TU WIEN Informatics

Design and Evaluation of a Novel Shape Changing Haptic Device for Virtual Reality

DIPLOMARBEIT

zur Erlangung des akademischen Grades

Diplom-Ingenieur

im Rahmen des Studiums

Media and Human-Centered Computing

eingereicht von

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Wien, 7. Dezember 2023

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DIPLOMA THESIS

submitted in partial fulfillment of the requirements for the degree of

Diplom-Ingenieur

in

Media and Human-Centered Computing

by

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to the Faculty of Informatics

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Vienna, 7th December, 2023

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Danksagung

Ich danke besonders Khrystyna Vasylevska und Hugo Brument für ihre Ratschläge, Ideen und hilfreichen Kommentare in unzähligen Meetings. Mein Dank gilt auch Hannes Kaufmann, den Teilnehmer*innen der User Studies, sowie allen Unterstützer*innen dieses Projekts.

Acknowledgements

I especially thank Khrystyna Vasylevska and Hugo Brument for their advice, ideas, and helpful comments in countless meetings. I also want to thank Hannes Kaufmann, all the participants of the user studies, as well as everyone else supporting this project.

Kurzfassung

Virtual Reality (VR) ist eine immersive, multisensorische Umgebung. In den letzten Jahrzehnten kam es zu deutlichen Verbesserungen der visuellen und auditiven Feedbacks in VR. Doch trotz des großen Potenzials wird der Tastsinn in den heutigen VR-Systemen nicht zufriedenstellend bedient. Daher entwickelt diese Arbeit das neuartige formwandelnde haptische Gerät Shiftly, das plausibles haptisches Feedback bei der Berührung von virtuellen Objekten in VR ermöglicht. Durch Veränderung der Form nähert sich Shiftly der Geometrie eines von einer Person berührten virtuellen Objekts an und erzeugt haptisches Feedback für die Hand. Das Gerät verwendet gebogenes Origami, das programmatisch gefaltet und entfaltet werden kann, um eine formverändernde Berührungsoberfläche von flach bis gekrümmt zu erzeugen. In dieser Arbeit wird das Design von Shiftly entwickelt, ein vollständig funktionsfähiger Prototyp erstellt, eine VR-Anwendung implementiert und Shiftly in zwei Studien evaluiert. Shiftly kann realistisches haptisches Feedback für flache Oberflächen, konvexe Formen unterschiedlicher Krümmung, Kanten und bis zu einem gewissen Grad auch für konkave Oberflächen und Objekte mit kleinen Details erzeugen. Das Gerät erreicht dies mit nur drei Aktoren – eine deutlich geringere Anzahl als der vergleichbare Stand der Technik.

Abstract

Virtual Reality (VR) is an immersive multisensory experience. Visual and auditory feedback in VR has improved significantly in the last decades. However, despite its great potential, the sense of touch is not satisfactorily served in today's virtual reality systems. Therefore, this thesis develops a novel shape-shifting haptic device named Shiftly, which renders plausible haptic feedback when touching virtual objects in VR. By changing its shape, Shiftly approximates the geometry of a virtual object touched by the user and provides haptic feedback for the hand. The device uses curved origami that is programmatically folded and unfolded to create a shape-changing touch surface that can be transformed from flat to curved. In this thesis, the design of Shiftly is described, a fully functional prototype is fabricated, a VR application is implemented, and Shiftly is evaluated in two user studies. Shiftly can render realistic haptic feedback for flat surfaces, convex shapes of different curvatures, shapes with edges, and, to some extent, concave surfaces and objects with small details. The device achieves this using only three actuators – a considerably smaller number than the comparable state-of-the-art.

Contents

CHAPTER 1

Introduction

Virtual Reality (VR) is a medium where users can experience multisensory immersion and interactions with a virtual environment. VR is not limited to visual and auditory channels to create a feeling of presence in the virtual environment. VR interfaces can also provide additional tactile-, force-, heat- and smell-feedback. [Sla09] Beyond visual and audio feedback often provided via *Head Mounted Disyplays* (HMDs) and headphones in VR systems, the sense of touch can play an important role when interacting with virtual environments — just as the sense of touch is of great importance when perceiving one's surroundings, manipulating objects, or sensing the texture and weight of an object in the physical world.

Many off-the-shelf VR systems include simple vibration feedback integrated into handheld controllers. But, haptic feedback in a virtual environment is not limited to abstract vibrational feedback, nor should the feedback only be provided to small portions of the user's hand when interacting with virtual objects. Instead, several different haptic exploratory processes of a virtual environment are conceivable, for example, hand contact, lateral hand movement, applying pressure, or grabbing and enclosing a virtual object [MML21].

In a VR system with realistic haptic feedback, users would be able to feel any object they touch and interact with [Sla09]. For example, in such a system, the user would get the impression of the surface geometry of a physical ball when grabbing and picking up a virtual one. The weight of the ball and, therefore, the required muscle activation of the user would be present. One would be able to feel the stiffness of the material the ball is made of when compressing it, and the fine details of the surface structure of the virtual ball would be perceivable by a user. When pushing against a virtual wall or another large virtual object, the user would experience a force and restriction of hand and arm movement, prohibiting the user from reaching through that wall and enabling the user to interact with a virtual environment naturally.

The visual sense often plays a more dominant role when perceiving the world around oneself, but there are also scenarios where haptics dominate the visual perception [CK19]. Studies showed that appropriate haptic feedback can increase the task performance [KHF+19, VdMS09, CMJ10] and presence [KHF+19, BGFOH18] compared to VR systems that rely exclusively on visual and auditory channels. Haptic feedback has great potential but has a rather limited implementation in most VR systems [ZK19, DYS+19, KMW19], especially compared to the development of the visual feedback. Many approaches have been developed to give users haptic feedback, but all have significant limitations, as outlined in Chapter 2. Many devices are limited in the haptic feedback they can produce when touching and interacting with differently shaped objects. They often fail to provide adequate haptic feedback when touching continuous curved geometries or shapes with edges. The mechanical complexity and the amount of electronic actuators many approaches require lead to high manufacturing costs and a high weight. Previously developed approaches, like traditional pin displays, are bulky and heavy devices with limited use cases due to their size, weight, costs, and variety of feedback they can produce.

The aim of this thesis is to investigate alternative approaches to creating haptic feedback in VR with a shape-changing haptic device. In particular, the thesis answers the research question: "*How can haptic feedback be provided to a user touching objects with various geometries in VR?*" and further, "*What are the capabilities and limitations of our chosen approach?*"

To answer these questions, a novel haptic device for interacting with objects in a VR environment is proposed and evaluated. We named this shape-changing haptic device *Shiftly*. It uses multiple curved origami that can be manipulated to create haptic feedback. By automatically adapting the shape of Shiftly, haptic feedback can be provided when one touches various surface geometries, ranging from convex curved surfaces of different curvatures to flat surfaces and edge features. Shiftly approximates the portion of the virtual object one touches, providing a continuous or partially continuous touch surface by deforming one or multiple curved origami structures, creating realistic haptic feedback. Shiftly focuses on providing haptic feedback to simulate the surface geometry of objects larger than hands. We fabricated multiple prototypes and conducted two user studies to evaluate Shiftly.

1.1 Contribution

This thesis's main contributions to the state of the art are listed below.

- In this thesis, the novel haptic device Shiftly is presented. It can create a variety of haptic feedback by manipulating curved origami requiring only three actuators.
- Design principles of a haptic device like Shiftly that creates the stimulus by emulating geometric properties of virtual objects that are touched, haptically explored, and grabbed are formulated.

- A kinematic model for Shiftly is outlined.
- The mechanics of how Shiftly can be integrated into a virtual environment are outlined.
- A VR application is proposed and implemented that uses Shiftly to create rich haptic feedback when touching and grabbing shapes with various surface geometries.
- A functional prototype of the Shiftly design is fabricated. The prototype can change shape via wireless or wired communication using the developed VR application.
- Shiftly is evaluated in two user studies with 161 participants combined. The first user study tests the plausibility of the haptic feedback created by Shiftly when users touch a virtual object. The second study evaluates the range of haptic feedback Shiftly can create.

1.2 Structure of this Thesis

First, Chapter 2 outlines relevant literature. This chapter first gives a general overview of haptic feedback in VR environments, how this feedback can be created, and what types of device categories have been proposed in previous works. Additionally, a short overview of encounter-type haptic devices is provided. It is followed by a detailed overview and analysis of haptic devices that create the stimulus by changing its physical shape. This overview includes various types of shape displays ranging from traditional pin displays to swarm robotic shape displays. Shiftly, the haptic device developed in this thesis, utilizes curved origami structures. Hence, a comprehensive overview of previously developed haptic devices that use an origami structure or are origami-inspired is given. Finally, an overview of origami robots and their actuators is given.

Chapter 3 describes the design and methodology of Shiftly. First, an overview of the design principles is given, followed by a description of prototypes and design ideas in the early design phase. In Section 3.3, a detailed explanation of the design of Shiftly is given, including the frame, the origami structure, and the electronic components. In this chapter, a kinematic model is outlined to compute the positions of the points on Shiftly that one is touching, and the range of the different surfaces the developed haptic device can produce is shown. Chapter 4 describes how Shiftly is integrated into a VR environment, and Chapter 5 explains how the physical prototype of Shiftly is fabricated and the software components are implemented.

Chapter 6 outlines the two user studies conducted to evaluate Shiftly and summarizes the results of those studies. In Chapter 7, the results of those studies are critically discussed, Shiftly is compared to previously developed haptic devices and the limitations of Shiftly are outlined. At the end of this thesis in Chapter 8, the findings of this thesis are summarized, and potential future work is proposed.

CHAPTER 2

State of the art

In this chapter, an overview of previous work that is relevant to this thesis is given. This thesis develops the novel shape-changing haptic device Shiftly intended for VR that follows a haptics-on-demand approach. Hence, in Section 2.1, a general overview of haptics in VR is given followed by an overview of encounter haptic devices and different methods to place a haptic device in space (Section 2.2). A more detailed analysis of previously developed haptic devices that create the haptic stimuli by changing their physical shape is given in Section 2.3, including an overview of shape displays and origami-inspired devices. Followed by a summary of different actuator approaches for programmatically folding and unfolding origami and origami-inspired structures. This summary is given in Section 2.4. It includes examples of mechanisms that utilize smart materials and motorized approaches and describes examples of soft and origami robots.

2.1 Haptics in Virtual Reality

Different types of haptic feedback can be created in VR, including tactile, kinesthetic, and thermal feedback. Tactile feedback is created by mechanoreceptors attached to the outer layer of the skin [TCLA20]. For example, small vibrations are tactile feedback. Kinesthetic feedback is sensed by receptors (in one's muscles, tendons, and joints) and can be stimulated by force-feedback devices that apply pressure on the user's body. For example, by resisting the force applied to the device be the user's hand when grabbing or touching the device. Thermal feedback reverses the perception of heat. This thesis focuses on kinesthetic feedback, proving the experience of touching objects with different geometries. Therefore, thermal feedback and tactile feedback are not discussed in detail.

There are different types of haptic feedback; hence, different types of haptic solutions and approaches have been developed. Some are bulky, grounded haptic devices with linkages and electronic motors that apply kinesthetic feedback by restricting the user's hand movement and can apply forces and torques to the user's hand. One example is the commercially available Phantom devices by 3D Systems Inc. [Inc23a]. In contrast to bulky devices with complex linkages, small vibrational motors are integrated into many off-the-shelf VR systems and smartphones. But these vibrational actuators can only poorly simulate friction or different textures [DYS+19], and vibration devices can render limited kinesthetic haptic feedback. For example, it can not simulate the restriction of hand movement when pushing virtual objects with one's hand. Vibrational feedback can also affect the user's haptic perception and lead to desensitization [HBR02].

The friction one experiences when touching a surface can be simulated by high-frequency vibrations that create an air film between the user's hand and a physical surface [DYS+19]. Further haptic feedback can be created by focused ultrasound created by a 2D array of ultrasound transducers [MOM+19, LSCS14, FAW+17]. These displays do not require a physical touch between the display and the skin of the user's hand. Instead, through ultrasound, pressure is applied to the user's hand, which is placed above the transducer's array. These devices cannot restrict the user's fingers and hand movements when touching an object in the same way as a physical shape display can. Shape displays are haptic devices that change their physical shape to emulate a virtual structure. These shape-changing devices and origami-inspired haptic devices are outlined in Subsection 2.3.1 and 2.3.2, respectively.

Several approaches have been developed for haptic devices worn and in constant contact with one's body. Among them is the widely investigated concept of haptic gloves. These devices often provide vibrotactile feedback on the user's hand and the ability to sense the user's finger movement and contact with physical surfaces [OD22]. Various haptic activators, often placed on the fingers of the glove, include vibration motors, electrotactile activators, electromagnetic activators, and thermoelectric devices [OD22]. Further approaches have been developed to restrict the user's finger movement by exoskeletons with complex kinematics. Often, the exoskeletons are connected to the user's fingers, limiting the motion of the fingers when interacting with virtual objects [ARK22]. Haptic gloves face, among other challenges, that the devices have to be adapted based on one's body and handsize [ARK22]. Users have to wear gloves to perceive haptic feedback, which can be uncomfortable in warmer environments. The devices could be challenging to clean, and additional weight is placed on the user's hand which could affect the user's haptic experience.

The illusion of haptic feedback (pseudo-haptic feedback) can also be created by visual or auditory rendering. Different senses interact with each other and influence the overall perception of a scenario. The leak of one sensory perception can be compensated by another one; for example, the lack of haptic feedback can be partially compensated by visual rendering [CK19], or haptic stimuli can be enhanced by visual ques [UB21]. Multiple approaches have been developed to create the illusion of haptic feedback visually, among them the displacement of hands and the altering of one hand's skin color [UB21].

2.2 Encountered-Type Haptic Displays

Many approaches require that the haptic device is in constant contact with the user, for example, wearable haptic devices [MBT15, HVSH18, FZDH20], or actuators integrated into a hand-held controller. Hence, one constantly feels the device. In contrast, *Encountered-Type Haptic Displays* (ETHD) exclusively provide haptic feedback when a contact in the virtual environment appears [MML21]. In an ETHD system, there is either a passive registered object in the physical environment of the user or a robot places a part of itself, for example, an attached shape display, to the place where the haptic encounter happens. Shiftly is an ETHD intended to be mounted on a robotic arm in future work. If the user wears an HMD, the user's view is blocked by the headset, and the presence of the robotic actuator is hidden from the user.

Various approaches have been developed that position a haptic display in space to generate haptic feedback when touching a virtual object using robotic arms or mobile platforms. Robotic arms mounted on a stationary platform are used by a large number of approaches [YHK96, VGK17, KLA+20, MML20, KKOK20]. Huang et al. [HNW+20] developed a system that can move haptic props around a stationary standing user, and Yamaguchi et al. [YSNK18] developed a system that moves haptic props along a single axis. Alternative mobile robotic platforms that can move around in space have been developed [GAF20, IYFN05, FI18]. Among them is the work of Siu et al. [SGY+18] with a pin display mounted on a small omnidirectional robot. The work of Mortezapoor et al. [MVVK23] combines a robotic arm mounted on an omnidirectional robot. Further, approaches have been developed to move a haptic device around to the desired touch location using drones [YKK+16, YJI+22, HKK+18].

2.3 Shape-changing Haptic Devices

This section outlines previous approaches and methods to create haptic feedback using shape-changing devices designed for immersive environments. First, in Subsection 2.3.1, an overview of different shape displays is given. In Subsection 2.3.2, different methods and devices are outlined that use an origami structure or are origami-inspired to create haptic feedback on the user's hands.

2.3.1 Shape Displays

Shape displays try to approximate the shape of a target surface to create haptic feedback for the user's body, specifically the user's hands. Typically, these haptic devices utilize an array of linear actuators that can change their height to form the target surface together. Often, the shape displays offer haptic feedback for the whole hand and naturally restrict users' fingers and hand movement with the surface contact.

In an early work, Hirota and Hirose [HH95] presented a haptic device for the users' fingertips, utilizing 16 pins that are controlled by servo motors. To create a touch surface rather than individual pins, they used a soft form over the top of the pins to interpolate

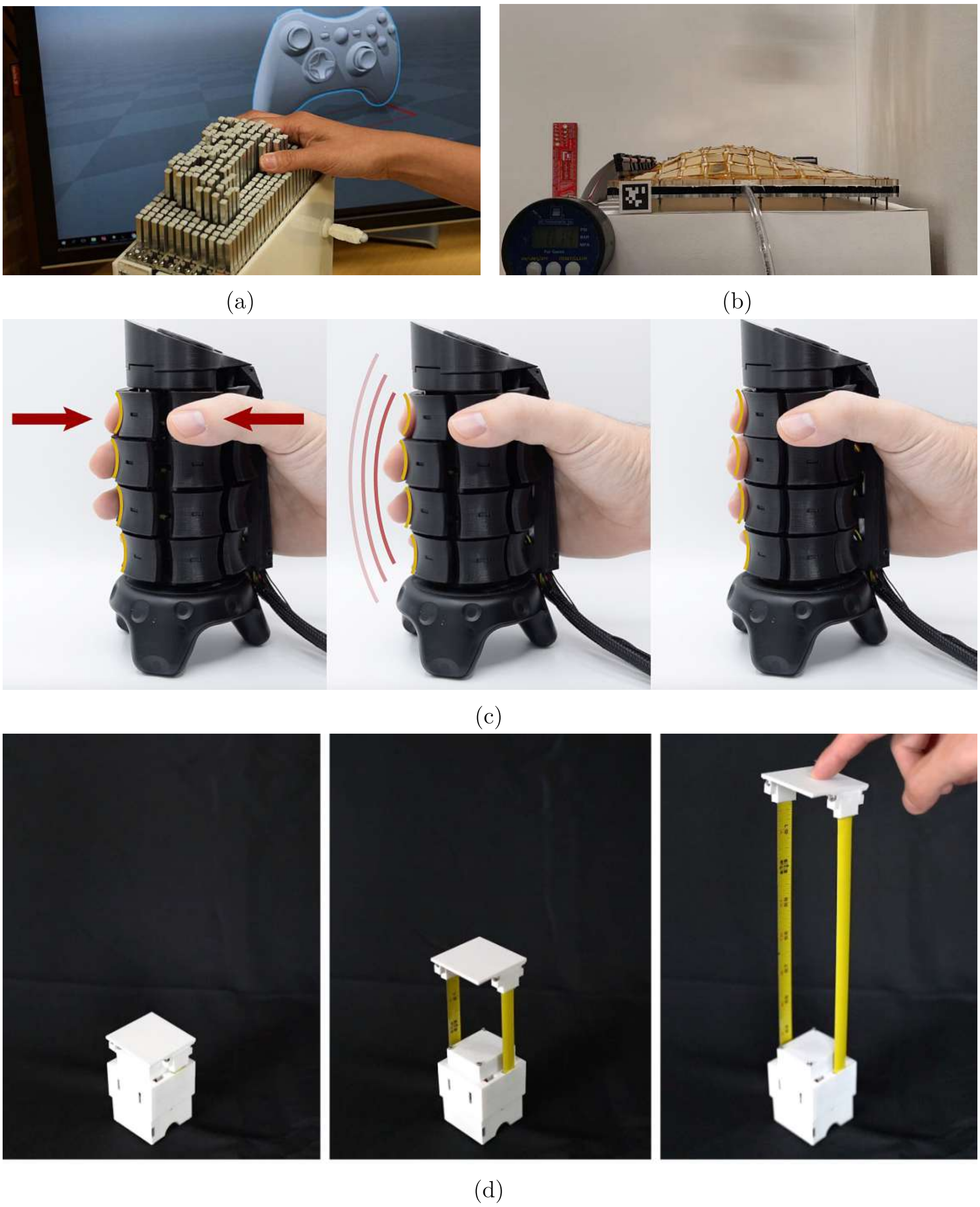


Figure 2.1: (a) Showing a pin display by Siu et al. [SGY+18]; (b) Shape display with an electroadhesive auxetic skin by Rauf et al. [RBF23]; (c) Cylindrical shape display by Gonzalez et al. [GOGFS21]; (d) Swarm robots by Suzuki et al. [SOS+21]

the heights. Similarly, Steed et al. [SOSGF21] developed a device utilizing nine linear actuators with an interpolation surface constructed of layers of acrylic and silicone rubber. While their device can simulate convex, flat, and concave surfaces for the whole hand of the user, it can only approximate continuous surfaces and cannot approximate edges. The touch surface is large enough for the whole user's hand, and they tested the device with a virtual reality application with an HMD and hand tracking. According to their study, users were able to detect small differences in curvature, but they have not studied the relationship between haptic and visual feedback.

To enable haptic feedback for a greater surface without increasing the size of the shape display, Siu et al. [SGY+18] presented a movable shape display. The shape display can be mounted on a unidirectional robot to move it around. By manipulating the position and rotation of the shape display, the pins adapt to the corresponding shape and position in the virtual world. Further, the shape display presented by Johnsen et al. [JNS+23] includes the ability to sense forces and touches applied to the top of the display.

Cylindrical shape displays are presented by Gonzalez et al. [GOGFS21] and Daniel et al. [DRC19]. The device developed by Gonzalez et al. is strapped onto the hand and consists of five rings that can change the diameter independently. Depending on the shape of the virtual object that the user aims to grab, the rings adapt their diameter accordingly. For example, if a narrower object is at the bottom, the bottom rings will contract, and the top rings will expand their diameter. Each ring consists of five discrete segments, so if the diameter of the ring is extended, a gap between the segments is created that can be felt by the user's hand. The cylindrical shape display is shown in Figure 2.1c

An alternative way to a single large-shaped display is the concept of swarm user interfaces. In such a system, multiple small robots are rearranged to create different shapes. Suzuki et al. [SZK+19] presented small shape-changing robots that can extend vertically or horizontally, and each robot can move independently on a flat surface. This concept was extended to small robots with a height-changing and tiltable platform [SOS+21]. By manipulating the robot's position and the platform while users touch the device with their fingertips, they simulate the touching of continuous surfaces. An image of the swarm robots is shown in Figure 2.1d.

Instead of increasing the number of actuators, several shape displays have been developed to create different surfaces with a limited number of actuators. Rauf et al. [RBF23] presented a skin consisting of tiles that can change the stiffness for individual regions programmatically. Combined with an inflatable pouch, they could transform this skin into a variety of convex curved surfaces. An image is shown in Figure 2.1b. Everitt and Alexander [EA19] developed an approach where surfaces are approximated by 3D printer interlocking tiles. The initially flat net of tiles is deformed, contracting the net in one direction or lifting one edge upwards. Kovacs et al. [KOGF+20] presented a single actuator wrist-mounted haptic device for grasping objects, and Yang et al. [YSFA+23] presented a pneumatic-activated wearable shape display. While not designed for haptic feedback, Tahouni et al. [TCW+20] presented a shape display utilizing shape memory alloy to create curved surfaces.

In general, the limitation of classic pin displays is that the complexity of shapes and surfaces that can be produced and, therefore, experienced by the users' haptic sense is limited by the number of motorized pins [SOSGF21]. Further, they are typically large, heavy, and costly to manufacture [SGY+18]. For example, the movable shape display presented by Siu et al. [SGY+18] consists of 288 actuators. Recently, approaches have been developed to overcome these limitations by creating rich haptic feedback without increasing the number of actuators. Shape displays have the potential to offer a natural way of providing kinesthetic haptic feedback. The user does not have to wear a (potentially disturbing) device, and Shape displays can restrict the user's body movements by resisting the force applied by the user's body to the device.

2.3.2 Origami Inspired Haptic Devices

Origami is a form of transforming a flat piece of paper into different shapes. Theoretically, one piece of flat paper can be folded into every possible polyhedron [DT17]. This art form inspired the development of multiple haptic devices that apply pressure on the user's hand or transform its shape.

Salerno et al. [SMC+18] developed a light and low-cost motorized origami platform mounted on a VR controller. The user's thumb can press the small platform capable of rendering different levels of stiffness and applying force to the user's thumb. According to them, it makes the interaction with virtual objects more realistic. The device is shown in Figure 2.2a. Williams et al. [WSCO22] and Giraud et al. [GJP21] (see Figure 2.2b) use a similar origami mechanism that is mounted on the fingertip. The approach by Williams has four individually controllable legs and can create complex haptic feedback to the users' fingers. Winston et al. [WZCO] presented a pneumatic-activated origami structure that creates haptic feedback on a fingertip. The structure is shown in Figure 2.2d. An interlocking tube origami structure has been used to simulate different material stiffness for whole hand interactions [VBB+23]. Origami patterns could also be used as interpolation surfaces. For example, by utilizing the flexible Sogame-ori crease pattern as presented in the work of Ohira et al. [OEOT22], and is shown in Figure 2.2c.

