VRHapticDrones: Providing Haptics in Virtual Reality through Quadcopters

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ABSTRACT
We present VRHapticDrones, a system utilizing quadcopters as levitating haptic feedback proxy. A touchable surface is attached to the side of the quadcopters to provide unintrusive, flexible, and programmable haptic feedback in virtual reality. Since the users' sense of presence in virtual reality is a crucial factor for the overall user experience, our system simulates haptic feedback of virtual objects. Quadcopters are dynamically positioned to provide haptic feedback relative to the physical interaction space of the user. In a first user study, we demonstrate that haptic feedback provided by VRHapticDrones significantly increases users' sense of presence compared to vibrotactile controllers and interactions without additional haptic feedback. In a second user study, we explored the quality of induced feedback regarding the expected feeling of different objects. Results show that VRHapticDrones is best suited to simulate objects that are expected to feel either light-weight or have yielding surfaces. With VRHapticDrones we contribute a solution to provide unintrusive and flexible feedback as well as insights for future VR haptic feedback systems.

CCS Concepts
•**Human-centered computing** → **Haptic devices; Virtual reality;**

Author Keywords
virtual reality; haptic feedback; force feedback; quadcopter; presence; immersion;

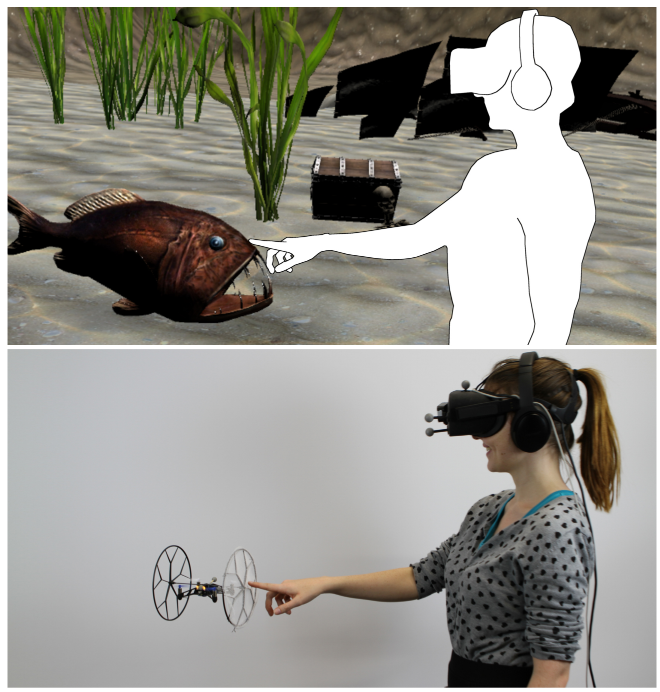

Figure 1. When the user reaches out to touch the virtual anglerfish, our system allows the user to experience a congruent haptic stimulus. Our system controls a quadcopter at the exact location of the virtual fish to provide a synchronized touchable surface.

INTRODUCTION
Virtual Reality (VR) technologies show a huge lack in giving appropriate haptic feedback. A consumer VR HMD offers to transform any living room into a highly engaging virtual environment of one's dreams and therefore VR technologies are becoming more and more popular. To achieve the current state of technological development and user expectations, academic and commercially-oriented research has especially focused on improving video and audio technologies. Recent developments show good results: the devices' high-resolution, near-eye displays combined with surround sound create an immersive audio-visual experience that induces a high level of presence felt by the user.

In comparison, there has been less emphasis on stimulating other sensory modalities, such as the different subcomponents of the haptic system. Nonetheless, the past decade has wit-

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nessed the development of a number of promising research prototypes. In particular, they have addressed the challenge of providing appropriate stimuli for simulating touch, pressure, and temperature at the hands or even providing realistic whole body haptic feedback in VR. Common solutions, such as vibrotactile gloves [7] or belts [36], can only provide feedback on specific body parts and require users to attach devices to their body. This extra gear can oftentimes feel cumbersome and constricting, which can diminish the user's interactive experience in turn.

An alternative approach is to provide haptic feedback via devices and objects that are located in the user vicinity. These can be robot arms that provide force-feedback at the location which the user reaches out for [3] or real props that emulate the virtual objects' forms [34]. Here, users are not required to wear a multitude of specialized devices. However, they have to remain close to the haptic feedback devices and cannot move freely in physical space.

In response to these problems, we developed VRHapticDrones, a system that provides haptic feedback in VR. Our proposed system does not require any additional wearable devices and provides the user with the freedom to move around even in large spaces. VRHapticDrones utilizes quadcopters that can simulate haptic user interaction with a large range of objects, such as a coffee mug or a wooden chair, in the VR environment. VRHapticDrones adds another dimension to VR by providing a haptic experience. It imitates stationary and moving objects by aligning its touchable surface with the surface of virtual visual objects, thereby allowing the user an active haptic exploration of the virtual object. In addition, the quadcopter can imitate active objects that physically impact the user, such as a snowball, by actively making contact with the user. Apart from simulating objects for active and passive haptic experiences, VRHapticDrones carry and position haptic tokens in any location of the virtual environment.

