ARm Haptics: 3D-Printed Wearable Haptics for Mobile Augmented Reality

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Fig. 1. We present the *ARm Haptics* system, which builds upon 3D-printed wearable input modules to provide haptics for Augmented Reality experiences. **Left:** 3D-printed mount for input modules. **Center:** *ARm Haptics* system with two mounted input modules. **Right:** Button in Augmented Reality linked to worn input module (full blue bar indicates successful linking).

Augmented Reality (AR) technology enables users to superpose virtual content onto their environments. However, interacting with virtual content while mobile often requires users to perform interactions in mid-air, resulting in a lack of haptic feedback. Hence, in this work, we present the *ARm Haptics* system, which is worn on the user's forearm and provides 3D-printed input modules, each representing well-known interaction components such as buttons, sliders, and rotary knobs. These modules can be changed quickly, thus allowing users to adapt them to their current use case. After an iterative development of our system, which involved a focus group with HCI researchers, we conducted a user study to compare the *ARm Haptics* system to hand-tracking-based interaction in mid-air (baseline). Our findings show that using our system results in significantly lower error rates for slider and rotary input. Moreover, use of the *ARm Haptics* system results in significantly higher pragmatic quality and lower effort, frustration, and physical demand. Following our findings, we discuss opportunities for haptics worn on the forearm.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**; **Haptic devices**.

Additional Key Words and Phrases: Augmented Reality, haptics, wearable, mobile, empirical evaluation

ACM Reference Format:

Anonymous Author(s). 2022. ARm Haptics: 3D-Printed Wearable Haptics for Mobile Augmented Reality. In *MobileHCI '22: ACM International Conference on Mobile Human-Computer Interaction, September 28–October 01, 2018, Vancouver, Canada.* ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/1122445.1122456

1 INTRODUCTION

With Augmented Reality (AR) technology, users can enrich their perception of reality with superposed virtual content [4]. From simple visual guidance [16] to spatially distributed interaction [35], AR content can manifest in different forms. In recent decades, researchers have demonstrated the potential of AR applications in various contexts, such as education [26], traffic [45], and assembly [24]. When AR is experienced in a head-mounted device (HMD), users are free to move around and use their hands to interact with the physical environment. Interaction with entirely virtual AR content not present in the physical environment, however, remains challenging [50].

One central element that can significantly enhance virtual environments is haptic feedback through "haptic devices" or "haptic props" [25]. Haptic feedback that is emitted by a device or prop can either be of "active" or "passive" nature [29]. Lindeman et al. define passive haptic devices as "physical objects which provide feedback to the user simply by their shape, texture or other inherent properties" [29]. They stand in contrast to "active-haptic feedback systems" which are controlled by a computer instead [29]. Passive haptic devices are in general associated with a number of benefits such as being "familiar" to manipulate and "obvious to use" [22], yet they are rarely deployed in realistic settings nowadays.

The current trend towards hand-tracking input in AR headsets (cf. Microsoft Hololens 2 or Magic Leap) amplifies the problem of missing haptic sensations because there is no haptic feedback when interacting in mid-air. This lack of haptics leads to reduced immersion and degraded interaction [13]. In addition, it has been shown that the presence of haptic feedback can have a positive effect on task completion time, error rate, and learning curve [7]. Without additional hardware, hand-tracking input can only provide haptic feedback when using one's own body [33] or additional objects in the environment [20, 21, 41]. Nevertheless, the physical properties that can be "simulated" by these approaches are limited by the properties of the available objects.

Hence, previous work has suggested various approaches to providing haptic feedback in AR using additional hardware. These approaches include, for example, controller-based [47], pen-based [46], and fingertip-based systems [44], which to some extent hinder interaction with real-world objects. Furthermore, the aim of these systems is to provide a universal solution that can communicate the haptic properties of many different objects. As a consequence, specific physical objects are not as well represented because their physical properties are only approximated. A different approach is to represent specific but frequently used objects as haptic props (for example, interface components such as sliders and rotary knobs [11]). So far, previous work investigated haptic props present in the environment, however, making them wearable is an approach towards providing haptic feedback while mobile and leaving users' hands free.

This work presents *ARm Haptics*, an approach to providing passive haptic feedback via a wearable system worn on the user's forearm using 3D printed input modules. We developed *ARm Haptics* based on findings from a focus group with HCI researchers and following an iterative development process. Furthermore, we motivate the selection of an initial set of interface components, namely buttons, sliders, and rotary knobs from our focus group findings as well. The *ARm Haptics* system consists of 3D printed input modules that can be worn on the forearm and synced with an Augmented Reality interface. For configuring the system, users can freely choose a set of input modules that fits their needs. Here, the idea behind these modules is not to provide haptic feedback for all interactions but only those that gain a clear benefit (e.g., higher input precision). Changing modules mid-usage is possible; however, not the focus of our explorations. We validated *ARm Haptics* with a user study ($N = 12$) in which we compared it to hand-tracking based interaction mid-air without haptic feedback (as supported by current AR headsets such as the Microsoft Hololens 2). We used quantitative methods to evaluate user performance and conducted semi-structured interviews with all participants. While our findings show that hand-tracking input is faster for button input, we found that participants made fewer errors with sliders and rotary knobs when using our system. Furthermore, participants gave our *ARm Haptics* system a higher rating for user experience and a lower rating for perceived task load. We conclude our work with application opportunities for haptics worn on the user's forearm.

Contribution Statement. We contribute a system for mobile AR that is worn on the forearm and provides haptics for frequently used interaction components such as buttons, sliders, and rotary knobs. The system and its components are 3D-printed, which allows users to quickly produce and change components as needed. We publish the system and its artifacts, including detailed instructions for replicating it and creating new modules, under an open source license. Moreover, we contribute empirical results from a comparative user study that highlights the benefits and drawbacks of our *ARm Haptics* system.

2 RELATED WORK

In the following, we discuss the related work for our *ARm Haptics* system, provide reasons for our taken technical approach, and present the design decisions derived from previous findings.

