PropellerHand: A Hand-Mounted, Propeller-Based Force Feedback Device

Alexander Achberger
Mercedes-Benz AG
Stuttgart, Germany
alexander.achberger@daimler.com

Frank Heyen
University of Stuttgart
Stuttgart, Germany
frank.heyen@visus.uni-stuttgart.de

Kresimir Vidackovic
Hochschule der Medien - University of Applied Sciences
Stuttgart, Germany
vidackovic@hdm-stuttgart.de

Michael Sedlmair
University of Stuttgart
Stuttgart, Germany
Michael.Sedlmair@visus.uni-stuttgart.de

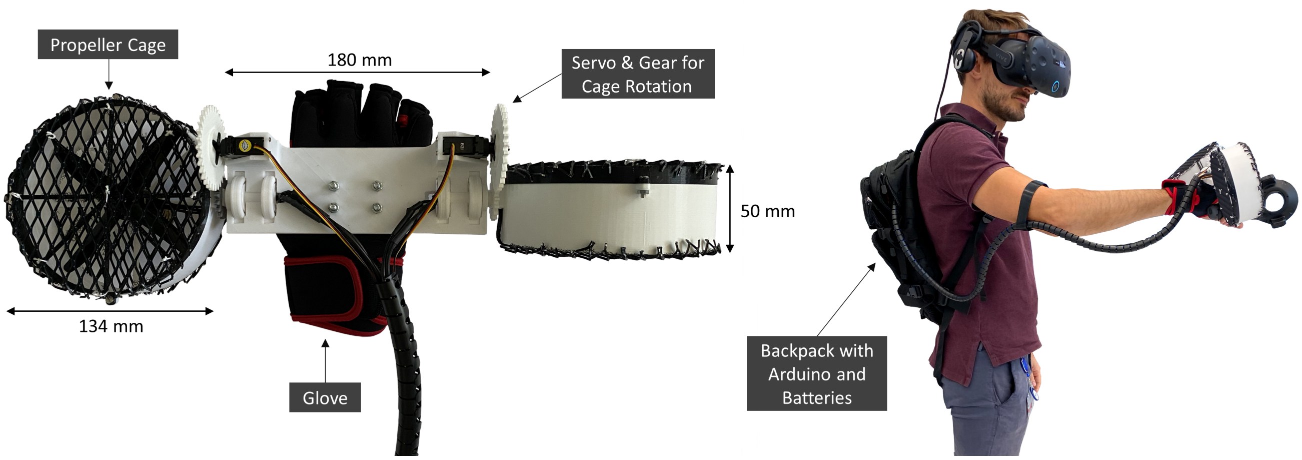

Figure 1: Left: PropellerHand consists of two propellers in rotatable cages attached to a glove. Right: A user wearing the device. The control unit and batteries are placed in a backpack to reduce the weight of the hand-mounted hardware.

ABSTRACT

Immersive analytics is a fast growing field that is often applied in virtual reality (VR). VR environments often lack immersion due to missing sensory feedback when interacting with data. Existing haptic devices are often expensive, stationary, or occupy the user's hand, preventing them from grasping objects or using a controller. We propose PropellerHand, an ungrounded hand-mounted haptic device with two rotatable propellers, that allows exerting forces on the hand without obstructing hand use. PropellerHand is able to simulate feedback such as weight and torque by generating thrust up to 11 N in 2-DOF and a torque of 1.87 Nm in 2-DOF. Its design builds on our experience from quantitative and qualitative experiments with different form factors and parts. We evaluated our final version through a qualitative user study in various VR scenarios that required participants to manipulate virtual objects in different ways, while changing between torques and directional forces. Results show that PropellerHand improves users' immersion in virtual reality.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices.*

KEYWORDS

Immersive analytics, haptics, ungrounded force feedback, propeller-based haptics, virtual reality

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1 INTRODUCTION

Virtual and augmented reality (VR/AR) enables users to inspect and interact directly with three-dimensional data, allowing for various applications in education, training, entertainment, immersive analytics, and visualization [19, 30, 34]. Current VR/AR headsets primarily rely on visual and auditory output, sometimes enriched with haptic feedback through vibrating controllers. Other types of haptic feedback, such as force feedback, can be of high interest in VR though, as they allow to "touch" virtual objects or data. Such devices can produce different force strengths and directions, and have shown praising results in classical VR applications [26, 27], telepresence [17], and also in data visualization [7, 9].

