants responded differently to this unfamiliarity. For some, the different shape-changing elements contributed

to curiosity and playfulness, while others found the prototype unusual or initially confusing. This response is consistent with the design rationale in Section 3.3, where the abstract octopus-inspired form was chosen to make the object recognizable while still leaving room for expressive shape change.

A recurring observation was that participants were not immediately sure how they were expected to interact with the object. Some participants were also hesitant to touch the prototype while it was displaying the different affective states because they could not predict its movements. After a short familiarization period, participants appeared more comfortable touching and handling the prototype. This uncertainty is important because the prototype was intended as an ambient object that should invite intuitive contact. The result suggests that the physical form was approachable, but that the interaction possibilities were not yet sufficiently legible through the object's behavior, placement, or initial state.

Perceived Physical Qualities

Participants also commented on the prototype's weight, surface finish, and perceived robustness. Participants noted that the object felt somewhat heavy and that some edges appeared rough or unfinished. They responded positively to the soft silicone on the top surface, including the goosebump, spike, and smooth surface states. The changing textures, especially the spikes, repeatedly encouraged them to touch the object. Some participants indicated that they would have preferred the side walls to be made from the same soft silicone as the top surface or from a foam material.

Material quality shaped the perceived affective character.

These comments show that participants judged the prototype not only through its movement and appearance, but also through tactile comfort, weight distribution, material integration, and perceived robustness. The texture shape-changing surface therefore acted as an invitation to touch. This connects to the prototype constraints discussed in Sec-

tion 5.1: material and technical integration shaped how participants interpreted the object during interaction.

5.2.3 Discussion of Findings

Findings are interpreted against the design requirements.

The following discussion relates the findings to the three design requirements introduced in Section 3.1: affective expression, shape-changing variety, and suitability as an ambient object.

The prototype invited body-proximate interaction.

The exploratory study suggests that the prototype supported the intended direction of a domestic ambient object for close bodily interaction. Participants approached it through touch, holding, lap placement, and other body-proximate behaviors rather than only distant observation. This matters because the prototype's affective expression depends not only on being seen, but also on being felt near the body. The texture-changing surface was especially relevant in this respect, because the changing goosebumps and spikes encouraged tactile exploration.

Approachability and legibility are separate qualities.

At the same time, the findings show that approachability and interaction legibility are separate qualities. The object was often perceived as cute, unusual, and creative, but some participants were initially unsure how to interact with it or hesitated while it moved. If users are expected to touch, hold, or keep an affective object near the body, it should communicate not only an affective state, but also whether it is safe, responsive, passive, or waiting for interaction. Future iterations should therefore consider clearer behavior, more predictable movement transitions, and stronger tactile affordances that invite contact without requiring verbal explanation.

Material and technical constraints shaped the experience.

The evaluation further shows that affective credibility depends on the material and technical implementation. The soft silicone surface supported tactile engagement, while weight, finish, motor noise, and external hardware made the object feel less integrated than the intended soft ambient artifact. For a body-proximate object, these qualities are

part of the affective experience rather than merely fabrication details.

Overall, the evaluation supports the prototype as a plausible foundation for future affective studies. It shows that the object can invite tactile engagement and curiosity, while also identifying the material, behavioral, and technical refinements needed before controlled affective evaluation.

The evaluation supports a design argument, not proof of mood induction.

5.3 Revisiting the Research Questions

The research questions are addressed throughout the thesis through related work, prototype design, implementation, and evaluation. This section relates the evaluation findings back to the broader thesis argument.

The research questions are discussed as a thesis-level synthesis.

For *Q1*, the thesis does not identify fixed one-to-one mappings between individual physical features and emotions. The related work instead supports a cue-family approach, in which affective interpretation emerges from combinations of form, movement, texture, stiffness, color, and interaction context [Hu and Hoffman, 2019; Lin et al., 2021; Rasmussen et al., 2012; Steer et al., 2024; Strohmeier et al., 2016]. Within this approach, curvature, softness, angularity, texture, and stiffness mainly shape valence-related impressions. Speed, rhythm, frequency, amplitude, and intensity support arousal-related expression [Hu and Hoffman, 2019; Liu et al., 2024; Russell, 1980; Strohmeier et al., 2016]. Color remains a secondary cue that can reinforce, but not replace, the physical expression of the object [Lin et al., 2021; Meliksetyan, 2025; Steer et al., 2024].

Q1: Which affective characteristics are associated with shape, motion, texture, and color?

For *Q2*, these cue families were translated into three coordinated prototype states rather than isolated output effects. The value of this translation lies in combining texture change, tentacle posture, movement dynamics, and optional color feedback within the same object. The calmness state remained less complete in this translation because the planned breathing-like volume change could not be implemented. As a result, low-arousal expression relied mainly on slow goosebump texture movement and color.

Q2: How can these characteristics become coordinated shape-changing behaviors?

The implemented states provide a defensible design translation, but not yet a fully balanced expressive repertoire across valence and arousal.