Haptics in Virtual Reality. Creating believable haptic experiences is a relevant problem beyond Augmented Reality technology. Virtual Reality (VR) in particular has received significant attention because it lacks the presence of physical objects. Here, researchers have proposed various approaches for integrating haptics in VR. One approach is to use turkers (i.e., bystanders that help create the haptic experiences) to generate motion [9], rearrange larger objects such as walls and doors [10], or reconfigure and actuate otherwise passive haptic props [8]. Another approach is to use robots to create haptic experiences (for example, with stationary robot arms [1] or actuated mobile robots [19]). In more recent work, researchers also investigated the use of drones flying around the user to provide haptics [2, 23]. An example of this is *Flyables*, which uses 3D-printed user interface components mounted to quadcopters that fly to specific locations to offer haptics for their virtual counterparts [2]. However, it remains a challenge to use these approaches in AR as, in this case, users still perceive their physical environment (i.e., users would see the humans and robots used to create the haptics). While previous work explored how haptic devices can be hidden from AR users [12], the suggested approaches create a visual mismatch between perceived and real space, resulting in users colliding with these devices. Hence, in the following, we focus on approaches that are more readily applicable to AR.

Tangibles and Haptic Props. Enriching existing physical objects with AR content allows us to introduce the versatility of AR technology to tangible objects [17]. For example, AR technology can be used to introduce more detail to 3D-printed objects [34]. Moreover, interactions with tangible objects can enhance task performance (e.g., via more precise input [11]), increase learning [39], and feel more natural [37]. However, AR interfaces are not often shaped around existing physical objects, but instead rely on additional virtual objects that lack a physical manifestation. As it is impractical to 3D print every virtual object, researchers have explored alternative approaches. One proposed approach is to leverage available physical objects in the environment to provide natural affordances [20] or substitute physical objects with virtual counterparts [21, 41]. While this approach is promising, the physical properties that can be presented to a user are largely determined by the user's environment. Another approach is to (re)use physical objects to represent (different) virtual ones [3, 22]. An example is *Embodied Axes*, which provides users with sliders and rotary knobs that can be used to control a 3D data space in AR [11]. Using physical interaction components was found to be more accurate overall than conventional tracked controllers. Still, the haptic devices are placed in the environment and therefore limit users' mobility. In contrast, the *ARm Haptics* system makes use of a wearable form factor which leverages input accuracy while allowing for mobility at the same time. Thus, we look into portable and wearable haptics in the next paragraph.

Portable and Wearable Haptics. Controllers for interacting with virtual content in AR as well as VR have been around for quite some time. Hence, it makes sense to not only use them to track users' hands, but also to provide haptic feedback. Researchers have proposed various ways to extend the functionality of controllers towards improved haptic feedback (for example, to feel different surfaces [6], textures [43, 47], shapes [15], or weights [49] of objects). Moreover, others have investigated controllers that resemble physical tools well known to users, such as pens [46]. Nevertheless, as these

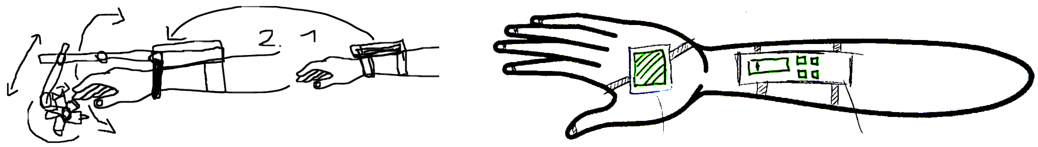

Fig. 2. Two sketches from two different participants of the focus group. **Left:** showing an apparatus that extends over the finger tips and which can be used for haptic input; **Right:** haptic input elements are strapped to the back of the hand and the lower arm.

are hand-worn controllers, they make it harder for users to continue interacting with their real-world environment. Additionally, we can observe a trend towards hand-tracking input for AR headsets (cf. Microsoft Hololens 2[1] or Magic Leap[2]), which enables users to interact more naturally by using their fingers and hands. As an alternative approach to controllers, researchers have also proposed various haptic devices that attach to the user's fingertips [40, 42, 44, 48], with some requiring a stationary or mobile device as a counterpart [27, 30]. Recently, Teng et al. suggested a device that can fold away to keep users' fingertips free in order to ensure unhindered interaction with real-world objects [44]. Another approach to provide haptics is to let users use their own body to see [33] and feel AR content [14]. However, most presented approaches aim to be universal solutions that communicate the haptic properties of many different objects while, to some degree, neglecting the realistic representation of specific ones. Hence, in our work, we focus on representing specific objects that are frequently used (i.e., interaction components such as buttons or sliders), similar to previous work (e.g., [11]). In addition, we make them wearable on the user's arm so that they do not hinder interaction with the physical environment but still stay with the user as they move around. Furthermore, we ensure that the objects are 3D-printable and quickly changeable, so that the resulting system remains flexible.

3 DESIGNING WEARABLE MODULAR HAPTICS

Striking a balance between accurate input with haptic feedback, flexibility in interface design and user mobility requires a wearable solution. Thus, we aimed for a modular wearable solution that embodies frequently used interface components as conveniently interchangeable props for haptic feedback. First, to identify which interface components should be initially provided and to come up with early ideas of how the modular haptic system could look, we conducted a focus group. After that, we continued on the early ideas with an iterative design process that at its end resulted in our final *ARm Haptics* system.

3.1 Focus Group

The focus group was conducted over the internet using an online whiteboard tool and synchronous audio and video communication. We invited a total of 5 participants (2f, 3m, 0d) with an average age of 30 years (SD=2 years). All participants were employed as researchers in different groups focusing on Human-Computer Interaction (HCI), all participants were PhD students with backgrounds in haptics and user experience. All participants stated that they had between two and four years of experience in their fields.