McClelland et al. [MTG17] presented an origami-inspired passive haptic device consisting of four rectangular panels connected by hinges. The user can control virtual objects by manipulating the creases and providing direct haptic feedback. The position and rotation of the device are tracked, as well as the angle of the creases. Chang et al. [CTN+20] use kirigami patterns to create physical buttons with different haptic properties. Castro et al. [MCBWK22] created a haptic feedback system that uses pneumatic activators to transform textile fabric, and Lücker et al. [LHLG23] presented a textile origami structure activated by a smart material and elastic springs intended for haptic feedback.

The shape transformation of origami has been shown to have the potential for haptic feedback. So far, origami structures have been primarily used for feedback applied to the user's fingertips or a portion of the user's hands. To our knowledge, no origami-inspired

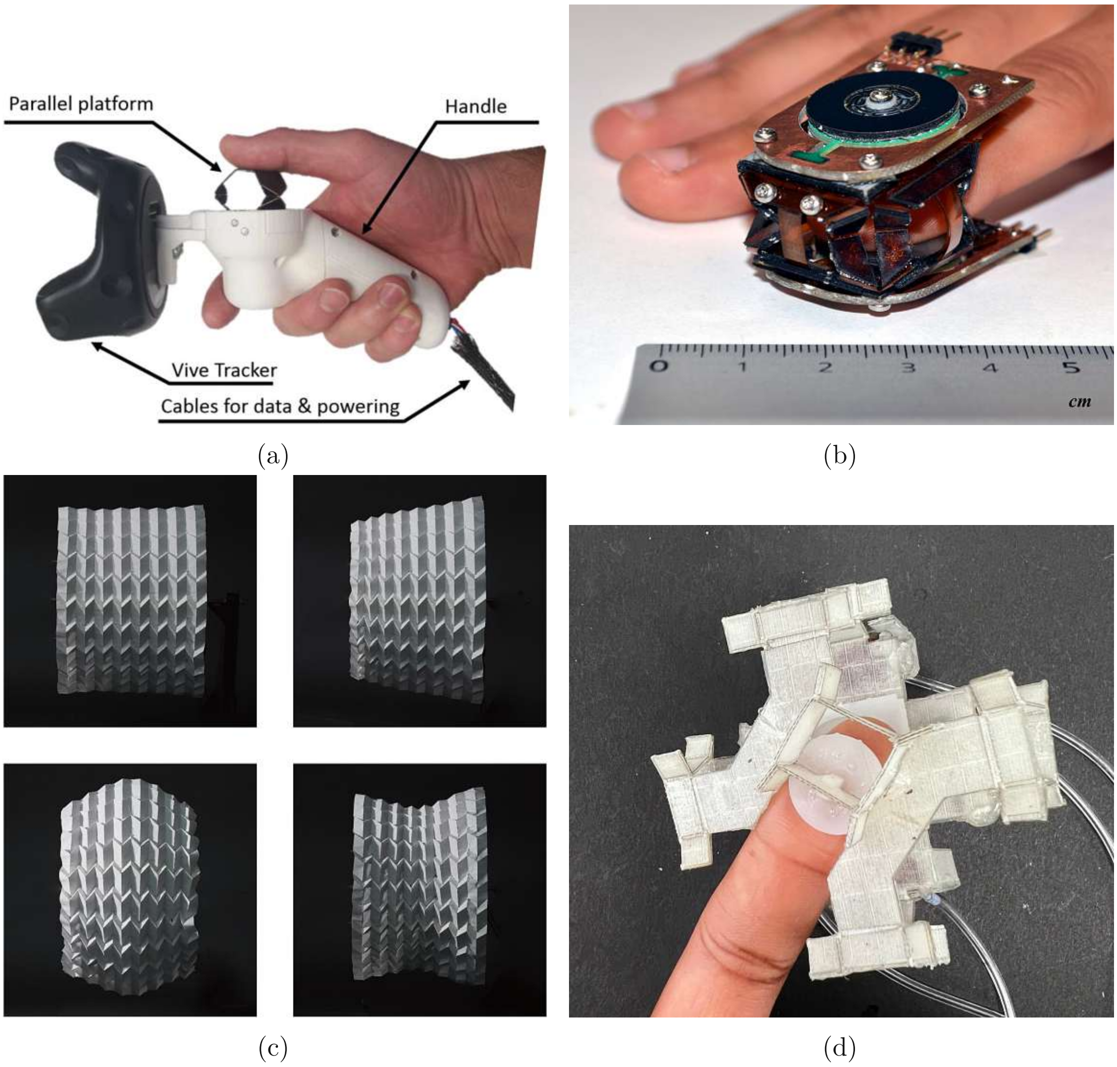
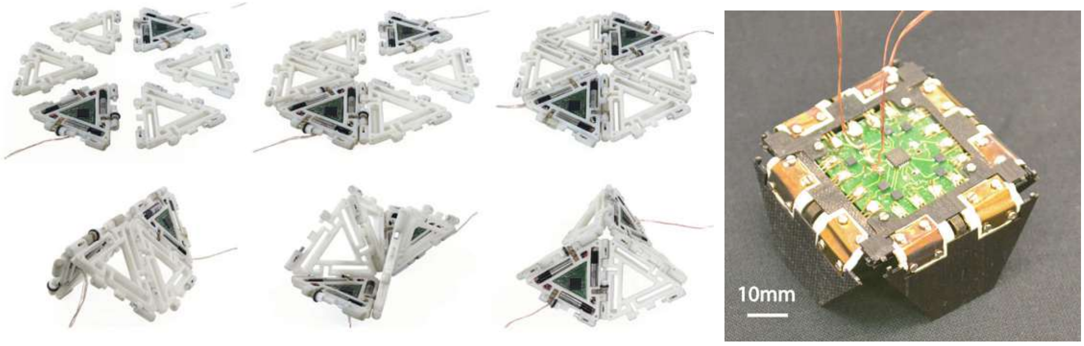


Figure 2.2: Four different origami-inspired haptic devices. (a) The motorized origami platform by Salerno et al. [SMC+18] mounted on a handheld controller, (b) a fingertip haptic device by Giraud et al. [GJP21], (c) the origami interpolation surface presented by Ohira et al. [OEOT22], and (d) the pneumatic-activated origami structure by Winston et al. [WZCO].



(a) (b)

Figure 2.3: Two origami-inspired robots. (a) A reconfigurable modular origami robot by Belke et al. [BP17], and (b) a small origami robot with SMA activators by Firouzeh et al. [FP15]

haptic device exists that can create rich haptic feedback for the whole hand, including the simulation of touching continuous curved surfaces or edge features.

2.4 Origami- and Soft Robots

Numerous approaches have been developed to automatically fold or unfold origami structures, including Smart Materials, systems that utilize small electro-motors, magnetic actuators, and pneumatic systems. Two examples of robots using an origami mechanism are shown in Figure 2.3.

Smart Materials

In research, a prevalent approach to fold creases is using smart materials. These materials change their shape when exposed to heat in a controlled way. Typically, it involves a training phase, where the material is formed to the target shape and heated. Afterward, the material "remembers" the shape. When the metal is then deformed, it only has to be exposed to heat again, and the material deforms back to the trained shape [RT18]. Typically, only folding back to the trained position can be realized. But by adding a second actuator to the opposite side, the crease can be folded in two directions, for example, as presented by Kohl et al. [KKC14] or Firouzeh and Paik [FP15].

A very common smart material is *Shape Memory Alloy* (SMA) that is used for numerous approaches for origami robots [ZMFP19, RT18, KKC14, KLA+20, PW12, HAB+10, FP15, LJS+13, LKK+13]. Typically this alloy has to be heated up to around 300 °C to 420 °C for the training phase and to around 70 °C to deform back [RT18, HAB+10]. Besides SMA other smart materials exist that are used for origami robots. Among them *Shape Memory Polymer* (SMP) [TFM+14, FP15, LSX+19], Low Melting Point

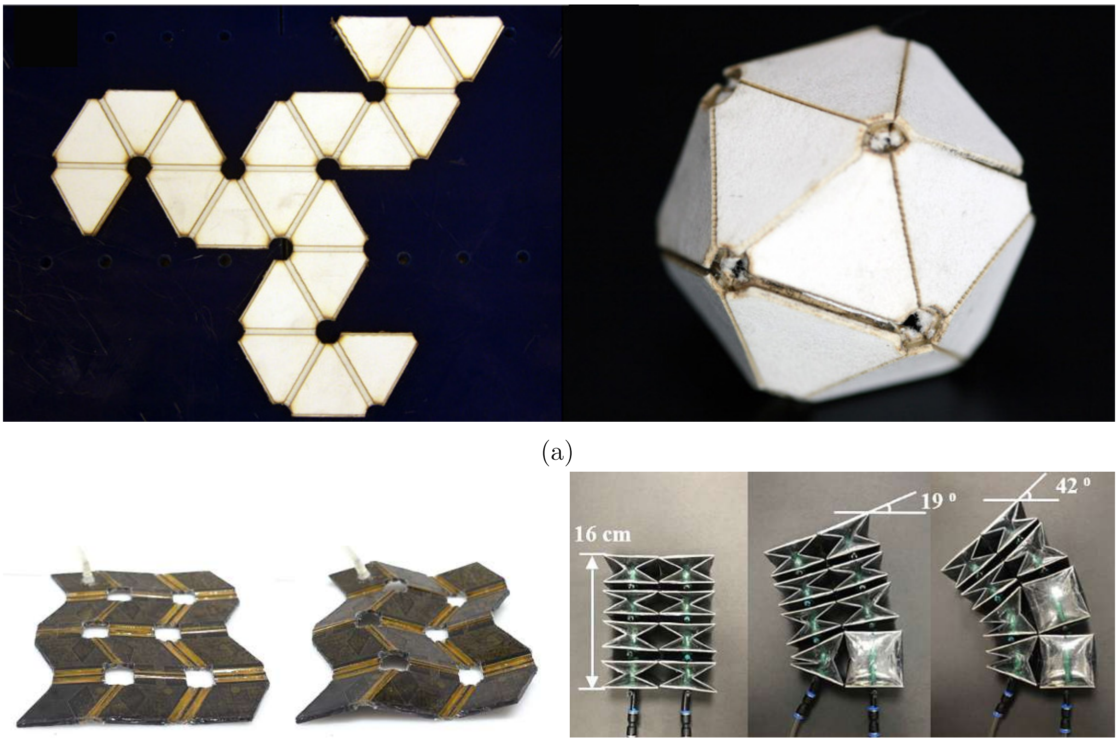


Figure 2.4: Three approaches for folding origami structures automatically. (a) An approach by Tolley et al. [TFM+14] to fold an origami structure using SMP. (b) The pneumatically activated origami structure created by Zhakypov et al. [ZMFP19] and (c) the multi-block origami system by Park et al. [PKN22].

Alloys [TMS+16], or Liquid Crystal Elastomer [MHG+20]. An example of an origami structure folded by SMP is shown in Figure 2.4a.

Smart Materials also have some relevant limitations when used in a haptic device. First, they are rather hard to control precisely, implying some sensing of the fold is needed [RT18]. Second, relatively high temperatures are required to activate the transformation, which can harm the user. Third, smart material actuators are relatively slow. They are requiring multiple seconds to fold a crease [KKC14]. Also, folding and unfolding the origami structure multiple times in a short amount of time could be problematic because it requires that the actuators cool down before they can transform again.

Pneumatic Approaches

Pneumatic approaches can control the folding of creases for origami structures. These approaches have a good power-to-weight ratio and generally can be faster than temperature-controlled approaches like smart materials [MP21, ZWJ21]. In some of these approaches, the rigid origami structure is embedded in an air-tight membrane. [ZMFP19, LVRW17, PKN22, LSX+19]. When the air is removed by a vacuum pump the origami structure deforms. A single airline can activate multiple structures by utilizing small-scale solenoid valves [RKP21, PKN22]. Instead of deflating the whole structure, small pouches can be connected with both sides of the crease to activate the folding motion [MP21, RKP21]. By adding pouches on both sides the crease can be folded in both directions [MP21]. Figures 2.4b and 2.4c show two pneumatic actuated structures. Besse et al. [BRZS17] used a SMP to control an array of 32 by 24 small cells by a single pneumatic intake.

Pneumatic-actuated approaches to haptic feedback for users have also been developed. For example, the work by Teng et al. [TKW+18] creates haptic feedback by an air-bag that is mounted to the user's hand, that is expanded (by injecting air) or contracted depending on the desired haptic feedback. Further, Yao et al. [YNO+13] presented numerous applications for pneumatically actuated shape-changing interfaces, and Harrison and Hudson [HH09] demonstrated a screen where physical buttons or other predefined patterns can be raised or sunk. To transform textile fabric Castro et al. [MCBWK22] uses pneumatic activators to create haptic feedback.

Motor-Based Folding

Small electric motors are also used to fold creases, for example, by driving each crease by a small stepper motor and gears [BP17]. Cable systems [LKP+14, KMC+20, LYW+18, VHJL14] can be used to compress an origami structure and activate the shape-changing. Motor-driven rigid linkages [GJP21, GZP19] or linear actuators [TVR+12] can be used to fold and unfold origami structures precisely with a single motor. To fold and partially unfold an origami structure with a single motor and a cable system, springs can be used as opposing actuators to unfold the structure again [GZZD23, BPR18]. Further, multiple actuation methods can be combined, like pneumatic actuators and cables [HZW+22] to enable fine control of the structure.

Motor-based folding has the ability to fold and unfold an origami structure precisely and rapidly. Motor-based systems are also typically easy to control and can be designed to have a high strength. Compared to smart materials, they are relatively heavy, especially if a larger number of individually controllable actuators are required, which makes them more suitable for a hand-sized scale or larger.

Previous works show that shape-changing haptic devices have great potential for creating haptic feedback without the limitation that the user has to wear or hold a device constantly. The variety of feedback previously developed shape-changing devices can create is often limited and cannot render different geometric features (like flat surfaces, edge features, or continuous surfaces). Many of those devices have many individually moving parts, making them expensive and heavy to produce. The use of origami structures could be used to create richer haptic feedback with a smaller number of actuators. But to our knowledge, no approach has been developed utilizing curved origami patterns to provide haptic feedback to the user's whole hand when interacting with differently shaped virtual objects.

CHAPTER 3

Shiftly: The Shape Shifting Device

This chapter outlines Shiftly, the novel shape-changing haptic device developed in this thesis. First, the haptic device's design principles are outlined (Section 3.1). Section 3.2 gives an overview of the design process of the haptic device, including some early prototypes. The final haptic device design is outlined in Section 3.3, including the used origami structure (Subsection 3.3.1), the rigid frames that hold and control the origami structures (Subsection 3.3.2), and the control mechanism (Subsection 3.3.4). Section 3.4 presents a kinematic model for the haptic device, and Section 3.5 outlines the range of motion and the possible shapes the device can emulate.

3.1 Design Principles

When designing haptic devices, one should consider that exploring an object haptically differs from exploring an object visually. Therefore, devices for rendering haptic feedback might follow different design principles than devices giving visual or auditory feedback. For example, depending on one's point of view, the visual sense enables one to see a good portion of a physical object at every given time. A cube with a 1.5 meters side at sufficient distance can be observed with the three sides visible at any moment. In contrast, the perception of an object when haptically explored is more local than global. In a single-hand interaction, a person can only haptically explore the surface that the hand is currently touching. Thereby, an object can only be fully explored by moving one's hand. Depending on the object's size, a full haptic overview might be impossible.

Coming back to the example of a cube, a person using a single hand can only experience a small portion of the cube. For example, a small part of a single surface or small sections of at most three of the twelve edges. Hence, without moving the object or one's hand, a user can not haptically distinguish two objects of different geometry when the surface geometry of the two points one is touching is identical. Therefore, our aim is not to design a haptic device that can approximate any arbitrary object in its entirety. Instead,

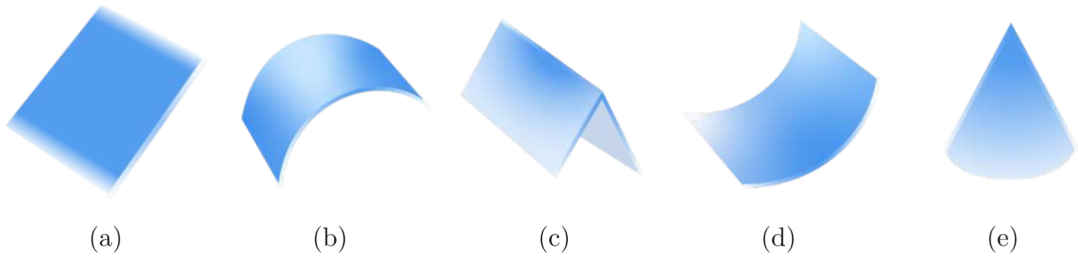


Figure 3.1: Different surface categories: (a) flat surface, (b) convex curved surface, (c) edge features, (d) concave curved surface, and (e) apex.

the haptic device matches the local surface geometry of the part of the object that the user is touching at the time.

In a more specific example, where a user touches a virtual object in a virtual world while wearing an HMD and the view of the real world is completely occluded. The user touches the virtual object, and a visual representation of the object is rendered on the HMD. The position of the physical haptic device is spatially aligned with the virtual object. Therefore, when the user touches the virtual object, the user also touches the physical device. At that moment, the haptic device's surface should approximate the virtual object's surface structure at the point where the user is touching the virtual object. Instead of emulating the surface geometry of an entire object, we approximate a small portion of the surface geometry that a user is interacting with at that particular moment. When the user moves the hand or the virtual object changes its shape, the device adapts to approximate the new surface geometry. By simultaneously relocating Shiftly when the user moves the hand, one can haptically explore and interact with large objects freely.

This thesis categorizes all possible large surface geometries one can touch into five categories. They are listed below and illustrated in Figure 3.1.

1. Flat surfaces
2. Convex curved surfaces
3. Edge features
4. Concave curved surfaces
5. Apices

Additionally, parts of objects can also be touched, which can be described as a combination of these categories. For example, one side of an edge can be flat while the other is slightly curved. This thesis focuses on creating haptic feedback for surfaces that can be described as flat surfaces, convex surfaces, and edges — as well as the combinations of these

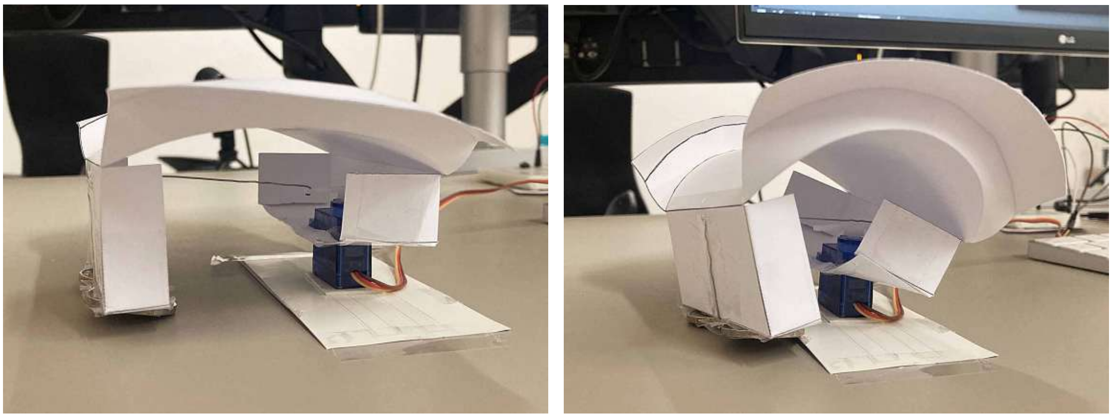


Figure 3.2: The first prototype of the haptic device. The prototype uses a servo motor to extend and contract the origami.

categories. This means that the developed device can not approximate every possible part of an arbitrary object. However, we argue that a haptic device does not have to have this ability because, in most real-world and virtual scenarios, the sense of touch is not isolated from the visual and auditory acuity and is influenced by their feedback [CK19]. This way, imperfect haptic feedback can be compensated when creating immersive user experiences.

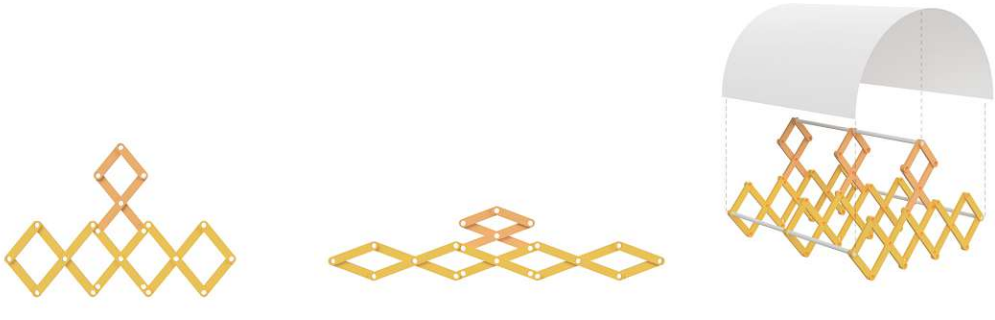
3.2 Design Process & Early Designs

During this thesis, multiple design iterations of haptic devices were conducted to create Shiftly. First, a state of the art research was conducted, summarized in Chapter 2. Following this research, different mechanics and systems were explored. Beginning with simple prototypes, we explored different folding actuators and origami combinations. Based on these initial prototypes, more advanced prototypes were created to further explore the haptic potential of the mechanism.

First Prototypes

Initially, we investigated pneumatic-activated origami structures. Multiple previous works have explored pneumatic actuators (Section 2.4). While the initial tests seemed promising, we became aware of some limitations. It would be rather difficult to manipulate an origami structure precisely, and multiple sensors would be required. Additionally, the pneumatic-activated structures we could prototype were not stable enough to emulate a solid object. Fabricating such a pneumatic structure would complicate and impose multiple difficulties in building a functional prototype that could be used for user testing.

Following the pneumatic activators, we investigated the direction of motor-activated origami structures. The first early prototype is shown in Figure 3.2. This prototype used an origami structure similar to the one used in the final Shiftly, outlined in Section 3.3.



(a) (b) (c)

Figure 3.3: Scissors mechanism to support a curved touched surface: (a) the mechanism in the contracted state and (b) in the extended state. (c) shows three of those support structures with a curved touch surface. The dashed lines indicate the mounting positions.

The prototype does not use a rigid frame. Instead, a small servo motor is mounted directly into the origami structure. A short piece of wire connected the servo arm and the origami structure. The origami structure is compressed or extended by rotating the servo, leading to the structure's folding and unfolding. The user is meant to touch the central part of the origami structure, and the curved origami pattern adds some stability to the structure created out of relatively thin paper. We also investigated the possibility of sensing the touch between the user's hand and the origami structure. By placing a conductive film over the origami structure and connecting it with the capacity sensor pins of an ESP32 [Co.23] microcontroller, the prototype could react when one was touching the origami structure.

The initial idea was to give the device the ability to simulate different elastic materials — by sensing the user's touch or the pressure applied by the user to the structure. The motor could react and unfold or fold the origami structure based on the user's pressure. For example, to simulate a material of a specific elasticity, the device could sense the pressure the user applies and unfold the structure to decrease the pressure the user applies. This concept was postponed to a future project and we decided to focus on simulating different geometries of solid objects.