There are several dimensions in the design space of haptic devices, such as the type of feedback and attachment. The sensory feedback they generate can be either tactile, for example using vibration motors [20], or kinesthetic, when they employ motion [12]. Haptic devices can also be categorized into grounded and ungrounded devices, based on attachment. Grounded devices [6] are fixed to the user's environment (see Haptipedia.org [23] for more examples). They are mostly large and expensive, but can generate strong forces with high accuracy. Ungrounded devices on the other hand can be handheld [12, 14], attached to the user's body [15], or even move on their own [3, 16]. We are focusing on ungrounded kinesthetic devices that are cheaper and lighter than grounded ones and can be used in mobile use cases.

We extend existing work on ungrounded haptics [3, 12, 14–16, 22] by creating a novel device that for the first time allows to generate force and torque directly on the hand via propellers. These two types of feedback are required to resist motion and/or rotation that result in a more immersive perception of a virtual environment or in immersive analytics. Example use cases for haptic devices include games, industrial design, virtual collaboration, or data visualization [28, 31]. Here, we can increase the immersion of interactions such as moving or rotating objects or collide against them. For instance, when opening a door, haptics can simulate the torque of turning the handle and the force of pushing the door open.

We propose PropellerHand, a hand-mounted haptic device that leverages propellers to create kinesthetic feedback through forces and torques in two degrees of freedom (2-DOF) each, directly on the hand. PropellerHand is able to generate a thrust of up to 11 Newton (N) and a torque up to 1.87 Newton-metres (Nm) with a weight of 480 g. As our device is mounted to the back of the user's hand, they are still able to interact with or hold objects, such as VR controllers or physical tools. This allows more flexible interaction possibilities and usages in more various domains. We also allow for a more mobile use by integrating Bluetooth communication and batteries into our design. When users hold a VR controller, there is no need for an additional tracking setup, as the controller is already tracked and moves together with the hand. As we demonstrate in our user study, game mechanics such as opening a drawer or lifting objects become more immersive when using PropellerHand.

To summarize, we contribute a novel hand-mounted propeller-based force feedback device, as well as details of our design process. This process includes a formative user study evaluating different form factors, and measurements investigating the relationship of noise versus thrust of different propellers, both of which we did not find in related work. We perform a qualitative user study to evaluate our final device regarding its usability and increased immersion. Our supplementary material includes 3D models and further details on our design and process.

2 RELATED WORK

In our related work section, we show how haptics has previously been used in visualization, what kind of haptic feedback devices exist, and how they differ from ours.

2.1 Haptics for Visualization

In the field of data visualization, haptics have become important to support users to understand their data more accurately and quickly [7]. Paneels et al. [19] summarized various haptic designs to provide haptic feedback for different data visualizations such as charts, maps, signs, networks, diagrams, images, and tables. Their results show that most of the research focused on chart visualization, where they also describe the challenges in potentials of haptics. In the field of scientific visualization, Avila et al. [5] present a haptic interaction method that is suitable for volume visualizations. Another area where haptics have a high potential in data visualization is to enable blind persons to observe and understand visualizations. Frith et al. [9] present various methods to observe data with haptics without the need for visual components, such as using texture or forces. Here, we propose a force feedback device called PropellerHand. As a first step, we study PropellerHand with classical VR scenes and tasks, as these build the foundations for more complex interactive scenarios as used in data visualization. We are confident that results can also be generalized to immersive data analytics though.

2.2 Haptic Devices

We review related work on ungrounded haptic devices in the following categories: air-based, drone-based, propeller-based, and other methods.

2.2.1 Air-Based. First, we discuss approaches that use air, but not propellers, to create force feedback. The AirGlove device [11] forces compressed air through six nozzles to create thrust in any direction. It is able to create a realistic sensation of weight and forces of about 7 N. A major drawback is the required compressor that limits the range of the user's movement due to its weight and power connection. We follow similar goals, but avoid fixed or heavy equipment to create a more portable solution. The AirWand [21] is a pen-shaped device with one nozzle at each end that can produce a force of about 3 N. Contrary to our approach, it only produces force feedback in one dimension. Suzuki and Kobayashi [24] propose an AR system comprising a projection-based stereo display and force feedback via air pressure. Nozzles inside a table blow air upwards, where users receive it with a cup-shaped object in their hand. Since compressor and nozzles are fixed to the table, users are not able to move in a larger area or receive feedback from directions other than upwards. Contrary to PropellerHand, the three above approaches cannot create torque.

