Beyond The Force: Using Quadcopters to Appropriate Objects and the Environment for Haptics in Virtual Reality

Parastoo Abtahi, Benoit Landry, Jackie (Junrui) Yang, Marco Pavone, Sean Follmer, James A. Landay
Stanford University, Stanford, CA
{parastoo,blandry,jackiey,pavone,sfollmer,landay}@stanford.edu

Figure 1: Haptic interactions using a quadcopter. Left: user touching fabrics attached to the quad for texture rendering. Middle: user picking up a physical hanger attached to the quad. Right: user picking up the turned off quad as a passive haptic device.

ABSTRACT

Quadcopters have been used as hovering encountered-type haptic devices in virtual reality. We suggest that quadcopters can facilitate rich haptic interactions beyond force feedback by appropriating physical objects and the environment. We present HoverHaptics, an autonomous safe-to-touch quadcopter and its integration with a virtual shopping experience. HoverHaptics highlights three affordances of quadcopters that enable these rich haptic interactions: (1) dynamic positioning of passive haptics, (2) texture mapping, and (3) animating passive props. We identify inherent challenges of hovering encountered-type haptic devices, such as their limited speed, inadequate control accuracy, and safety concerns. We then detail our approach for tackling these challenges, including the use of display techniques, visuo-haptic illusions, and collision avoidance. We conclude by describing a preliminary study (n = 9) to better understand the subjective user experience when interacting with a quadcopter in virtual reality using these techniques.

ACM ISBN 978-1-4503-5970-2/19/05.
https://doi.org/10.1145/3290605.3300589

CCS CONCEPTS

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

KEYWORDS

Quadcopter, Drone, UAV, Encountered-Type, Human-Drone Interaction, Robotic Graphics, Haptics, Virtual Reality.

ACM Reference Format:
Parastoo Abtahi, Benoit Landry, Jackie (Junrui) Yang, Marco Pavone, Sean Follmer, James A. Landay. 2019. Beyond The Force:, Using Quadcopters to Appropriate Objects and, the Environment for Haptics in Virtual Reality. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland Uk.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3290605.3300589

1 INTRODUCTION

Recent advances in audio and visual renderings in Virtual Reality (VR) have made virtual experiences more immersive and have led to the proliferation of commercially available VR hardware. Haptic feedback technology, however, has not kept up with these audiovisual improvements, and the illusion of reality often breaks upon users coming in contact with the virtual objects. Research in haptics aims to bridge this gap by designing novel devices that simulate the sensation of force and tactile feedback. The most prevalent haptic solutions can be categorized into four groups: wearable, hand-held (grounded or non-grounded), mid-air, and encountered-type (conventionally grounded). Wearable, hand-held, and mid-air haptics require the user to carry a device, and the interactivity space is often limited to the users' hands, as virtual objects cannot be felt with other body parts.

Encountered-type haptic devices are most commonly grounded robotic arms that move such that users encounter the end-effector of the robotic arm when they make contact with a virtual object. These devices do not require the user to wear a device or hold a tool, enabling contact with all body parts. More importantly, unlike other forms of haptic solutions, encountered-type haptics present a physical surface to users allowing them to directly touch and manipulate objects. Despite these advantages, grounded encountered-type haptics have shortcomings that restrict their usage, such as their high cost and limited workspace. The working volume is restricted by the space that the robotic arm spans, and even a mobile robot on wheels will impose a limit on the height of the workspace. Moreover, robotic arms require complex motion planning to navigate around obstacles in the environment.

To address these limitations, researchers have begun to explore hovering encountered-type haptic devices that use quadcopters in virtual reality. Quadcopters are capable of flying quickly almost anywhere within the workspace and they may be more affordable than large robotic arms. Recent efforts in this area have focused on the force feedback that can be provided by quadcopters. However, quadcopters can provide limited force feedback, lack accuracy, and impose safety concerns in VR. We address these limitations and suggest that beyond force feedback, quadcopters can facilitate rich haptic interactions by appropriating existing objects and the environment. To enable these haptic interactions, we suggest three techniques shown in Figure 1: (1) dynamic positioning of passive haptics, (2) texture mapping, and (3) animating passive props. We highlight these techniques with the use of *HoverHaptics*, an autonomous system comprising of a safe-to-touch quadcopter and an infrastructure for its integration with a virtual environment. Prior research in this space has not utilized a fully enclosed quadcopter and the exposure of the rotating propellers ultimately limits the interaction. We built a quadcopter cage with a fully enclosed mesh to enable rich haptic interactions.

We identify inherent challenges of hovering encountered-type haptic devices that stem from competing requirements, including high perceived comfort and safety, carrying capacity, control accuracy, and speed. For example, by increasing carrying capacity the quadcopter can lift the safe-to-touch cage and other passive props; however, the added thrust may cause safety concerns. Limiting the speed of the quadcopter is then necessary to ensure safety and adequate control accuracy. We detail our approach for tackling these challenges, including the use of display techniques for communicating the state of the quad, visuo-haptic illusions to compensate for the lack of control accuracy, and collision avoidance as a safety measure.

We conducted a preliminary study with 9 participants to better understand the subjective user experience when interacting with a quadcopter in VR using these techniques. We found that with the safety measures in place, 8 out of 9 participants felt safe interacting with the quadcopter in VR. Participants were most excited by the animation of passive props, as they were able to grasp and move objects. All participants reported that they were not distracted or bothered by the quad. We conclude with a discussion on the limitations of our system and challenges that need to be addressed in future work.

Contributions

(1) Introducing haptic interactions mediated through quadcopters by appropriating objects and the environment.
(2) *HoverHaptics*: an autonomous safe-to-touch quadcopter prototype and its integration with a VR system.
(3) Design considerations for overcoming inherent challenges in the implementation of hovering encountered-type haptics.
(4) A preliminary study of the user's experience when interacting with a safe-to-touch quadcopter in VR.

2 RELATED WORK

We begin by providing a brief overview of existing haptic solutions, their use cases, and their inherent limitations. We then describe the recent advances in quadcopter technology that enable the exploration of hovering encountered-type haptic devices. Finally, we review prior research investigating the use of quadcopters in VR and highlight the advantages of this new haptic technology.

Haptic Devices in Virtual Reality

Haptic solutions in VR fall on a spectrum from passive, utilizing existing physical objects [20, 24] to active [54]. Passive haptics are limited as the shape, position, and properties of the physical prop have to closely match their virtual counterparts. Researchers have explored the use of pseudo haptics, a form of haptic illusions, to manipulate the perception of passive haptic devices [12, 36]. However, certain virtual elements such as dynamic objects can only be represented using an active device. Active haptic devices can be broadly categorized into four groups: wearable, hand-held (grounded or non-grounded), mid-air, and encountered-type.

Wearable Haptics. Wearable haptics consist of devices that are placed on the user's body and provide a large working volume. These could be glove-style devices with vibrotactile actuators [37], wrist grounded exoskeleton [17, 33], exoskeleton for grasping objects [9], or full body suits [30, 48]. These devices require the user to wear an apparatus and the feedback is often limited to the area on the user's body that is in contact with the wearable.