Scissor Mechanisms

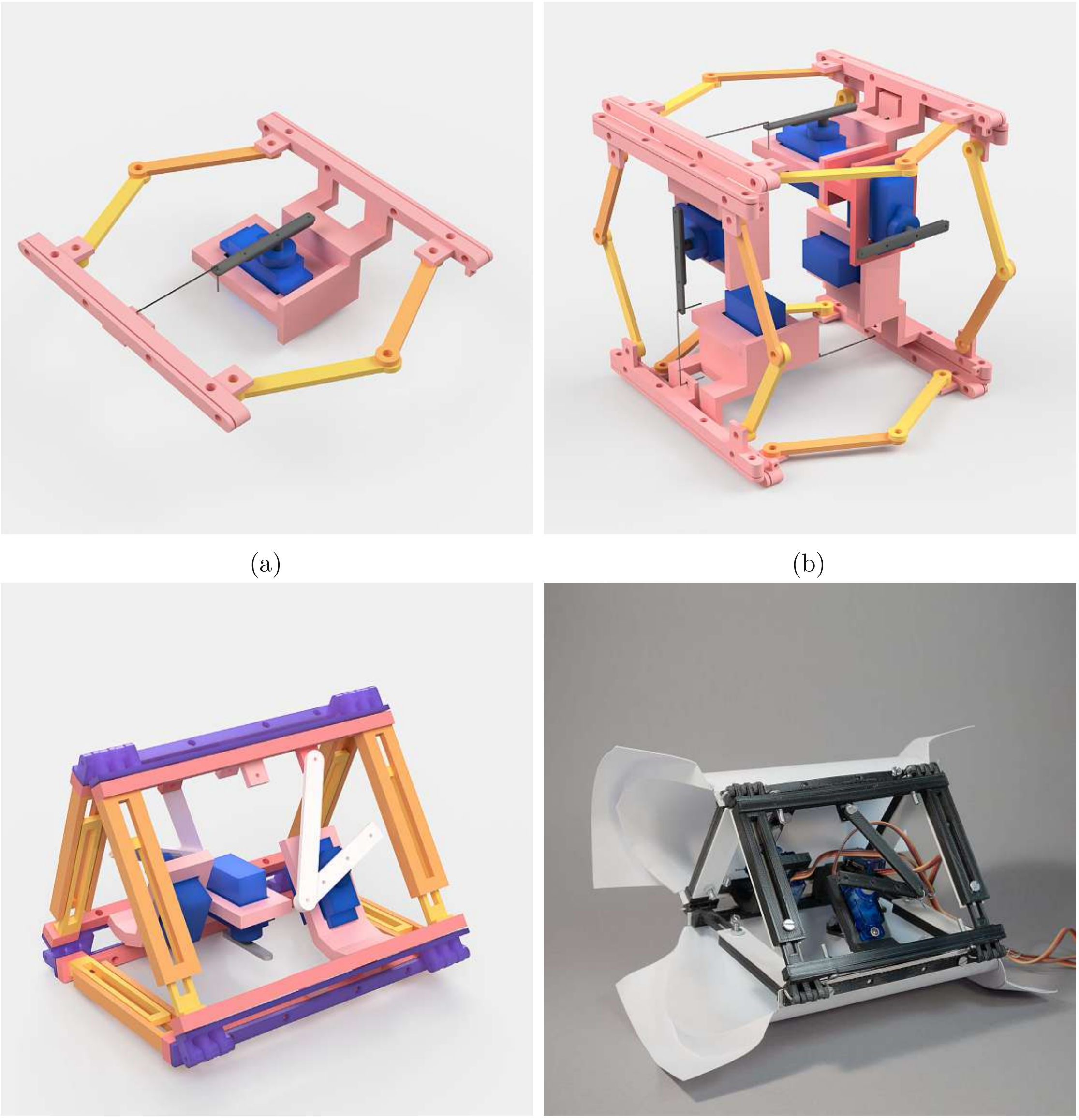
Shiftly should be able to transform into different curved shapes and, therefore, involve the bending of a surface. This is challenging in the context of a haptic device. The structure must be stable enough not to deform when touched. However, the material and structure must be flexible enough to be bent by a reasonably sized activator. Therefore, we investigated different support structures for the touch surface.

One approach involved the use of a scissors meschanism [CXF13]. In this mechanism, the bars are connected by revolute joints, forming interconnected diamond shapes. The bars are connected so that the whole structure deforms when one angle inside one of the diamonds is manipulated. The developed scissors structure, shown in Figure 3.3, would be connected to a bendable touch surface in three locations. The two ends of the touch surface would be connected to the left and right sides of the scissor structure and the top part of the scissors structure to the center of the touch surface, as illustrated in Figure 3.3c. A support structure should have several properties. When a circular arc is drawn from one side of the support structure to the other side, this arc goes through the center point. This circular arc should always have the same length independent of the distance between the connection points on the left and right ends of the structure. This means that if the support structure is fixed to the touch surface, without the ability to slide, the touch surface is not obstructed by the support structure when folded or pressed flat. An additional support element under a bent touch surface would enhance the structure's stability when a user touches it without needing more powerful motorized activators.

The downside of such a support structure is that it adds mechanical complexity and increases the overall number of individual parts that must be manufactured. We decided that the additional strength created by folding the structure along curved creases is sufficient for a device of the planned size and actuators. The proposed scissor structure would also greatly increase the mechanical complexity and add additional challenges to the manufacturing of the prototype.

Modular Design

After abandoning the idea of an additional support structure, we developed multiple versions of rigid frames that hold and activate the origami structure. These frames are connected to the curved origami structure and could extend and contract in one dimension. This extension movement should activate the folding process of the mounted origami. All prototypes were designed in a way that they were interchangeable. The frames utilized the same mounting mechanism for the origami structure, and the different rigid frames partially connected with each other. Multiple modules could be connected to form a larger structure, increasing the variety of shapes that can be approximated. The designs were developed in CAD, using Fusion 360 [Inc23b]. The first frames used small servo motors, as shown in Figure 3.4a. The first version could not compress the two sides of the origami structure reliably and equally. Figure 3.4b shows four frames arranged in a cube — covering four touch surfaces. The next iteration included rails on each side of the frame, ensuring that the origami structure was equally compressed on each side and did not twist when folded. A prism configuration of this design is shown in Figure 3.4c. In the 3D printed and assembled version of the design (Figure 3.4d), it was clear that the servo motors were not strong enough, and the device overall was too small to fit a whole hand. The following iterations of the haptic device utilized NEMA 17 stepper motors [Ste] instead of the smaller servo motors and the used origami was large enough for a user's hand. In this iteration, the frame module did not use a gear system, and the frame was contracted and extended by a less reliable 28 mm long crank. The design is



(a) (b)

(c) (d)

Figure 3.4: Early versions of Shiftly: (a) shows the first version of the frame and (b) four frames arranged in a cube. (c) shows a revised version consisting of three modules and (d) the 3D printed prototype with two mounted origami structures.

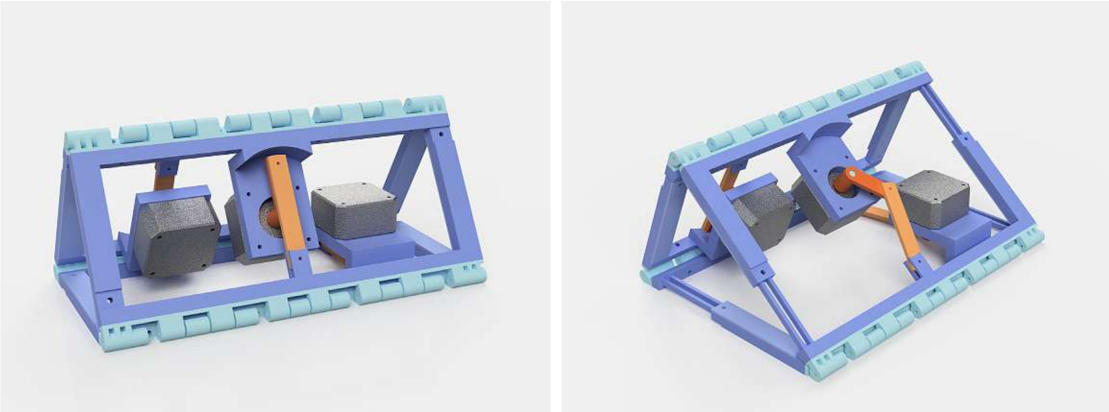


Figure 3.5: Two renderings of a draft design, the frame modules use NEMA 17 stepper motors.

shown in Figure 3.5. However, the motors' holding torque turned out insufficient during the testing of the 3D-printed prototype, and a user could unintentionally compress the structure. Compared to this prototype, in the final design outlined in Section 3.3, the mount for the motor was enforced, as well as the frame, by adding curved elements in the frame's inner edges. A gear system was added, and the hinge that connected two modules was refined.

3.3 Design of Shiftly

Shiftly can create haptic feedback for various larger surfaces with different geometric properties. As outlined in Section 3.1, in this thesis, we focus on flat surfaces, convex surfaces, and edges. Shiftly transforms its shape to resemble the local geometric surface properties of a virtual object by approximating the overall surface structure instead of fine details like textures. A flexible origami structure with curved creases forms the main part of the devices. By electro-machanically folding and unfolding this origami structure, various curvatures and edge features can be created to emulate the local geometry of virtual objects.

Three modules that are connected build the shape-changing haptic device. Each module has a rigid frame that can extend and contract in one linear direction. An electronically controlled stepper motor actuates the extension and contraction of the frame. By attaching a curved origami structure to each frame, the origami structure can fold or unfold when contracting and extending the frame.

Arrangements with different numbers of modules are possible. However this thesis focuses on a prism arrangement consisting of three modules, as shown in Figure 3.6. The prism design enables six areas the users can touch and interact with. The surface of each of the three origami structures allows approximating differently tilted flat surfaces and surfaces of varying curvature. This also enables emulating cylindrical shapes of different sizes

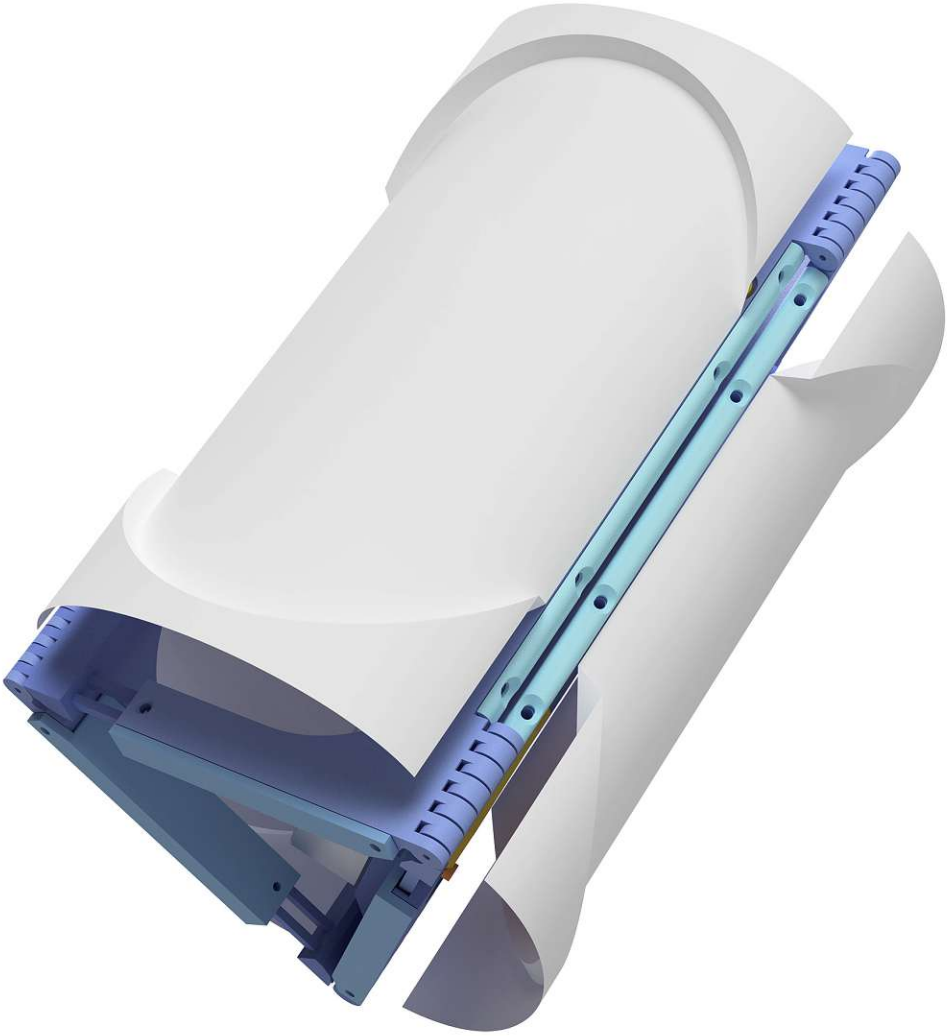
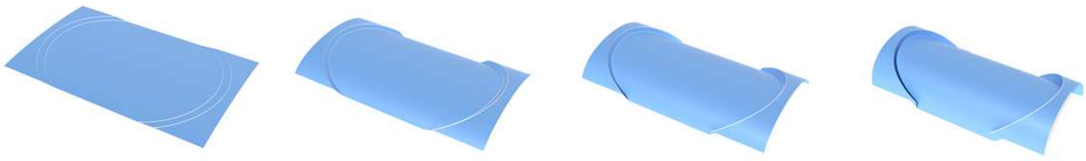


Figure 3.6: Shiftly forming a cylindrical shape.



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

Figure 3.7: Origami structure from the flat unfolded state (a) to the folded state (d).

when using two or three modules. Where the three modules are connected, edges are formed, which are the other three areas of interaction. Depending on the extension or contraction of the modules, edges with different angles are shaped.

The origami structure is described in Section 3.3.1 in more detail. The frame is outlined in Subsection 3.3.2, and Section 3.3.4 describes the electronic components of Shiftly.

3.3.1 Origami Structure

The used origami structure has four curved creases and is inspired by the work of Mitani [Mit19] and Rabinovich et al. [RHSH19] On two sides of the origami, two creases shaped as concentric circular segments are placed. The inner creases are valley folds, whereas the outer creases are folded in the opposite direction. The curved creases are activated by compressing the origami along the shorter side, transforming a flat surface into a cylindrical shape. By gradually folding the structure, surfaces of different curvatures can be formed, as illustrated in Figure 3.7. The user touches the central part of the structure, as shown in light gray in Figure 3.8. Multiple such modules can be connected along the longer side. At the area where two modules connect, a straight edge is formed.

Using curved folds instead of a sheet that is just bent and has no complex origami elements has two advantages. Firstly, the curved creases help increase the stability and stiffness of the structure [ZWL+20]. This effect becomes more substantial the further the structure is folded. Secondly, the curved creases ensure the controlled and reproducible formation of the origami. The radius of the crease lines and how strongly the structure is compressed define the curvature of the surface. Even if a user applies force onto the origami, the origami is more resilient against deformation. On the other hand, if we used a structure without creases, the area where the user applied force would have flattened, and the area on the opposite side of the structure would have gained in curvature.

The origami structure can be folded and unfolded by manipulating the length of the shorter side of the structure. Because paper-like materials can only be bent in one direction and can not be stretched, each crease does not have to be folded individually by an actuator. Instead, the material folds along curved creases almost “automatically”. That is because the folding of one curved crease restricts the folding direction of the

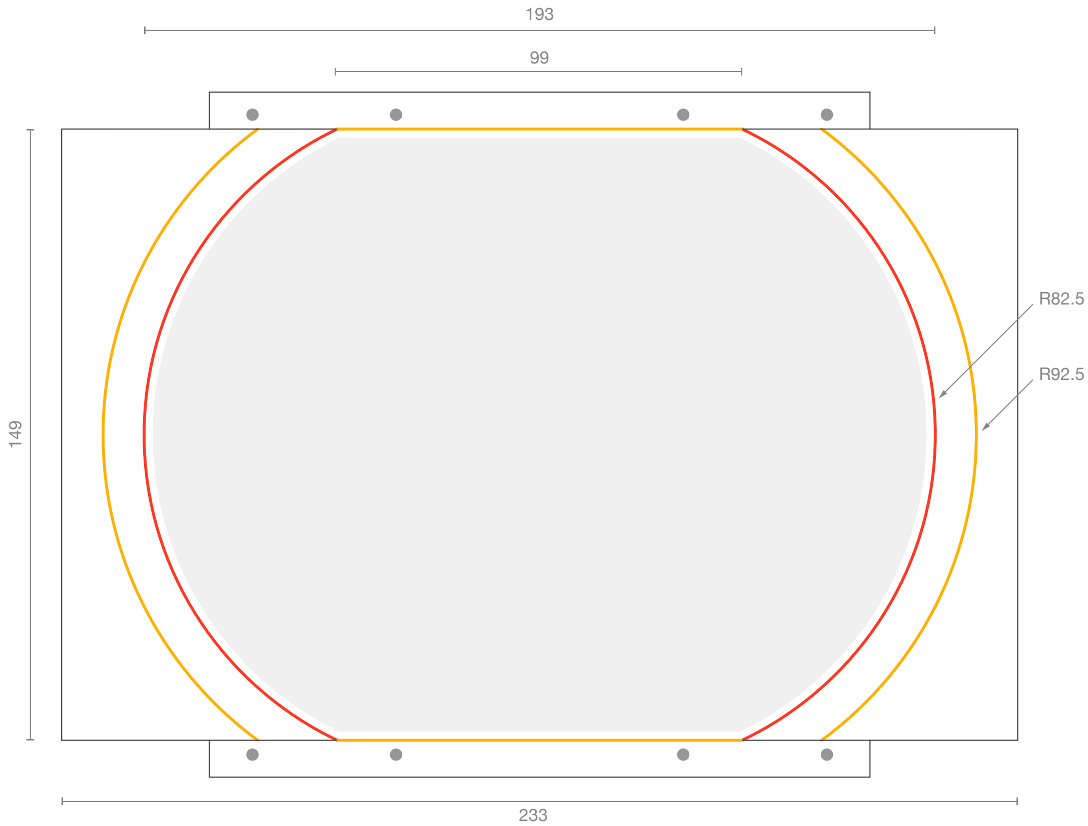


Figure 3.8: Folding pattern of the origami used for Shiftly. Yellow strokes indicate mountain creases and red strokes valley creases. Black lines indicate where the structure is cut, and the light gray surface indicates the area the user touches. All dimensions are given in millimeters.

remaining creases – the origami structure is deformed globally [RHSH19]. Without greater force and without destroying the origami structure, the inner creases on each side of the origami structure can only be folded in the same direction, and the outer creases on each side of the structure can only be folded in the direction opposite to that [Mit19]. Therefore, compressing the structure along the shorter side can only lead to two different crease-direction combinations. The inner folds, shown in red in Figure 3.8, become valley folds, and the outer become mountain folds, forming a convex touch surface. Assigning opposite crease directions would create a concave surface. However, because the frames holding the origami structure prohibit concave folding, the used origami structure can only deform to the convex case.

The used origami structure is 233 mm wide and 149 mm deep. The radius of the inner curved creases is 82.5 mm, and 92.5 mm for the outer crease lines. By manipulating the radius of the curved creases, the structure's stiffness can be tuned [ZWL+20] to fit the

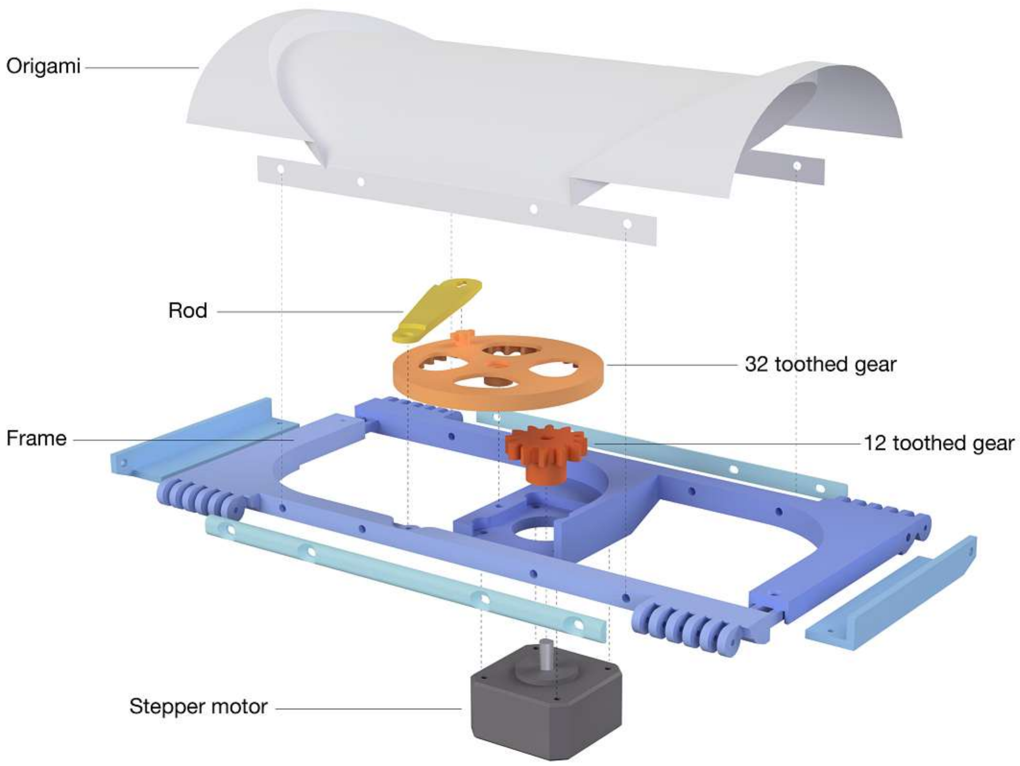


Figure 3.9: Individual parts of a module of Shiftly. The origami is located at the top, the frame elements are in the center, and the stepper motor is at the bottom.

desired use-case and electronic activator setup. The structure has a touch area with a width of about 193 mm on the longest and 99 mm on the shortest part of the surface. Additionally, the longer sides of the origami hold flaps with four holes so that the origami structures can be screwed onto the frames.

3.3.2 Design of the Frame

The frame is the rigid structure that holds and activates the origami. Shiftly consists of three modules where each has a frame with an origami attached. Each frame can change its width—contracting and extending based on the required state. Fully contracted the frame has a width of 92 mm and can extend to 148 mm. Two linear sliders connect the two main parts of the frame. To enhance stability when the structure is extended, the sliders open in opposite directions. Each frame has a length of 233 mm.

Motor and Gearing

Each frame can extend and contract with the rotation of a motor. This motor is screwed to the frame along with a two-gear gear system. Onto the larger gear of two, a rod is

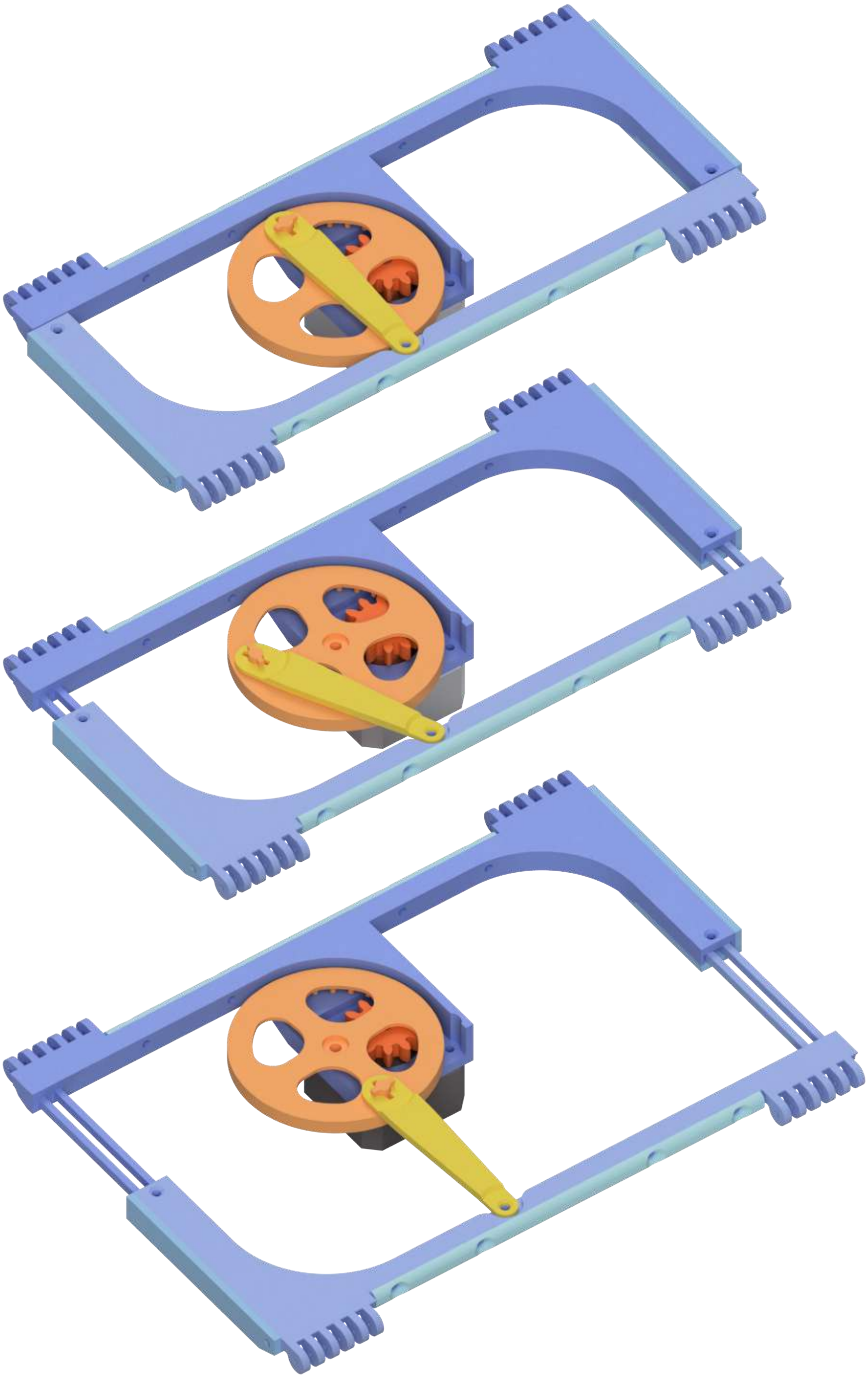


Figure 3.10: Frame with a center-mounted motor, from fully contracted (top) to fully extended (bottom).

mounted, connecting both sides of the frame. An overview of the parts of the frame can be seen in Figure 3.9. The motor rotates the gears and pushes the other side of the frame away or pulls it toward the motor. The range of motion of the frame depends on the distance between the pivot point of the larger gear and the connection point of the rod. In the developed design the distance is 28 mm. Figure 3.10 shows how the motor extends the frame.