In the beginning of the focus group, we introduced them to the topic and presented them with an official demonstration video of the hand-tracking-based interaction of the Microsoft Hololens 2[3]. In the video, the presenter demonstrates how to interact with interface components such as buttons or sliders. As these interactions take place in mid-air, no haptic

[1]Microsoft Hololens 2. https://www.microsoft.com/en-us/hololens, last retrieved May 18, 2022.
[2]Magic Leap. https://www.magicleap.com, last retrieved May 18, 2022.
[3]Demonstration of the Hololens 2. https://www.youtube.com/watch?v=uIHPPtPBgHk, last retrieved May 18, 2022.

feedback is present. Following the video, we communicated that the goal of the focus group was to offer wearable haptics for interface components that provide an alternative to mid-air interactions in Augmented Reality. Thereafter, we started the first discussion among participants, which was on the topic of user interface components. Participants were asked to consider on their own which user interface components would benefit from haptics. They were given three minutes to do this, during which time they created notes for their ideas in the digital whiteboard tool. As a result, we obtained a ranking of the user interface components that would benefit the most from haptics. Here, our participants listed the following three components as most relevant (in descending order): rotary knobs, buttons/checkboxes, and sliders (participants grouped buttons and checkboxes).

The second and last discussion among participants was on the topic of designing a wearable system to enable haptics in AR. We asked participants to think of a solution and to draw a sketch of their wearable prototype that is attached to the human lower arm and hand. We provided a corresponding template to the participants to draw upon. Selected sketches from the focus group are provided in raw (see Figure 2) and simplified form (see Figure 3). Most sketches located the haptics device on the user's forearm using a flexible, strap-based mounting system (cf., Figure 2), more specifically on the wrist (similar to wearing a watch). Furthermore, participants envisioned different approaches for presenting the various interface components. Some imagined an automatic mechanism that would switch between the different interface components (cf., Figure 2 – left), while one participant suggested that users could simply rotate their arm to access the different components (see Figure 3 – bottom left). In the following discussion, the need for interchangeability of the different user interface components was specifically mentioned, as it was considered that embedding too many components into one design might clutter it. Two designs reflected this in using exchangeable plates that embed the user interface component (cf., Figure 2), while the designs by three participants in total were using straps to attach the prototype to the arm. The discussion within the focus group yielded the result that straps provided the necessary flexibility and adaptability of mounting a prototype on the human arm; particularly if the arms can be individual in terms of size and extent.

Following the group's designs and discussions and in addition to the earlier derived list of relevant user interface components, we derive three design requirements from the focus group for the construction of the prototype: i) a *flexible mounting system* should be provided on the arm, e. g., by using straps, to enable flexibility and adaptability of such a prototype to the human arm; ii) *interchangeability* of the user interface components should be provided so that multiple elements can be fitted on one base unit; iii) a modular design (i. e., *modularity*) of two or more units can enable interchangeability of the components and reduce clutter.

To follow up on our focus group, we decided to iteratively implement a wearable haptics system that initially provides buttons, sliders, and rotary knobs to users without any automatic mechanism, relying instead on users to rotate their arm to access the different components. Participants grouped buttons and checkboxes into one category as they provide very similar functionality. Nonetheless, we will focus on buttons, not making any assumption about checkboxes here.

3.2 Iterative Development

After obtaining the insights from the focus group, we iteratively developed a prototype of our *ARm Haptics* system (inspired by the iterative enhancement method [5]). Since the experts from our focus group had a diverse range of opinions, including which user interface components to represent, we decided that a *modular design* would be useful. Designing the prototype in a modular way enables the exchange of parts, which in turn enables *adaptivity* to different usage scenarios. Due to the iterative development approach, we further opted for low-cost hardware components that can be exchanged, such as a NodeMCU-microcontroller that connects to Augmented Reality devices through the

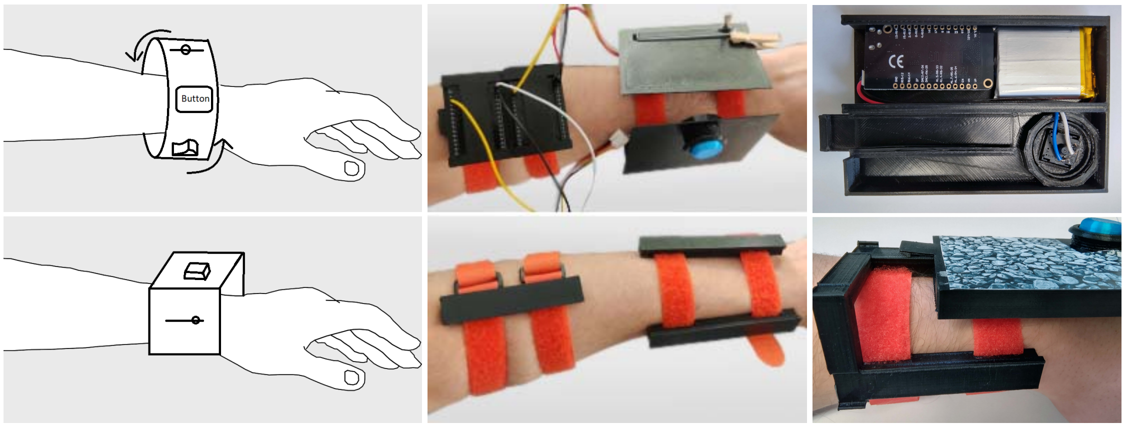

Fig. 3. Artifacts of the design process for the *ARm Haptics* system. **Left:** Simplified sketches from the focus group suggesting potential designs for haptics worn on the forearm. **Center:** Earlier prototype of our system (bottom: individual rails to mount 3D-printed components; top: NodeMCU, mounted separately, for controlling the interface components). **Right:** Final prototype of our *ARm Haptics* system (bottom: rail mechanism with clip to mount modules; top: inside of a haptic module with battery and NodeMCU).

MQTT-protocol[4]. To create the actual components, we made use of 3D printing, as it allows rapid prototyping at a low operational cost (more details on how to create new modules at the end of the section).