CONTRIBUTION STATEMENT

The main contribution of this paper is VRHapticDrones, a new system that provides unintrusive, flexible feedback methods which are able to provide three feedback modalities: active, passive, and proxy-based haptic feedback. Through the use of quadcopters, we can render detailed and complex, unintrusive, haptic feedback which results in a significantly higher sense of presence that does not require to wear additional devices. We illustrate our vision of the new range of stimuli and explain them in detail through the example of an immersive underwater world. Furthermore, we explore limits of the passive haptic feedback in two studies. The user reaches out to interact with virtual objects and perceives haptic feedback provided by quadcopters. We investigate the subjectively perceived realism between the shown scene and the recognized haptic stimulation. Finally, we contribute guidelines for building convincing haptic experiences using VRHapticDrones.

RELATED WORK

The VRHapticDrones system is inspired by two strands of research: enabling haptic feedback in VR and quadcopters, which provide haptic feedback.

Haptic Feedback in VR

Most commercial VR devices provide haptic feedback through vibrotactile actuators, integrated into handheld controllers. However, there are other wearable devices to provide haptic feedback in VR, e.g. using electrical muscle stimulation [27, 28], vibrotactile vests [26], head-worn motors [16] and gloves [8], and exoskeletons [29]. Previous work also developed approaches for providing realistic feedback for handheld devices. For example, [19] presented a new handheld haptic device which uses propeller propulsion to generate 3-DOF force feedback that is generated by six motors that are attached to a handheld frame. Benko et al. [6] proposed to augment a handheld controller with a device that can convey the shape of an object in VR and its texture using a 4×4 matrix actuated pins. To overcome the fact that the users still have to hold a controller, Gu et al. [15] presented an exoskeleton which is mounted on the user's hand to provide haptic feedback in VR. As the exoskeleton prevents fingers from moving when a virtual object is in reach, the user has the feeling of haptic resistance from the virtual object. To provide haptic feedback at different body locations, Signer and Curtin [33] developed a body-worn construction, which is overlaid by holograms for providing a tangible and haptic Augmented Reality (AR) experience. Systems using this technique will soon become commercially available. Further, Schmidt et al. [31] created a user-mounted device for simulating steps in VR.

To provide highly realistic haptic feedback, Simeone et al. [34] proposed to repurpose objects that are already in the environment of the user. The authors arrange a virtual environment according to the physical environment to use existing objects for their – already existing – haptic capabilities. By scaling this down to an object granularity, Hettiarachchi and Wigdor [20] use the physical properties of objects to spontaneously create haptic experiences, while Sun et al [35] scale up this approach to a world level. Furthermore, Cheng et al. [9] recognized the capabilities of using humans for their ability to spontaneously create haptic experiences, which they could scale up to providing haptic walls [10].

Another trend is to build systems for providing haptic feedback that is scalable, programmable, and can be placed in the environment. For example, Araujo et al. [3] use a robotic arm and a cube with different surfaces for providing different haptic experiences to a user wearing an head-mounted display (HMD). Depending on where the user touches a virtual object, the robotic arm rotates the cube in a way such that always the correct surface is being touched. Furthermore, He et al. [18] suggest using small mobile robots as a haptic proxy for VR tabletop applications, while Jeong et al. [21] suggests creating haptic experiences using movable wires. Also, regular objects, e.g. furniture can be augmented to create a haptic experience [17]. Another system that augments a tabletop has been presented by Follmer et al. [12]. The authors purpose a dynamic shape display for displaying forms and shapes according to the digital input. This can be used to dynamically provide haptic feedback for VR scenarios at a fixed position. Conversely, instead of making the environment scalable, other research focuses on making the user believe that the haptics of the environment is matching the virtual scene. Azmandian et al. [5] propose a technique called haptic retargeting for physical feedback in VR. Thereby, the user's hand is redirected to touch a single object that is in the user's proximity, while the user believes that multiple objects are present.

Human-Quadcopter-Interaction

Since the proliferation of small quadcopters in the research domain of Human-Computer Interaction [13], they were mostly used for navigation purposes [4, 11, 24] or as a flying camera [30]. This changed when Gomes et al. [14] proposed BitDrones, quadcopters that can be tracked and controlled. The quadcopters are equipped with LEDs, screens, and a cage to make them graspable. The BitDrones project is one of the first approaches to use quadcopters as flying input devices. In contrary, Kosch et al. [25] show how a remote control can be used as input for quadcopters. Abtahi et al. [2] investigated the social interaction properties of quadcopters in a cage and quadcopters without a cage. Additionally, Yamaguchi et al. [39] proposed using a quadcopter that is carrying a canvas as a haptic target for a sword fight. In their prototype, they use the drone as a resistor that the user feels to have hit the enemy. Recently, Knierim et al. [22, 23] showcased using autonomous drones as haptic agents that make contact with the users to provide feedback that is passively received by the user. Abdullah et al. [1] use a quadcopter and hand tracking for providing 1D haptic feedback.