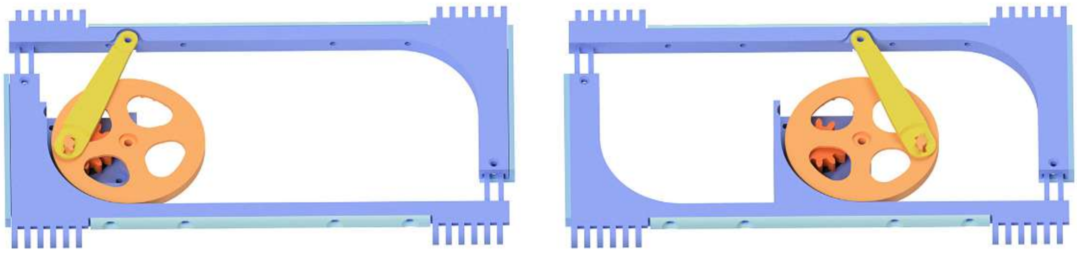
The larger wheel is designed as an inner gear with teeth on the inside of the wheel. This larger wheel is rotated by a smaller gear mounted on the motor's shaft. In the developed prototype, the larger gear has 32 teeth, whereas the smaller gear has 12 teeth, resulting in a gear reduction of 32/12. The pitch diameter of the 32 teeth gear is 64 mm, and 24 mm for the 12 teeth gear. This makes relatively large teeth that can easily be 3D printed. One could also use gears with smaller teeth, enabling larger gear reduction, which would enhance the strength of the device and enable the use of smaller, weaker, and less power-consuming motors without compromising on the stability of the system. But gears with smaller teeth are more challenging to fabricate with a 3D printer.

The motor is mounted onto the inner side of the frame, and is held into place by three screws. The prototype is designed to hold NEMA 17 motors and has about 31 mm between each screw hole. When using a 10 mm spacer component that is placed between the motor and the inner side of the frame, the motor can have a maximum shaft length of 20 mm. Alternatively one could also use a motor with a shorter shaft (10 mm). In this case, a spacer is not needed. The body height of the motor should not exceed 20.5 mm. If motors of bigger size are used, the motors will touch the origami structure of the opposite module when arranged in a prism configuration. Each frame can be connected to another frame with a hinge system added to the longer sides on all four corners of a frame. A metal pin is run through the interlocking teeth of two modules, connecting them. Two frame designs that differ in the position of the motor were developed. In one, the motor is mounted centrally in the frame, and in the other case, on the side. Both designs are shown in Figure 3.11. These two frame designs are required to ensure that none of the motors touch an opposite origami structure or interfere with a gear of another module. In the prism configuration of Shiftly, two modules with a left-mounted motor are used and one with a motor central-mounted.

The origami structure is securely mounted to the frame with eight screws. The origami structure has a 161 mm long and 10 mm wide flap with four holes on both longer sides of the surface. The flaps of each origami structure are then placed between the frame and a ledge that is screwed onto the frame.

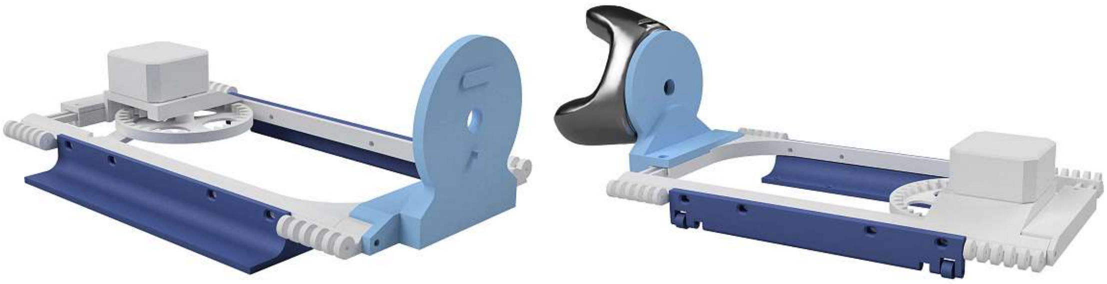
3.3.3 Frame Attachments

In addition, an attachment was designed in order to be able to connect a Vive Tracker to one side of a frame. The tracker is connected to the attachment with a standard tripod screw, which is then attached to the frame with two screws.



(a) (b)

Figure 3.11: Different frame designs of Shiftly. (a) shows a frame with a stepper motor on the side and (b) a frame with a center-mounted motor.



(a) (b)

Figure 3.12: Frame with an attached stand and the VIVE tracker attachment. The stand is shown in dark blue, and the VIVE tracker attachment is rendered in light blue. (a) shows the front side with no VIVE tracker mounted, and (b) shows the back side with a tracker mounted.

We also designed a holder for the device that enables securing the device to a table or larger base plate. The VIVE Tracker attachment and the table attachment are shown in Figure 3.12. To use the table attachment, the bottom origami needs to be removed; however, the device's bottom module can still extend and contract. The holder consists of two main parts: one part is screwed to a table or larger base plate, and the other part moves along the table or base plate when the connected frame contracts or extends. On this movable part of the holder, two small wheels are mounted, enabling a smooth transition between the contracted and extended state of the frame. Both parts of the holder are connected with four screws with the frame. The parts of the holder utilize the same holes in the frame that are also used for securing the origami structure.

3.3.4 Electronics & Control

Shiftly creates different haptic feedback by folding and unfolding its independent modules. To enable this, each module has an electric motor that actuates the folding and unfolding process. The transformation pace between a folded and unfolded origami structure can be altered with varying motor speeds. Shiftly is designed for NEMA 17 stepper motors. Alternatively, one could also use servo motors because they typically have a position feedback sensor built-in. However, most of the readily available servo motors are not shaped ideally. The prism configuration of Shiftly demands a flatter motor, whereas standard servos motors often have a relatively high body.

The stepper motors used in Shiftly are each controlled by motor drivers and a microcontroller. This enables one to change the speed of the motors (by microstepping the stepper motors) and precisely use a certain number of steps to turn the motor shaft. The motors used in this prototype have a resolution of 200 steps per revolution. As outlined in Section 3.3.2, the device demonstrated utilizes a gear reduction of 32/12, resulting in 533 steps per revolution. As the device is equally extended after a rotation of k degrees as after $k + 180$ degree, each frame can be extended in 266 different widths. Hence, the origami structure can be transformed into 266 different states. The resolution could be further increased by utilizing a higher gear reduction or a motor with more steps per revolution. The microcontroller and motor drivers of the device are housed in a small box connected with a detachable cable to the haptic device.

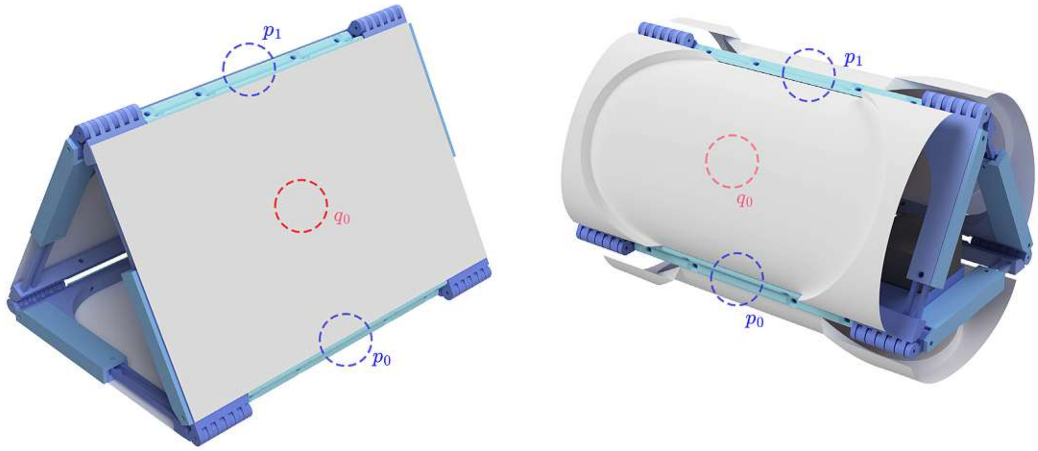
3.4 Kinematic Model

To create the haptic feedback described in Section 3.1 and to use the device in a VR context, it is necessary to understand the motion of Shiftly. Hence, this section gives a kinematic model describing the device's transformation.

The idea of the model is to denote the spatial position of the six touch points of Shiftly, given the current motor rotation state, and the position of one tracked point of Shiftly. Additionally, the geometric properties (curvature and angle of an edge) should be derivable at the touch points to control the haptic feedback precisely. Shiftly uses three modules (each consisting of a frame with a mounted origami) arranged in a prism configuration. First in Subsection 3.4.1, the six touch points of Shiftly are outlined. In Subsection 3.4.2, a description of the model for a single module is given. This is followed by Subsection 3.4.3, where the definition for the complete Shiftly is given.

3.4.1 Touch Points

This kinematic model defines six touch points for Shiftly, illustrated in Figure 3.13. A touch point is a single point on Shiftly that the user can touches. Each folding module contains one touch point q_i located in the center of the origami. The center points are denoted by q_0, q_1, and q_2 for the front, back, and bottom modules, respectively. Further, three touch points are defined in the centers of the edges between the two modules. p_0



(a) (b)

Figure 3.13: Touch points of Shiftly in two states. Touch points on an origami structure are shown by the magenta dash-lined circles, and edge touch points are shown by the blue circles. (a) Shiftly state when all frames are extended, (b) Shiftly in a cylindrical configuration.

denotes the edge formed by the front and bottom module, p_1 between the front and back module, and p_2 between the back and bottom module.

3.4.2 Kinematic Model of a Single Module of Shiftly

Each frame is equipped with a motor that rotates a gear connected to a rod. Sliding rails on both ends of each frame enable it to extend and contract. The model assumes that the long sides of the frame are always parallel. Hence, in the model, the modules contracts and expands equally at any point. We denote the points in the center of the top and bottom sides of the frame by p_i and p_j. Further, the vector $v_i = p_j - p_i$ describes the extension and rotation of the module. The distance between the two sides of the frame is referred to as w_i, where $w_i = \|v_i\|$. By actuating the motor, the large gear is rotated. This rotation actuates the extension and contractions of the module. We write the large gear's rotation as θ, where $\theta = 0$ in the state where the module is fully contracted. Note that θ does not refer to the actual motor rotation because of a gear ratio between the large gear and the motor but corresponds to the rotation of the larger gear. The width w_i of a module depending on its θ_i and can be modeled as

$$w_i = d_1 + d_2 + \sqrt{c^2 - r^2 \sin(\theta_i)^2} + \operatorname{sign}(\theta)\sqrt{r^2 - r^2 \sin(\theta_i)^2}, \tag{3.1}$$

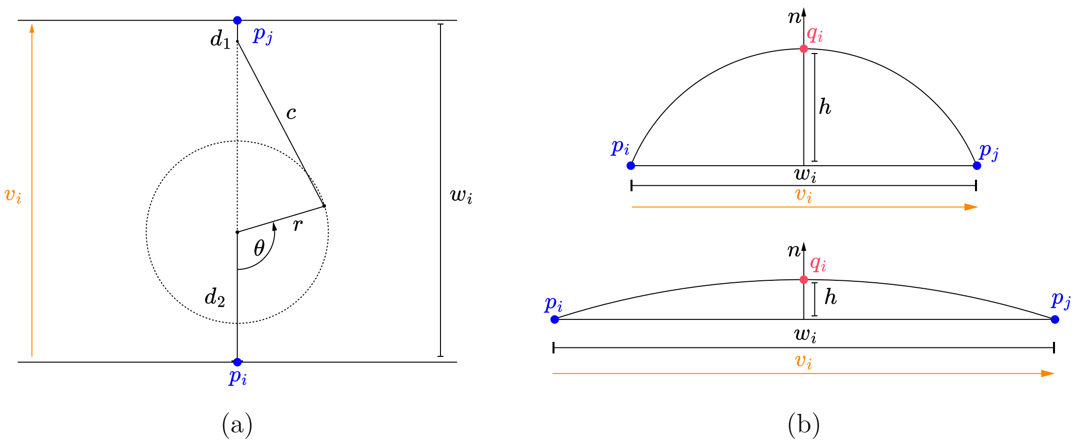


Figure 3.14: Overview of the notation used is in the kinematic model. Edge touch points are shown in blue and touch points located on the origami structure are drawn in magenta. The approximated origami structure is drawn as a circular arc. (a) The top view of the schematic representation of one folding module. Including the larger gear with an diameter r and the length of the rod c. (b) The cross-section of one folding element. The top figure illustrates the origami in a contracted state and the bottom one in an unfolded state.

$$\text{with: } \operatorname{sign}(\theta) = \begin{cases} 1, & \frac{\pi}{2} < \theta \leq \pi \text{ or } -\pi \leq \theta < \frac{-\pi}{2} \\ -1, & \frac{-\pi}{2} \leq \theta \leq \frac{\pi}{2} \end{cases} .$$

Here c denotes the length of the rod and r is the distance between the center of the large gear and the connection point between the rod and the gear. See Figure 3.14 for an overview of the used notation. d_1 denotes the constant distance between the rotation wheel center and the bottom edge of the frame, and d_2 the distance between the end of the rod and the top edge as illustrated in Figure 3.14b. The inverse case, where the width of the module w_i is known, and the rotation of the wheel θ should be derived, can be modeled as

$$\theta_i = \pi - \arccos\left(\frac{(w_i - d_1 - d_2)^2 + r^2 - c^2}{2(w_i - d_1 - d_2)r}\right) . \tag{3.2}$$

To model the origami structure and the touch point in its center, we assume that a part of a cylinder can approximate the area where the user touches the structure. Therefore, the cross-section of the origami is approximated as a circular arc with a fixed length. The width of the origami structure gives the length of the circular arc and equals the frame's maximum width $w_{\max}$. We compute q_i by offsetting the center of the module $p_i + \frac{v_i}{2}$ by the sagitta h_i of the arc. This can be formulated as

$$q_i = n_i h_i + p_i + \frac{v_i}{2} , \tag{3.3}$$

where n denotes the unit normal vector to the frame module as illustrated in Figure 3.14b. The radius s_i of the circular arc, and therefore also the radius of the cylindrical structure that approximated the origami, is given as

$$s_i = \frac{w_{\max}}{\xi}, \tag{3.4}$$

where ξ is the unknown angle of the circular arc. To compute radius s_i, one must first compute ξ. To do so the equation for the paper width $w_i = 2s_i \sin(\frac{\xi}{2})$ that corresponds to the length of the arc can be transformed to $s_i = \frac{w_i}{2\sin(\frac{\xi}{2})}$. ξ can be computed by solving the equation

$$\frac{\xi}{2\sin(\frac{\xi}{2})} = \frac{w_{\max}}{w_i}, \tag{3.5}$$

following s_i can be computed by Equation 3.4. If the radius of the circular arc s_i is known, the sagitta h_i of the arc can be computed to get the touch point position q_i by Equation 3.3. The height of the arc h_i is then computed for $0 < \xi < \pi$ as

$$h_i = s_i - \sqrt{s_i^2 - \frac{w_i^2}{4}}. \tag{3.6}$$

In case $\xi = \pi$, the module is completely extended, the origami structure is flatend, and $h_i = 0$. For the case the angle exceeds for for $\pi < \xi < 2\pi$ as

$$h_i = 2s_i - \left(s_i - \sqrt{s_i^2 - \frac{w_i^2}{4}}\right). \tag{3.7}$$

With the above outlined kinematic model for an individual module of Shiftly and its corresponding origami structure, the width of the module w_i and the position of the touch point q_i can be computed from the rotation of the larger gear θ.

3.4.3 Kinematic Model of the Arranged Three Modules of Shiftly

In this subsection, a model is given to compute the position and geometric properties of the six touch points on Shiftly as shown in Figure 3.13. While the physical modules might differ regarding motor position, the parameters relevant to the kinematic model outlined in Section 3.4.2 are equal, and the model is applied to both module designs. We assume that in the reference state , the device is aligned with the x-axis, and $\theta_0 = \theta_1 = \theta_2 = 0$. Figure 3.15 shows an overview of the annotation.

Based on the prism shape of Shiftly, given the three widths w_0, w_1, and w_2 of the modules, we can derive the inner angles between the modules. β denotes the inner angle between

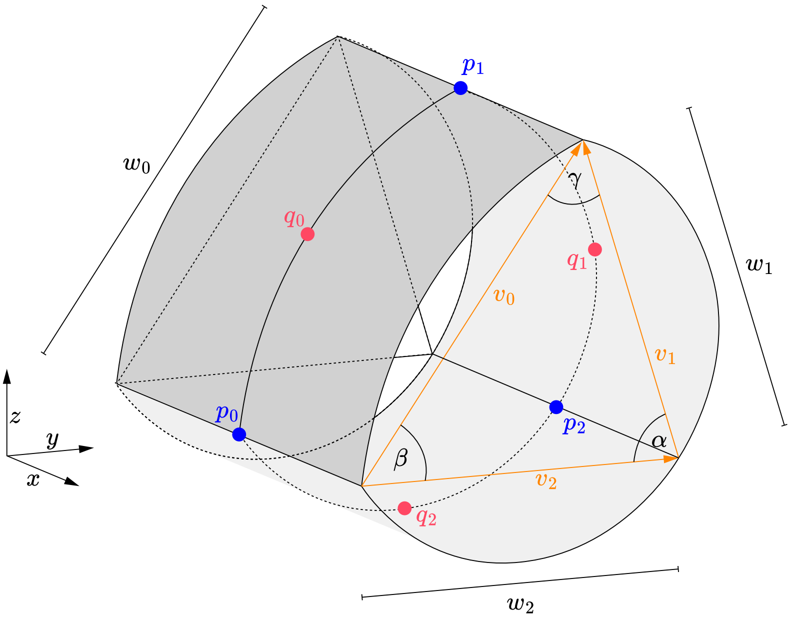


Figure 3.15: Overview of the notation used for the kinematic model of Shiftly. Touch points on the origami are shown in magenta, and edge touch points are in blue. The parts of cylinders that approximate the origami are drawn in gray.

the front and bottom module, α between the back and bottom module, and γ the inner angle between the front and back module. These angles can be computed by

$$\alpha = \measuredangle v_1 v_2 = \arccos \frac{w_1^2 + w_2^2 - w_0^2}{2 w_1 w_2} \; , \tag{3.8}$$

$$\beta = \measuredangle v_0 v_2 = \arccos \frac{w_0^2 + w_2^2 - w_1^2}{2 w_0 w_2} \; , \tag{3.9}$$

$$\gamma = \pi - \alpha - \beta \; . \tag{3.10}$$

To compute the position of the edge points, the model assumes that there is one point from which the current position t' and rotation matrix R_t' are known. This point is constantly related to one of the edge's touch points p_i. Naturally, in a VR context, this point would describe the position and rotation of a 6-DOF tracking device. In this thesis, we define this point as a constant offset to the front edge point p_0. This offset c is given as $c = p_0 - t$. Whereas t and p_0 are the positions in the reference state. Following, the current position of the front edge point p_0' can be computed by

$$p_0' = t' + cR_t' \; . \tag{3.11}$$

Given R'_t the vectors v_0, v_1 and v_2 can be computed. This is done by rotating a unit vector by the corresponding inner angle and applying the current rotational matrix of the tracked point R'_t This is formulated as

$$v_0 = w_0 \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} R_{x,\beta} R'_t \ , \tag{3.12}$$

$$v_1 = w_1 \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} R_{x,-\alpha} R'_t \ , \tag{3.13}$$

$$v_2 = w_2 \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} R'_t \ , \tag{3.14}$$

where v_i is computed as defined in Equation 3.1. $R_{x,\beta}$ and $R_{x,-\alpha}$ denotes the rotational matrix with an angle β or $-\alpha$ around the x axis respectively. Given v_0, v_1, v_2, and p'_0 the two remaining edge touch points can be computed by

$$p'_1 = p'_0 + v_0 \ , \tag{3.15}$$

$$p'_2 = p'_0 + v_2 \ , \tag{3.16}$$

The three origami structure touch points q_0, q_1, and q_2 are computed by the Equation 3.3 outlined in the previous Subsection 3.3.2.

3.5 Range of Motion

This section analyzes the different shapes Shiftly can transform into. Depending on the point where the user should touch, different shapes can be emulated, including cylindrical shapes, edge features, and flat surfaces. The calculation in this section is based on the kinematic model outlined in the previous Section 3.4 and uses the same notation. An overview of several different shapes Shiftly can transform into is given in Figure 3.16.

Shiftly can approximate cylindrical shapes ranging from a radius of around 46 mm to a theoretically infinitely large radius resulting in a flat surface. A single module can approximate only a part of any cylindrical shape. In this case, the user is restricted to touching only one of the three modules, and at the end of the origami structure, there will be an edge. By fully compressing a module, the corresponding origami structure will approximate 51% of a cylinder with a radius of around 46 mm. A larger cylinder is formed by extending the frame gradually, and when the frame is fully extended, a flat surface is approximated.