Drag:on [35] does not generate airflow by itself, but instead uses two flamenco fans that cause drag when moving the handheld device. By controlling the extent of the surface of each fan separately, the device can create different amounts of drag and torque. Due to its passive nature, this device cannot generate feedback, when the user's hand is not moving. Furthermore, drag can only be felt perpendicular to the fans' surfaces which makes the effect dependant on the device's orientation.

2.2.2 Drone-Based. Some related work uses drones to provide haptic feedback for objects that can move around the user. Yamaguchi et al. [32] propose an approach where a piece of paper, fixed to a drone and stabilized by its airflow, serves as an interaction surface. BitDrones [10] uses drones that are equipped with either an RGB LED, a shape formed by an acrylic mesh and a frame, or a small touch screen. These allow for augmented reality scenarios without the need for head mounted displays. HapticDrone [2] uses a quadcopter to create force feedback either up- or downwards with about 1.5 and 3 N. TactileDrones [16] provides tactile feedback through small drones. By hitting the user with differently shaped tips, this approach can convey the impact of arrows or the sting of a bumblebee. The drones of VRHapticDrones [13] are fitted with mesh surfaces or objects, to provide either a surface the user can touch or an actuator that touches the user. Alternatively, the user can also grab and move the drone to move the virtual object. Abtahi et al. [3] employ a drone to simulate physical touch events with realistic texture, by attaching different materials, such as cloth, to each side of the drone.

These drone-based approaches allow for physical representations of virtual objects, but the use cases for drones as haptic feedback devices are limited. None of the above approaches can provide much force and they cannot be used for torque feedback.

2.2.3 Propeller-Based Handheld or User-Attached Devices. Closest to our work are the following propeller-based approaches: Thor's Hammer [12] is a handheld force feedback device resembling a hammer with a large cubic head. The hammer's head contains six propellers, one on each face, allowing to propulse the hammer into any direction with up to 4 N. Aero-plane [14] uses two propellers that are fixed to a stick and can generate different downward forces to create the sensation of varying centers of mass. The device is able to convey scenarios such as a ball rolling on a plane. Leviopole [22] consists of two quadcopters mounted to a pole. Depending on the thrust of each of the eight propellers, it can create linear force in one and torque in two degrees of freedom.

A major drawback of these handheld devices is that they occupy the user's hand, which therefore cannot be used to interact with virtual or physical objects or controllers. Most of the current VR applications require controller interaction or direct hand interaction. If the user has to hold a feedback device such as Thor's Hammer, the interaction possibilities with data or virtual objects are very limited. We aim to transfer their propeller-based concept to a free-handed, less obstructing device.

Wind-Blaster [15] is most closely related to our contribution. It uses two rotatable ducted propellers that are fixed to the user's wrist. Participants of the conducted user study mentioned a weaker than expected force, which is something we want to improve on by using more powerful hardware. If the maximum force is too low, the user will not be able to perceive a sufficient number of different levels of force strength, which would substantially limit the interaction possibilities. The evaluation also misses to test rotating the thrust direction of the propellers during usage, as their user study only tested feedback in one direction. Instead of the wrist, we attach our device directly to the user's hand by using a glove. This position allows for a more direct and stable feedback and was preferred by the participants of our pre-study on form factors.

2.2.4 Other Approaches. This last part of related work consists of ungrounded haptics that use neither air nor propellers.

The handheld device by Yano et al. [33] as well as the iTorqU [29] employ a rotatable flywheel to create directional torques through the gyroscopic effect. Since we also want to generate force and not only torque, these approaches do not fit our goals. Lopes et al. [18] propose an approach that delivers feedback via eight electric muscle stimulation pads. The electric current causes the user's muscles to contract and thereby resist the opposing muscles, creating the illusion of a physical surface. This technique requires all pads to be connected to a power source through lots of cables, constricting freedom of movement. HapticSerpent [4] is a snake-like robotic arm, that is attached to the user's waist and is able to hold objects or perform actions such as poking. While it enables interesting use cases, it cannot create haptic feedback on the user's hand without obstructing hand usage. Wireality [8] uses strings to hold back the user's hand and fingers in order to prevent them from moving inside virtual objects. When an object's surface is touched, the system locks the spools of the corresponding strings, which are fixed to the user's shoulder, and the hand or finger cannot move further. This device can only generate feedback *towards* the user and bears a high complexity.