Hand-Held Haptics. Hand-held haptic devices may or may not be grounded. Non-grounded hand-held devices include controllers with movement actuation [10], vibrotactile actuation [29, 47, 50], shape displays [6], and propeller propulsion [18]. Grounded pen-based hand-held devices [15, 25, 49] exert an accurately controlled force vector and are used for virtual manipulation tasks that require high precision. Hand-held devices require the user to hold the device during interaction and, similar to wearable interfaces, do not allow the users to feel virtual objects with all parts of their body.

Mid-Air Haptics. Mid-air solutions do not require the user to wear an additional device and are capable of providing hands-free haptic feedback. A class of mid-air devices manipulate air pressure directly and use compressed air pressure fields in the form of air jets [45] or air vortices [43]. An example of indirect air pressure manipulation is ultrasonic haptic feedback, in which arrays of ultrasound transducers create air pressure waves [35, 39, 52]. These solutions are well suited for providing tactile feedback for user-interface elements, but does not provide kinesthetic force feedback.

Encountered-Type Haptics. Encountered-type haptic devices move such that when users make contact with a virtual object they encounter the haptic device. McNeely introduces the term Robotic Graphics to describe these solutions, and draws an analogy between graphics displays simulating the appearance of an object and a robot simulating its feel [31]. Conventional encountered-type haptic devices are grounded robotic arms with end-effectors that enable rendering of various object characteristics. For example, Active Environment Display [46], Surface Display [21], and ShapeShift [42] are designed to render surfaces and shapes, while Snake Charmer [4] demonstrates rendering surface textures and temperatures. Encountered-type solutions present a physical surface to users as opposed to creating the sensation of force or tactile feedback; however, the high cost and small workspace limits the use of these devices, motivating the use of quadcopters as hovering encountered-type haptic devices. Note that in our categorization of haptic solutions, mid-air haptics are distinct from hovering encountered-type haptics: mid-air solutions only manipulate air pressure to create the sensation of tactile feedback and users do not encounter any physical objects.

Quadcopter Technology

Personal drones (or quadcopters) are becoming increasingly prevalent. Some quadcopter designs are completely safe-to-touch [3, 13] and others have increased safety by adding a protective cage [7, 14] or propeller guards [11, 38]. These safe-to-touch designs motivate the exploration of new forms of human-drone interaction using touch. In a prior study it was shown that 90% of participants felt comfortable touching a safe drone and 58% instinctively used touch as a means of interacting with such drones [2]. Safe-to-touch drones enable a new set of applications based on direct touch. For example, HoverBall is a ball-shaped quadcopter that can hover and change its behavior and location based on the context [34]. Gomes et al. use nano-quadcopters as 3D tangible displays and present input techniques, such as touching, dragging, throwing and resizing [16]. In this work, we use safe-to-touch quadcopters as hovering encountered-type haptic devices in virtual reality. Since fully safe-to-touch quadcopters are not commercially available, we have built a custom quadcopter to eliminate the possibility of the user coming in contact with the propellers.

Quadcopters for Haptics in Virtual Reality

Prior literature has used quadcopters for haptics in VR, both as hand-held and encountered-type haptic devices, and it has been shown that quadcopters increase users' sense of presence in VR compared to hand-held controllers [22].

Hand-Held. LevioPole is a rod-like hand-held haptic device with two quadcopters mounted on each end of the rod that can generate controlled rotational and linear forces [40]. Thor's Hammer is a hand-held haptic device that can produce up to 4N of force using propeller propulsion [18]. Despite being a hand-held device, the preliminary evaluation of Thor's Hammer provides insights relevant to hovering encountered-type haptics, such as users' concerns about the noise generated by the propellers.

Encountered-Type. Yamaguchi et al. attach a piece of paper to a quadcopter and allow users to make contact with the paper using a prop [53]. TactileDrones are quadcopters with sharp end-effectors that poke users to simulate sensations such as the feeling of a bug bite in a virtual environment [27]. In both examples due to the absence of a safe quadcopter, users are unable to directly touch the end-effector and the interaction is limited to probing. Abdullah et al. introduce HapticDrone, a commercially available drone with a safe cover on top that flies below the user's hand and provides 1D vertical force feedback [1]. HapticDrone can exert up to 2.97N downwards force for weight simulation (Figure 2a) and 1.53N upwards force for surface stiffness simulation (Figure 2b). However, quadcopters are unable to provide sufficient lateral force feedback due to their under-actuated nature (Figure 2c). The ability to provide highly accurate force feedback at relatively large magnitudes is crucial for the use of quadcopters as haptic devices in VR. We build on this work and argue that quadcopters can mediate a variety of rich haptic interaction beyond force feedback by appropriating physical objects and the environment.

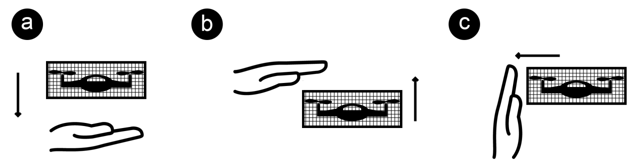

Figure 2: Affordances of quadcopters as haptic devices in VR, focused on force feedback: (a) weight simulation (b) surface stiffness simulation (c) lateral force feedback.

3 HOVERING ENCOUNTERED-TYPE HAPTICS

Safe-to-touch quadcopters (or quads) can be used as encountered-type haptic devices in virtual reality. Quadcopters can fly quickly to almost anywhere within the workspace and land on various surfaces. Moreover, compared to grounded encountered-type haptic devices with a large working volume, quadcopters may be more affordable. Prior research has demonstrated the use of quadcopters for force feedback in virtual reality [1]. In this work, however, we present haptic interaction techniques mediated through quadcopters that animate existing physical objects and appropriate the environment.

Appropriating Objects and the Environment

We introduce three affordances of quadcopters that enable haptic interactions beyond force feedback. First, we use the quadcopter as a moving passive haptic device (Figure 3a). We then show how properties such as textures can be rendered by attaching various end-effectors to the quad (Figure 3b). Finally, we animate passive props, by augmenting the quadcopter with existing physical objects (Figure 3c).

Dynamic Positioning of Passive Haptics. Passive haptics can be used to provide haptic feedback in virtual reality, however repositioning passive props remains a challenge. Prior work has suggested techniques for mapping virtual objects

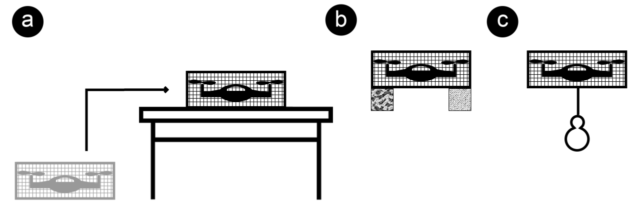

Figure 3: We present three techniques for appropriating objects and the environment: (a) dynamic positioning of passive haptics (b) texture mapping (c) animating passive props.

to passive objects in the environment, based on their form factor in real-time [19]. Due to the limitations of passive haptics, previous research has also investigated the use of haptic illusions for mapping multiple virtual objects to a single passive box [5]. We suggest that a quadcopter enclosed in a safe-to-touch cage can also be used as a passive haptic device in virtual reality. To represent a virtual object, the quad can quickly fly and land on any surface in the environment. Once the user's haptic exploration of that virtual object is complete, the quad can fly to a different location to represent another virtual object. In our user evaluation, we use this technique to provide haptics for shoeboxes in a virtual boutique.