Cylindrical shapes can be formed by a single origami and multiple ones (e.g., by choosing the width of the three frames so that two or three origamis form a C_1 continuous surface). When approximating a cylindrical shape with two surfaces, the two origamis should

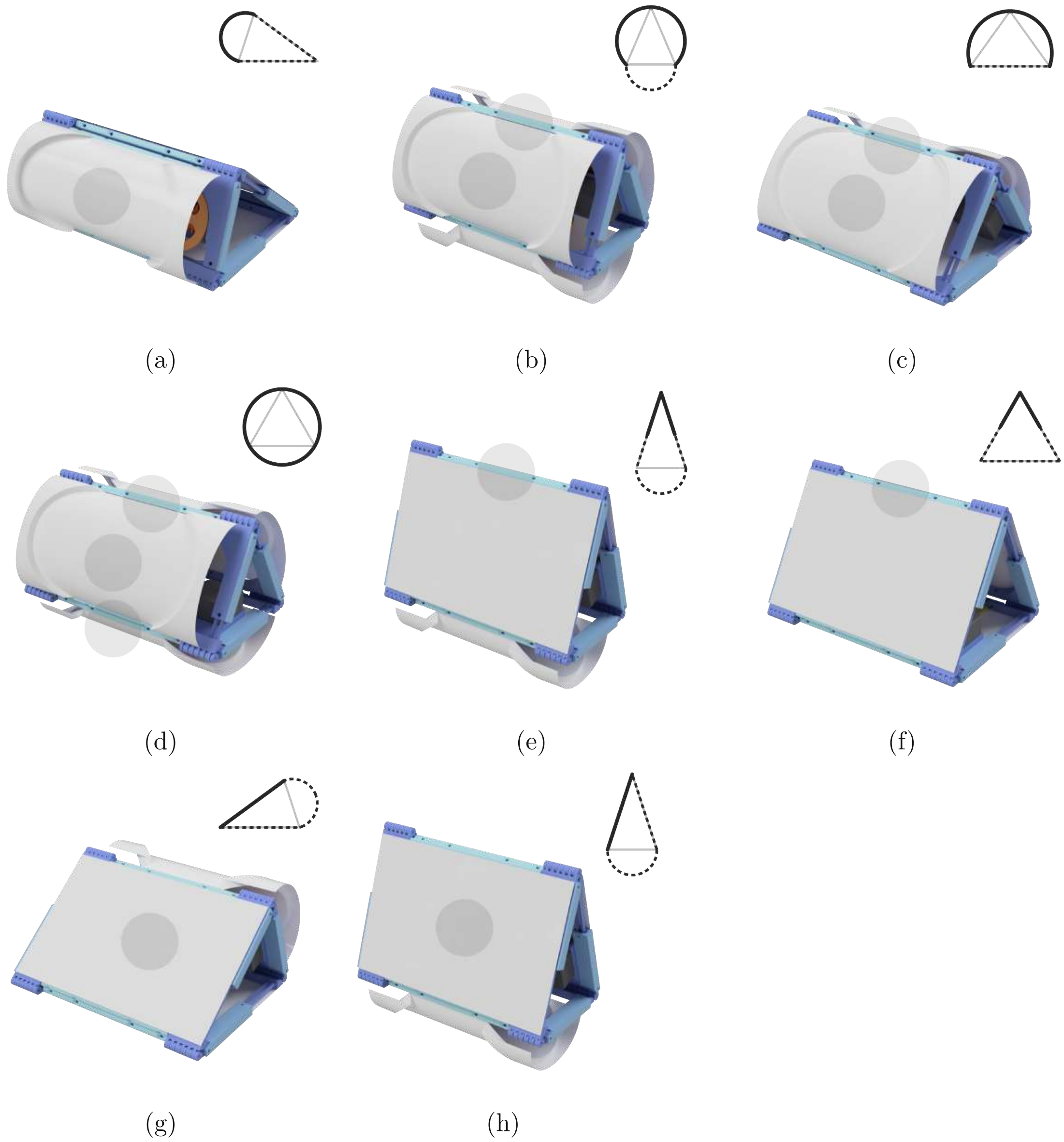


Figure 3.16: Different configurations of Shiftly. The gray circles indicate the ideal point for the touch by hand and the best approximation of the virtual shape. The greyscale scheme on the top right of each subfigure shows the simplified profile of Shiftly. Solid black lines indicate the targeted touch area, and dashed lines are the supporting parts of the origami structure. (a)-(d) show curved surfaces, (e) and (f) show different edge variations, and (g) and (h) show flat surfaces with different steepness. Tables 3.1-3.3 lists more details about the configurations.

not form an edge where they meet. Notice that even if only two origamis are used to approximate the cylindrical shape, the third module width can not be randomly picked, but should ensure that no edge is formed between the two modules the user is interacting with. By using two origamis, cylindrical shapes ranging from a radius of 63 mm to a radius of 78 mm can be correctly emulated. If the two top modules approximate the cylindrical shape, the bottom module is fully contracted in the first and wholly extended in the second. Figure 3.16b and Figure 3.16c show two configurations where Shiftly approximates cylindrical shapes with two origamis. A complete cylinder is formed if all three origamis are used. Give one the ability to touch a complete cylindrical shape without rearranging the device and without changing one of the module widths. This cylinder has a radius of 71 mm and forms a 360-degree C_1 continuous surface, as shown in Figure 3.16d. Table 3.1 lists different configurations approximating a cylindrical surface. This includes the smallest cylinder that can be approximated using a single origami, the minimum and maximum cylindrical shape that can be approximated using the top and back origami modules, and the cylindrical configuration that utilizes all three panels. This configuration are shown in the Figures 3.16a-3.16d.

If two modules are fully extended and from a flat surface each, they form an edge where they meet. The angle of this edge is manipulated by extending and contracting the third module. By entirely contracting the opposing module, a sharp edge is formed, and by gradually extending the module, a blunter edge is created. The sharpest edge has an angle of 0.63 radians, and the bluntest edge has an angle of 1.05 radians. The Shiftly configuration of these two edges is listed in Table 3.2 and is shown in Figures 3.16e and 3.16f. Flat surfaces can be approximated if one is meant to touch only a single origami structure. This flat surface is tilted by contracting and extending the two other modules. Assuming the flat surface is formed by the front origami structure, the surface is tilted to an angle of 0.63 radians when the back module is fully contracted and the bottom one fully extended. Extending the back module raises the front structure, and if the back module is fully extended, the front surface approximates a flat surface with a tilt of 1.25 radians. Table 3.3 lists the two extreme cases for the flat surface, and the configurations are shown in Figures 3.16g and 3.16h.

The configurations outlined above approximate corresponding geometric shapes, while in some scenarios, a less precise approximation of a shape is acceptable. For example, by allowing a blunt edge where two origami structures meet when a curved surface should be approximated. By allowing such an incontinuity, surfaces with a varying curvature can be emulated by two or three origamis. A round edge can be formed by contracting the two modules that form the edge slightly. Further, the configurations outlined are created without rotating the device in space. For example, a flat surface with every tilt can be approximated by rotating Shiftly.

Category	Radius (mm)	Origamis	θ_0, θ_1, θ_2	w_0, w_1, w_2	Figure
Curved surface	≈ 46	1	0, π, π	92, 148, 148	3.16a
Curved surface	≈ 63	2	≈ 1.67, ≈ 1.67, 0	≈ 1.17, ≈ 1.17, 92	3.16b
Curved surface	≈ 78	2	≈ 2.01, ≈ 2.01, π	≈ 127, ≈ 127, 148	3.16c
Curved surface	≈ 71	3	≈ 1.86, ≈ 1.86, ≈ 1.86	≈ 122, ≈ 122, ≈ 122	3.16d

Table 3.1: Different configurations of Shiftly approximating cylindricial structures. The radius corresponds to the radius of the cylinder that is approximated. The column origamis refers to the number of origamis that approximate the cylinder. θ_i refers to the rotation of the largest gear wheel and w_i to the width of the frame module (see Section 3.4).

Category	Angle (γ)	Origamis	θ_0, θ_1, θ_2	w_0, w_1, w_2	Figure
Edge feature	≈ 0.63	2	π, π, 0	148, 148, 92	3.16e
Edge feature	≈ 1.05	2	π, π, π	148, 148, 148	3.16f

Table 3.2: Different configurations of Shiftly approximating an Edge. The column origamis refers to the number of origamis that approximate the edge. θ_i refers to the rotation of the largest gear wheel and w_i to the width of the frame module (see Section 3.4).

Category	Tilt (β)	Origamis	θ_0, θ_1, θ_2	w_0, w_1, w_2	Figure
Flat surface	≈ 0.63	1	π, 0, π	148, 92, 148	3.16g
Flat surface	≈ 1.25	1	π, π, 0	148, 148, 148	3.16h

Table 3.3: Different configurations of Shiftly approximating a flat surface. The column origamis refers to the number of origamis that approximate the flat surface. θ_i refers to the rotation of the largest gear wheel and w_i to the width of the frame module (see Section 3.4).

CHAPTER 4

VR Integration

This chapter outlines the integration of Shiftly in the VR system. First, Section 4.1 gives an overview of the requirements and general mechanics of a VR system for Shiftly. Followed by a description of the developed VR application that uses Shiftly (Section 4.2).

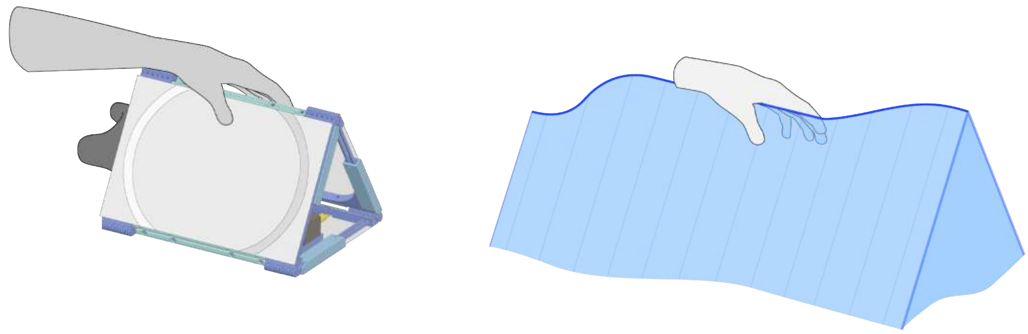
4.1 Requirements Definition

Shiftly is designed to be used in a Virtual Reality environment. Primarily with an HMD, other forms of virtual reality environments are also possible but are not explored in this thesis. The following approach focuses on providing haptic feedback to the user's hand when interacting with larger virtual objects, for example, placing the hand on the surface of a virtual object or grabbing an object on its edge. This Section outlines the general mechanics of how Shiftly provides haptic feedback, the challenges of tracking the device and the user's hand in space, and the transformation and alignment between Shiftly and the virtual object.

4.1.1 General Mechanic

The general mechanic is that when the user touches the virtual object at a specific point, this point of the virtual object is spatially aligned with the physical device. So when the user touches the virtual object in the virtual environment, the user also touches a part of the physical device. The Shiftly's point aligned with the virtual touch point approximates the geometry of the virtual object around the touch point on the virtual object.

The user is wearing an HMD. Thus, one can neither see the haptic device nor is there an indicator of the device in the virtual environment that lets the user know what part of the device is presented to the hand. The HMD provides visual feedback with the correct renderings of the user's hand and the virtual object one interacts with. For example, when the user is grabbing a virtual object's sharp edge, the user simultaneously grabs a



(a) (b)

Figure 4.1: Schematic visualization of the mechanic of Shiftly in VR. (a) A user's hand touching the top edge of Shiftly in the physical world. (b) A virtual representation of the hand and the virtual object (shown in blue) that the user touches in VR.

part of Shiftly. The haptic device transforms into a state where a specific part of the device – in this case, the top edge – forms an edge with a similar angle to the one the user is grabbing virtually. Figure 4.1 illustrates this example.

4.1.2 Tracking

To create the illusion that the user is feeling the virtual object, two critical aspects regarding tracking are fundamental. The user's hands have to be accurately tracked, and the relative position of the controller must be known whenever the user is meant to interact with a virtual object and receive haptic feedback. In exclusively virtual VR applications where the user exclusively interacts with virtual objects, a constant offset of the hand position might be unnoticeable by the user. However, the use of Shiftly requires, as for any physical haptic prop in VR, accurate positional tracking of the hands and Shiftly. Otherwise, when a user touches the virtual object and does not touch Shiftly at the intended position — this breaks the illusion of touching the virtual object.

Besides the device's position and orientation, the state of transformation of Shiftly has to be tracked. The VR application must precisely determine all six touch points of Shiftly– the center point of all three edges and the center point of each origami structure. This is achieved by tracking the rotation and position of a single device's point. Based on the tracked point's rotation and position, all the potential touch points of the device can be accurately reconstructed – utilizing the kinematic model described in Section 3.4.

4.1.3 Transformation & Alignement

When the next point on a virtual object the user will interact with is determined, the following two steps have to be performed.

1. **Transformation:** Shiftly has to transform so that a specific point on the device approximates the surface geometry of the virtual objects.

2. **Alignment:** The virtual point the user is going to touch and the physical point of Shiftly the user should feel when interacting with the device must be aligned.

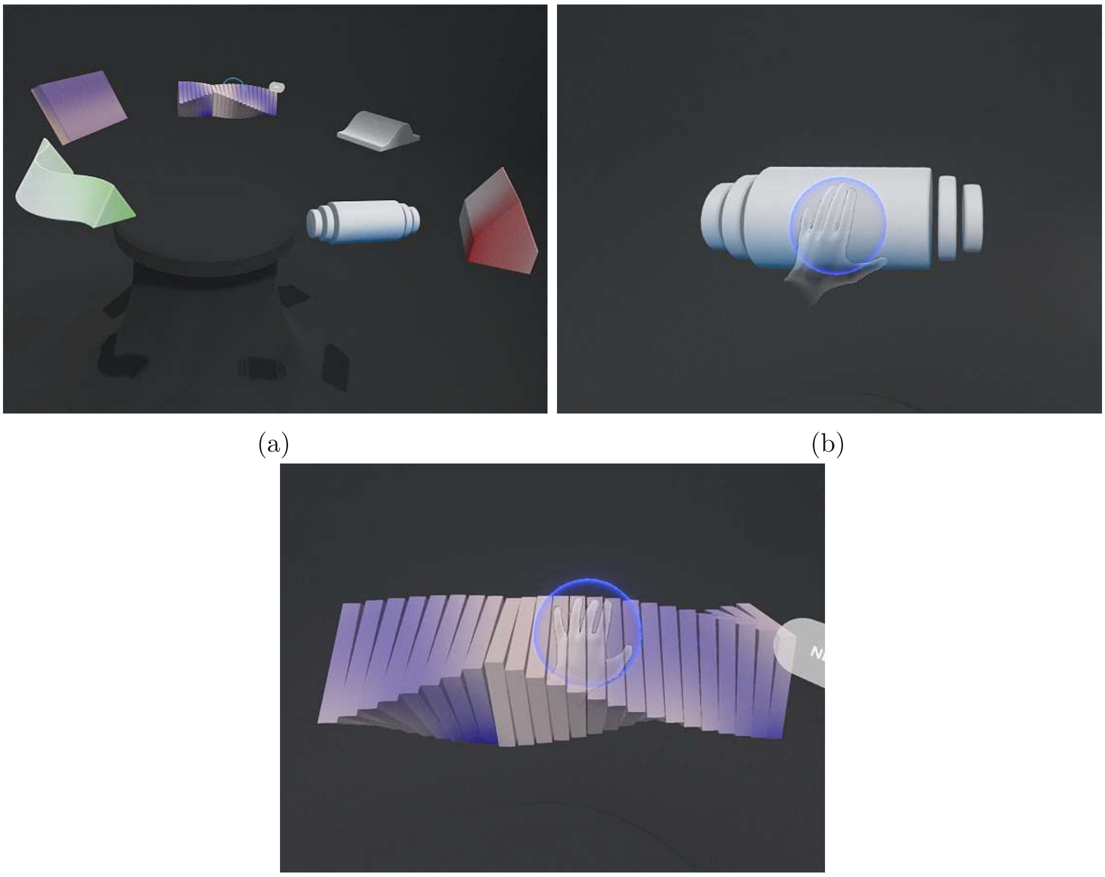
To determine the haptic device's target state, we must decide which part of the device should be touched by the user's hand and, therefore, approximate the virtual object's surface geometry. It also has to be decided, if the user's hand center should touch one of the three edges or if the user's hand should align with the center of one of the origami structures. Then, the extension level of each side of Shiftly must be determined to achieve the desired transformation. Following, the information of the extension or, more precisely, the target rotation of the largest gear of the device has to be transmitted to the haptic device's control unit, which initiates the transformation of Shiftly.

To create the illusion for the user of touching and feeling the virtual object, the touch points on the virtual object and the physical device have to be spatially aligned in position and orientation. This can be achieved in two ways. (a) Shiftly is moved by a sophisticated mechanism to align with the virtual touch point. For example Shiftly can be used as an end effector of a robotic arm. In this case, the robotic arm's range only limits the virtual touch point positions. Or (b) the haptic device is stationary, and the virtual objects are translated and rotated. This approach does not require a complex robotic arm or similar machinery and only requires an attachment to mount the device on a tripod or onto the table, as presented in Section 3.3.2.

Shiftly being at a fixed position in space might be limiting in some scenarios. For example, when a user wants to explore a virtual space, the design space of that virtual environment is minimal. However, a stationary haptic device could be beneficial and practical in a more object-centered scenario. In systems where users should explore virtual objects rather than spaces. For instance, for a shopping application or museum experience for historical artifacts.

4.2 VR application

The developed application in this thesis works with a stationary Shiftly, and objects are translated and rotated to align with the haptic device. One object after another is presented to the user, including a visual indicator of where to touch the virtual object. The location of the individual touch points and the corresponding Shiftly configurations are prepared in advance and are calculated using the kinematic model outlined in Section 3.4. The different objects are arranged in a circle around the user. If the user decides to try out the next object, the object circle is rotated till the next object aligns with the physical device. An overview of the virtual environment is shown in Figure 4.2a. While the virtual object is selected for interaction, the position of the object is constantly aligned with the haptic device. So, in case the haptic device is translated or rotated, the virtual objects



(a) (b)

(c)

Figure 4.2: Screenshots of the VR application. In (a), the application's environment is shown, with the different shapes arranged in a circle. (b) shows how a user is touching a cylindrical shape. The blue sphere indicates the touch point; the user's hand is tracked and visually represented with an outline material. (c) shows a user touching a shape that can not accurately approximated by Shiftly.

(a) (b)

Figure 4.3: User touching a rounded shape in VR while touching the aligned Shiftly in the physical world. (a) The user's hand touching the top of Shiftly, and (b) the virtual world, with the virtual object (orange), the user's semi-transparent tracked hand, and the blue sphere indicating the touch area.

move the same way. Ensuring that the user is touching the haptic device simultaneously with touching the virtual object. Figure 4.3 pictures a user touching a curved surface in VR while feeling the curved surface of Shiftly.

The objects the VR users can grab and touch are all larger than the haptic device and the user's hand. Hence, the user only interacts with a portion of the object surface. A screenshot of a user touching a cylindrical object is shown in Figure 4.2b. Further, not only objects are tested that can be well approximated by Shiftly but also surface structures that can not be fully emulated. For example, surfaces that are concave or consisting of small discrete steps, like in the example shown in Figure 4.2c. We assume in combination with the visual feedback, Shiftly can provide good haptic feedback even in those challenging cases — resulting in an immersive experience and better task performance.

Objects that users can try out in the test environment are rendered with an artificial-looking material. The partially glowing materials have a multi-color pattern and an undefinable rough structure. We aimed to reduce the expectations of the haptic experience based on the real world when touching a virtual object if it is similar to something the user has experienced previously. Therefore, the application focuses more on the geometric surface approximation of our test virtual objects rather than influencing the user's haptic experience with additional visual and contextual information. A screenshot of some material used in this thesis project is shown in Figure 4.2b and Figure 4.2c.

CHAPTER 5

Fabrication and Implementation of Shiftly

This chapter outlines the implementation of the concepts and ideas described in the previous sections. We fabricated and assembled two Shiftly prototypes, plus spare parts, including designing and assembling the electronic components, frames, and origamis. We implemented an immersive VR application that uses Shiftly to provide haptic feedback to the user. The final software and hardware prototype was used in all user evaluations and is resilient enough to withstand daylong user testing.

First, the fabrication process of the 3D-printed frames (Section 5.1) and the origamis (Sections 5.2) are described, followed by the electronic hardware that is used (Section 5.3) to control the haptic device, including the actuators with the custom-designed *Printed Circuit Board* (PCB) and the control program for the main microcontroller (Section 5.4). Finally, the implementation of the VR application and the used VR hardware devices are discussed (Section 5.5).

5.1 Frame

Each Shiftly consists of three frames that are entirely 3D printed (except the screws). Each of these modules consists of twelve individual parts, whereas the two largest elements were split in half to fit the dimensions of the 3D printer. The parts are printed with an UltiMaker 2+ [Ult23] printer with a 20% infill and resolution of 0.15 mm. All elements, including the gears and sliding elements, are printed with standard PLA filament. The mechanical and movable parts required intensive post-processing and sanding to remove all irregularities and create a smooth surface where two 3D-printed parts rub against each other—for example, the sliding rails on both ends of each frame module. Additionally, the rails are lubricated with silicon spray to ensure that the modules can reliably extend and contract.

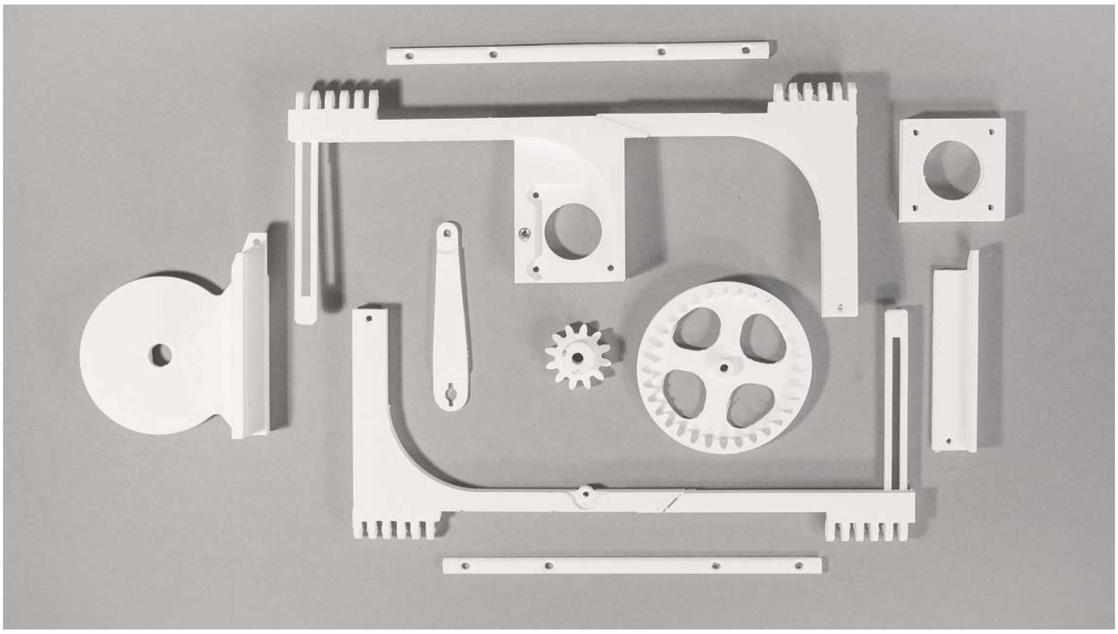


Figure 5.1: 3D printed parts of one frame.

Threaded bolts with a diameter of 3mm are used to connect the individual parts. For the screw that secures the large rotational gear, metal tread inserts are used because the placement above the motor did not allow the use of a nut at the end of the screw. The inserts were heated with a soldering iron and pressed into the 3D-printed elements. An overview of the fabricated parts can be seen in Figure 5.1 and Figure 5.2 shows the fully assembled frames of Shiftly.

5.2 Origami

The origami outlined in Section 3.3.1 are cut and folded by hand. A thick paper with a weight of $380g/m^2$ and coating on the top side is used. The coated side is used as the side that users are touching. In our testing, the stiffness of the paper was sufficient for testing purposes and could be bent and folded without complication. They resulted only in minimal unwanted deformation when users touched the origami gently, in the unfolded, and in the folded state. The touch area becomes stiffer the more the origami is folded. Further, the paper was also resistant, and the same origamis could be used for day-long user testing before they needed to be replaced.