In the first iteration, we created a prototype that consists of two parts: a mounting that can be worn on the user's arm (using soft velcro wrap easily adjustable in length) and a foundation for extension modules on top. The latter could be used for interface components, but also to provide housing for the microcontroller (see Figure 3 – center). The base module is attached with flexible straps to the arm and includes rails on which the extension module can be attached. This module can then be strapped to the arm as shown in Figure 3. The modular design of the mounting base unit and the extension module reflects the focus group's design requirements of interchangeability and modularity, while the strap-based mounting solution was directly suggested. Our design here added railings to facilitate the interchangeability so that the extension module can easily be exchanged. In this iteration, our prototype had the microcontroller and interface components in different extension modules, which were connected via cables. Furthermore, we created an extension module for each interface component (button, slider, and rotary knob) and gave them the same appearances as the mid-air interface components used for the Hololens 2. Here, we used the Mixed Reality Toolkit[5] as the reference for the visual appearance.

In the second and final iteration, we refined our first prototype. Here, three authors of the paper tested the first prototype and looked for opportunities to improve it. First, we added a clip-based mechanism that would make the mounting of the extension modules more robust (see Figure 3 – right). Moreover, we integrated the microcontroller and an additional battery with the different interface components in one extension module, meaning each interface component, such as the button or slider (see Figure 4), became one stand-alone extension module, increasing the interchangeability requirement of the focus group even further as reattaching the cable connections from the first iteration is not necessary anymore. After that, we added image markers to allow tracking of our haptic modules with the cameras of the AR headset (see Figure 1 – right). Finally, we used Unity3D[6] and extended the MRTK library to

[4]MQTT-prototcol. https://mqtt.org, last retrieved May 18, 2022.
[5]Mixed Reality Toolkit. https://github.com/microsoft/MixedRealityToolkit-Unity, last retrieved May 18, 2022.
[6]Unity3D. https://unity.com, last retrieved May 18, 2022.

Fig. 4. Three example modules developed as an initial set for the *ARm Haptics* system. **Left:** button module (binary input: pressed, not pressed). **Center:** slider module (discrete input: 100 levels). **Right:** knob module (discrete input: 100 levels).

support our wearable haptic components. We implemented a linking mechanism for which users need to hold the haptic component next to the MRTK interface component to link them (see Figure 1 – right). This linking mechanism was required as one interface component such as a slider can exist more than once within the same interface and the system would not know which to control otherwise. A progress bar that fills up over the duration of one second visualizes the linking process. On the contrary, users need to move the haptic component away from the virtual counterpart and as soon as the progress bar is empty the components are unlinked. Here, to track the image targets of the haptic components, we used Vuforia[7]. 3D-printable files, instructions and the source code of our *Arm Haptics* system are available for free on GitHub[8].

3.3 Prototyping Input Modules

To create new input modules, we provide a blank 3D model that contains all basic components (e.g., rail and clip for mounting, mounts for microcontroller and battery, space for marker). The model can be adjusted before 3D printing, including the dimensions of the module. However, it may require adapting the module mount as well because increasing the size will reduce the number of possible module slots (possible by default are four module slots with one slot unused – no slot on the backside, as an unnatural arm tilt would be required). There after, one can adapt our Arduino sample code by adding new MQTT events for the new input module and compile the code onto the NodeMCU board. Finally, a virtual counterpart needs to be developed in Unity3D (extending an existing blank prefab) and an image marker needs to be added to the hardware and virtual counterpart (which can be controlled with the MQTT events).

4 USER STUDY

To examine the performance (task completion time, error rate), subjectively perceived user experience, and task load for our *ARm Haptics* system, we compare it in a user study to mid-air interactions based on the hand tracking capabilities of the Hololens 2 (baseline condition), meaning complete tracking of all fingers and joints in 3D space. In the baseline, users can "touch" and interact with the different interface components; however, no haptic feedback is provided.

4.1 Study Design

We conducted a within-subjects laboratory user study in Augmented Reality using the Microsoft Hololens 2. We decided for *input type* and *input task* as independent variables. The first variable, *input type*, had two levels: *haptic input* and *MRTK input*. *Haptic input* refers to our *ARm Haptics* system and *MRTK input* represents the Mixed Reality Toolkit

[7]Vuforia. https://developer.vuforia.com, last retireved May 18, 2022.
[8]Removed for reviewing process.

(MRTK). The MRTK is frequently used with the Hololens 2 and makes use of its hand-tracking capabilities to enable mid-air interactions. It furthermore provides various interface components, including the ones integrated in *ARm Haptics*, namely buttons, sliders, and rotary knobs. For *haptic input*, hand tracking is disabled and input results from the hardware. The second variable, *input task*, has four levels (*buttons* vs. *sliders* vs. *rotary knobs* vs. *combined*). We chose *input task* (representing different modules) as an independent variable, to understand the influence of the different modules on users' performance. Each of these tasks consists of five interface components (except combined, which consists of four components). In the first three tasks, each task presents one of the interface component (*buttons*, *sliders*, or *rotary knobs*) five times, while *combined* contains two sliders and two buttons (to test multiple components attached to our system; maximum of prototype is two; see Figure 1 – center). Moreover, the first three tasks involved a pilot trial that contained one interface component to become familiar with the task. We tested all four tasks for each input type within a block, resulting in two blocks. Thereby, participants only had to put on and remove the *ARm Haptics* system once. We counterbalanced both blocks and the first three levels of the *input task* within each block, using a Latin-square design that resulted in six different orders. As *combined* contains both buttons and sliders, which are levels of their own, we tested it last within each block. We quantitatively evaluated user performance, taking task completion time, error rate, user experience with the user experience questionnaire (UEQ) [28], task load with the NASA Raw-TLX (NASA Raw-TLX) [18], and individual Likert-items as our dependent variables. Furthermore, we conducted semi-structured interviews to gain further insights.