Texture Mapping. Rendering other object characteristics, beyond geometric shapes, has been an active topic of research in haptics. Haptic revolver is a hand-held controller with a wheel attachment that can render multiple physical textures [51]. SnakeCharmer is a grounded encountered-type haptic device with multiple end-effectors for simulating different textures, temperatures, or airflow [4]. Similarly, we can attach multiple end-effectors to the quad for rendering object characteristics, such as textures. For example, distinct pieces of fabric can be placed around the quad, as shown in Figure 3b. These materials can then be mapped to different virtual objects by rotating the quad. We demonstrate this concept in a virtual shopping experience by allowing users to feel the texture of various clothing items.

Animating Passive Props. Dynamic positioning of passive haptics, as described earlier, is limited by the quadcopter's form factor; if the quadcopter is a cube it is most suited as a proxy for a cubic virtual object. This limitation motivates animating existing physical objects using the quadcopter [41]. Our safe-to-touch cage has a 3D printed slot for attaching physical props to the quad. In our user evaluation we fasten a hanger to the quad, such that users can pick up the virtual shoebox that they would like to purchase and place them in their shopping cart. More generally, the quad can be equipped with a grasping mechanism capable of picking up various light-weight objects.

Design Considerations

Designing quadcopter interactions in VR is notably different from designing other forms of human-drone interactions. High control accuracy is required to position the quad exactly where the virtual object is located. High speed as well as prediction algorithms are needed to reduce response time and to fly the quad near the next potential target. Once the quad is present at the target, users need to be informed that the virtual object is ready for haptic exploration. In order to carry the safe-to-touch cage and other passive props, a quadcopter with high thrust-to-weight ratio is necessary. Finally, safety is particularly crucial in this setting, as users are wearing a VR headset and are unable to see the quad. These requirements are inherently dependent and cannot be satisfied simultaneously. For example, a quad with high thrust-to-weight ratio travelling at a high speed may pose safety concerns. Below we summarize our approach to optimizing these requirements in the design of *HoverHaptics*.

Visualizing Touchable Regions. Using quadcopters as haptic devices enables haptic exploration of various components of the virtual scene. However, not all virtual elements can be physically rendered with the quad. We first mark all virtual objects that can be touched in the scene. For texture rendering, we mark all patches on the virtual clothes that can be touched by excluding the edges of fabrics and the areas with highly varying curvature. To predict the region of interest, we compute the intersection of the extension of the user's hand trajectory with the virtual scene. We then highlight the closest renderable patch to that predicted region, shown in Figure 4. We use a heuristic algorithm to determine if the user is moving towards the predicted object and lock the marked patch based on two conditions: (1) if the user's right hand travels 10cm closer to the highlighted patch, while the prediction target remains inside that patch (2) or if the user's hand is less than 10cm away from the patch.

Figure 4: Based on the prediction algorithm, the closest renderable patch is shown to the user.

Control Accuracy. At all times during the interaction the exact location of the quad in the workspace is known, as highly accurate position tracking can be obtained from an external motion capture system. On the other hand, due to the heavy weight of the quad and the uneven weight distribution from the passive props, it is difficult to position the quad accurately at the target location. Prior work has shown that the accuracy of an interactive quad with a frame can deviate up to 5cm along each axis [16]. However, in the context of hovering encountered-type haptic devices, an exceptionally high control accuracy is required. Since the user is unable to see the quad in the virtual environment, even slight deviations from the position of the virtual object will prevent the user from making contact with the quad.

To overcome the lack of control accuracy, we use visuo-haptic illusions based on the visual dominance effect, the concept that vision often dominates when our sensory inputs are at conflict. We use haptic retargeting, similar to Sparse Haptic Proxy [8], to correct for the offset between the quad and the position of the virtual object of interest. As the user reaches out to touch a virtual object, their hand is retargeted such that upon contacting the virtual object, their real hand makes contact with the quadcopter, as shown in Figure 5b.

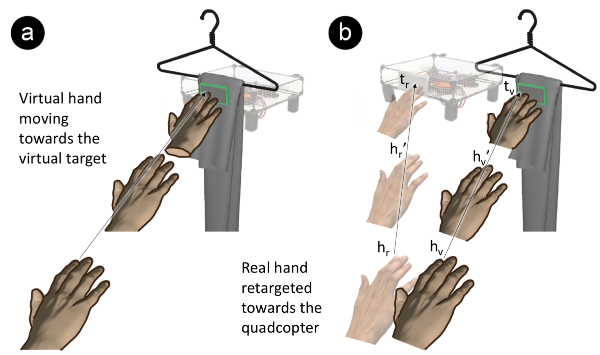

Figure 5: Visuo-haptic illusions are used to compensate for lack of control accuracy. (a) Quad is accurately positioned and no illusion is needed. (b) To correct for the position offset, as the virtual hand touches the virtual target, body warping is used to retarget the hand towards the quad.

In the retargeting on-the-fly technique [8], the user's hand is retargeted towards a static physical prop; however, in our scenario the physical target (the quad) constantly moves during retargeting. We slightly modified this technique to apply retargeting based on the movements of the quad and the movements of the user's hand in two consecutive frames. Given the real target which is the quad (t_r), the virtual target (t_v), the real hand position in two consecutive frames (h_r and h_r'), and the previous virtual hand position (h_v), the current virtual hand position can be calculated using

$$h_v' = h_v + (h_r' - h_r) + \alpha[(t_v - t_r) - (h_v - h_r)] \quad (1)$$

$$\alpha = \frac{||h_r' - h_r||}{||h_r' - h_r|| + ||h_r - t_r||} \quad (2)$$

This modification ensures that when the user's hand is stationary, the virtual hand does not move as a result of the quadcopter's movements. However, as the user reaches out to touch the virtual object the retargeting direction and magnitude continuously changes due to the constant movements of the quad. We found in our experimentation that with relatively accurate control accuracy (position errors $< 7cm$) these continuous changes do not hinder the user's ability to make contact with the virtual object. Moreover, to avoid the accumulation of retargeting offset, we pause the retargeting algorithm once the user makes contact with the virtual object, by keeping the existing offset between the virtual and the real hand, and resume it when the next renderable patch is activated.

Safety. During the interaction, the user is wearing a head-mounted display and the quadcopter is invisible in the virtual environment. Ensuring users' safety is challenging, as they are isolated from the real world. We implemented four safety mechanisms, addressing both physical and psychological safety. The goal of physical safety measures is to reduce the chance of unwanted contact and to diminish physical discomfort or injury in the unlikely event of collision [28]. To lower the likelihood of unwanted contact we implemented (1) a critical landing mode and (2) a collision avoidance algorithm. For reducing the exerted impact force, (3) we limited the speed of the quadcopter. As a psychological safety measure (4) we created an emergency scene to better communicate the state of the system to users.