Q3: How can multiple mechanisms be integrated into one ambient prototype?

For Q3, the prototype demonstrates integration within one ambient artifact. The final design combines pneumatic texture change, tendon-driven tentacle orientation, and optional LED feedback. It therefore combines texture change and orientation change, two transformation types described in shape-change taxonomies [Rasmussen et al., 2012]. The omitted breathing mechanism would have added volume change as a further expressive layer. The pneumatic silicone surface and tendon-driven tentacle motion also build on soft-robotic approaches for texture modulation and flexible arm movement [Hu et al., 2018; Wu et al., 2020, 2022]. The evaluation supports this integration at the interaction level: participants approached the object through close bodily contact and explored the changing surface by touch.

Taken together, the thesis answers the research questions as a design and implementation contribution. It shows how affective cue associations can be selected, translated into coordinated shape-changing behavior, and implemented in a multi-mechanism ambient object.

5.4 Limitations

This section discusses limitations concerning both the implemented prototype and the exploratory study design.

Implementation constraints may have affected interpretation.

First, the study cannot fully separate participants' responses to the intended design concept from their responses to the current prototype implementation. For example, comments about approachability, comfort, or affective quality may have been influenced by the prototype's weight, mechanical noise, visible cables, rough finish, setup complexity, and external hardware. This is especially relevant for a body-proximate ambient object, where integration, quietness, softness, and comfort are part of the affective experience being evaluated.

The prototype did not operate autonomously in response to an external system or context. The implemented states were triggered through direct commands rather than being connected to entertainment media, notification systems, ambient sensing, or another source that would determine when a state should be displayed. As a result, the thesis evaluates the prototype as a demonstrator of affective shape change, but not as a fully contextual ambient object that responds autonomously during everyday use. It therefore remains unclear how the affective states would be selected, timed, and interpreted when embedded in a real domestic or entertainment-related system.

The prototype was evaluated as a manually triggered demonstrator.

The evaluation was exploratory and qualitative. The study involved a small, non-representative participant group and focused on first impressions, interaction behavior, and perceived physical qualities. The findings therefore provide design-oriented insights, but they do not allow statistical generalization to a broader population. Because no formal coding scheme or inter-rater analysis was used, the themes should also be read as formative design observations rather than as validated categories.

The small qualitative sample limits generalization.

Finally, the study did not test whether users could reliably recognize the intended affective states or whether interaction with the prototype influenced users' mood. The affective interpretation and mood-related effects of the implemented states therefore remain open for future controlled studies.

Affective recognition and mood effects were not tested.

Chapter 6

Summary and Future Work

This chapter concludes the thesis by summarizing the main contributions and outlining directions for future work.

6.1 Summary and Contributions

This thesis investigated how shape-changing interfaces can be designed as physically present ambient stimuli for affective expression and as a basis for later studies on atmospheric mood induction. It addressed the gap between prior work on affective associations with individual shape-changing cues and the open question of how multiple cues can be combined in one coherent physical interface.

Shape-changing interfaces as ambient affective stimuli.

To develop a design rationale, the thesis synthesized findings from shape-changing interfaces, soft robotics, mood induction, affective expression, and crossmodal associations between shape, touch, movement, and color. The synthesis showed that geometry, angularity, curvature, texture, and stiffness are especially relevant for valence-related expression, while speed, rhythm, frequency, and intensity primarily support arousal-related expression. Color was

Design rationale from affective and crossmodal associations.

treated as a secondary cue that can reinforce, but not replace, physical shape-changing behavior.

Affective cues
translated into
prototype states.

These insights were translated into three prototype states: happiness/excitement, anger, and calmness. Each state combined texture change, tentacle posture, movement dynamics, and optional color feedback to express different affective qualities. The mappings were implemented in an abstract octopus-inspired ambient prototype combining a pneumatically actuated silicone texture surface, tendon-driven tentacle movement, and optional LED-based color feedback.

First-contact interaction
and prototype
limitations.

An exploratory evaluation showed that participants often interacted with the object through close bodily contact, such as holding, hugging, or placing it on the lap, supporting its intended body-proximate ambient character. At the same time, weight, motor noise, visible cables, wired control, and external pneumatic actuation limited comfort, integration, and legibility.

Contributions and
scope of the thesis.

Overall, the thesis contributes a literature-based affective design rationale, a concrete mapping from affective cues to shape-changing behavior, an implemented multi-mechanism prototype, and early qualitative insights into first-contact interaction.

6.2 Future Work

A lighter, more
expressive, and
self-contained
prototype.

Future work should first address the technical and material limitations of the current prototype. The breathing-like volume change originally planned for the calmness state should be revisited, as prior work suggests that slow volume changes could support the perception of calmness. The weight of the object should also be reduced, for example by reconsidering the silicone side walls and exploring lighter foam-based structures. In addition, a more integrated power and control architecture would make the prototype easier to set up and allow it to be experienced as a self-contained ambient object.