To answer the research question **(RQ)** whether and to what extent the interaction with Augmented Reality (AR) user interfaces can be improved using wearable haptic modules representing interface components, we investigate following hypotheses:

H_1 We expect that the interaction times differ between *MRTK input* and *haptic input*. As *haptic input* requires the additional step of first linking the virtual counterpart, we expect it to be slower.

H_2 We hypothesize that *haptic input* will result in fewer input errors than *MRTK input* because we directly track the input and not the user's hands (translated to input), which could introduce additional noise.

H_3 We predict that *haptic input* results in a better user experience because it contributes additional haptic sensations and is potentially familiar to the participants.

H_4 We expect higher subjectively perceived task load for *haptic input* because it requires additional effort to first select the virtual counterpart.

4.2 Procedure

In the beginning, we introduced our participants to the purpose and procedure of the user study. Thereafter, we asked for their consent to the study conditions. Then, we introduced them to the Hololens AR headset and, if they started with the *haptic input* block, we asked them to also wear the *ARm Haptics* system. Next, participants started with their first of four *input tasks* (for each block). Each task started with a test trial with one input component (except *combined*, which always was the last task in each block and had no test trial; see Figure 5). After, participants continued with the actual task, which contained five input components (four for *combined*). Components were *buttons* that needed to be pressed, *sliders* that needed to be set to random position (ranging from 1 to 100), and *rotary knobs* (same as *sliders*). For each task, we asked participants to interact as quickly and precisely as possible. Moreover, each task was introduced as an AR dialog with a small 3D object which participants had to manipulate with their interaction (see Figure 5 – center and right). After each task, participants were asked to provide ratings for two statements on a 7-point Likert

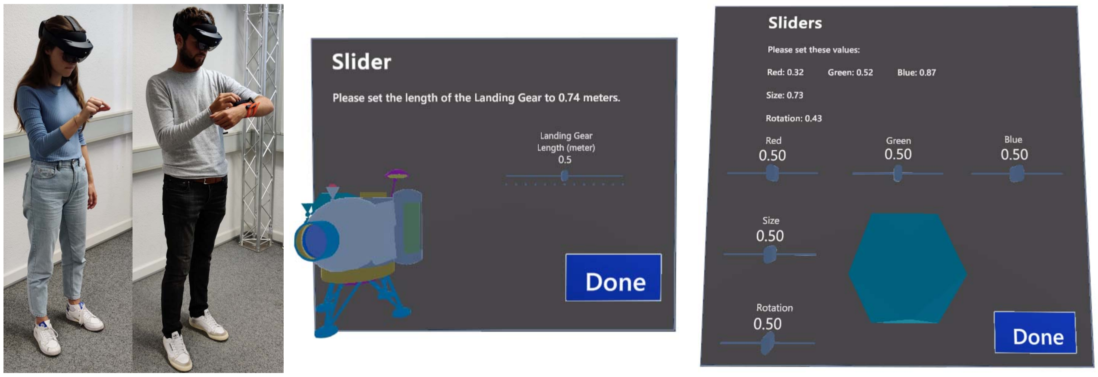

Fig. 5. Impressions from the user study. **Left:** Two participants using the two different *input types* (left: *MRTK input*, right: *haptic input*). **Center:** Pilot trial for *input task sliders*. **Right:** Measured trial for *input task sliders*.

scale. When finished with the first block, participants performed the same tasks again in the second block. After each block, we asked participants to fill out the UEQ and NASA Raw-TLX. After all blocks, we conducted a semi-structured interview with all participants. The study took 45 to 60 minutes for each participant.

4.3 Apparatus

We conducted the user study in an empty office space (dimensions: 4m x 4m). For AR, we used the Microsoft Hololens 2 headset, which offers a diagonal field of view of 52 degrees and hand-tracking capabilities with 30 Hz. We developed our software with Unity3D and additionally used the MRTK library to implement the user interface (including the dialog boxes and interface components, namely *buttons*, *sliders*, and *rotary knobs*). Each task participants had to perform during the study contained a dialogue box with a short task description and different interface components (depending on the task). The dialog box always spawned in front of the participant, 30cm lower than the headset position. The distance to the dialog box could be controlled by moving closer or stepping away. For the *MRTK input*, participants could use their hands, tracked by the Hololens, to perform the interactions in mid-air. For the *haptic input*, we disabled the hand-tracking capabilities and participants had to use the *ARm Haptics* system. We ensured that the MRTK components have the same size as their input module counterpart.

4.4 Participants

We recruited 12 volunteers (8m, 4f, 0d), aged between 21 and 34 years (M=24, SD=4) through mailing lists and bulletin boards at our university. Participants were not compensated for the study. Eleven participants said they were right handed, while one participant was left handed. Moreover, eleven participants stated that they did not have any prior experience with AR headsets.

4.5 Results

Task Completion Times. For both conditions (*haptic input*, *MRTK input*), participants completed each of the four tasks. For each task, we logged the task completion times (see Figure 6). The maximum time of each task was limited to 180 seconds. All task completion times are compared in Table 1 and tested with a Wilcoxon Signed-rank test. Here, we can conclude that for buttons, *MRTK input* is significantly faster than *haptic input*.

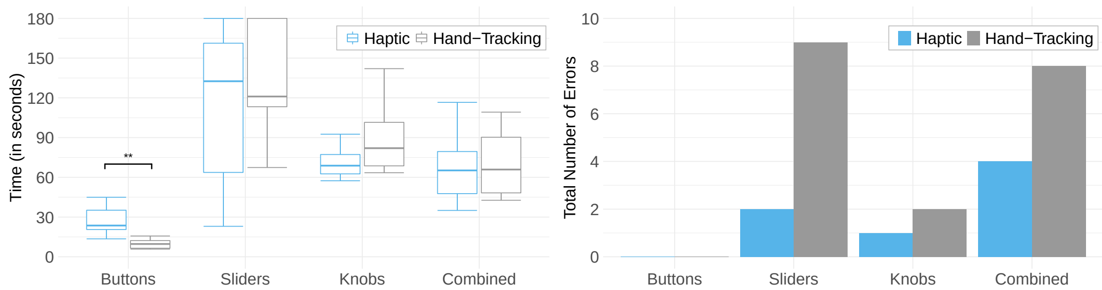

Fig. 6. Results from the analysis of the recorded logging data (hand tracking represents *MRTK input*. **Left:** Boxplots of the task completion times within each condition. **Right:** Total number of errors for all tasks within each condition.