The first safety mechanism is the critical landing mode. If at any point during flight communication to the quadcopter fails, the critical mode is activated causing it to land immediately. Throughout the interaction, we ensure that the quadcopter never flies above the user's head. We also activate critical landing mode if the motion capture camera streaming stops for a period longer than a safe threshold ($2sec$ in our system).

For the second safety measure we leverage an obstacle avoidance scheme equivalent to the well-established potential fields approach [26]. Our algorithm is implemented as a filter applied to the quad's position waypoints. If the current position of the quad x_q is found to be within some radius R of the user's position x_u, the desired position x_d is modified temporarily by projecting it outside of a cylinder around the user. The closer the quad is to the user, the more aggressively the waypoint is adjusted. We also guarantee progress toward the true desired position by biasing the resulting waypoint slightly towards the goal. When the quad is inside the safety radius, the adjustment of the waypoint can be written as

$$\tilde{x}_d = w_g \frac{x_d - x_q}{||x_d - x_q||} + (1 - w_g)R^2 \frac{x_q - x_u}{||x_q - x_u||^2} + x_q \qquad (3)$$

where $\tilde{x}_d$ is the adjusted waypoint sent to the quadcopter and w_g is a weight between 0 and 1. In the user study we set w_g to 0.3 and R to $0.25m$ such that users could reach outside the safety region and voluntarily interact with the quad.

The third safety measure is to reduce potential impact forces from a collision by limiting the maximum velocity of the quadcopter. Other design strategies to reduce impact include reducing the weight, adding soft materials for absorbing impact forces, or shape alterations for reducing impact stress [23]. The quadcopters used as haptic devices are relatively heavy due to the added weight of the safe-to-touch cage and the passive props. It is also challenging to introduce soft materials or to modify the shape of the quad, as airflow problems are likely to arise. Therefore, to reduce impact forces during collision, it is necessary to limit the velocity of the quadcopter. We empirically chose a maximum velocity of $0.5m/s$ through pilot testing and out of concern for our users, taking into account the relatively heavy weight of our quadcopter ($638g$) and the sharp corners of the quad's cage.

Finally to ensure psychological safety, we communicate the state of the system to the user during an emergency. We activate an emergency mode that turns off the virtual scene and shows a virtual representation of the quad to the user instead. If the user is facing away from the quad, we place warning signs in the virtual world that point to where the quad is located, shown in Figure 6. This allows the user to locate the quad and prevent crashes. We put in place two conditions for detecting unexpected behavior. The first condition is used to detect dangerous jerking motions and it is triggered if the quad travels away from the target and towards the user for more than $10cm$ in $0.5sec$. The second condition is used for gradual deviation from the target and is triggered when the quad flies away from the target and towards the user for more than $30cm$ throughout the path.

Figure 6: The emergency scene: the box in the center represents the current position of the quadcopter and warning signs pointing towards the quad are placed around the user.

Delays. The speed limit imposed as a safety measure results in delays from when the next target is detected to when the quad is present at the target location. To communicate to the user when the virtual object is ready to be touched, we highlight the marked patch in green when the quad is stabilized at the target, as shown in Figure 7.

Figure 7: Upon the quad's arrival the patch is highlighted in green, indicating that the user can touch the virtual object.

Noise. Prior research has shown that the noise generated by the quad can be distracting in a virtual environment [18]. To reduce the perceived noise we use the HTC Vive in-ear headphones that connect to the HMD, as well as the $37dB$ NRR protective earmuffs. We found protective earmuffs to be more effective than active noise cancelling headphones for our quad.

System Implementation

In the following section we describe the implementation of *HoverHaptics*, an autonomous safe-to-touch quadcopter integrated with a virtual reality environment.

Safe-To-Touch Quadcopter. The quadcopter used needed to have two main characteristics. First, it needed to be programmable so that it could be integrated with the rest of the software. Second, to provide flexibility in the design of its protective cage, it needed to have a relatively high thrust-to-weight ratio. We opted to use racing quad parts along with an STM32-based autopilot running PX4 that together fulfilled those requirements. The quad frame used has a $180mm$ wheelbase, is equipped with four $2600KV$ brushless motors, and a 3-cell LiPo battery. The autopilot is the Pixfalcon, which is a smaller form factor derivative of the popular Pixhawk autopilot. We built a lightweight protective cage using carbon fiber tubes, 3D printed joints, and a Polypropylene mesh, shown in Figure 8. The propellers are fully enclosed in the cage ($27cm$ x $24cm$ x $5cm$) such that fingers cannot come into contact with them. The weight of the caged quad is $407g$ without the battery, and $590g$ with the battery.

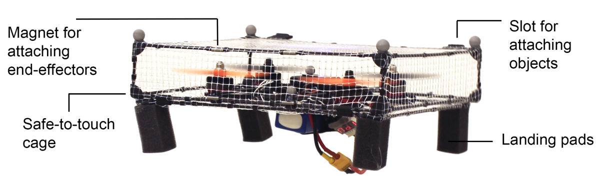

Figure 8: Safe-to-touch quadcopter with the protective cage.

Control System. The quad stabilizes itself using a simple PID position controller that is part of the PX4 autopilot. The controller consists of cascaded position and attitude controllers similar to [32]. The PID loops are tuned to accommodate for the extra inertia and loss of thrust generated by the cage. The quad's position estimate is generated by feeding its position from the motion tracking system into the PX4's Extended Kalman Filter (EKF). In the event that interactions with the drone obstruct it from the tracking system, the EKF provides a level of robustness for preventing crashes.

Quadcopter Communication. The quad is equipped with a $915MHz$ telemetry radio that allows it to communicate with a ground station using a similar radio. The ground station uses the Mavlink protocol to communicate with the quad. It also translates all Mavlink communications to Robot Operating System (ROS) messages using the software package Mavros. ZeroMQ, a high-performance distributed messaging library is used to send target positions from the virtual environment. Mavros manages all of the communications with the quadcopter, including motion tracking data coming over ROS topics and desired positions coming over ZeroMQ.

Tracking. We use Vicon motion capture cameras for real-time rigid-body tracking. Retro-reflective markers are placed on the user's hands, the quadcopter, and the Head-Mounted Display (HMD). The tracking information is streamed from the Vicon Tracker software to the Unity game engine directly and to the rest of the software components using ROS.

Virtual Environment. The virtual scene is created using Unity. Path planning is done in Unity, using the current position of the drone streamed from the Vicon cameras and the target position based on the virtual scene. Each waypoint is then sent to the ground station through ZeroMQ. The content of the virtual scene is presented to the participant using the HTC Vive head-mounted display.

4 TECHNICAL EVALUATION

Prior research has measured the force feedback provided by different quadcopters [1, 18]. However, for appropriating objects and the environment, we are especially concerned with the responsiveness and the control accuracy of our system. In the following section we measure the maximum time needed for our quad to travel to a target position and the control accuracy achieved once it arrives at that target.