3 DESIGN OF PROPELLERHAND

We designed a force feedback device that consists of two propeller cages attached to a hand-mounted bridge (Figure 1). Those cages can be rotated via servo motors to be able to generate thrust and torque in two degrees of freedom (2-DOF) each (4-DOF in total). We used mostly 3D printed parts and commonly used electronic components to facilitate rapid prototyping and reproducability.

3.1 Propeller Cage Design Study

As moving propellers can be dangerous, we encapsulate them in cylindrical cages covered with aluminium meshes to prevent them from getting in contact with fingers or objects in the room, that might be pulled by the airflow. We conducted a small user study to find a cage size that does not obstruct movement of the arm and hand or cause collisions with other body parts. Six people (5m, 1f; 24-27 years) participated in this study.

The participants played one level of a VR game (Tumble VR for PlayStation). In this game, players have to stack objects onto a plate, requiring them to move and rotate their hand while holding a controller. We repeated this procedure six times with differently sized and weighted paper mockups of our approximate device design (Figure 2). The mockups' shapes reflect the dimensions of possible propeller choices and we tested cylinders with a height of 60, 65, and 70 mm and diameters of 76, 102, and 127 mm. We added different amounts of weight to the mockups (132, 198, and 290 g) to simulate the small, medium, and large versions of the device. The participants were sitting on a chair, to allow investigating collisions with the legs, and the mockups were fixed to either wrist or hand.

To avoid biases, we made sure that the participants did not know which mockup they wore, by attaching those in a random order and only after putting on the head-mounted display. On average, each participant spent about 17 minutes in total playing Tumble VR.

Figure 2: The paper mockup used in our form factor pre-study. Left/right: attached to the wrist/hand.

We registered a total of 11 collisions, 5 with the head and HMD and 6 with legs. We asked the participants, if they noticed any difference between the sizes and weights of the mockups, if they were restricted in their movement, and if they consciously moved differently. Four participants did not notice any differences in size and three no difference in weight. Only two participants felt slightly restricted in their movements, but only with wrist-mounting. Just one participant reported that s/he consciously moved differently because of the mockup. Overall, the participants' answers to our questionnaires show that even the largest and heaviest model did not obstruct usage. They also preferred mounting the device to their hand instead of their wrist, since this is more stable when moving. The hand-mounted version seems also more comfortable, since two participants reported to sweat less with this configuration.

Based on these results, we chose the biggest of our three candidate shapes, as we assume that this allows for the most thrust. We also decided to mount our device to the hand instead of the wrist.

3.2 Hardware

We chose an Arduino UNO micro controller board due to its ease of use and wide support. The brushless motors we use to drive the propellers, are of the type T-Motor F40 PROIII [25] and are similar to the ones used in Thor's Hammer [12], but slightly stronger. To select the servo motors that rotate the propeller cages, we compared about 40 different products to find the best compromise between torque and weight (see supplemental material). We chose the Hitec HS-81 Micro Servo. As all servos we found either provide 180 degrees or continuous rotation, we opted to use gears to obtain a larger range (330 degrees). We recommend using metal gear servos, as one of our plastic ones broke during the user study. For batteries, we used the Conrad Energy Lipo with 2400 mAh and 14.8 V, and for the electronic speed controllers (ESCs), we used Pulsar A-50 with 50 A. We chose these components because they match the motors' power requirements. For the communication between a PC and the Arduino we use a HC-05 Bluetooth module.

We compared four propellers with different diameter, shape, and blade count that fit the cage size we found in our pre-study. For this comparison, we performed experiments to measure thrust and noise at different power levels using a custom-build thrust stand. Based on the results of these experiments, we chose a four-bladed propeller with a diameter of 127 mm.

3.3 Software

Our software consists of several parts. For controlling motors and measuring thrust with the load cell, we wrote small C/C++ programs for the Arduino. The VR scenarios for our user study and the code for sending commands to the Arduino are written in C# using Unity. We implemented two safety measures: propellers turn off when they get too close to the user's head or when the controller's trigger is double-clicked.