Table 1. Pairwise comparisons of conditions (*haptic input*, *MRTK input*) concerning the different tasks. W and Z from Wilcoxon Signed-rank test. Effect size (r): > 0.1 small, > 0.3 medium, and > 0.5 large effect.

	Haptic Input		*MRTK Input*					
Task	Md	IQR	Md	IQR	W	Z	p	r
Buttons	23.60s	14.58s	9.66s	5.79s	78	3.06	0.002	0.62
Sliders	132.55s	97.57s	121.01s	66.70s	19	-1.30	0.871	-
Rotary Knobs	68.82s	14.61s	82.00s	32.86s	22	-1.33	0.814	-
Combined	65.22s	31.79s	65.89s	42.05s	29	-0.78	1	-

Error Rate. In the following, we discuss the number of errors that occurred within each task grouped by condition (see Figure 6). Each of the four tasks contained five interface elements (except for *combined* which contained four). For each interface element, one error could occur. An error would be a button not triggered or a slider/rotary knob on the wrong level (both interpreted as discrete scales with 100 levels). Overall, participants made a total of 7 errors with *haptic input* (2.92%) and 19 with *MRTK input* (7.92%). All errors occurred with *sliders* and *knobs*. A one-tailed Wilcoxon Signed-rank test revealed a significant difference between the conditions (W=0, Z=-2.22, p=0.031, r=0.45). We perform a one-tailed test because we assume *haptic input* to result in fewer errors (see H_2). For *haptic input*, the errors resulted from four participants (median error of 1 level), while for *MRTK input* six participants made errors (median error of 2 levels).

Individual Likert-Items. After each task, we presented participants with two statements and asked them to rate them on a 7-point Likert scale (1=strongly disagree, 4=neutral, 7=strongly agree). All responses (grouped by *input task* and *input type*) are shown in Figure 7.

The first statement was "It was easy to perform the interaction." Overall, participants agreed for *haptic input* (Md=6, IQR=2.25), while they were neutral for *MRTK input* (Md=3.5, IQR=4). A Wilcoxon Signed-rank test revealed a significant difference between the conditions (W=687, Z=4.83, p<0.001, r=0.49). We can conclude that *haptic input* was rated as significantly easier in the interaction than *MRTK input*.

The second statement was "The interaction felt real." Over all tasks, participants agreed that *haptic input* (Md=6, IQR=2) felt more real than *MRTK input* (Md=3, IQR=3). A Wilcoxon Signed-rank test revealed a significant difference between the conditions (W=812, Z=5.12, p<0.001, r=0.52). We can conclude that *haptic input* was perceived as significantly more real than *MRTK input*.

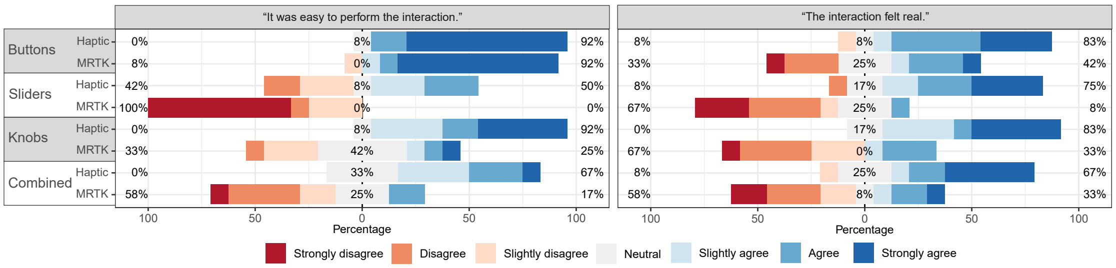

Fig. 7. Subjective ratings with 7-point Likert-items for the different input components evaluated. The task with button and slider combined is not shown. **Left:** Subjective ratings for "The interaction was easy." **Right:** Subjective ratings for "The interaction felt real."

User Experience Questionnaire. After each condition, we asked participants to fill out the User Experience Questionnaire UEQ [28]. For attractiveness, participants rated *haptic input* (Md=1.83, IQR=0.63) higher than *MRTK input* (Md=1.67, IQR=0.92). However, a Wilcoxon Signed-rank did not reveal an effect (W=29.5, Z=0.91, p=0.391). For hedonic quality, *haptic input* (Md=2.13, IQR=0.84) was rated higher than *MRTK input* (Md=1.88, IQR=0.59). Again, a Wilcoxon Signed-rank did not reveal a significant difference (W=39, Z=0.59, p=0.594). For pragmatic quality, participants rated *haptic input* (Md=1.42, IQR=0.33) higher than *MRTK input* (Md=1.04, IQR=0.96). Here, a Wilcoxon Signed-rank revealed a significant effect (W=58.5, Z=2.28, p=0.020, r=0.46).

NASA Raw-TLX. We asked participants to answer the NASA Raw Task Load Index (Raw-TLX) questionnaire[18], for which a lower score indicates lower task load. The resulting score for *haptic input* (Md=35, IQR=20.63) is significantly lower than for *MRTK input* (Md=53.75, IQR=9.79) (W=74, Z=2.75, p=0.003, r=0.56). Moreover, we compared the results on the subscales of the NASA Raw-TLX and found that haptic has a significantly lower score on physical demand, effort, and frustration (see Table 2).

Table 2. Pairwise comparisons of conditions (*haptic input*, *MRTK input*) concerning the subscales of the NASA Raw-TLX. W and Z from Wilcoxon Signed-rank test. Effect size (r): > 0.1 small, > 0.3 medium, and > 0.5 large effect.