Speed Measurement

As described in the Design Considerations section, for safety concerns, we limited the maximum velocity of our quad to $0.5m/s$ and its horizontal acceleration to $0.5m/s^2$. For safety, we also capped the height of our working volume to the users' height, preventing the quad from flying above their head. For this reason we were less concerned about fast vertical movements and set the maximum vertical acceleration to $2m/s^2$. Since our control system consisted of two different controllers for horizontal positioning along the x and y axes and vertical positioning along the z axis, we measured the horizontal and vertical speeds separately. These measurements were averaged over 10 trials. The time taken for the quad to take off to 0.5m above the ground was on average 3.90s and the average landing time from that height was 1.48s. Due to the size of our room, the physical working volume and consequently the virtual space were constrained to a 2.5m^3 cube. The longest horizontal path possible in our working volume was 3.5m along the diagonal of a 2.5m^2 square, and the average time taken to travel this distance while hovering was 8.79s. The average time taken for the quad to travel 1m vertically was 3.21s while flying up and 2.57s while flying down. We also limited the maximum angular speed to 45°/s, and the average time for a 180° rotation over 10 trials was 4.54s.

Accuracy Measurement

In order to evaluate the accuracy of our control system, we measured the average distance and the average rotational difference between the quadcopter and the target. Once the quad arrived at the target, we recorded its position and orientation at 60Hz for 10 seconds. We repeated this process 10 times and computed the mean distance and rotational difference during each 10 second interval. Note that we define "arriving at the target" as the point in time where the quad is less than 10cm away from the target position and the rotational difference is less than 30°. The results showed that on average the position error was less than 7cm ($\mu = 6.68, \sigma = 2.94$) which is comparable to similar interactive drone systems with a frame (BitDrones error = 8.5cm [16]). The average rotational difference between the quad and the target was around 3° ($\mu = 3.07, \sigma = 1.31$). Note that adding any prop with an uneven weight distribution will further increase the position error. Such errors are an inherent limitation of hovering encountered-type haptic devices, due to the relatively heavy weight of the quads and the high thrust-to-weight ratio needed. In our system, we use dynamic retargeting, a type of visuo-haptic illusion described by [5, 8], to compensate for the lack of control accuracy.

5 USER EVALUATION

We conducted a study to better understand what users experience when interacting with a safe-to-touch quad in virtual reality. We integrated *HoverHaptics* with a virtual boutique scene, shown in Figure 9. We included three interactive components in this virtual experience to demonstrate the concept of appropriating physical objects and the environment. We first allow users to feel the material of different clothing items to showcase *texture mapping*. We then enable users to pick up an item of clothing by the hanger and place it in their shopping basket, an example of *animating passive props*. Finally, we let users pick up a shoebox that they would like to purchase and ask them to place it in their shopping basket, highlighting *dynamic positioning of passive haptics*.

Figure 9: Virtual boutique scene.

Participants

We recruited 9 participants (4 female, 5 male), ages 22 to 29 ($\mu = 25$) from our institution and nearby companies. All participants had previously experienced virtual reality and 3 people were regular VR users. All participants had seen a quad before, but only 2 had flown a quad before. Those 2 participants flew quads frequently and had touched a quad during flight before; one had touched a miniature quad and the other had an accident in which she cut her hand. Each person received a $15 gift card for an hour of their time.

Experimental Setup

Our setup, shown in Figure 10, consisted of a safe-to-touch quadcopter, Vicon motion capture cameras, two HTC Vive lighthouses, and the HTC Vive Head-Mounted Display (HMD). The tracking space was constrained to a 2.5m^3 cube and a small table was placed in this tracking space. Retro-reflective markers were used to track the quadcopter, the HMD, and the user's hands. HTC Vive in-ear headphones connected to the HMD and Protective earmuffs (37dB NRR) were used for noise cancellation.

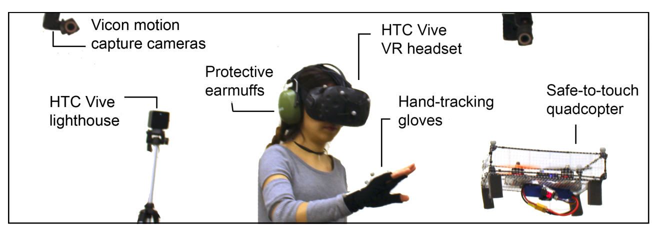

Figure 10: Experimental Setup.

Procedure

At the beginning of the study, participants were informed about the technology that was being studied: a safe-to-touch quadcopter used for haptics in virtual reality. They were then presented with a photo of the virtual boutique and were briefed that during the study they will be touching different virtual objects in the scene: clothing items, hangers, and shoeboxes. They were instructed that virtual objects will turn green once the quad is present at that location, implying that it is ready to be touched. An image of the emergency scene was also shown to the participants, and they were told that if the quad acts unexpectedly at any point during the study, the emergency scene will appear. After these instructions, participants entered the tracking space and put on the tracking gloves, in-ear headphones, and protective earmuffs. Relaxing music, complimentary to the ambience of the virtual boutique, was playing through the headphones. In addition to all the safety mechanisms in place, to ensure participants' safety, one experimenter was present in the tracking space throughout the study. Note that all tasks were performed consecutively, and all fabrics and objects were manually attached to the quadcopter prior to the start of the experiment.

Task 1: Texture Rendering. Once participants entered the virtual environment, their first task was to touch and feel the fabric of two clothing items placed at the front of each rack. Participants moved towards the clothing item, waited until the patch on the fabric was highlighted in green, and then slowly reached out to touch the fabric. Similar to previous haptic devices [4, 51] two pieces of fabric were attached to the quad with magnets: a smooth silk-like material for the scarf and a cotton fabric with rough patterns for the shirt (Figure 11). The two materials were mapped to the corresponding virtual clothes by rotating the quad 180°.

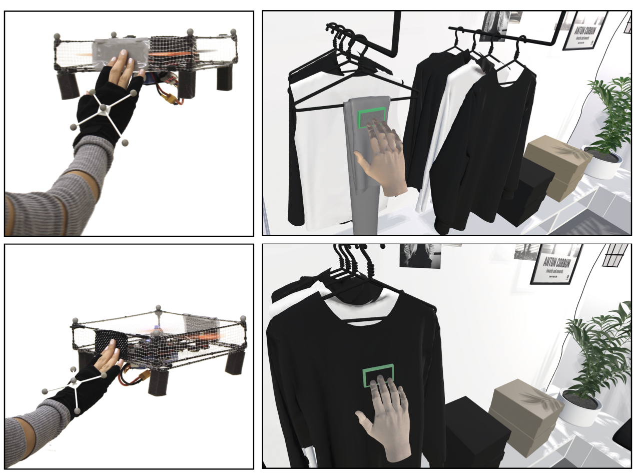

Figure 11: Texture rendering: user feeling the material of a scarf and a shirt.

Task 2: Animating Passive Props. The second task was to pick up one of the clothing items by the hanger and place it in the shopping cart on the opposite side of the virtual scene. Participants first waited for the hanger to turn green, then slowly reached out and held the hanger, as shown in Figure 12. A physical hanger, with an addition weight of $48g$, was manually mounted on to the quadcopter. Collision detectors in Unity 3D were used to determine when users were holding the hanger. The quad then entered a hovering mode in which the position PID controller was turned off, but attitude was stabilized, and throttle was kept at around 50% (close to hover). The users moved the hanger across the room and placed it in their shopping basket. Once the users moved away from the basket, the quad switched back to flight mode.