3.4 Resulting Device

PropellerHand (including the glove) measures about 470×135×50 mm and weighs about 480 g (Figure 1). We are confident that we can further reduce the weight with a more sophisticated 3D design, as motors, propellers, and cables weight less than 130 g. The total cost of components amounts to about 225 Euros (about 270 USD), excluding 3D printed parts. Controller, batteries, and Bluetooth module (840 g in total) are placed in a small backpack to minimize the mass attached to the user's hand. With our current battery capacity of 2×2400 mAh, PropellerHand could provide feedback for at least two hours. The actual operating time will vary depending on the duration and strength of feedback, but batteries are quick to change and can be replaced by ones with higher capacities when needed. Our device does not require any calibration or tracking setup prior to use, as we assume that the hand will be tracked anyway in a usual VR use case, either via controller or VR glove, to which PropellerHand could be directly attached.

4 TECHNICAL EVALUATION

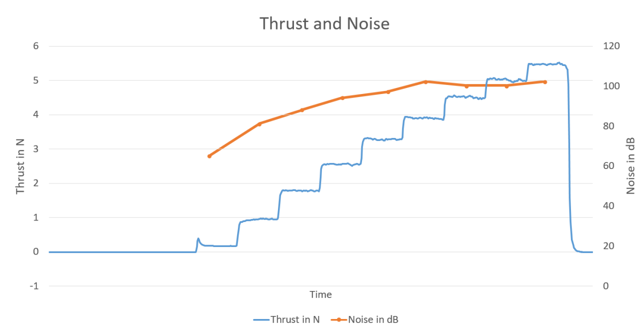

Figure 3: The thrust and noise measurement of one propeller. We increased the power every 5 seconds, therefore we can see steps in the thrust measurements.

To avoid unnecessary noise, and since the generated thrust seemed already strong enough, we did not use the maximum amount of power, but only 55.6 percent of it (as regulated by pulse-width modulation (PWM)). For our force measurements, we used a load cell from which we suspended one of the propeller cages such that it created a downward thrust. We measured a maximum force of 11 N, a minimum force of 0.17 N, and a maximum torque of 1.87 Nm, see Figure 3.

This means that PropellerHand can provide more thrust than Wind-Blaster [15] (1.5 N) and Thor's Hammer [12] (4 N) and less than Aero-Plane [14] (14 N).

Another important metric is the consistency of thrust, since users might notice fluctuations and therefore feel less immersed. When running the propeller for 10 seconds, all measured values were inside a range of 0.03 N (SD: $5.3E^{-5}$ N). We did not perceive these fluctuations ourselves, and they are even smaller when less thrust is generated. This is a low value, which means PropellerHand can produce the same amount of force over a long time, which is important for many use cases.

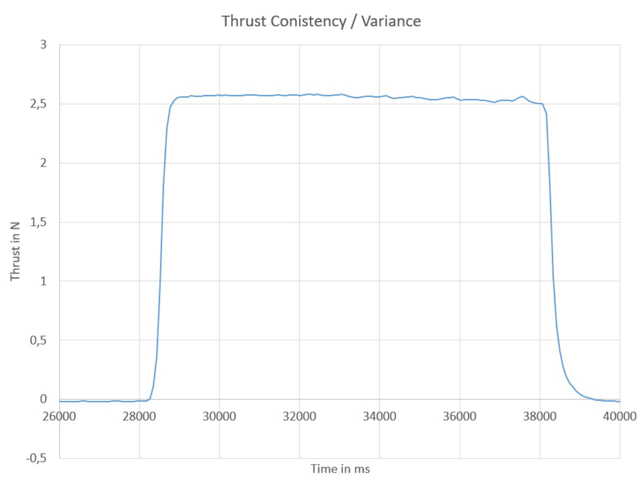

Figure 4: The thrust consistency measured with a single propeller with an intensity of 27%.

As our device can produce varying amounts of thrust as well as rotate the propeller cages, we measured two kinds of latency: the reaction time from a control signal to full target thrust and the time needed to rotate the cage to a target angle. We measured a latency of 683 ms for a still-standing propeller to reach full thrust. Compared to non-propeller-based force feedback devices, this is a high value, therefore we recommend to calculate collision prediction in order to reduce the latency. For a 330 degree rotation of the cage, our device requires 429 ms with standing propellers and 833 ms when running at full thrust.

We measured the noise level of PropellerHand with a decibel meter placed 1 m apart, we got a maximum sound pressure of 102 dB and a minimum sound pressure of 65 dB.

5 USER STUDY

We evaluated the influence of our device on immersion in a user study with four scenarios that require PropellerHand to simulate force and torque in varying amounts and directions.

5.1 Study Design

We recruited six people from our university's campus to participate in the study (5 m, 1 f; 24-34 years). Five assessed their VR experience as beginner and one as advanced. None of them have had previous experience with kinesthetic haptic feedback.