Overall, related work recognized the need for haptic feedback to make VR experiences more immersive. Other related work used quadcopters as an input device and a haptic target. To combine these two aspects a scalable platform for managing quadcopters to stimulate the user at the right body positions is required. With the VRHapticDrones system, we extend previous work by using quadcopters to provide active haptic feedback in VR, where the user is actively reaching out to make contact with quadcopters that are used as haptic proxies in order to simulate the surfaces of virtual objects. Furthermore, we present our vision of quadcopters that can not only be programmed and react to changes in the VR scenario immediately but also offer additional quadcopter extensions that provide three different haptic experiences. This vision is complemented by suggesting how input can be designed in VR using quadcopters.

HAPTIC FEEDBACK THROUGH VRHAPTICDRONES

We present VRHapticDrones to provide haptic feedback in VR. VRHapticDrones adds haptics to virtual objects and allows the user to sense a haptic stimulus while immersed in VR. Our overall vision of VRHapticDrones is to provide three different types of haptic feedback in VR: passive, active, and positioning haptic proxies. We showcase these three types of haptic feedback using the underwater world scenario depicted in Figure 2.

Passive Feedback

While users are immersed in our underwater world, they begin in a dim surrounding with only one glowing sphere floating in front of them. Users can explore the dark space by walking and looking around. Not being limited to looking and walking users can also haptically explore the surroundings. When reaching out with their hands to touch the glowing sphere, they can feel the resistance of it. An encased quadcopter is providing a passive surface by levitating at the virtual position of the sphere. For any virtual object which should provide a haptic stimulus when touched VRHapticDrones can dynamically align a touchable surface of a quadcopter with the virtual objects. After touching the sphere, the scene gets illuminated. An anglerfish (Figure 2a) becomes visible and swims away. Figure 3a shows the modified quadcopter.

Active Feedback

As a second feedback category, our underwater scenario contains elements which actively engage with the user. A shark is appearing in the users' vicinity and directly swims towards them. Active feedback is provided to amplify the impact of the shark nudging the user. In such a scenario quadcopters are controlled to actively contact user's body-parts according to the location of the virtual object. The shark nudging the user is illustrated in Figure 2b. Figure 3b shows how we implemented the concept using a quadcopter.

Haptic Proxy Feedback

For more complex haptic feedback which goes beyond active and passive exploration, VRHapticDrones can provide haptic proxies. Haptic proxies are small and lightweight tokens the user can touch and interact with. Quadcopters place these proxies at the required position to enable seamless interaction. Figure 2c shows a worm attached to a fish hook which is lowered to the seabed. Users can grab the worm and take it as a trophy. To enable this kind of interaction a rubber worm is attached to the quadcopter as a proxy. The quadcopter is hovering whereby the proxy's physical location matches the virtual one. Figure 3c shows a quadcopter capable of providing haptic proxy feedback.

Application Scenarios

The ability to provide passive, active, and feedback via haptic proxies makes VRHapticDrones very versatile. We envision to deploy VRHapticDrones in a number of use cases. Here, we demonstrate further use-cases to showcase the flexibility.

Gaming and Entertainment

Besides the described underwater world, VRHapticDrones offers the potential to further enhance games and entertainment. Passive feedback for almost any virtual object can be provided. We esteem feedback to be especially valuable when users interact with the environment. In a game, players could be asked to open a door (passive feedback). When the door swings open arrows are shot at the player from behind the door (active feedback). To stop getting shot by arrows the player must pull out a spring from a device to disarm the arrow trap.

Construction and Design

We also envision application scenarios in the construction and design domains. Car designers can benefit from VRHapticDrones during the design process while potential customers can virtually touch (passive feedback) their new car before ordering. Further, customers could go for a virtual ride supported by several haptic proxies surrounding the user, such as the knob to turn on the air condition.

(a) (b) (c)

Figure 2. VRHapticDrones supports three different feedback modes: (a) Passive: The object is levitating and the user can touch it. (b) Active: The object is proactively bumping into the user. (c) Proxy: The object can be grasp and moved by the user.

(a) (b) (c)

Figure 3. Quadcopter prototypes to deliver different types of feedback. (a) passive feedback, (b) active feedback, (c) haptic proxy feedback.

User Interface Elements

While using cameras that track the user's hands in VR, such as the Leap Motion, no haptic feedback is provided when interacting with user interface elements. VRHapticDrones can represent haptic virtual buttons (passive feedback) while maintaining hands-free interaction. Further, elements or notifications not in the field of view of the user could gain attention by nudging the users' left or right shoulder (active feedback). Finally, virtual sliders could have a haptic proxy anywhere in space to facilitate intuitive usage (haptic proxy).