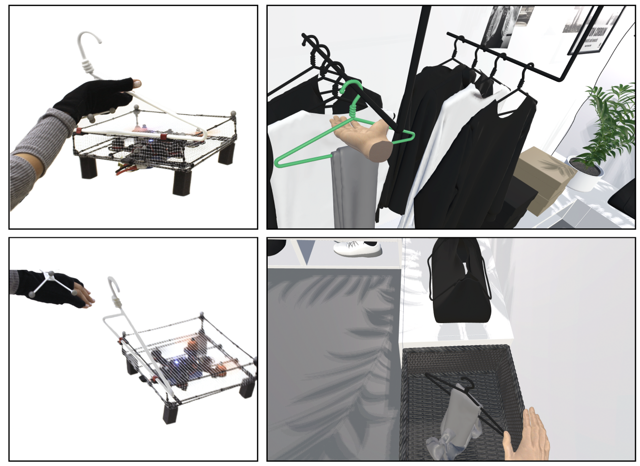

Figure 12: Animating passive props: user picking up a hanger and dropping it in the shopping basket.

Task 3: Dynamic Positioning of Passive Haptics. During the final task, users picked up a shoebox and put it in their shopping basket. The quad flew to a waypoint above a small table that was placed in the tracking space. Once it was accurately positioned on top of the table, it lowered itself and landed on the table. The participants then reached out and picked up the quad in off mode, shown in Figure 13, and placed it in their shopping basket.

Figure 13: Dynamic positioning of passive haptics: quad landing on a table in the room to render a shoebox, and user picking up the shoebox.

After the VR experience, participants were asked about their overall impression and if *HoverHaptics* improved their virtual experience. They then filled out a post-study questionnaire that included a series of statements about their perception of safety, response time, propeller noise, and wind generated by the quad. Participants indicated their level of agreement with each statement by choosing a number from 1 (strongly disagree) to 5 (strongly agree) on a Likert scale. Finally, we conducted a semi-structured interview to expand on the questions in the survey and to learn more about the haptic interactions.

Results and Discussion

All participants, except one, found the experience very enjoyable and reported that the haptics provided by the quad improved their VR experience. P9 was indifferent (3 out of 5 on the survey) and reported that he was highly focused on avoiding contact with the quad, which diverted his attention away from the shopping experience.

Texture Rendering. In our system, we attached pieces of fabric to the sides of the quadcopter, providing a rigid surface to users, similar to previous haptic devices [4, 51]. Four participants were able to identify the texture of the two fabrics. However, users were expecting a soft-body representation for the fabrics and wished that they could hold the edge of the material in their hand. P3 said *"if I were to feel clothing, I would pinch the material between my fingers"*. They also stated that the quad applied more force than expected. P5 noted that *"the defining quality of fabric is that... it has a texture to it, but also some fluidity"*, and the second element was missing. In this scenario, to enhance the texture rendering we can simply hang the fabrics from the quad's frame, similar to the end-effector in [53].

Dynamic Retargeting. With dynamic haptic retargeting, all participants were able to reach out and touch the fabrics, hanger, and shoebox during the study. This suggests that retargeting user's hand is a promising approach for overcoming the problem of limited control accuracy. Prior to the study, we expected that once users make contact with the fabric, they will remain in contact to feel the texture. Based on this assumption, to prevent the accumulation of retargeting offset, our algorithm paused the retargeting upon the user coming in contact with the quad. However, we found that a few participants reached out, briefly made contact with the quad, and then retracted their hand immediately before making another attempt. This behavior may be a result of uncertainty in touching virtual objects, unexpected haptic feedback, or vibrations from the drone, and future work should investigate these potential causes. The challenge of continuous dynamic retargeting while avoiding the accumulation of large offsets remains an open research question. One possible solution is to gradually undo the retargeting to eliminate the offset between the user's real and virtual hand without users noticing.

Animating Passive Props. Participants were most fascinated by the task of picking up the hanger. P4 said *"the coolest part for me was being able to hold on to the object and move it"*. P5 argued that this task was exciting *"because it was interactive. My touch actually mattered and it affected the world"*. The task of picking up the hanger went beyond exploration of the virtual scene and enabled active manipulation of a virtual objects. Hovering encountered-type haptic devices provide an effective mechanism for supporting active manipulation tasks in midair; the quad can enter a hovering mode, the position PID controller can be turned off, and attitude can be stabilized by keeping a low throttle (in our case at 50%). During such tasks, the quad can also render additional object properties such as weight.

Response Time. For the first two tasks (touching the fabric and picking up the hanger), participants commented that the response time was shorter than they had expected. 4 people reported that they waited longer for the third task. Picking up the shoebox (third task) required the quad to switch between three modes, from *hovering* to *flight mode* and then to *off mode* for landing. The mode switching as well as the distance from the shopping basket to the shoebox, increased the delay to roughly $35 sec$. P2 said *"I was just waiting there for something to happen."* and P5 said *"I was surprised at how long it took for the shoebox to materialize"*. Such delays are an inherent limitation of hovering encountered-type haptics, as low speeds are needed to ensure safety and comfort when using quads with high carrying capacity. Highlighting the virtual object in green upon quadcopter's arrival may have not been sufficient to accommodate this limitation. To address this, future work can explore: (1) better communicating the state of the system to users perhaps by showing a progress bar, (2) presenting alternative activities that users can engage in while waiting, (3) reducing delays with multiple quadcopters or other space warping techniques [44].

Noise. Despite the in-ear headphones and protective earmuffs, 2/3 of participants were able to hear the noise generated by the quad. However, all participants reported that they were not distracted or bothered by the noise. P4 said *"Your brain kind of filters it out after a few seconds"*. To further mitigate these effects, future work can explore the use of active noise cancelling that specifically targets the noise generated by the quad. We hypothesize that most future VR applications will present users with audio output and as a result will require the use of headphones.

Wind. All participants reported that they could feel the wind generated by the quadcopter. However, similar to the noise, all participants reported that they were not distracted or bothered by the wind. To our surprise, 4 participants mentioned that they appreciated the wind as an ambient feedback for where the quad was located and used it to gauge where the quad was relative to them. The wind generated by the propellers was most noticeable when users' hands were underneath the quad or when they were near the quad while wearing loose fitting clothes.

Safety & Comfort. All participants, except one, reported that they felt safe throughout the study. P9 scored safety 2 out of 5 on the survey and said *"I was cautious in my movements... and not super comfortable"*. Others mentioned that they were not concerned because of the meshed cage or that they forgot they were touching a drone. P5 noted that he was more concerned about damaging the drone than about his own safety. No unexpected behavior occurred during the user studies, therefore none of the participants encountered the emergency scene in VR. 2/3 of participants reported that knowing about the emergency scene made them feel safer, while 1/3 were indifferent. P5 and P9 thought the change of background in the emergency scene might be jarring and frightening. P5 preferred to see the quad in the same virtual scene and a warning text on the screen. The most suitable way of communicating unexpected behavior to users remains an open research question.