	Haptic Input		*MRTK Input*					
Subscale	Md	IQR	Md	IQR	W	Z	p	r
Physical Demand	4.50	7.25	12.00	5.50	66	3.03	0.006	0.62
Effort	8.00	5.50	13.00	5.25	4	-2.64	0.041	0.54
Frustration	8.00	6.50	12.00	3.25	4	-2.64	0.029	0.54

Semi-structured Interviews. During our semi-structured interviews, we asked participants the following questions:

"Which of the two input alternatives did you like better and why?" In total, eight people named the haptic input device as the better alternative in general because of the simpler setting of values and the "better feel" (P10). One person was indecisive and added that, although setting values was easier with a haptic input device, they found the device on her wrist irritating. Two people noted that they found the hand tracking to be more innovative.

"What did you like about the MRTK input*?"* Three people mentioned the button and three people noted the lack of the distracting device as an advantage. One person found it to be faster due to the lack of linking. While another person noted that it was "something you've never done before" (P7). Familiar interaction also played a role: One person liked that the virtual elements could be operated like real elements and another that the interaction was "already somewhat familiar from the touchscreen" (P11).

"What did you not like about the MRTK input*?"* For this question, the participants mainly gave answers that refer to the difficulty of setting values, especially with the slider, but also with the rotary knob. Thus, seven participants mentioned the sensitivity of the slider as a problem. Three mentioned that the values were readjusted when they released the slider. Four of the participants also disliked the beginning of the interaction. Here, two people stated that they did not know exactly where to reach. Regarding the rotary knob, one person remarked about interacting with a purely virtual knob: "You didn't even have it in your hand yet and it already started" (P6). They also criticized the lack of feedback. In addition, one person commented that "it didn't feel particularly real" (P10).

"What did you like about the ARm Haptics *system?"* Nine people noted the easier setting of values, while one person commented: "It was easier to set the values, so you had more of a sense of achievement, which made it nicer and more fun" (P9). Seven people emphasized the advantage of being able to touch something, making it feel more real.

"What did you not like about the ARm Haptics *system?"* Among the negative aspects of the haptic input device, six participants mentioned the linking process, as it sometimes took a while and did not work perfectly. One person noted that the haptic button was unnecessary. Five people referred to the rather large device that one must wear on the wrist. In addition, one person reported the necessity of always using both hands as a negative aspect.

"For which interaction component (button, slider, rotary knob) was the ARm Haptics *system the most helpful and why?"* Here, nine people named the slider because of the easier setting of values, but also because of the improved termination of the interaction, since the haptic slider "does not jump when released" (P8). One person mentioned both the rotary knob and the slider, and for another person, the slider ranked directly after the rotary knob.

"Would you use such a haptic input device in the future and why (not)?" This question was asked under the assumption that participants would have to use an AR headset. All participants stated that they could imagine using such a haptic input device. Three participants tied their willingness to use it to the improvement of the rather large device: it should be smaller and not require "unnatural arm movement" (P10). Three further participants stated that it depends on hand tracking. They would try hand tracking first and then decide based on further experience.

5 DISCUSSION

In the following, we discuss the findings of our work. We decided to primarily shape the discussion around the hypotheses presented in section 4.1. Moreover, we discuss potential applications for our *ARm Haptics* system as well as limitations and future work.

Task Completion Times (H_1). The interaction with interface components differs between *haptic input* with our *ARm Haptics* system and the *MRTK input* because, for the *haptic input*, an additional step is required in which users need to link it to the virtual counterpart they would like to interact with. This linking process requires users to hold the *haptic input* close to the virtual counterpart and wait for one second for the linking to be complete. However, this additional step is not present for the *MRTK input*; thus, we hypothesized that it would result in differing interaction times compared to the *haptic input* (see H_1). In our analysis, **we found that button input resulted in significantly faster task completion times for *MRTK input* than for *haptic input*; however, we did not find any significant differences for *sliders* and *knobs***, and hence, cannot accept our hypothesis H_1. Compared to sliders and rotary knobs, button input can be understood as binary input – a button is either pressed or it is not pressed. As this interaction is rather simple and does not require much precision, the interaction in mid-air seems sufficient. While previous work has shown that connecting physical objects with virtual interface components can reduce interaction times [20], the additional linking process in combination with button input resulted in an opposite effect in our study.

The **linking process might not be necessary for all applications.** If the number of existing elements is low and they are far apart then it might be suitable to skip the linking process by automatically link the haptic elements to their virtual counterparts based on closest proximity. Yet, if many elements are cluttered together, as it is for example the case in many menus, then this might lead to an increase in error rate as the haptic element might connect to the wrong virtual element. It thereby is a trade-off between task completion time and error rate.

Another option to accelerate the linking process could be the usage of eye-tracking and gaze selection. If users' gaze focuses the virtual interface element for a short time, then the **linking could be automated through gaze selection.** The creation of the link might still be necessary, as users' might divert their gaze onto *ARm haptics* to find and press the haptic element. Yet, if it is expected that the hand is near *ARm haptics* anyways, for example during an ongoing interaction or during rapid repeated interactions, then it could be possible to completely skip the linking and direct the haptic input directly at the focused virtual user interface element. Similar gaze- and hand-based interactions have already been combined [31, 32], yet it is important to account for the "Midas Touch"-problem. We nevertheless would expect a reduction in task completion time.

Error Rates (H_2). One of the motivating factors for developing a haptic input system was to achieve higher precision in the interaction and thereby cause fewer errors when interacting (see H_2). To analyze this, we compared both types of input and found that *haptic input* resulted in significantly fewer errors than *MRTK input*. Thus, in line with previous work on stationary haptics [11], we can accept our hypothesis H_2. Since we did not register any errors for button input in either condition (meaning a participant would have failed to press a button), all errors resulted from interaction with *sliders* and *rotary knobs*. Here, *rotary knobs* resulted in a total of three errors and *sliders* caused 23 errors (while there were five knobs, the *combined* task added two additional sliders, resulting in overall seven per participant and *input type*). During our study, **we often observed that the slider value would jump for participants in the *MRTK input* condition after they had already set the correct value.** What caused this effect was that when participants let go of the slider, MRTK interpreted that as continued input and proceeded in changing the value. During the interviews, participants mentioned this as annoying and highlighted that the haptic slider "does not jump when released" (P8).