IMPLEMENTATION

VRHapticDrones, comprises a high-speed motion tracking system, quadcopters as haptic feedback appliance, a VR HMD and a software backend. The motion tracking System captures the position of the user's HMD and the quadcopter and streams it to the VRHapticDronesbackend core. The core processes all data and sends updates regarding the quadcopter's position to the PID-Controller and scene events to the VR Renderer. The PID-Controller takes care of maneuvering the quadcopters, while the VR renderer processes updates from the core and displays the VR scene on the HMD. An overview of all components and connections is shown in Figure 4.

Tracking System

The system tracks the HMD, quadcopters and defined body parts. All data is streamed to the VRHapticDrones backend. We set up a Motive OptiTrack motion capturing system with 12 Flex 3 cameras covering an interaction space of $4\,\text{m} \times 4\,\text{m} \times 3\,\text{m}$. It samples with 100 Hz at a millimeter accuracy. Quadcopters can hover anywhere around the user inside this volume. A Leap Motion sensor is mounted at the front of the HMD and is used for tracking the user's hands, which enables to include them into the VRHapticDrones system.

Haptic Drone

Each quadcopter is used as a haptic feedback interface. Different lightweight haptic extentions can be attached to the quadcopters (see figure 3). Our implementation is based on the commercially available Parrot Rolling Spider quadcopter. They are powered by a 550 mAh battery, providing approximately 6 min of flight time depending on the attached haptic proxy. We removed all the unnecessary panels, such as casings, to increase the payload capacity. The maximum weight of the haptic proxy including the markers for the tracking system is 10 g. The quadcopter connects via Bluetooth low energy to our VRHapticDrones backend. The underlying Linux OS processes steering commands with 20 Hz.

VRHapticDrones Backend

The VRHapticDrones Backend interconnects the VR rendering engine, the quadcopter control, and the motion tracking system. Our system runs on a workstation with an Intel i7-6700 processor, 16 GB of RAM, and an NVIDIA GeForce GTX 970 running Windows 10.

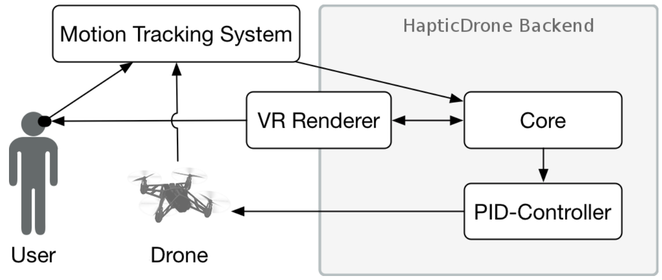

Figure 4. All components of the VRHapticDrones system.

Core

Our software backend core processes the streamed location data and controls the quadcopter. Furthermore, trajectory planning and synchronization with the virtual world renderer are processed inside this component. Further, it maintains quadcopter, users, and interaction states and manages the application behavior.

VR Renderer

The VR scenarios are rendered by the Unity3D game engine and are displayed on an Oculus Rift HMD. The VR Headset equipped with a Leap Motion for displaying the user's hands within VR. As proposed by Schwind et al. [32], we used a neutral hand style representation to avoid potential biases of our participants. A set of reflective markers are attached to the HMD. Positional data is forwarded from the VRHapticDrones core to the rendering engine and is rendered accordingly. The game engine further calculates collisions between virtual objects represented by either quadcopters or human body parts and reports back to the VRHapticDrones core.

PID-Controller

The PID-Controller component wirelessly sends control signals to the quadcopter over Bluetooth LE to direct the quadcopter to a particular location. Data transmission is exposed through a local nodeJS server application. A set of four Proportional, Integral and Differential (PID) loops to control the movement of the quadcopter towards the positions managed by the VRHapticDrones core. During hovering, the quadcopter relies on its own IMU, ultrasonic sensor and down facing the camera to stay at a fixed position.

Limitations

Our current implementation of VRHapticDrones still requires the user to attach a reflective marker to specific body parts to support full body tracking. This is in particular necessary for interactive application scenarios where the user closely interacts with the quadcopters. For scenarios with lower accuracy requirements, the VRHapticDrones core estimates the body part position depending on the location of the HMD and hand positions as tracked by the Leap Motion sensor.

During the study, we used only one quadcopter at a time. This choice reduces the complexity of our flight control component in a first place. However, the used Bluetooth stack supports simultaneous connection to up to five quadcopters. Using several quadcopters at the same time may increase complexity in trajectory planning, collision prevention, and noise level, but it allows higher frequencies of multiple feedback interfaces at a time. As future work, we will extend the capabilities of our prototype to support several simultaneously flying quadcopters.

Our quadcopters' flight time is limited to approximately 6 minutes which makes VR experiences quite short. As mentioned, multiple alternating quadcopters could solve this issue. The increased audible noise will be covered up by music and sounds, as most VR experiences include a strong audible component. Additionally, the produced noise can be addressed by using active noise canceling headphones as we did in the studies.