6 LIMITATIONS & FUTURE WORK

The results of the user evaluation revealed many research questions that motivate future work on the topic of hovering encountered-type haptics. In the following section we discuss limitations and research opportunities beyond those findings.

Passive Props

In our virtual boutique scenario, we manually attached a hanger to the quad. We hope that future work can explore the design of a mechanism capable of grasping light-weight objects. This allows the quad to pick up various objects and present them to users as needed. Similar to prior work in augmented reality [19], the quad can search the environment in real-time for physical objects that closely resemble the characteristics of the virtual object of interest. Alternatively, developers can distribute 3D models of objects present in their virtual applications that users can then 3D print.

Limited Force Feedback

One approach for increasing the force feedback provided by *HoverHaptics* is to externally support the quad. For example, when touching the fabric, the quad can position itself between the user's hand and the wall. We found this technique to be only effective when the quad is not moving vertically (up or down) during contact. Quadcopters are unable to provide lateral force feedback due to their under-actuated nature. However, lateral force feedback can be perceived as a result of tolerating some pitch change during contact. Future work could also explore the use of a gimbal drone cage, similar to [14], that allows the drone to rotate relative to the cage. This technique will enable pitch variation without moving the contact point itself.

Limited Speed

As a safety measure, to reduce the potential impact forces in a collision, we limited the maximum velocity of our quadcopter to $0.5m/s$. This speed limit was determined empirically through pilot testings, taking into account the relatively heavy weight of our quadcopter ($638g$) and the sharp corners of the quad's cage. However, a rigorous investigation of an optimal quadcopter velocity is needed to reduce delays during haptic interactions while ensuring both physical and psychological safety.

Multiple Quadcopters

The current implementation of our system is limited to one quadcopter. Using more than one quad will enable two-handed haptic explorations and make the haptic system more responsive by reducing delays. With multiple quads it is also possible to render complex geometries such as a corner, shown in Figure 14a. Moreover, an illusion of a surface with no boundaries can be created by positioning a sequence of quads along the user's hand trajectory, shown in Figure 14b. In practice, due to turbulence, controlling multiple quads in close proximity is challenging. To overcome this challenge, future work should consider using a large cage or a cage extension to allow quadcopters to make contact with one another without significant airflow interference.

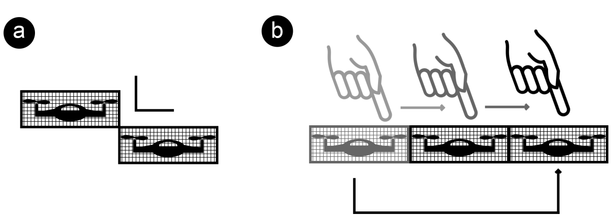

Figure 14: Affordances of multiple quads for haptics in VR: (a) complex geometry and (b) continuous surface rendering.

7 CONCLUSION

In this paper, we presented *HoverHaptics*, an autonomous safe-to-touch quadcopter used as an encountered-type haptic device in virtual reality. We demonstrated that quadcopters can appropriate objects and the environment, using three techniques: dynamic positioning of passive haptics, texture mapping, and animating passive props. We identified important design considerations when implementing such system and described our approach for addressing them. We conducted a user study to evaluate our approach and to better understand the subjective user experience when interacting with quadcopters in virtual reality.

ACKNOWLEDGMENTS

We would like to thank Tavishi Gupta for iterating on various virtual reality applications. We also thank Inrak Choi and Griffin Dietz for their feedback, and Jane E and Alexa Siu for their help with figures and videos.

REFERENCES

[1] Muhammad Abdullah, Minji Kim, Waseem Hassan, Yoshihiro Kuroda, and Seokhee Jeon. 2018. HapticDrone: An Encountered-Type Kinesthetic Haptic Interface with Controllable Force Feedback: Example of Stiffness and Weight Rendering. In *Proceedings of Haptics Symposium 2018*.

[2] Parastoo Abtahi, David Y. Zhao, Jane L. E, and James A. Landay. 2017. Drone Near Me: Exploring Touch-Based Human-Drone Interaction. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 3, Article 34 (Sept. 2017), 8 pages. https://doi.org/10.1145/3130899

[3] Aerotain. 2017. Aerotain. (2017). http://www.aerotain.com/

[4] Bruno Araujo, Ricardo Jota, Varun Perumal, Jia Xian Yao, Karan Singh, and Daniel Wigdor. 2016. Snake Charmer: Physically Enabling Virtual Objects. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 218–226.

[5] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2016. Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1968–1979. https://doi.org/10.1145/2858036.2858226

[6] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. NormalTouch and TextureTouch: High-fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 717–728.

[7] Hover Camera. 2017. Aerotain. (2017). https://gethover.com/

[8] Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D. Wilson. 2017. Sparse Haptic Proxy: Touch Feedback in Virtual Environments Using a General Passive Prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3718–3728. https://doi.org/10.1145/3025453.3025753

[9] Inrak Choi and Sean Follmer. 2016. Wolverine: A Wearable Haptic Interface for Grasping in VR. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 117–119.

[10] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 654, 13 pages. https://doi.org/10.1145/3173574.3174228

[11] DJI. 2017. DJI Mavic Pro. (2017). http://www.dji.com/

[12] Lionel Dominjon, Anatole Lécuyer, Jean-Marie Burkhardt, Paul Richard, and Simon Richir. 2005. Influence of Color/Display Ratio on the Perception of Mass of Manipulated Objects in Virtual Environments. In *IEEE Virtual Reality Conference 2005, VR 2005, Bonn, Germany, March 12-16, 2005*. 19–25. https://doi.org/10.1109/VR.2005.49

[13] Fleye. 2017. Your personal Flying Robot. (2017). http://gofleye.com/

[14] Flyability. 2017. Safe Drones for Inaccesibles Places. (2017). http://www.flyability.com/

[15] Philippe Garrec, Jean-Pierre Friconneau, and Francois Louveaux. 2004. Virtuose 6D: a new force-control master arm using innovative ball-screw actuators. In *ISR 2004: 35th International Symposium on Robotics*.

[16] Antonio Gomes, Calvin Rubens, Sean Braley, and Roel Vertegaal. 2016. Bitdrones: Towards using 3d nanocopter displays as interactive self-levitating programmable matter. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 770–780.

[17] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Zhou Dao, and Per Ola Kristensson. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1991–1995.

[18] Seongkook Heo, Christina Chung, Geehyuk Lee, and Daniel Wigdor. 2018. Thor's Hammer: An Ungrounded Force Feedback Device using Propeller Propulsion. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, to be presented*. ACM.

[19] Anuruddha Hettiarachchi and Daniel Wigdor. 2016. Annexing Reality: Enabling Opportunistic Use of Everyday Objects As Tangible Proxies in Augmented Reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1957–1967. https://doi.org/10.1145/2858036.2858134

[20] Ken Hinckley, Randy Pausch, John C. Goble, and Neal F. Kassell. 1994. Passive Real-world Interface Props for Neurosurgical Visualization. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '94)*. ACM, New York, NY, USA, 452–458. https://doi.org/10.1145/191666.191821

[21] Koichi Hirota and Michitaka Hirose. 1995. Simulation and presentation of curved surface in virtual reality environment through surface display. In *Virtual Reality Annual International Symposium*. IEEE, 211–216.