The thickness of the paper required that the curved creases be scored. Utilizing a cardboard stencil, slots were cut out along the crease lines. Then the scoring tool was moved along these slots to score the paper. Depending on the folding direction of the crease, the paper is scored on the front or back. The holes that are used to screw the origami to the frame are punched out by a circular punching iron with a diameter of

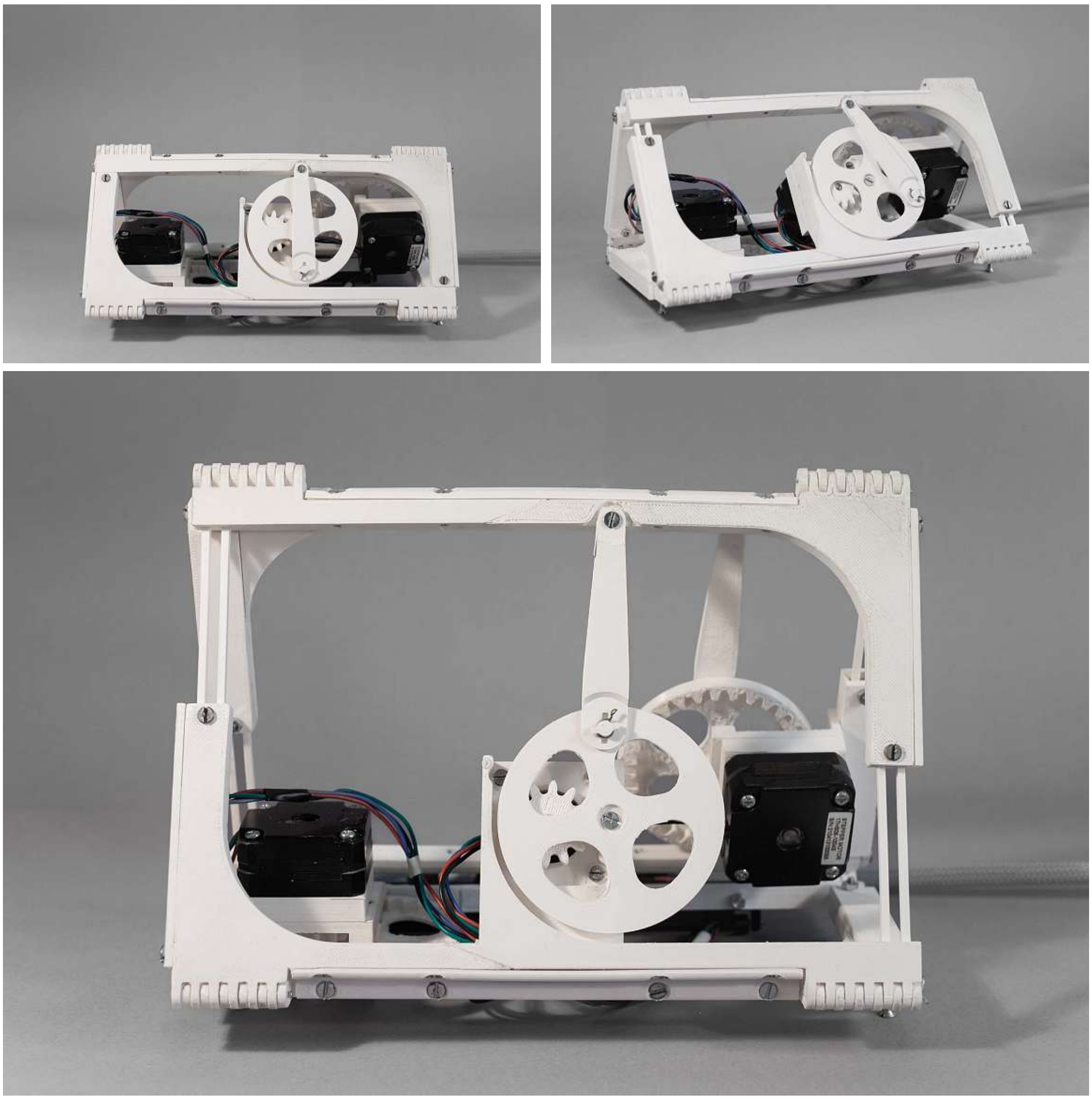


Figure 5.2: Three assembled and connected frames of Shiftly. The frames are shown with different levels of extension.

Figure 5.3: Fabricated origami structure

3 mm. Figure 5.3 shows the manufactured origami in different folding states.

5.3 Electronic Components

The main electronic components used for the haptic device are stepper motors and suitable stepper motor controllers, an ESP32 development board, and a custom-designed PCB to connect the components. As the main microcontroller, an ESP32-DevKitC V4 [ESSC23] development board was used. The board uses an ESP-WROOM-32 module [Co.23] with a chip that has two CPU cores. The development board has 32 I/O pins, an onboard Wi-Fi module, and a micro USB port.

Each module is equipped with a Nema 17 bipolar stepper motor that has body dimensions of 42 mm by 42 mm by 21 mm. According to the manufacturer's data-sheet [Ste], the motors produce a holding torque of 16 Ncm and have a resolution of 200 steps per revolution. The motors, together with a gear reduction of 32/12, result in an appropriate stiffness of the Shiftly. A more powerful motor and reduction gear resolution could potentially harm the user's hand when the device transforms – for example, pinching the user's finger. Therefore, it would require additional safety mechanisms. On the other side, with a weaker motor and gear combination, the haptic device would not withstand the force when a user pushed with the hand against the device and could unintentionally contract or extend. The motors are controlled by A4988 [Mic14] driver boards that over the possibility of micro-stepping. Because of design simplicity, we do not measure the rotation of the motors. Hence, the software has to record the rotation and number of steps as outlined in Subsection 5.4. A custom two-layer PCB was designed to connect the EPS32 development board to the motor controllers. The PCB has a width of 67.3 mm and a depth of 78.4 mm and includes four holes to mount the board in a housing. The board contains three motor drivers to control all three motors of Shiftly. The ESP32 development board is powered via the Micro USB port, and the motors are powered with an external 12V power supply. The schematic of the board can be seen in Figure 5.4. Shiftly's motors are connected by a detachable cable to the PCB, whereas each motor utilizes four wires. The PCB was designed using Autodesk Fusion 360 [Inc23b] and was manufactured by Multi Leiterplatten GmbH. Figure 5.5a shows the scheme of the two-layered PCB, and Figure 5.5b shows the manufactured and manually assembled board. While the PCB was manufactured, the components were soldered to the PCB by

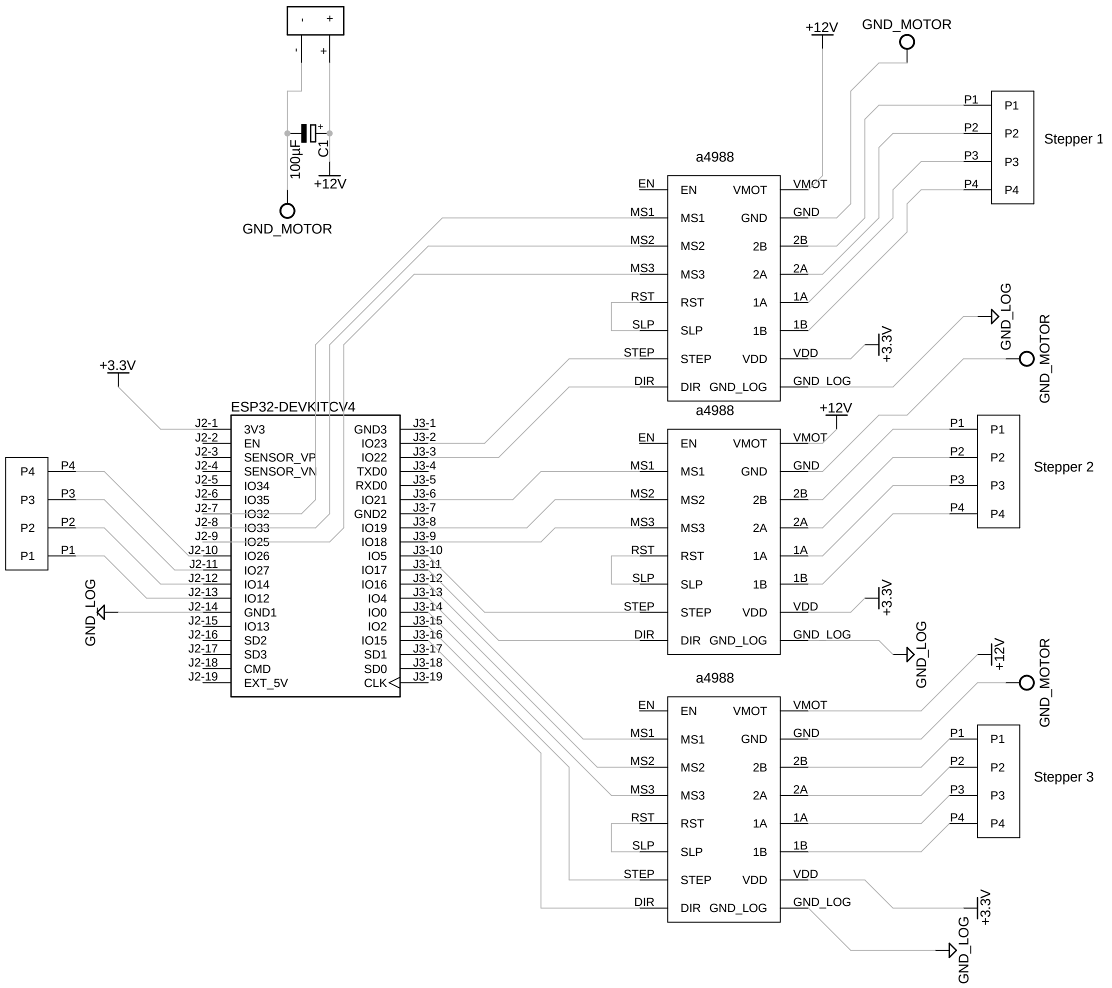
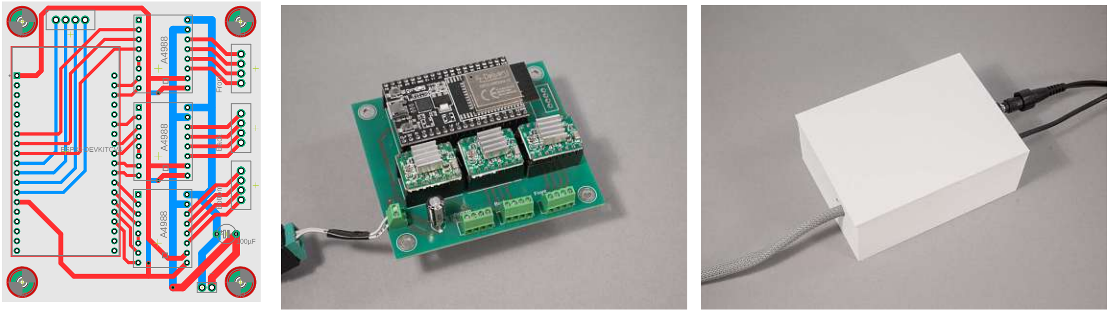


Figure 5.4: Circuit diagram of the PCB. The circuit containing the ESP32-DevKitC V4 microcontroller development board is placed on the left side. The three stepper motor controllers A4988, and the corresponding exposed pins are named Stepper 1 to 3. The GND_LOG labels the ground line of the 3.3V logic circuit, and GND_MOTOR the ground line of the 12V motor circuit. Additionally, four pins of the ESP32 are exposed, shown on the left.



(a) (b) (c)

Figure 5.5: Custom PCB board. (a) shows the circuit scheme design. Connections placed on the top layer are drawn in red and the lines of the bottom layer in blue. (b) manufactured and assembled PCB. (c) the 3D printed housing of the PCB.

hand. To house the PCB, a small 3D-printed box was designed. A picture of the PCB housing can be seen in Figure 5.5c.

5.4 Control Program

The prototype is controlled by an ESP32 chip, programmed with MicroPython 1.21.0 [PGS23]. The program aims to receive instructions for extending or contracting the modules of Shiftly and control the stepper motors accordingly. For that purpose, two communication APIs are developed — one for wired communication via micro-USB and one for wireless utilizing the onboard wifi module of the ESP32.

As mentioned in Subsection 5.3, no sensor measures the rotation state of the motor. Hence, the control program has to keep track of the rotation of the motors. This is accomplished by counting the steps of each motor. Depending on the rotation direction, the counter is increased or decreased. This step counter s_i can be easily converted to the current rotation θ_i of the large gear of the motor i with the following equation:

$$\theta_i = 2\pi G \frac{s_i}{S}, \tag{5.1}$$

where S denotes the number of steps per motor revolution, and G is the gear ratio. In the case of the used stepper motors, $s = 200$, and the used gear ratio is $G = 32/12$. The control program assumes the device is fully contracted ($\theta = 0$) at the program's start. Otherwise, the counter of each motor has to be manually initialized using the communication APIs. This is done either by sending the instructions to rotate the motors without updating the step counter or editing the step counter without turning the corresponding motor. The program utilizes the two cores and multi-thread capabilities of the ESP32. It controls each stepper motor in a separate thread, enabling the simultaneous control of multiple stepper motors.

API Commands
Command Line: `stepper=<int> degree=<int> microsteps=<int>` REST: `PUT ?stepper=<int>&degree=<int>&microsteps=<int>` Rotates the stepper motor to the corresponding degree. After the rotation is completed, the motor is rotated to the given number of degrees. `microsteps` manipulate the speed of the rotation.
Command Line: `set stepper=<int> degree=<int>` REST: `PUT /set?stepper=<int>&degree=<int>` The `set` command is used to set the internal step counter. When executed, the internal step counter is set to the provided value without rotating the motor. This command is used to adjust the counter after the system loses track of the rotation of the motor.
Command Line: `step stepper=<int> degree=<int> microsteps=<int>` REST: `PUT /step?stepper=<int>&degree=<int>&microsteps=<int>` The `step` command rotates the motor by a certain number of degrees. In contrast to the above command, the large gear is rotated by the given degrees, but the step counter is unchanged. This command is used for the initialization of the physical device.

Table 5.1: List of the control program's APIs. Including the serial commands, the HTTP endpoints, and a description.

To control the stepper motor's rotation wirelessly, a light HTTP server runs on the ESP32. The client, for example, a VR application, sends the information about the wanted extension of the modules of Shiftly via HTTP requests to the server running on the ESP32. The HTTP endpoints follow a REST style [Fie00] and include parameters for the stepper motor that should be manipulated, the final degree of the large rotation gear, and the speed of the rotation of the motor. For wired communication, a similar command line interface is provided. In total, three commands are implemented. (1) To transform a stepper motor to a desired state, (2) to rotate the large rotation gear by a certain degree without updating the internal rotation counter, and (3) a command to overwrite this counter with a provided value. Table 5.1 gives a detailed overview of the two APIs.

5.5 Virtual Reality Application

The VR application was developed with Unity3D 2021.3 [Tec23b] using the OpenXR platform [Inc23c] and C# [Mic23]. The shapes the user is touching were created in Autodesk Fusion360 [Inc23b], and the render material for those shapes was implemented in Unity's shader graph system [Tec23a]. As HMD, a HTC Vive Pro [Cor18] with a Leap Motion Controller [Ult19] for hand tracking was used. We explored the camera-based hand tracking of the HTC Vive, and we encountered tracking issues of the hands in some scenarios with artificial lighting, leading to imprecise and unresponsive hand tracking.

The haptic device is tracked by a 6-degree-of-freedom HTC Vive Tracker [Cop18] that is mounted on Shiftly's frame. To precisely align the virtual objects and the correct parts of the haptic device, a digital replication of the haptic device was implemented, including the position of all six touch points of Shiftly. The developed application can communicate with the control unit of Shiftly via the wireless or the wired communication API outlined in Section 5.4. The application sends the rotation instructions for each stepper motor after a new shape is selected to touch by the user. For the instructing person, shortcuts are provided to initialize the state of Shiftly after a restart of the haptic device's control unit. As outlined in Chapter 4, the VR application aligns virtual objects and the haptic device by translating and rotating the virtual objects.

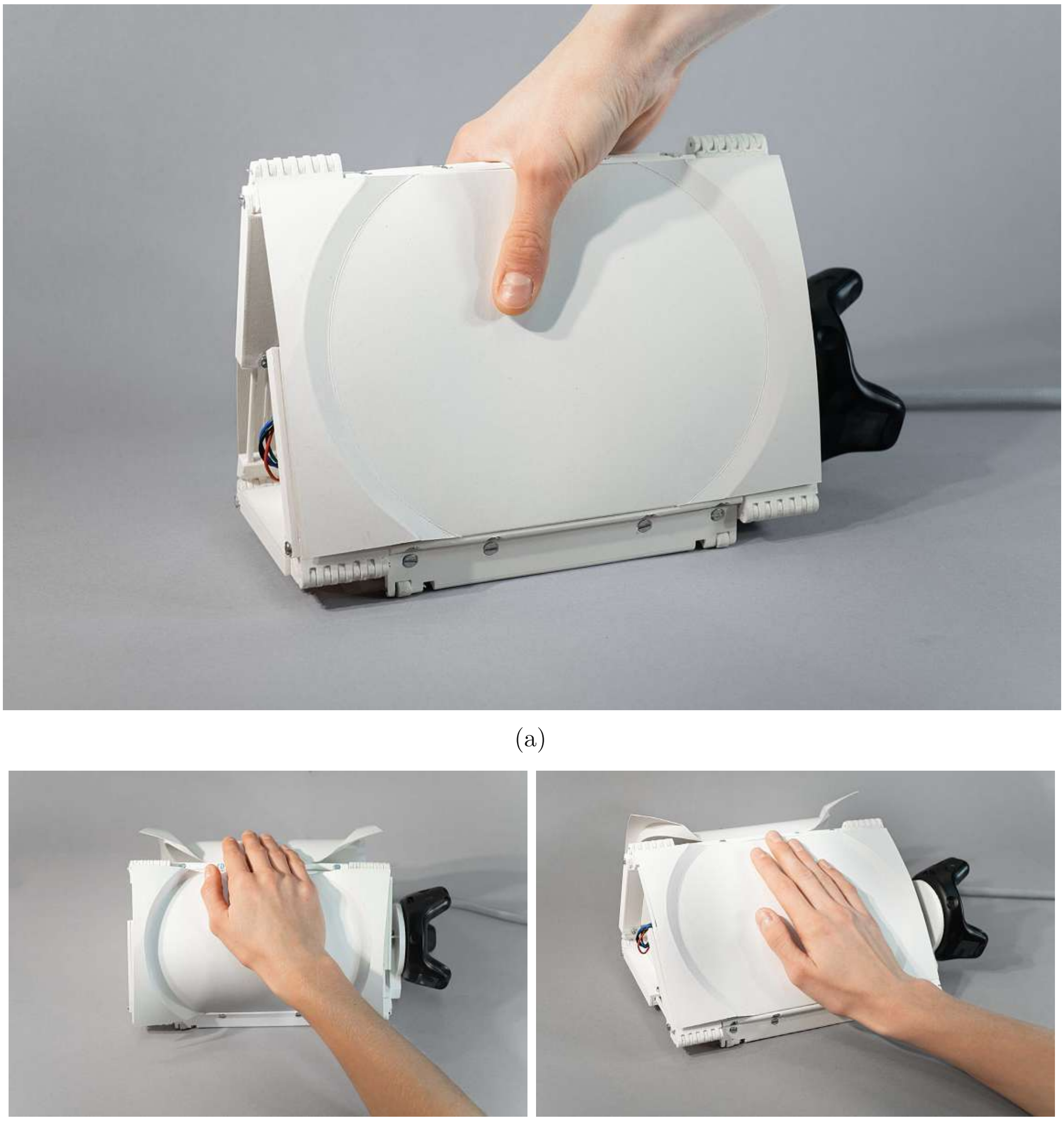
A point of an object for which haptic feedback is provided is defined as the point on Shiftly that aligns with the virtual object, the three motor rotations, and the relative position to the virtual object the user touches. Additional visual indicators for where the users place their hands are defined.

The UI elements of the virtual reality application were positioned relative to the current position and rotation of the haptic device. The UI elements are controlled by tapping the virtual buttons with the tracked hands or by a ray-casting method [Min95] using the HMD's handheld controllers. Additionally, the experimenter can control the whole control interface via the keyboard in case participants struggle to interact with the UI elements.

Figure 5.6 shows Shiftly as we have used it in all user testing — mounted on the table and with a Vive tracker on the right side. Pictures of one user touching Shiftly can be seen in Figure 5.7.

(a) (b)

Figure 5.6: Shiftly mounted on the table and with an attacked Vive tracker. In (a), the origami is extended, and in (b) the origami is contracted.



(a)

(b)

(c)

Figure 5.7: User touching Shiftly. A tracker is attached on the right side of Shiftly. The user touches a sharp edge in (a), in (b) a curved surface, and in (c) a flat surface.

CHAPTER 6

Evaluation

Two user studies were conducted to evaluate the capabilities of Shiftly. Booth studies focus on a VR use case where the user wears an HMD, and the haptic device is not seen by the user when interacting with the device. The first study investigates the realism of the haptic feedback when the user virtually touches a real object shaped to match what is visually rendered. The study and its results are outlined in Section 6.1. The second study evaluates the range of haptic feedback the device can render. Section 6.2 summarizes the study design and its results.

6.1 User Study 1: A Principle Mass Experience Testing

This user study investigates the ability of Shiftly to give haptic feedback to a user when touching a virtual object. The plausibility and realism of the haptic feedback for differently shaped objects and the general experience with the device were tested. The users had to touch six different shapes in a VR application. An overview of the conditions, including the visually rendered shape and an indicator where users had to touch the shape, is shown in Figure 6.1. Not all of the shapes could be accurately approximated by the haptic device. The concave surface of the green objects (Figure 6.1f) and the small steps of the purple object, shown in Figure 6.1c could not be emulated by Shiftly.

6.1.1 Procedure

In the study, participants had to touch the virtual objects one after another. They were instructed to touch the virtual objects primarily with their dominant hand — where the indicator was placed. Users were allowed to move their hands around by a few centimeters, and it was explained that they could use their fingertips and their whole hands to explore the virtual object at that point. After touching each object, they were asked to answer the following question: “How realistic was the shape simulation?” on a

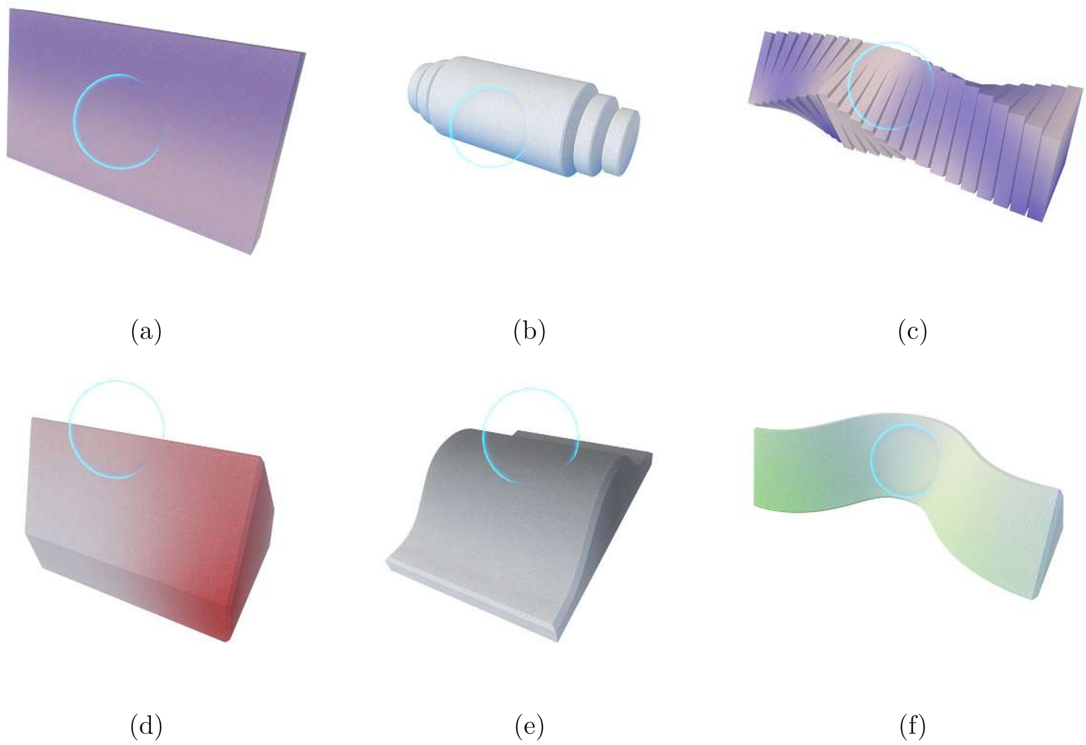
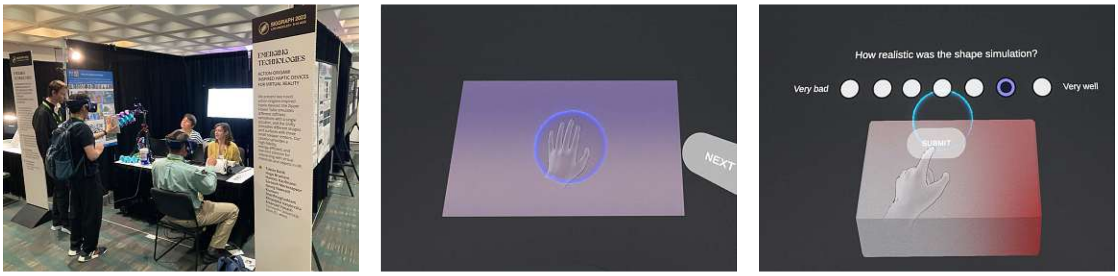


Figure 6.1: Overview of test shapes. (a) Flat Surface, (b) Cylinder, (c) Rotated Diamonds, (d) House, (e) Wave, and (f) Concave Surface. (c) and (f) can not be accurately emulated by Shiftly.

seven-point Likert scale, ranging from (1) very bad to (7) very well. The order in which the users were experiencing the shape was counterbalanced through a Latin square. One repetition per shape was proceeded. No time limit was given on how long they could explore and touch the virtual object.

To evaluate the overall haptic experience, after the participant experienced all six objects, they were asked: "How would you rate your haptic experience?", and to evaluate the usefulness of the device: "Would you use such a device for haptics in VR, for example for virtual shopping?". Both questions had to be answered on a seven-point Likert scale. For the usability question, the Likert scale ranged from (1) very bad to (7) very good and from (1) very unlikely to (7) very likely for the question that investigated the usefulness of the device.