STUDY 1: IMPACT ON PRESENCE

In this study, we focused on providing a physical surface that delivers haptic feedback when the user explores virtual objects. We assume that interactions that involve the user's hands result in a higher presence when hand-held devices are not needed for interaction or haptic feedback. Therefore, we conducted a user study to examine the increase of presence which typically accompanies increased immersion.

Methodology

We used Unity3D to create a scene that resembles a birthday party. Participants interacted playfully with a balloon in VR. We hypothesized that adding haptic feedback via a quadcopter-positioned surface to hand tracking would result in a higher presence than providing no haptic feedback while using hand tracking or providing state-of-the-art feedback through a controller with vibration.

Independent Variables

We defined the feedback modality as the only independent variable with three levels: *No Haptic Feedback* (1), *Vibrotactile Feedback* (2), and *Quadcopter Feedback* (3) delivered by VRHapticDrones (3a). In each of the experimental conditions, participants saw a virtual representation of their hands, as such visualizations are essential parts of interactions. Haptic feedback is only triggered when the balloon in the virtual scene is touched by the participant.

Participants

We recruited 12 students and international interns (6 female; 6 male; mean age of 21.58 years with a SD of 1.84) of the local university via mailing lists. All participants had normal or corrected-to-normal vision. Participants who were in need of vision correction had to wear contact lenses to avoid wearing glasses under the HMD.

Five participants had no VR experience, seven had minor experience with VR, i.e. five minutes up to three hours. Except for one participant, none had experience with the Leap Motion sensor.

Apparatus

The apparatus consists of an Oculus Rift and noise-canceling headphones to negate the buzzing produced by the drone. For the *Vibrotactile Feedback* condition (2), we used the Oculus Touch controller as well as the Oculus tracking system. For the *No Haptic Feedback* (1) and *Quadcopter Feedback* (3)

Figure 5. Participant exploring the virtual balloon during the first user study through touching and pushing.

conditions we used a Leap Motion sensor attached to the front of the HMD for hand tracking. The positional tracking of the participant's hands was of equal quality in each condition. The hand models were adjusted to look like the Oculus Touch hand models used in the *Vibrotactile Feedback* condition (2).

We used the OptiTrack system for positional tracking during the *Vibrotactile Feedback* (2) and *Quadcopter Feedback* (3) condition. For the *Quadcopter Feedback* condition (3), we used a Parrot Rolling Spider quadcopter, including attached wheels with tulle-textile covers as the touchable surface (as depicted in Figure 5).

The physical interaction with the balloon was only affecting the back and forward movement of the balloon i.e. moving away from the participant in the room. The up and down and sideways movement was animated via unity physics to ensure a balloon-like behavior. This restriction ensured comparable balloon behaviors between the three conditions. As participants only interacted with the front-side of the objects, the touch surface did not only provided feedback but also served as a protection to not get in contact with the quadcopter's rotors.

Procedure

After being introduced to the system and task the participant filled out the consent form and the demographic questionnaire. When the participant put on the HMD, he or she was immersed by the virtual birthday party scene. The experimenter asked the participant to interact with the balloon. The balloons responded naturally to interactions such as touching and pushing.

We used a within-subject design, hence each participant performed all three conditions. The order of the conditions was counter-balanced across participants using a Balanced Latin Square design. Participants interacted with the balloon for 3-5 minutes and were encouraged to start with an extended index finger and to try out different hand postures in each condition. After each condition, participants filled out a Presence Questionnaire (PQ) [37]. While being interviewed by the experimenter, the participants were encouraged to provide suggestions and concerns about the system. After completing each condition, the participants answered questions regarding the comparison and liking of each condition.

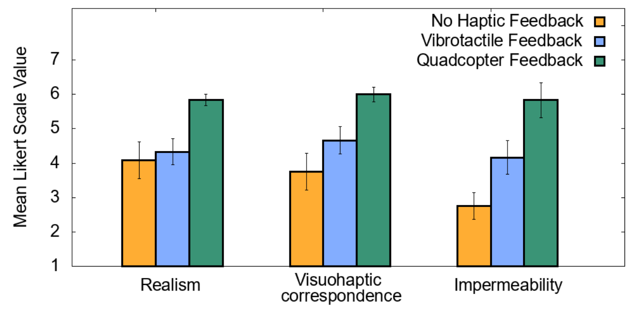

Figure 6. Mean values of visuohaptic correspondence, realism, and impermeability for each condition. Error bars show standard error of the mean (SE).

Results

The results of the full-scale PQ for each condition are: *No Haptic Feedback* 142.5 points (SD = 20.2), *Vibrotactile Feedback* 142.0 points (SD = 16.1), *Quadcopter Feedback* 164.5 points (SD = 15.8) (see Figure 7). Presence ratings differed significantly between the three conditions (Friedman test, $\chi^2(2) = 18.681$, $p < .05$). Wilcoxon tests were used to follow-up on this finding (Holm-Bonferroni corrections were applied to control the family-wise error rate). We found that using *Quadcopter Feedback* (3) significantly improved presence ratings compared to using *No Haptic Feedback* (1) (p = .004) or using *Vibrotactile Feedback* (2) (p = .003). Using a controller does not increase presence when compared to the hands only condition (p = .326).