The participants used an HTC Vive Pro head-mounted display (HMD) and it's controller and wore earplugs during the study. For increased hygiene, we provided each participant with their own single-use rubber glove and sanitized the HMD after each use. We attached our device to the participant's dominant hand (all were right-handed). The participants were standing and free to move in an area of about 4×4 m. To reduce noise and especially annoying frequencies, we limited the power through PWM to 28 percent of the maximum, limiting thrust to 5.1 N and torque to 0.87 Nm.

We proceeded as follows: After the participant signed a consent form, we gave a brief introduction to the safety features and study procedure. Each participant experienced four scenarios, each of them first without haptic feedback and then with PropellerHand. In each of the scenarios, the participants had to complete a different task, as described in detail in the following subsection. The participants were allowed to familiarize themselves with the virtual environment for as long as they wished, but for at least 30 seconds. After each scenario, the participants answered a questionnaire that included 7-point Likert scale questions (1: very strongly disagree - 7: very strongly agree). The questions asked in how far PropellerHand increased the immersion in VR. After all four scenarios, a concluding questionnaire inquired about general feedback for PropellerHand, possible improvements, and which scenario the participants preferred and why.

5.2 Scenarios

We created four scenarios that allowed us to evaluate our device with different types of user-object interactions. To provide a more comfortable environment, we situated these scenarios in a virtual room and a grove which we retrieved from the Unity Asset Store [1] (Figure 5). The scenarios require PropellerHand to simulate both force and torque separately for the first three scenarios and to switch between them within the last scenario. This differentiates our scenarios from those used in related work, which only tested either force or torque [12, 14, 15].

S1: Moving Objects with Different Weights. In order to investigate the simulation of physical weight, we told participants to sort five identically-looking pieces of cheese by weight into boxes (Figure 5a). We assigned each piece a different weight that PropellerHand then simulated by varying the produced thrust. Once a user grabbed and lifted a piece, PropellerHand oriented its propeller cages such that the produced thrust was directed downwards (airflow upwards), using the HTC controller's pitch value.

S2: Daggers Producing Different Torques. In this scenario, participants grabbed identically-looking daggers at their grip and held them horizontally, with the blade pointing to their left (Figure 5b). Each blade had a different weight and therefore produced a different torque on the participant's hand. Here, PropellerHand oriented one propeller's thrust downwards and the other one's upwards, creating torque around the arm. As before, the participants sorted the daggers by weight and placed them in empty boxes.

S3: Catching Falling Items. To also test torque in another direction, this scenario employs items that fall from the sky and have to be caught by the participant (Figure 5c). For this task, we provided a virtual catching device that resembles two pans glued together

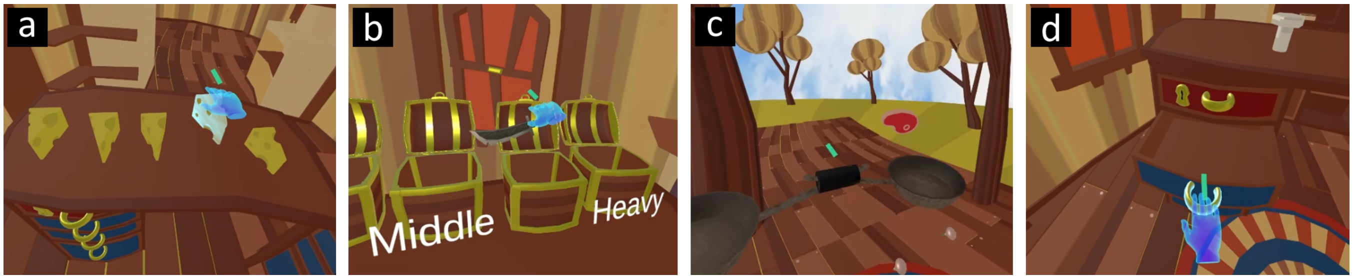

Figure 5: The four scenarios of our user study. (a) and (b) Blocks of cheese and daggers that participants had to sort by weight. (c) A catching device with which items falling from the sky were to be caught. (d) Participants had to unfasten screws and place them in drawers.

at their handles. Depending on the items' weight, the torque will be slightly different, allowing the user to perceive collisions with different object weights. We implemented three different falling objects with different weights: a block of cheese, a piece of meat, and an onion. The catching device itself was not assigned a weight to reduce strain and allow us to measure the effect more clearly.