The users were interacting with the UI by poking a button with their index finger. If a participant struggled with the interaction, the experimenter could control the interface via keyboard shortcuts. Figure 6.2c shows an example of the UI. Participants were told that they could stop at any time and take off the HMD. Touching the six objects and answering the question took around 5 minutes, including the instructions for the



(a) (b) (c)

Figure 6.2: Overview of the first user study. (a) shows the test setup at ACM SIGGRAPH 23. (b) shows a screenshot while touching an object, and (c) the UI for rating the realism of the haptic feedback.

participants. For evaluation, we only used the data of participants who completed all the shapes and answered all questions.

6.1.2 Test Setup

For this study, Shiftly was mounted on a table, with two origamis mounted on the two upper modules. The participants were sitting in front of the device and wore an HMD (Vive Pro) with a hand-tracking device (Leap Motion Controller) attached for that purpose. The user's hands are tracked and visually rendered. An indicator placed on the surface of the virtual object guided the user's hand to the right place where the object should be touched. Figure 6.2b shows a screenshot of a participant touching a flat surface. The user study occurred during a conference (ACM SIGGRAPH 23, Los Angeles), where we were showcasing Shiftly for five days, six hours per day. Figure 6.2a shows a photo of the test environment.

6.1.3 Participants

The experiment involved 170 participants who attended the conference. Due to the constraints of the event, we did not collect the demographic data of the participants, but the study sample mainly consisted of students and professionals in the fields of Computer Graphics, VR, AR, and Virtual Cinematography. Since the experiment was on a voluntary basis while showcasing, participants were free to stop at any time. Among the 170 participants who tried Shiftly, 147 participants completed the entire experiment.

6.1.4 Experience Study Results and Discussion

The question about the realism of the haptic experience was asked after each shape trial. Figure 6.3 shows the answers reported by participants per shape and Table 6.1 reports the mean and standard deviation of the answer after each trial. Participants rated the Cylinder the highest (Mean=5.57), followed by the Wave (Mean=5.42). The two shapes that the haptic device can not accurately emulate performed the worst. The Rotated

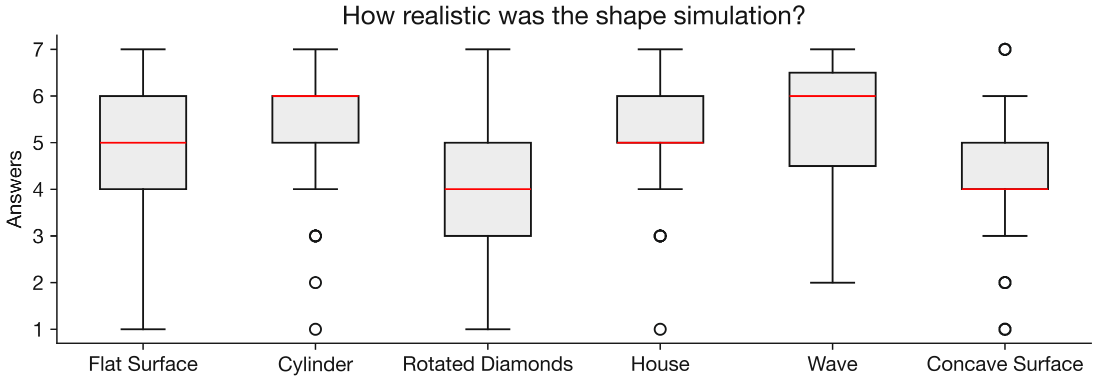


Figure 6.3: Box plots of the user's answers to the question: "How realistic was the shape simulation?" for each shape. The seven-point Likert scale ranged from (1) very bad to (7) very well. The median is drawn in red.

Shape	Mean	SD
Flat Surface	4.748299	1.484364
Cylinder	5.571429	1.216327
Rotated Diamonds	3.925170	1.544271
House	5.285714	1.199315
Wave	5.421769	1.297654
Concave Surface	4.401361	1.483516

Table 6.1: The table shows the mean and the standard deviation of the user's answers to the question: "How realistic was the shape simulation?" for each shape.

Diamonds were rated the lowest, with a mean of 3.92, followed by the Concave Surface with a mean of 4.4.

A Kruskal–Wallis test showed that there was a significant effect of the shape on the answer provided by the participants ($\chi^2(5) = 135.01$, $p < 0.001$), where pairwise comparisons using Wilcoxon rank sum test with continuity correction showed that Rotated Diamonds scores were significantly lower than the other shapes ($p < 0.05$).

As for the post-experience questions, Figure 6.4 shows the frequency of participant's answers. Overall, participants rather enjoyed the haptic experience ("How would you rate your haptic experience?": Mean=5.18; SD=1.14), where participants reported they were impressed by the haptic feedback provided by Shiftly. Yet, participants were not entirely convinced regarding the use of such a device for virtual shopping in VR ("Would you use such a device for haptics in VR, for example for virtual shopping?": Mean=4.44; SD=1.69), where some participants reported that they would rather imagine such device for different applications such as product design for larger objects or games.

Further, participants pointed out that the possibility of haptic feedback is affected by

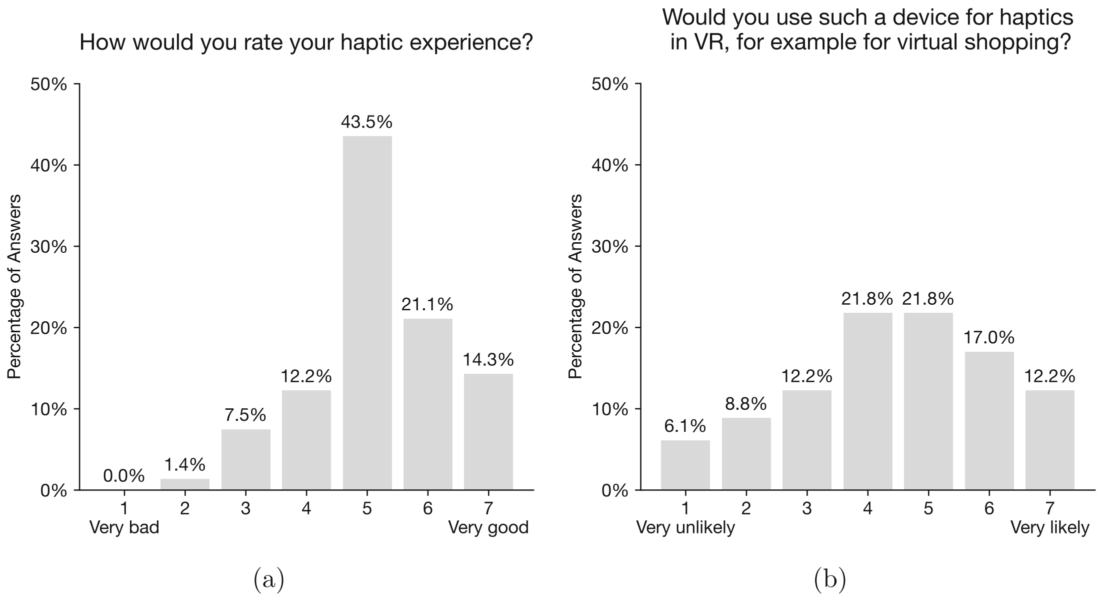
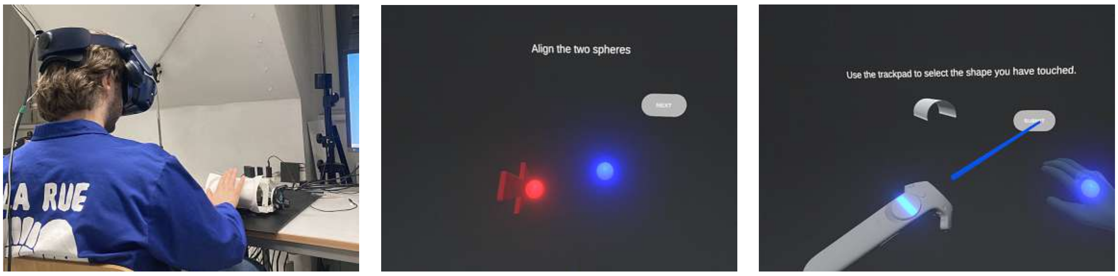


Figure 6.4: Results of the post-exposure questions. (a) “How would you rate your haptic experience?”, and (b) “Would you use such a device for haptics in VR, for example, for virtual shopping?”

the precision of the hand tracking and, therefore, of the alignment of the virtual world and the virtual objects and hands. Multiple participants pointed out that touching the virtual object was plausible when the tracking was good. In the other case, this illusion was less present when the hand tracking was not precise.



(a) (b) (c)

Figure 6.5: Overview of the Qualitative user study. (a) shows the users study setting. (b) shows a screenshot of the participant's view before touching the haptic device, with the blue sphere indicating the position of the participant's palm and the right sphere indicating where the haptic device should be touched. (c) shows the stage after participants had touched the device and selected a shape that is most similar to the one they had touched.

6.2 User study 2: Qualitative Evaluation

Unlike the first study, qualitative evaluation was carried out as a controlled experiment in a dedicated setup with little disturbance. The study was conducted without direct visual feedback to evaluate the range of haptic feedback that Shiftly can provide.

The task of the participants was to touch Shiftly in different configurations and, after each configuration, had to select a virtual shape that is the most similar to the haptically rendered one by Shiftly. Compared to the evaluation outlined in Section 6.1, no visual representation of an object or surface was provided when the user touched the device. Only a visual indicator where the user should place the hand was shown. The participants had to wear an HMD with a hand-tracking device (Leap Motion Controller) attached. The haptic device was mounted on the table with two origami pieces attached to the top two frames. During the study, when the participant was not wearing the HMD Shiftly was covered by a fabric. Hence the participants saw Shiftly for the first time after completing the study. Figure 6.5a shows a photo of the study setup.

6.2.1 Procedure

Participants were instructed to touch Shiftly with their dominant hand to interact with the virtual objects displayed in the Virtual Environment. A blue sphere indicated the user's dominant hand's palm, and a red sphere indicated where the participant should touch the device. The participants were instructed to align the two spheres, and they were informed that they would touch the real haptic device with their hand when they aligned the two spheres. Additionally, a red arrow was pointing to the red sphere. This arrow indicated the ideal trajectory of the participant's hand when aligning the two spheres. A screenshot from the participant's perspective is provided in Figure 6.5b. To give no indications of the shape of the current device, nor through a visual representation of the user's hand, the user's hand and the haptic device were not visually rendered.

Index	Category	Shiftly Configuration	Diameter	Curvature	Inner angle	Tilt angle
F1	Flat surface	×	∞	0	180°	90°
F2	Flat surface	×	∞	0	180°	80.94°
F3	Flat surface	✓	∞	0	180°	71.89°
F4	Flat surface	×	∞	0	180°	54.05°
F5	Flat surface	✓	∞	0	180°	36.21°
F6	Flat surface	✓	∞	0	180°	18.11°
F7	Flat surface	×	∞	0	180°	0°
FE	Flat Edge	×	∞	0	126°	0°
E1	Edge feature	×	∞	0	72°	0°
E2	Edge feature	×	∞	0	66°	0°
E3	Edge feature	✓	∞	0	60°	0°
E4	Edge feature	×	∞	0	48°	0°
E5	Edge feature	✓	∞	0	36°	0°
E6	Edge feature	×	∞	0	30°	0°
E7	Edge feature	×	∞	0	24°	0°
CE	Curved Edge	×	86.2	≈0.023	≈111.0	0°
C1	Curved surface	×	60	≈0.033	180°	0°
C2	Curved surface	×	76	≈0.026	180°	0°
C3	Curved surface	✓	92	≈0.022	180°	0°
C4	Curved surface	×	125	≈0.016	180°	0°
C5	Curved surface	✓	156	≈0.013	180°	0°
C6	Curved surface	×	173	≈0.011	180°	0°
C7	Curved surface	×	188	≈0.010	180°	0°

Table 6.2: Table outlining the geometric properties of all the possible visual shapes participants could choose from when selecting the surface most similar to the one they have touched in the previous step. In case the shape was one of the six shapes Shiftly emulated in the user study in the column Shiftly Configuration a ✓ is shown, × otherwise. The diameter is given in millimeters, the curvature in mm^{-1}, and the angles in degrees.

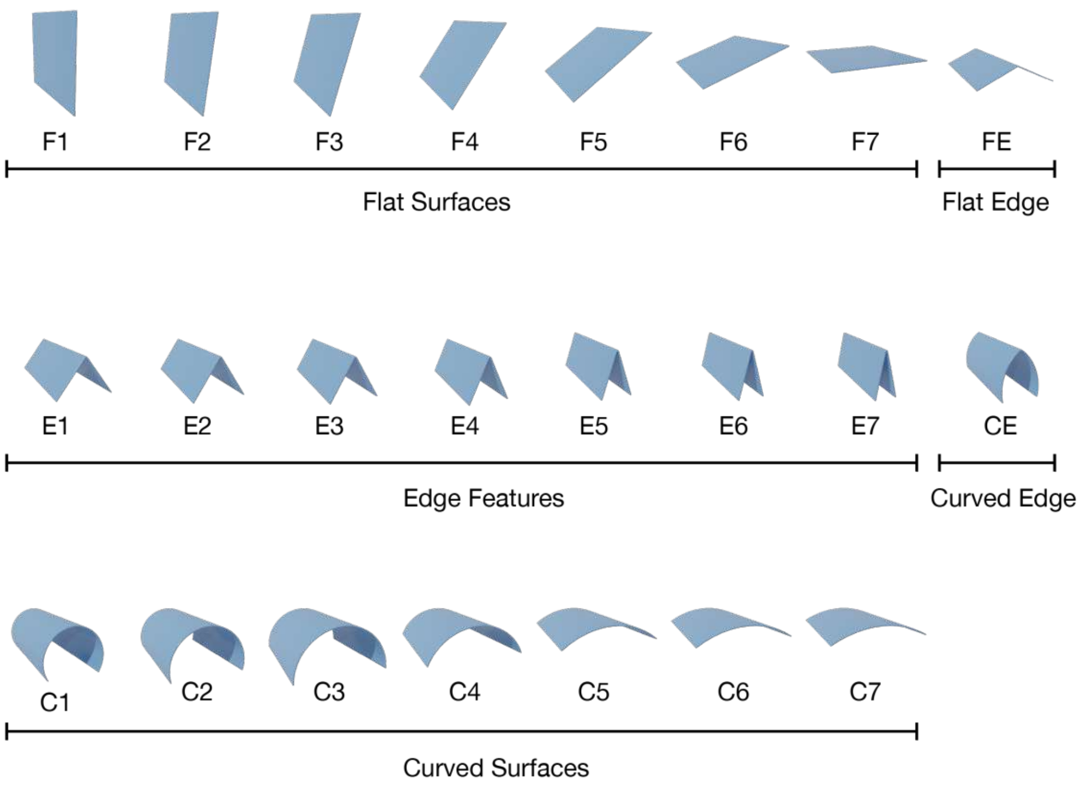


Figure 6.6: All the possible visual shapes participants could choose from when selecting the surface most similar to the one they have touched in the previous step. The index of the 32 shapes is shown, as well as the category (Flat Surface, Flat Edge, Edge Feature, Curved Edge, and Curved Surface) they belong to.

Hence, while interacting with Shiftly, the participants could only see the blue and red spheres, the direction arrow, and an instruction message.

When touching the haptic device, participants were instructed to try to remember the geometry and shape of the surface rendered by the haptic device. No time limit was given on how long they were allowed to touch the device, but participants were instructed not to move their hands while touching the device and that they were only allowed to touch the device once per test case.

The user study included six different configurations of Shiftly. Two flat surfaces with different steepness, a sharp edge, and a blunter edge, and two curved surfaces. The geometric properties of those six shapes that Shiftly emulates are listed in Table 6.2 (marked with an ✓ in the row "Shiftly Configuration"). Every participant tried each Shiftly configuration three times — resulting in 18 trials. The order of the six configurations in each of the three blocks was counterbalanced through a Latin square.

After the participant touched one configuration of Shiftly and no longer touched the device, they had to proceed to the selection task using the VIVE controller in their non-dominant hand. The participants were presented with an animation showing a three-dimensional surface that morphed between different shapes. The users could scroll through that animation by tapping on the VIVE controller's touchpad. During the selection task, the dominant hand of the user was rendered. A screenshot of the participant's view during the selection stage can be seen in Figure 6.5c.

Participants could select between 23 different options. The options included flat surfaces with different tilts, edges with different angles, and curved surfaces with different curvatures. An overview of all shapes participants could choose from is shown in Figure 6.6. The geometric properties of the shapes are outlined in Table 6.2.

After the participants selected one shape, they had to rate their confidence regarding their selection, on a seven-point Likert Scale ranging from (1) not at all to (7) very confident. After the selection, the next test trial started. In total each participant had to complete 18 trials. During that time, participants wore the HMD constantly. A break between the trails was not scheduled.

6.2.2 Participants

In total, 21 participants took part in the user study, and all participants completed all test cases. All participants took part in the study voluntarily and received no compensation. The data was collected from 20th October to 2nd November 2023.

The average age of the participants was 29.7 years, with a standard deviation of 8.7. The oldest participant was 57, and the youngest was 25 years old. Participants were free to state their gender in an open-text optional field. Ten (48%) of the participants described themselves as male or equivalent designations, seven (33%) as female, one (4%) as non-binary, and three participants had not provided their gender. Three participants (14%) were left-handed, and 18 right-handed (86%). Most participants had little or minimal experience with VR or haptic devices. They had to rate their experience with VR on a seven-point Likert scale ranging from (1) not at all to (7) a lot. On average, people answered 2.8 (SD=1.83) regarding prior experience with VR with an HMD and 1.6 (SD=1.28) regarding previous experience with haptic interfaces. None of the participants reported issues with their hands' sensory and motor capabilities. All participants had normal or corrected to normal vision and had no issues with their visual perception of space. No participants reported significant issues regarding simulator sickness after completing the study. Each participant performed each configuration three times. Hence we recorded a total of 378 test cases and 63 for each Shiftly configuration.

6.2.3 Qualitative Study Results

The results of the user study can be seen in Figures 6.7, 6.8, and 6.9. The first figure shows the visually selected shape grouped by category for each category. The second one

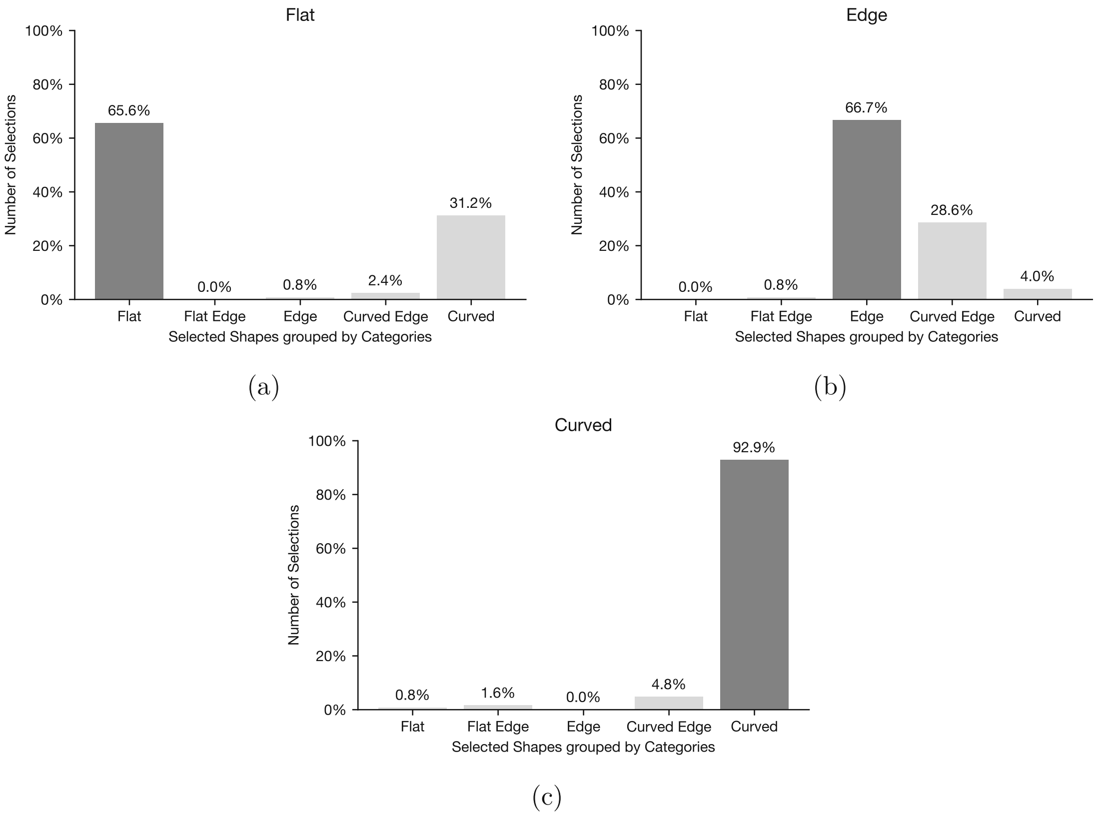


Figure 6.7: The graphs show, for each Shiftly configuration category, the selected shapes grouped by the categories (Flat surfaces, Flat edge, Edge features, Edge curved, and Curved surface. The correct category is shown in dark gray.

shows the selected geometry grouped by category for each test case, and the last figure shows the selected options chosen for each test case.

In all three configuration categories, in most cases, an option of the same category was selected as the device tried to approximate, as shown in Figure 6.7. In 92.9% of all test cases where Shiftly emulated a curved surface (a cylindrical shape with 92 mm or 156 mm diameter), participants selected an option that also represented a curved surface. In the test cases where the haptic device approximated an edge feature, 66.7% of the participants selected a shape with an edge feature. In 28.6% of these cases, the shape with an edge and curved faces was selected. The shape has the index “CE” in Figure 6.6.