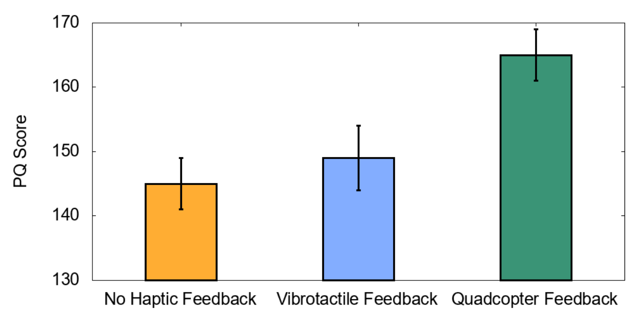

Figure 7. Mean values of presence score (PQ) for each condition. Error bars show standard error of the mean (SE).

A closer look at the subscales of the PQ reveals that the difference in presence can be traced back to an increase in the *Haptic Visual Fidelity*-subscale ratings. The quadcopter condition is rated higher than the controller (p = .002) and the hands-only condition (p = .006). Furthermore, the *Adaptation/Immersion*-subscale rating of the quadcopter condition is rated higher than the controller (p = .004) and the hands-only condition (p = .019).

To further evaluate the experience provided by VRHapticDrones, we presented three Likert-items to the participants, that specifically targeted the haptic feedback. In particular, we asked participants to rate on a scale from 1 to 7 how much they agree with each of the following statements: (1) "The visuals match what I feel.", (2) "How realistic did it feel? " and (3) "I was able to pass through the object." We used Wilcoxon tests to perform pair-wise comparisons between the ratings for the conditions. The results demonstrate that our system improves the correspondence between haptic and visual feedback. The quadcopter condition is rated higher than the controller ($p = .003$) and the hands-only condition ($p = .003$). It also increases the realism. The *Quadcopter Feedback* condition is rated higher than either the *Vibrotactile Feedback* ($p = .005$) or *No Haptic Feedback* condition ($p = .008$). Furthermore, it improves the perceived solidity of objects. The *Quadcopter Feedback* condition is rated higher than either the *Vibrotactile Feedback* ($p = .041$) or *No Haptic Feedback* ($p = .012$). Overall, the results show that providing haptic feedback via a quadcopter creates a higher level of immersion compared to state-of-the-art controllers. Therefore, this induces a stronger feeling of presence in the participants as this kind of feedback represents an exploration that is closer to the real world experience of touching an object.

Subjective Comments

One participant mentioned that using the controller (*Vibrotactile Feedback*) felt like holding an object that is used to push the balloon. Another participant noted the same experience and added that

> *"[...]it did not feel like a balloon because you can feel the controller and the vibration was only in the palm and not on the fingertips."* (P1)

These comment show that interacting with a controller lacks direct and unintrusive feedback and interaction and is hence inappropriate / not mature enough for a having a realistic VR experience.

Two participants commented that they preferred the hand tracking via the Leap Motion sensor.

> *"[...]the controller was not able to detect that [hand posture] type of detail and did not reflect it visually"* (P6)

The state-of-the-art Oculus Touch controllers do not allow accurate hand tracking and are only able to provide a fixed approximation of hands divided into discrete hands postures.

Nine participants explicitly valued that the quadcopter combined both a mature hand tracking while still being able to provide haptic feedback. Six participants remarked that the quadcopter feedback felt real and natural.

> *"It is really exciting! I didn't expect it to work that well already. Even the "Hands-Only" condition was working really well, despite the lack of feedback. Controllers are annoying because you have to hold something in your hands. The "quadcopter" was cool because there even was something there where I touched the balloon."* (P2)

After experiencing the quadcopter's haptic feedback, participants already imagined further use cases. The quadcopter could be used for providing improved feedback in 3D drawing apps. These do not have any feedback other than vibration while drawing in the air or when two brush strokes collide. A further use case was using the quadcopter as and flying inventory to select usable items.

Discussion

The results demonstrate that our system outperforms on state-of-the-art interactions in VR environments when it comes to hapticly exploring and interacting with virtual objects. The feedback is perceived as more immersive, realistic and better suited to the visual virtual object than feedback provided by a controller, which are currently the most readily available technology for haptic feedback. Therefore, when quadcopter-mediated haptic feedback is provided, participants report a higher sense of presence and find the interaction method less intrusive.