Beyond improving the current prototype, future work could further extend the affective design space. The current prototype focuses on three states that cover different combinations of valence and arousal, but additional affective states could be explored. These states could be derived from prior research in the same way as the current mappings, by identifying associations between affective qualities and specific shape, movement, texture, and color characteristics. Alternatively, future work could take a more exploratory approach by testing different combinations of physical transformations and studying how users interpret them.

Extending the affective design space.

A further implementation direction would be to connect the prototype more directly to the contexts in which it is intended to operate. For example, the software could be extended so that the prototype responds automatically to entertainment media, such as film scenes or music. It could also be integrated with notification systems or ambient sensing systems, allowing it to react to everyday events and influence the atmosphere of a space without requiring manual state selection. These extensions would make it possible to investigate the prototype not only as a demonstrator of affective shape change, but also as an interactive ambient object embedded in domestic or entertainment-related settings.

Implementing context-aware behavior.

Finally, future work should include controlled user studies that examine affect recognition and mood induction. The exploratory study in this thesis examined first impressions and interaction behavior, but it did not test whether users recognized the intended affective states or whether the prototype influenced their mood. Such a study would make it possible to determine whether the implemented shape-changing prototype communicates the intended affective states reliably, and whether it can contribute to atmospheric mood induction in its intended contexts of use.

Evaluating affect recognition and mood induction.

Appendix A

Prototype Setup and Operation

This appendix provides practical operating instructions for the prototype. It documents the components required for operation, the upload procedure for the control software, the startup sequence, the available serial commands, and the shutdown procedure.

A.1 Required Components

The following components are required to operate the prototype:

- Laptop with Visual Studio Code and the PlatformIO extension.
- The ESP32 development board and USB cable.
- Prototype repository containing the control software in `src/main.cpp`.
- External 5 V power supply for the PCA9685 servo driver board, with a current limit of 2 A.
- External 12.5 V power supply for the stepper motor drivers, with a current limit of 1 A.

A.2 Setup and Operation

A.2.1 Preparing and Uploading the Control Software

To prepare the prototype and upload the control software, proceed as follows:

1. Open Visual Studio Code and clone the prototype repository, if it is not already available locally.
2. Install the PlatformIO extension for Visual Studio Code.
3. Ensure that the `src` folder contains only the intended `main.cpp` file with the prototype control code.
4. Connect the ESP32 to the laptop via a USB cable. This connection is required to upload the code and use the serial monitor.
5. In PlatformIO, run *Build* and verify that the project compiles without errors.
6. If the build succeeds, run *Upload*.
7. During upload, monitor the terminal output. When prompted, press and hold the *BOOT* button on the ESP32 until the upload starts.
8. Open the PlatformIO serial monitor, select the correct serial port, and start monitoring. Press the *RESET* button on the ESP32 once to restart the program after upload.
9. Connect the PCA9685 board to *GND* and *V+* using the external 5 V power supply with a current limit of 2 A.
10. Connect the stepper motor drivers to the 12.5 V power supply with a current limit of 1 A, in the following order: *GND*, then *V+*.

A.2.2 Operating the Prototype

After the setup is complete, the prototype can be controlled through the serial monitor. Enter one of the following abbreviations and confirm the input:

- E: happiness/excitement.
- A: anger.
- C: calmness.
- S: stop the current working state.

A.2.3 Troubleshooting

If the upload fails, repeat the upload process and hold the *BOOT* button on the ESP32 when PlatformIO starts connecting to the board. If no serial output is shown, verify that the correct serial port and baud rate are selected in the PlatformIO serial monitor, then press the *RESET* button on the ESP32. If the servos or stepper motors do not move after a valid command, check the external power supplies and confirm that the ground connections are shared with the ESP32.

A.2.4 Disconnecting the Prototype

To disconnect the prototype, shut the system down in the following order:

1. Disconnect *V+* from the stepper motor drivers.
2. Disconnect the external power supply from the PCA9685 servo driver board.
3. Disconnect the USB cable from the laptop.

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Index

actuator mounting	57–60
affective expression	15–23
affective state mappings	37
affective states	25
anger	37
bouba/kiki effect	19
breathing mechanism	53
cable-driven actuation	13
calmness	37
circumplex model	14
crossmodal correspondences	18
design criteria	26–28
electronics	54–60
evaluation	63–73
exploratory interviews	31
fabrication	41–61
final prototype design	33–39
future work	76–77
happiness/excitement	37
mood induction	13
octopus-inspired form	29

paper prototype	30
physical construction	41–53
pneumatic actuation	11
prototype design	25–39
related work	7–23
SCIs	<i>see</i> shape-changing interfaces
shape-change mechanisms	34
shape-changing interfaces	7–11
soft robotics	11–13
software	60–61
summary and contributions	75–76
syringe-based pneumatic system	54
tendon actuation	55
tentacle fabrication	50–52
tentacle orientation	34
texture change	34
texture surface fabrication	44–50
types of shape change	8