S4: Multiple Desk Interactions. In this scenario, we tasked participants with unfastening three screws and placing them in three drawers (Figure 5d). This motion required PropellerHand to quickly switch between producing force and thrust. When the participants grabbed and twisted the screw, the propellers were rotated such that they produced a torque simulating the screw's friction. After removing the screw, PropellerHand simulated its weight by orienting the thrust downwards. Next, the participants had to place each screw in one of the drawers. We simulated the drawers resistance during opening and closing by orienting the thrust against the direction of movement. When completely opened, increased thrust conveyed the drawers being stopped from moving further.

5.3 Results

Overall, participants enjoyed using our device. They strongly agreed that PropellerHand increased the immersion in VR (mean (M) of 7-point Likert scale: 5.9).

S1: Moving Objects with Different Weights. We asked the participants whether they felt the weight of the objects and whether they perceived these weights to be different. All of them described the weight perception as very distinct (M: 5.8, SD: 0.8) and easy to distinguish (M: 6, SD: 0.9), see Figure 6. One participant reported that s/he noticed louder noise for higher weight values and that the *"lag between picking up things and the fans turning on feels odd"*. All agreed that PropellerHand increased the immersion of the virtual environment (M: 6, SD: 0.9). Everyone sorted the pieces correctly.

S2: Daggers Producing Different Torques. In this scenario, we asked the participants about their perception of torque. All participants stated that they could feel the torque when grabbing the daggers (M: 6.5, SD: 0.5) and a torque difference between the different blades (M: 6.5, SD: 0.5), see Figure 6. One participant mentioned that some torques did not fit the daggers because they were visually identical, but felt different. However, this was necessary to avoid visual biases from influencing the results. As in the first scenario, all participants reported feeling more immersed when using PropellerHand (M: 6.5, SD: 0.8), with one participant mentioning that the *"torque was captured well"*. Again, all objects were sorted correctly.

S3: Catching Falling Items. After they finished the third scenario, we asked participants whether they were able to feel the impact of falling objects as well as a difference depending on the object's type. Each participants reported to have felt a significant difference between the strength of impacts (M: 6, SD: 1.3), see Figure 6. All participants clearly perceived the impact of falling objects (M: 5.7, SD: 0.8), but three mentioned a significant delay between seeing and feeling it. Due to this delay, participants reported less increased immersion than in S1 and S2 (M: 5.5, SD: 1.4). Furthermore, it seems that fast hand movements make it harder to perceive impacts.

S4: Multiple Desk Interactions. In this scenario, the participants were asked whether they perceived forces with different strengths and directions depending on the object they interacted with. They strongly agreed that they felt different strengths (M: 6.2, SD: 0.8) and directions (M: 6, SD: 1.3), see Figure 6. While interacting with the drawers, one participant said *"oh that is cool"* when he felt the drawer's collision with the stopper. Others described the torques as easier to feel than the forces and stated that there is *"only a slight delay in the haptic feedback when pulling out a drawer to the limit"*. All participants told us they enjoyed this scenario and agreed that PropellerHand made them feel more immersed in the virtual environment (M: 5.7, SD: 1.5).

Concluding Questionnaire and Summary. After participants finished all the scenarios, we asked them to answer a final questionnaire with general questions about PropellerHand. The questions included which use case they prefer, if the noise or wind flow was disturbing, and if the weight of PropellerHand was too heavy. We also asked them to give general feedback about PropellerHand. The participants agreed that the noise was disturbing the immersion (M: 5.7, SD: 0.8), although one said that *"the noise is not that bad since you are distracted"*. When asked whether the airflow negatively impacted the immersion, the average answer was between neutral and disagree (M: 3.5, SD: 1.6).

The answers about PropellerHand's weight were mixed, they neither agreed nor disagreed that our device is too heavy (M: 4.3, SD: 2.2): *"Keeping your arm in the same position for long periods of time is tiring."*, *"The device definitely increases immersion. At the*