While haptic feedback that is mediated via quadcopter-positioned surfaces has various advantages, the variety of objects that can be simulated is limited by the force that the quadcopter can generate. Objects with a large mass such as tables and cars or stationary objects such as walls do not easily yield to pressure when touched or prodded. In contrast, the quadcopter-positioned surface will not remain stationary if the force applied by the user is larger than the counterforce provided by the quadcopter. On the other hand, this allows providing a more dynamic feedback. This can result in objects exhibiting haptic properties that do not comply with the physical expectation, such as a solid wall feeling wobbly. This also can be used intentionally as other state-of-the-art feedback methods are not able to provide such a feeling. While humans tolerate some discrepancy between visual and haptic experiences, the cohesion of the multisensory percept will be diminished if the discrepancy becomes too large. In other words, the haptic experience will no longer appear realistic. In the following study, we investigated the influence of the expected mass and behavior of different objects.

STUDY 2: INFLUENCE OF OBJECT COMPLIANCE

The previous study showed that a higher sense of presence is induced by providing haptic feedback via VRHapticDrones. As the study compared different haptic feedback methods by interacting with a balloon, we investigate how the object's perceived mass and an expected behavior impacts the perceived presence regarding haptic feedback provided by drones in this follow-up study.

Methodology

We used Unity3D to create a scene resembling a living room. We propose that the suitability of quadcopters to simulate the haptic experience of different objects depends on the object's perceived mass but also on the object's surface consistency and pliability. We will refer to the two corresponding haptic attributes as global and local compliance, respectively.

Global compliance - is the tendency of how easy or hard it is to relocate an object as a whole by applying force. Objects with small mass have high global compliance—that is, they are easy to push and move around. They are better suited to be simulated by quadcopter-positioned surfaces than objects with low global compliance.

Local compliance - is the tendency of an object's surface to yield locally when pressure is applied. For instance, a cushion propped on a sofa has high local compliance: when prodded, the surface will yield to a certain degree and the finger will displace part of the object. We hypothesize that objects with high local compliance are better suited to be simulated by quadcopter-positioned surfaces. Importantly, objects with a low global compliance (i.e., with a large mass) can be successfully simulated using quadcopter if users expect them to exhibit high local compliance.

Prestudy

To choose the objects and quantify their compliance, we conducted an informal pre-study with 12 participants. We asked the participants to judge 15 different objects regard their local and global compliance on a scale from 1 to 10 (where 10 indicated high compliance). This was done by marking for each object its location within a 10x10 grid with surface/local compliance being judged along one axis and global compliance along the other axis. Participants were instructed to think of local compliance as "how easy or hard a surface is deformable by touching the surface" and of global compliance as "how easy or hard it is to move the whole object by touching it". We chose the four objects that, on average, received the most extreme ratings within the four possible combinations of high and low as well as local and global compliance. These objects were (1) Wall (low local/low global compliance), (2) Balloon stuck to a wall (high local, low global compliance), (3) Coffee mug (low local, high global compliance), and (4) Pillow (high local, high global compliance). Additionally, we chose a fifth object with a medium rating on global compliance, (5) Chair, since we were most interested in simulating objects with different mass.

Independent Variables

We define the objects as the only independent variable with five levels. This comprises as a result of the prestudy: (1) wall, (2) balloon stuck on a wall, (3) chair, (4) coffee mug and (5) pillow. In each of the conditions, participants saw a virtual representation of their hands. Haptic feedback is only triggered when the balloon in the virtual scene is touched by participants.

Participants

The participants were students and international interns of the local university. Fifteen participants (7 female; 8 male; mean age 23.66 years with a SD of 4.09) took part in the experiment. All participants had normal or corrected-to-normal vision. Participants who were in need of vision correction had to wear contact lenses to avoid wearing glasses under the HMD.

Apparatus

We used the same basic apparatus as in study 1. However, haptic feedback was always provided by the Parrot Rolling Spider Drone and hand tracking was always done via Leap Motion. Instead, we varied the visual objects that the participants interacted with. In particular, we used five objects of different local- and global compliances.

Figure 8. The five objects we evaluated with different local and global compliance. From left to right: wall, balloon, chair, coffee mug, and pillow.

Procedure

After being introduced to the setup the participants were placed in a virtual room where all five objects were shown. After the participants got used to their new virtual hands and environment they were successively presented with every object. The presentation order was randomly determined for each participant. After interacting with each object for two minutes the participants got presented with four questions regarding the objects, in form of several 7-point Likert-type in-VR items. The questions were designed to investigate the visuohaptic correspondence quality ("What I see and what I feel, match."), the perceived matching of the haptic experience ("The object feels like I expected it to feel."), how fitting the local compliance felt ("The hardness/softness of the object felt like I expected it.") and how fitting the experienced weight and resistance of the object felt ("The resistance/drag of the object felt like I expected it."). After interacting with all objects the participants were asked to choose the object that felt most realistic.

Results

We performed four linear mixed effects model analyses, one for each of the four ratings provided by the participants after interacting with the objects (i.e., participants' ratings on one of the four questions served as the dependent variable in one analysis). As fixed effects, we entered the local- and global compliance ratings for the different objects obtained in the prestudy. As random effects, we entered the participants. P-values were obtained using a likelihood ratio test that compared the full model against a null model without the fixed effect in question.