Flat Test Cases

In 65.6% of all test cases where a flat surface was created by Shiftly participants selected a flat surface correctly. In 31.2% of the test cases, when a flat surface was emulated, the participants picked a curved surface. For both test cases with a flat surface, participants around equal frequently selected a curved surface as illustrated in the bar charts shown

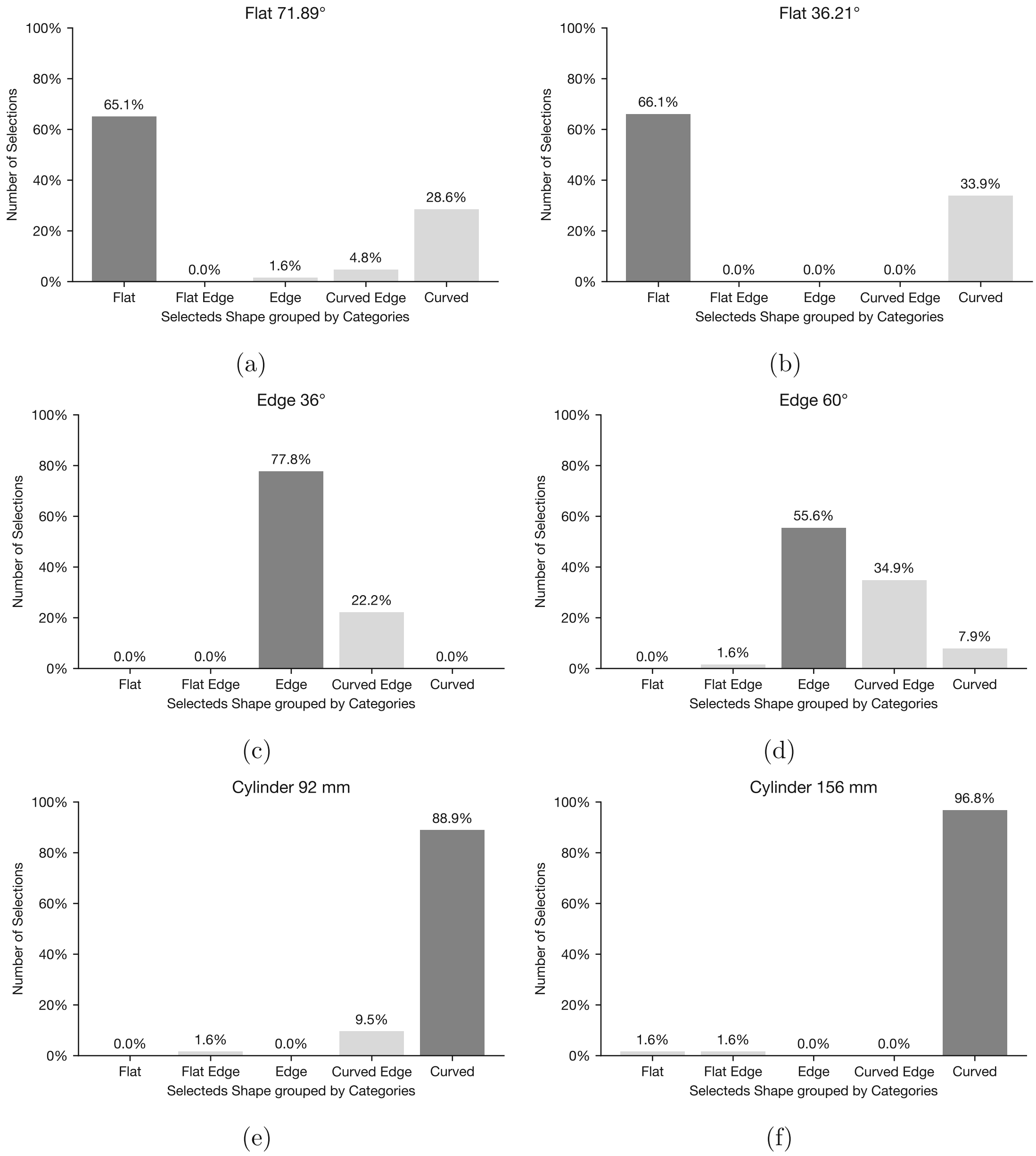
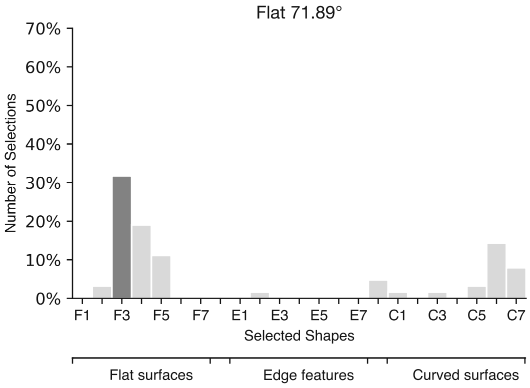
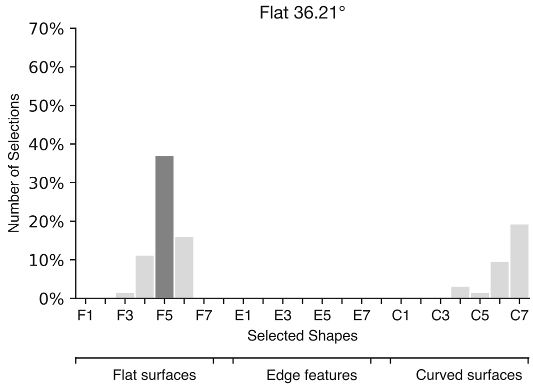


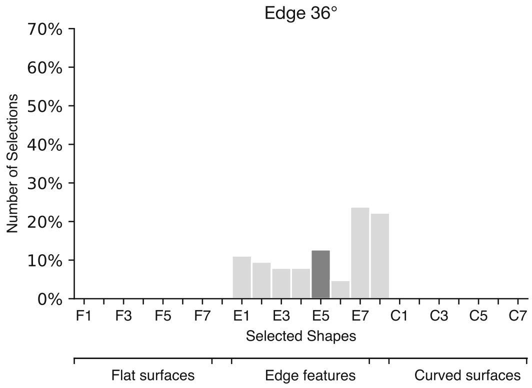
Figure 6.8: The graphs show, for each tested Shiftly configuration, the selected shapes grouped by the categories (Flat surfaces, Flat edge, Edge features, Edge Curved, and Curved Surface). The correct category is shown in dark grey.



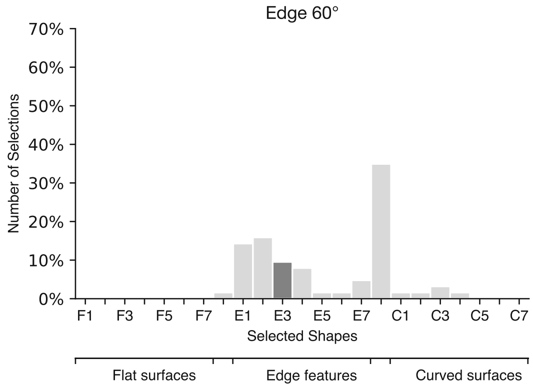
(a)



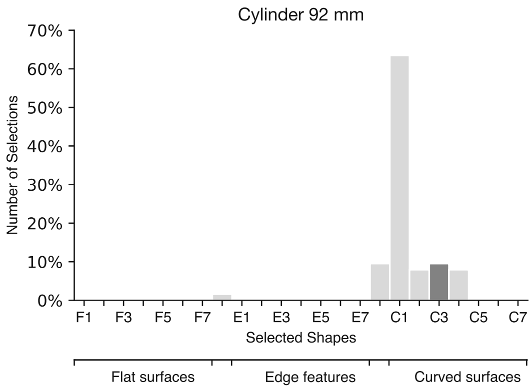
(b)



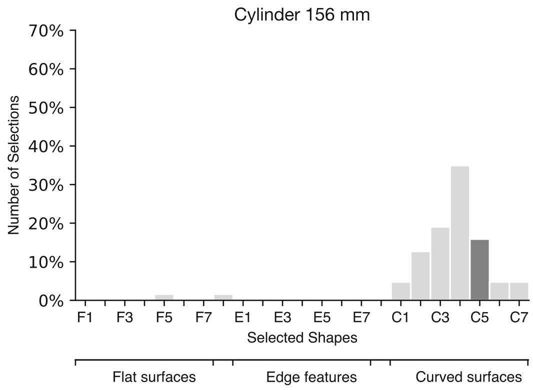
(c)



(d)



(e)



(f)

Figure 6.9: The graphs show the number of selected shapes for each Shiftly configuration. The indices on the x-axis refer to the indices used in Figure 6.6. The correct shape is shown in dark gray.

in Figure 6.8a and 6.8b. The most frequently selected option for both configurations was the correct answer (32% for the 72° and 37% for the 36° tilted flat surface).

Curved Test Cases

The results are similar between the test case emulating a cylindrical surface with a diameter of 92 mm and one with 156 mm. Regarding the larger cylinders, 96.8% selected a curved surface and 88.9% for the small cylinder, respectively. In both configurations, the two most frequently selected curved surfaces were smaller than the correct option for the respective test case, as shown in the graphs in Figures 6.9e and 6.9f. In the case of the test case that emulated a cylinder with a diameter of 92 mm, in 63% of the cases, participants selected the curved surface with the smallest diameter of 60 mm ($\approx$ 60% of the diameter of the ground truth). Whereas for the test case with the larger cylinder with a diameter of 156 mm, selections were more evenly distributed. However, the most frequently selected one was the curved surface representing a curved surface with a diameter of 125 mm ($\approx$ 80% of the diameter of the ground truth).

Edge Feature Test Cases

While in most cases, participants selected a geometry that showed an edge when Shiftly emulated an edge feature, frequently, participants also picked a geometry where the faces of the edge were slightly curved. As shown in Figure 6.9c and 6.9d, in the case of the edge with an inner angle of 36° around 22% and 35% for the 60° edge. We observed a tendency that the selection for edge configurations was more evenly distributed than in the other categories, especially considering only the cases where participants correctly selected a shape in the same category as the ground truth. For edge configurations where participants had correctly selected an option showing an edge feature, participants were off by 1.71 selectable options on average, with a standard deviation of 1.2. For the curved surface, a mean of 1.55 and a standard deviation of 0.9, and for the flat surfaces, a mean of 0.57 and a standard deviation of 0.67 were recorded.

On average, participants reported around equal confidence for all test cases, as shown in Table 6.3.

Post Questionnaire

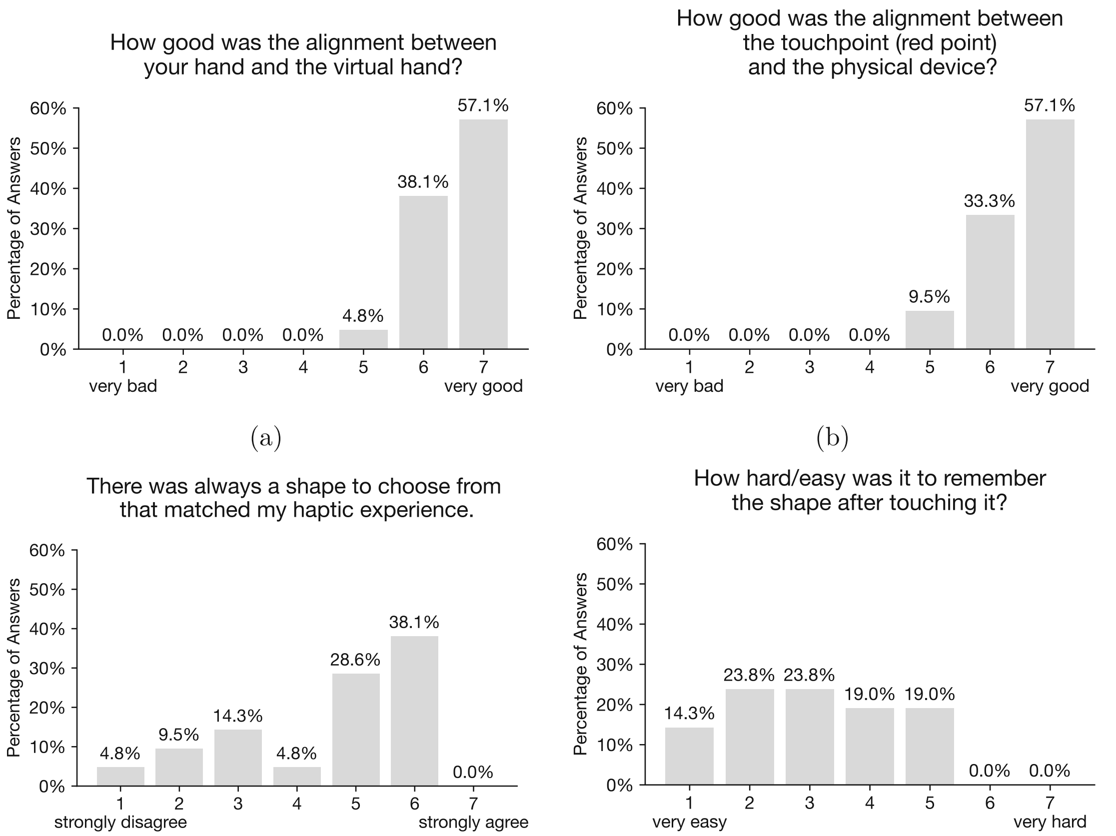
When asked afterward what type of shapes was the hardest to identify, 33% reported shapes with edge features, 1% – curved surfaces, and 52% – flat surfaces. In the case of the easiest identifiable category, most referred to curved surfaces (71%), 19% to edges features, and 1% to flat surfaces.

After the VR part of the user study, participants were asked to rate the alignment between their hand and the virtual one and the alignment between the touch indicator and the physical device. On average, participants rated the alignment of the hands as 6.52 (SD=0.60) and the alignment between the physical device and the touch indicator as

Test Case	Mean	SD
Flat 71.89°	3.95	1.31
Flat 36.21°	4.11	1.4
Edge 60°	4.02	1.2
Cylinder 156 mm	3.98	1.17
Cylinder 92 mm	4.33	1.3
Edge 36°	4.05	1.33
All flat surfaces	4.03	1.36
All edges features	4.03	1.26
All curved surfaces	4.16	1.24

Table 6.3: Average of the confidence that was reported by participants after each trial. The scale ranged from (1) not at all to (7) very confident.

6.48 (SD=0.68) on a seven-point Likert scale ranging from (1) very bad to (7) very good. The distribution of the answers is shown in Figure 6.10a and Figure 6.10b respectively. Participants partially agreed that there was always a shape to choose from that matched the physical one (Mean=4.57, SD=1.6), and on average, participants rated on a seven-point Likert scale ((1) very easy, (7) very hard) the question "How hard/easy was it to remember the shape after touching it" with 3.05 (SD=1.36). The distribution of the answers is shown in Figure 6.10c and Figure 6.10d.



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

Figure 6.10: Distribution of answers for the questions of the post questionnaire. (a) shows the results for the alignment of the virtual hand and the physical one, (b) the alignment between the physical device and the touch point indicator, (c) the availability of the shape that they have touched before and (d) how hard/easy it was to remember the shape after touching it.

CHAPTER 7

Discussion

This chapter discusses the Shiftly device developed in this thesis. First, the evaluation results are discussed in Section 7.1. This Section is followed by Section 7.2 comparing the developed haptic device to related work, and finally, the limitations are outlined in Section 7.3.

7.1 Discussion

The results of the first user study – the experience testing, are discussed, followed by the discussion of the results of the qualitative study.

7.1.1 Principle Mass Experience Testing

The recorded data in the experience testing, as well as the oral response of participants after they have tested Shiftly, shows that it can provide realistic haptic feedback in combination with the visual rendering, and people enjoyed the haptic experience. The device performed especially well with shapes that can be closely emulated, like cylindrical surfaces, edges, and flat surfaces. The Rotated Diamonds shape and the concave surfaces were rated worse than the other shapes since Shiftly cannot precisely emulate the surface of these shapes. In the case of the Rotated Diamonds, the proposed approach cannot render the discrete steps and gaps between the individual modules. For the concave surface, Shiftly can only emulate the tilt of the surface. We did expect lower scores for those two test cases than for the other test cases. Still, we aimed to evaluate the capabilities of Shiftly beyond shapes and geometries that can be accurately approximated. Even though the shapes in these two tests could only be partially approximated, the haptic feedback was rated acceptable by participants, and multiple participants revered these two shapes as interesting to touch. Therefore, we can assume that Shiftly can also be used to provide haptic feedback for shapes and geometries that can be partially emulated. For example, in the case of the Rotated Diamonds — the small details can not be emulated by Shiftly. Still, the user touches a physical surface equally tilted as the test case. Participants experienced a restriction of hand and finger movement and experienced the object's overall shape haptically. For the test case Concave Surface, Shiftly can not emulate the curvature of the surface, but users can feel the tilt of the virtual surface. For the test cases Cylinder and Wave, participants rated the feedback as realistic, and for the Flat Surface and House as more than "somewhat realistic" on average.

In the test setup Shiftly was stationary, and participants were allowed to move their hands. Rotating Shiftly while users touch the concave surface and move their hand around could increase the plausibility of the haptic feedback that users receive. Further, manipulating the pose of the virtual representation of the user's hand while touching the virtual object could improve the overall sensory experience.

Therefore, we reason that Shiftly can create realistic haptic feedback for geometries that can be approximated or nearly approximated. For geometries that can be only partially approximated Shiftly has great potential when combined with additional mechanisms. The study also showed that the presented design of Shiftly is durable and reliable. For the five-day testing with 170 participants, we used the same Shiftly without incidents, and only minimal maintenance work was done after each testing day.

7.1.2 Qualitative Study

The second user study showed that Shiftly can render haptic feedback for a variety of different shapes. Participants selected geometries that were close to the one we had aimed to approximate, and therefore, we assume that Shiftly can create precise haptic feedback for the tested shapes.

The results in Figure 6.9 show that participants could distinguish the two test cases of the same category. For the smaller cylinder, as expected, a smaller cylindrical shape was picked more frequently compared to the larger cylinder test case.

We observed a similar behavior in the case of the two flat surface configurations. For the test case where we intended to approximate a steep surface, a steep surface was more frequently selected than in the test case where we emulated a lightly inclined surface. When we aimed to approximate a slightly inclined flat surface, participants picked a slightly inclined surface more frequently than in the stepper flat surface test case. Participants also often picked a shape that indicated a slight curvature of the surface, even though we aimed to approximate a flat surface. Similarly, in the case of the edge feature test cases, the option that showed an edge with slightly curved faces was often selected. We think that is a limitation of the fabrication of the developed prototype, which does not unfold the origami completely with some tension needed for a truly flat surface. This issue is discussed further in Section 7.3.

Interestingly, the participants selected more often a curved surface with a smaller radius than the radius we intended to approximate. We observed this for both cylindrical test cases. While previous studies have shown that differences between different surfaces can be precisely distinguished when a visual representation of the surface is rendered while touching a physical surface [SOSGF21], our results indicate that it is relatively difficult to match geometric properties that are only haptically explored to a visual representation afterward. For the curved surface test cases, they frequently picked a stronger curved one, and when we aimed to emulate an edge, it seemed hard to judge the angle of the edge. While this observation needs further investigation, it could suggest that the physical prompt the user touches does not have to have the same shape as the virtual surface to create plausible haptic feedback. For Shiftly and similar shape-changing haptic devices, this would indicate that plausible haptic feedback can be created for a greater variety of virtual geometries that shapes Shiftly or other devices can physically approximate.

7.2 Comparison With Related Work

Compared to the state of the art, we think that the presented haptic device can produce a large variety of haptic feedback by utilizing only a small number of activators. The device is able to render plausible haptic feedback for a variety of different curved continuous surfaces, flat surfaces, and edges. Other full-hand haptic devices can only render one or two of the three categories. For example, classic pin displays fail to emulate continuous surfaces as long they are not entirely flat, and small discrete steps are always noticeable, even when using many electronic activators [GOGFS21, SGY+18]. Pin displays with an interpolation surface have shown that they can render well various complex bent surfaces but cannot render any form of edge feature [SOSGF21, RBF23]. The haptic device presented in this thesis solves this issue by deforming three curved origami structures. These origamis provide a continuous manipulatable touch surface that a single activator can precisely manipulate.

Further, a single haptic display is limited only to relief like geometries — providing haptic feedback when touching an object from behind is difficult. To a certain extent, the design of Shiftly enables touching virtual objects from multiple directions and receiving haptic feedback. For example, the developed haptic device can simulate touching a cylinder from multiple directions relative to the user.

Shiftly, like many other on-demand shape-changing haptic devices, has the potential to create natural haptic feedback and a way of interacting with virtual objects. By approximating the virtual surface that is touched, the fingers are naturally restricted when touching this surface. There is no need for a complex exoskeleton that connects only to portions of the fingers to restrict them in their movement. As present in some wearable haptic devices [MBT15, FZDH20]. Also, the haptic feedback is provided along the whole hand and not only on discrete points, as is often the case for finger-worn haptic devices [GJP21].

Further Shiftly or a larger version of it could work well for two-handed interactions. Because no device is attached to one's fingers or hands, touching one's own fingers is not limited. For example, in the case of haptic gloves with rigid elements, when a user touches their own fingers, the gloves would be noticeable to the user.

Moreover, many haptic devices use a larger number of actuators [SOSGF21, SGY+18]. In contrast, Shiftly uses only three stepper motors and is still able to create a large variety of haptic feedback. Ultimately, Shiftly is a great device offering a high variability of shapes it can simulate.

7.3 Limitations

The results of both user studies (outlined in Chapter 6) showed that the current prototype has some limitations. Multiple users pointed out that they can always feel a slight curvature when the device emulates a flat surface. This slight curvature results from the extension mechanism's precision of the frame. The device sometimes fails when trying to unfold the structure completely.

Many users also pointed out that the gap between two modules and the screws that hold the origami structure in place is too large and, therefore, noticeable and affects the possibility of haptic feedback when touching one edge of Shiftly. We think both issues can be addressed by increasing the build quality of the prototype and are not fundamental limitations of the developed haptic device concept.

While the developed prototype worked well for testing and demonstration purposes, multiple things must be adapted for potential end-user scenarios and more extensive field tests. The stiffness and durability of the paper origami are sufficient for prototyping and testing purposes. During the Principle Mass Experience Testing, we only changed the origamis after 30 to 40 user runs precautionary. More durable and complicated-to-assemble materials would be needed for a real-world scenario, for example, producing the origami elements out of a flexible plastic composite. The developed prototype does not sense the extension of each module. Therefore, a manual calibration process of each module is required after each restart of Shiftly.

The current frame design is developed to be entirely manufactured on a relatively old 3D printer with a standard 0.4 mm printing head. The three frames of Shiftly took around 20 hours to print. Hence, the tolerances of mechanical and moving parts are rather large, affecting the over-stability and precision of the device. A better 3D printer would allow for further reduction in the teeth size of the gears connected to the motor. This would enable a more significant reduction in gear ratio, which could enhance the overall strength of the individual folding modules.

The haptic device has limitations in emulating the haptic experience when touching objects smaller than the device and having a complex surface geometry. While the study results in Section 6.1 showed that acceptable haptic feedback can also be rendered for shapes that cannot be precisely emulated by Shiftly, the device still has limitations when rendering concave surfaces and apices. Furthermore, in this project, we mainly explored the possibilities of the haptic device creating plausible feedback when touching surfaces bent along a single axis. Surfaces with a significant curvature in two directions could only be partially emulated by Shiftly.

So far, we have only tested the haptic device in a table-mounted scenario. In this configuration, only a limited number of possible positions of virtual objects is feasible, reducing the design space for possible scenarios. For example, for a static mount of Shiftly, when creating haptic feedback of an object with an edge feature, the object's edge has to align with the edge of Shiftly. Alternative mounting possibilities, for example, using Shiftly as an end-effector of a robotic arm, must be explored in future work. While this approach might be promising and potentially enable full-room VR experiences with haptic feedback, such a system is also complex. It requires additional hardware like a robotic arm and possibly a moving robotic platform [MVVK23] for even bigger-scale haptic feedback.

Furthermore, the users of the haptic device could only move their hands to a limited extent when touching a virtual object and, at the same time, the physical device. Simulation of larger haptic surfaces that the user explores by moving the hand along the surface can be achieved by moving a shape displays in space, as previous works have demonstrated [SOS+21, SGY+18].

CHAPTER 8

Conclusion and Future Work

This chapter summarizes this thesis's results, followed by a description of potential future work. Further 3D CAD files of Shiftly and the source code for the microcontroller and the VR application can be found on https://github.com/TobiasBat/Shiftly.

8.1 Conclusion

This thesis presented a novel haptic device Shiftly for VR, that uses curved origami to create rich haptic feedback. The device uses only three electronic actuators to deform the origami elements to approximate various geometries to give a person haptic feedback when touching the surface of virtual objects. In contrast to traditional pin displays, the device can render plausible haptic feedback when touching a continuous curved touch surface and can render edge features.

As part of this thesis, multiple functional prototypes of the proposed design are fabricated and tested. We have conducted two user studies to evaluate the capabilities of the Shiftly. The first one evaluates how realistic the haptic feedback is when touching virtual objects that are also visible to the user. The second user study evaluates the range of haptic feedback the device can create without visual feedback. The two user studies indicated that the proposed haptic device is able to provide realistic haptic feedback for a variety of surface geometries — ones that can be accurately emulated (flat surfaces, convex curved surfaces, and edges) and, to some extent, ones that can be only partially approximated (concave surfaces and objects with small details) by Shiftly.

Shiftly is designed to enable the ability to feel and touch virtual objects in VR. By adding realistic haptic feedback to VR, virtual environments can become more immersive, the interaction with objects can become more natural, and task performance in such virtual environments could be increased.

8.2 Future Work

In this thesis, we only explored a scenario where the haptic device is statically mounted on the table, with no ability to move the device in space or rotate it around its axes. In the future, it would be interesting to explore the possibility of using Shiftly as an end effector of a robotic arm, enabling a room-scale VR experience with haptic feedback.

So far, the positions where one can touch virtual objects, as well as the configurations of the haptic device, were pre-defined and pre-computed. By predicting the user's touch point and analyzing the virtual object's local geometry properties around the expected point of touch, one could haptically explore arbitrary objects as a whole. Further, by translating and rotating the device in space while the user touches it, Shiftly could provide continuous haptic feedback for potentially infinitely large objects.

So far, we have only developed an approach to create haptic feedback for static virtual objects. But because of the rapid and precise transformation capabilities of Shiftly, haptic feedback could be provided when touching animated and shape-changing virtual objects. Furthermore, material properties like stiffness and flexibility could be simulated by sensing the contact between one's hand and the origami and the force applied to the device. This could be achieved by continuously measuring the force applied to the origami structure and unfolding the origami structure in a controlled way according to the simulated material properties. The developed approach could also be combined with vibrotactile and electrotactile activators to simulate different textures. In our opinion Shiftly could be beneficial in various virtual and Mixed Reality applications.

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