User Experience (H_3). In terms of user experience, we hypothesized that *haptic input* results in better user experience. As it is not recommended to sum up attractiveness with hedonic and pragmatic quality, we compared each of the categories individually. Here, we found a significant effect of *input type* on pragmatic quality, meaning **the perceived usefulness, efficiency, and ease of use were greater for *haptic input* than *MRTK input*.** Hence, we argue that we can partially accept our hypothesis H_3. Interestingly, we did not find any differences in hedonic quality or attractiveness. Nevertheless, both *haptic input* and *MRTK input* resulted in good to excellent scores for the individual items (except for dependability, which was above average).

Task Load (H_4). For task load, we expected a higher load for *haptic input* than for *MRTK input* (see H_4). However, when comparing the six different items, **we found three significant differences (physical demand, effort, and frustration) that all indicated better results for *haptic input*.** Hence, we cannot accept our hypothesis H_4. This is especially interesting for physical demand and effort, as it implies that interacting in mid-air is more demanding than via a haptic device, even when an additional step has to be performed (linking of haptics with virtual counterpart).

Designing Interfaces with ARm Haptics in Mind. In the last decades, researchers presented various ideas improving haptic feedback such as improved controller [47] or drones with haptic elements [2]. With *ARm Haptics*, we investigate a wearable system for providing haptics. Thus, *ARm Haptics* allows in contrast to the controllers to interact with both hands in mid air. While drones can provide a similar type of feedback, the robustness and precision of *ARm Haptics* could provide a benefit. The fact that *ARm Haptics* is placed at the users arm also has the drawback that users need to place the arm to map the physical interface element with the virtual counterpart. This challenge, however, can be addressed by designing interfaces with *ARm Haptics* in mind. Thus, **designers should place UI components, for which haptics is beneficial, in a way that the user can also comfortably place their arm to match the virtual elements.**

Automated Switching of Haptic Elements. We designed the *ARm Haptics* system in a modular way. Users can easily attach and remove the modules. However, this process still takes time. We envision that in the future, the **interface elements change automatically to match the currently needed input module** similar to the Haptic Revolver [47] providing feedback in VR. The exchange of haptic elements could also be enabled through the context of the users' interaction [38].

Future Interface Components. In this work, we focus on standard interface elements known from classical UIs as well as the MRTK. These elements provide a solid base for our approach. However, the presented approach can also be used to provide a more diverse type of feedback. This could be realized by combining the approach with shape changing displays capable to mimic different virtual objects [36].

3D printing and off-the-shelf hardware components enable researchers and developers to quickly create and explore new input modules with the *ARm Haptics* system. In this regard, especially **3D printing opens up the possibilities to replicate existing haptic input techniques from previous work or develop new input devices that do not exist yet.**

Applications Opportunities for the ARm Haptics System. This work contributes actionable insights on when it makes sense to use the *ARm Haptics* system. Our findings indicate that it depends. First, like mid-air input, our *ARm Haptics* system is not well-suited for longer interaction durations because in both cases, users will have a hard time keeping their arms up over time. Here, it would make sense to investigate different ways of linking the haptic device to virtual counterparts that allow users to keep their arms in a more natural pose, thus allowing for longer use.

Nevertheless, we can see the *ARm Haptics* system as a great addition to an existing interface. It could be **useful when there is higher precision input required that directly translates to actions of a system or machine.** This could be, for example, adjusting the volume of music, the brightness of lights, or the speed of a fan. In such cases, it would be problematic if the mid-air input resulted in a jump of the slider value. Here, our *ARm Haptics* system can be a useful addition to provide precise input.

Limitations. A limitation of our work is the limited number of interface components considered. Our findings already indicate that there are significant differences between the different components. Accordingly, no generalization can be made for all components, especially those not tested. It should also be noted that we conducted a laboratory study in which participants were only asked to interact with the input components we chose to implement in *ARm Haptics*. Users might react differently to the haptic input device in real applications. This might especially be the case if users also have to interact with physical objects at the same time. Although the concept of *ARm Haptics* takes it already into account that both hands remain free (when not interacting with AR content), the participants already noted in the study that the device can be bulky. The perceived bulkiness, if any, could become a burden in the long run, just like the required permanent holding up of the arm. Such temporal effects cannot be adequately determined in a relatively short study totaling less than one hour.

Future Work. In future work, various aspects of such a haptic input device should be evaluated. This relates in particular to the consideration of further interface components. Furthermore, the haptic input device must be tested in non-laboratory scenarios, especially those in which users must also interact with real objects. Also, the influence of the duration of use should be evaluated. In this regard, it makes sense to investigate smaller form factors. Currently, the haptic modules are rather large, as they use simple image targets for tracking. However, future iterations could use other tracking approaches, resulting in smaller and lighter modules.

6 CONCLUSION

In this paper, we presented our *ARm Haptics* system, which provides 3D-printed easily-changeable interface components that provide haptics for interaction in mobile Augmented Reality. After an iterative development process, we evaluated our system in a user study in which we compared it to hand-tracking input based on the Mixed Reality Toolkit (MRTK). Our results show that our system can benefit user interaction for some components (i.e., *sliders*, *rotary knobs*), while it offers fewer benefits for more simplistic interaction components (i.e., *buttons*). Given the better user experience and lower task load, we believe that the *ARm Haptics* system provides users with a good alternative to mid-air interactions that provides haptic feedback to users. Especially in combination with other forms of interactions, the *haptic input* can be a effective solution for precise input in Augmented Reality.

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