While both the dependent and the independent variables are numeric, it is unclear whether they can be considered truly interval-scaled rather than ordered categories. Therefore, we treat significant co-variation of the independent variables (i.e., the compliance ratings) and dependent variables (participants' ratings on the Likert-style items) as monotonous rather than linear increases in participants' ratings. This means participants' ratings increase from one compliance level to the next—however, not necessarily by the same subjective amount.

In the following, we report the results for each of the four ratings obtained from participants. For reasons of conciseness, results and discussions will focus mainly on significant results.

Crossmodal Correspondence ("What I see and what I feel, match.") and **Appropriate Resistance** ("The resistance of the object felt like I expected it."). Increases in global compliance lead to higher ratings of both crossmodal correspondence ($\chi^2(1) = 4.8, p = .029$) and appropriateness of the resistance provided by the drone ($\chi^2(1) = 5.8, p = .016$). This provides support for our prediction that the haptic stimulation in our system is better suited for objects that are perceived to be easily moveable as a whole.

Appropriated softness/hardness ("The hardness/softness of the object felt like I expected it."). Participants ratings increase with local compliance of the object ($\chi^2(1) = 10.2, p = .001$). This provides support for our prediction that the haptic stimulation provided by our system is well suited to simulate objects that are locally deformable or soft.

Appropriate overall haptic sensation ("The object feels like I expected it to feel."). There was not sufficient evidence for a monotonous co-variation between compliance and the overall haptic sensation provided by the drone. One possible reason for this is that the question is phrased very broadly, leaving room for personal interpretations of the term 'feel'. For instance, some participants may have included the tactile feeling provided by the surface material into their judgment while others did not.

Qualitative results. Generally, the comments by the participants were in favor of light and small objects. As they behave or feel similar to the drones haptic feedback and touch surface.

This is backed up by the rating done after the participants interacted with each object. The objects that got rated most realistic are: Mug: 5 votes; Pillow: 5 votes; Balloon on a wall: 3 votes; Chair: 2 votes; Wall: 0 votes.

Three participants commented that they chose the mug because

> *"[. . .] the touch and following displacement of the cup felt most realistic. The feeling of displacing the drone was the most fitting to the feeling of moving a cup. "*

Three participants commented that the material of the drones' touch surface felt most realistic when it was representing a pillow, as they would expect such a material used on pillows. Three other participants said that

> *"[. . .] the fabric of the drone was compliant in the same way the material of a balloon would feel."*

Two participants commented that they expected the pillow to deform on touch and therefore found it less realistic. The wall was commented on to be too compliant, as it was not fitting the visual representation due to the lack of displacement and that it was feeling not "hard enough".

Discussion

Small-scale drones are generally not well-suited to simulate heavy objects since they cannot provide sufficient force to prevent the user from displacing the drone. This results in a mismatch between the seen and the felt position of the user's hand or the hand penetrating into the object. The present study demonstrates one way of approaching this problem. We show that the feedback provided by drones is rated as more realistic if the corresponding visual object implies a lightweight object with a hard surface or alternatively a soft or yielding surface, independent of the object's weight. Thus, credible haptic interactions with objects with large mass can be created, as long as the user believes that the felt displacement of the drone reflects an attribute of the object. This effect can most likely be increased if the visual object surface is locally deformed upon touch. Simulated visual surface deformations have been shown to induce the illusion of softness, even on hard surfaces [38].

CONCLUSION AND FUTURE WORK

We present VRHapticDrones, a haptic feedback system for Virtual Reality environments. VRHapticDrones supports three different types of haptic feedback, namely, passive, active, and proxy-based feedback. Through two user studies, we found that the haptic feedback provided by VRHapticDrones increases the user's sense of presence in the VR environment compared to traditional vibrotactile feedback and a control condition without haptic feedback. Furthermore, we found that the feedback provided by drones is perceived as more realistic if the corresponding visual object implies a lightweight object with a hard surface or a soft or yielding surface, independent of the object's weight. Therefore, to achieve credible haptic interactions lightweight objects should either be movable or objects with large mass should have a yielding surface that reflects the felt displacement of the drone with a visual deformation upon touch.

VRHapticDrones contributes to the field of providing scalable haptic feedback for VR systems, which is unintrusive and does not require augmenting the user and is only dependent on the environment's tracking technology. As VRHapticDrones are hovering in the air around the user, they are only providing haptic feedback when necessary. Moreover, we are capable of providing different types of feedback with various positions and various intensities depending on the current VR environment the user is interacting with.

In future work, we plan to investigate different materials that can be attached to the quadcopter to provide not only realistic haptic feedback but also tactile exploration of objects. Further, we are planning to integrate the tracking of the quadcopters into the HTC Vive's lighthouse tracking system to build a flexible haptic solution that can be used out-of-the-box with existing hardware.

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