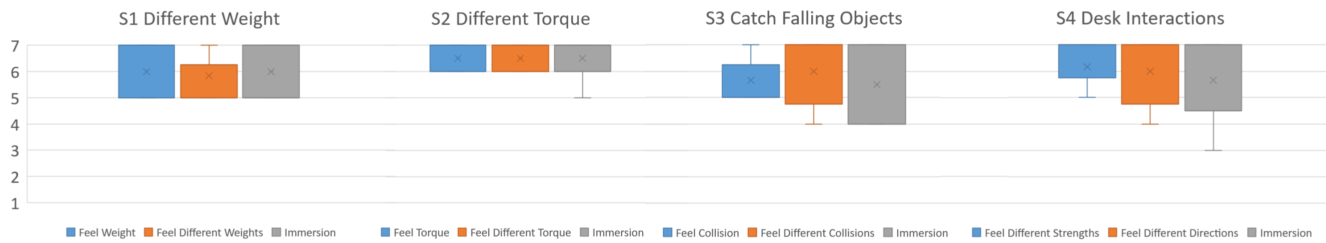

Figure 6: The results of the 7-point Likert Scale of the 6 participants (7 means very strongly agree and 1 very strongly disagree). The boxes indicate the first and third quartile, the lines the minimum and maximum values, and the X-symbols the mean value.

same time it is also tiring for your arms, first due to its own weight and second because most forces are generated in the same direction as gravity."

The general opinions on PropellerHand were positive: *"Totally awesome to have these haptics, this changes a lot"*. Participants described their experience as *"very interesting and immersive"* and said that the *"haptic device emphasises the feeling of actually doing something in reality"*. Interestingly, *"torque was more clearly tangible than directional force"*. There were also some suggestions and criticisms, for example that *"it would be more realistic if momentum was simulated [as well]"* and that *"picking up things seems more realistic, but the lag feels off"*.

Regarding the feedback, participants told us that *"it was extremely helpful to feel the drawer's stopping"* and that they *"like that it gives you more information about the virtual environment"*.

When asked for their favorite scenario, participants preferred those including torques: *"I preferred the use case with torques, in that case I found the reaction of forces on the human body (arm) the most appropriate." "The falling object use case was my favorite, because you could feel the impact, even if you did not look at it."*

One participant suggested to keep the propellers running at all time, such that the device carries itself and the noise is more constant. Further proposals included adding another DOF for rotation, increased forces, and using both hands for the feedback.

6 LIMITATIONS AND DISCUSSION

The current version of PropellerHand still has several limitations. Due to its propeller-based design, noise will be an issue even when wearing earplugs or headphones. In practice, users should wear active noise canceling headphones to further reduce the noise level compared to standard headphones or earplugs. Currently, the device cannot provide thrust in the left-right direction or rotate and move the user's hand in different directions at the same time. This also means that users have to hold their hand in certain ways depending on the intended direction of thrust.

Some participants mentioned that PropellerHand is too heavy, an issue that we plan to address with an improved design. Both force and torque are produced with a certain delay that decreases the immersion in some use cases. This delay between visual and haptic feedback could be reduced by letting the propellers always run at low RPM. Furthermore, software-side methods such as collision prediction could be used. Our user study only had six participants, which means we cannot generalize to a broader population. However, this was not our goal and is left for future work.

Despite these limitations, there are many use cases where PropellerHand can simulate force and torque convincingly. For example, the participants in our user study enjoyed being able to perceive the stopping of drawers and impact of caught objects, feedback that does not require them to keep their eyes on objects while interacting with them. However, due to the latency and maximum force of PropellerHand, it has limitations in simulating realistic collisions. We see more potential in the simulation of soft resistances than impact forces, such as weight simulation, pressing against soft objects, or simulating current. The noise level increases with the strength of the force, so we recommend reducing the power of the motors, if communication is more important than high forces during the task. We believe PropellerHand can also be used in general mid-air haptics to enable interaction, but we see a limitation when PropellerHand obscures important information due to its size. In addition, the study results showed that PropellerHand was capable of providing perceivable torque for different abstract use cases. Our studies focused on simple VR scenes and tasks. In the future, we want to use PropellerHand for immersive data analytics and investigate how findings will generalize to this application area.

7 CONCLUSION

We propose a new ungrounded force feedback device that is worn on the user's hand. Compared to prior work, we include more powerful motors and propellers. Additionally, PropellerHand can produce thrust and torque and can quickly switch between them. We also contribute our design process, including a user study on form factors and quantitative experiments on propellers.

The user study we conducted to evaluate our final design shows promising results regarding the improved immersion. It also revealed current limitations and provided us with ideas and suggestions for further improvements.

In the future, we plan to combine our device with haptic-feedback gloves such as the Manus Prime II Haptic. We also want to further improve our design and evaluate upcoming versions with more extensive user studies. For example, we could add two more propellers or another rotation axis for additional degrees of freedom.

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