[22] Matthias Hoppe, Pascal Knierim, Thomas Kosch, Markus Funk, Lauren Futami, Stefan Schneegass, Niels Henze, Albrecht Schmidt, and Tonja Machulla. 2018. VRHapticDrones: Providing Haptics in Virtual Reality through Quadcopters. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia*. ACM, 7–18.

[23] Koji Ikuta, Hideki Ishii, and Makoto Nokata. 2003. Safety Evaluation Method of Design and Control for Human-Care Robots. *The International Journal of Robotics Research* 22, 5 (2003), 281–297. https://doi.org/10.1177/0278364903022005001

[24] Brent Edward Insko. 2001. *Passive haptics significantly enhances virtual environments*. Ph.D. Dissertation. University of North Carolina at Chapel Hill.

[25] Hiroo Iwata. 1993. Pen-based haptic virtual environment. In *Virtual Reality Annual International Symposium*. IEEE, 287–292.

[26] Oussama Khatib. 1986. Real-time obstacle avoidance for manipulators and mobile robots. In *Autonomous robot vehicles*. Springer, 396–404.

[27] Pascal Knierim, Thomas Kosch, Valentin Schwind, Markus Funk, Francisco Kiss, Stefan Schneegass, and Niels Henze. 2017. Tactile Drones - Providing Immersive Tactile Feedback in Virtual Reality Through Quadcopters. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '17)*. ACM, New York, NY, USA, 433–436. https://doi.org/10.1145/3027063.3050426

[28] Przemyslaw A Lasota, Terrence Fong, and Julie A Shah. 2017. A survey of methods for safe human-robot interaction. *Foundations and Trends® in Robotics* 5, 4 (2017), 261–349.

[29] Johnny C Lee. 2008. Hacking the nintendo wii remote. *IEEE Pervasive Computing* 7, 3 (2008).

[30] Robert W Lindeman, Page Robert, Yasuyuki Yanagida, and John L Sibert. 2004. Towards full-body haptic feedback: the design and deployment of a spatialized vibrotactile feedback system. In *Proceedings of the ACM symposium on Virtual reality software and technology*. ACM, 146–149.

[31] William A McNeely. 1993. Robotic graphics: A new approach to force feedback for virtual reality. In *Virtual Reality Annual International Symposium*. IEEE, 336–341.

[32] Nathan Michael, Daniel Mellinger, Quentin Lindsey, and Vijay Kumar. 2010. The grasp multiple micro-uav testbed. *IEEE Robotics & Automation Magazine* 17, 3 (2010), 56–65.

[33] Georgios Nikolakis, Dimitrios Tzovaras, Serafim Moustakidis, and Michael G Strintzis. 2004. Cybergrasp and phantom integration: Enhanced haptic access for visually impaired users. In *9th Conference Speech and Computer*.

[34] Kei Nitta, Keita Higuchi, and Jun Rekimoto. 2014. HoverBall: augmented sports with a flying ball. In *Proceedings of the 5th Augmented Human International Conference*. ACM.

[35] Yoichi Ochiai, Kota Kumagai, Takayuki Hoshi, Satoshi Hasegawa, and Yoshio Hayasaki. 2016. Cross-field aerial haptics: Rendering haptic feedback in air with light and acoustic fields. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 3238–3247.

[36] Michael Rietzler, Florian Geiselhart, Jan Gugenheimer, and Enrico Rukzio. 2018. Breaking the Tracking: Enabling Weight Perception Using Perceivable Tracking Offsets. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 128, 12 pages. https://doi.org/10.1145/3173574.3173702

[37] MW Riley, DJ Cochran, and CA Schanbacher. 1985. Force capability differences due to gloves. *Ergonomics* 28, 2 (1985), 441–447.

[38] Vantage Robotics. 2017. Snap Flying Camera from Vantage Robotic. (2017). https://vantagerobotics.com/

[39] Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori. 2015. Head-mounted display with midair tactile feedback. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology*. ACM, 51–58.

[40] Tomoya Sasaki, Richard Sahala Hartanto, Kao-Hua Liu, Keitarou Tsuchiya, Atsushi Hiyama, and Masahiko Inami. 2018. Leviopole: Mid-air Haptic Interactions Using Multirotor. In *ACM SIGGRAPH 2018 Emerging Technologies (SIGGRAPH '18)*. ACM, New York, NY, USA, Article 12, 2 pages. https://doi.org/10.1145/3214907.3214913

[41] Lior Shapira and Microsoft Technology Licensing LLC. 2017. Autonomous drones for tactile feedback in immersive virtual reality. US Patent 20160349835A1. Filed May 28, 2015.

[42] Alexa F Siu, Eric J Gonzalez, Shenli Yuan, Jason B Ginsberg, and Sean Follmer. 2018. shapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 291.

[43] Rajinder Sodhi, Matthew Glisson, and Ivan Poupyrev. 2013. AIREAL: tactile gaming experiences in free air. In *ACM SIGGRAPH 2013 Emerging Technologies*. ACM.

[44] Qi Sun, Li-Yi Wei, and Arie Kaufman. 2016. Mapping Virtual and Physical Reality. *ACM Trans. Graph.* 35, 4, Article 64 (July 2016), 12 pages. https://doi.org/10.1145/2897824.2925883

[45] Yuriko Suzuki and Minoru Kobayashi. 2005. Air jet driven force feedback in virtual reality. *IEEE computer graphics and applications* 25, 1 (2005), 44–47.

[46] Susuma Tachi, Taro Maeda, Ryokichi Hirata, and Hiroshi Hoshino. 1994. A construction method of virtual haptic space. In *Proceedings of the 4th International Conference on Artificial Reality and Tele-Existence (ICAT'94)*. 131–138.

[47] Kazumoto Tanaka, Jim Parker, Graham Baradoy, Dwayne Sheehan, John R Holash, and Larry Katz. 2012. A comparison of exergaming interfaces for use in rehabilitation programs and research. *Loading* 6, 9 (2012), 69–81.

[48] Teslasuit. 2017. Teslasuit - full body haptic suit. (2017). https://teslasuit.io/

[49] Lode Vanacken, Joan De Boeck, and Karin Coninx. 2010. The phantom versus the falcon: Force feedback magnitude effects on user performance during target acquisition. In *International Workshop on Haptic and Audio Interaction Design*. Springer, 179–188.

[50] Vive. 2017. Vive. (2017). https://www.vive.com/us/

[51] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. 2018. Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfgurable Virtual Reality Controller.. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, to be presented*. ACM.

[52] Graham Wilson, Thomas Carter, Sriram Subramanian, and Stephen A Brewster. 2014. Perception of ultrasonic haptic feedback on the hand: localisation and apparent motion. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. ACM, 1133–1142.

[53] Kotaro Yamaguchi, Ginga Kato, Yoshihiro Kuroda, Kiyoshi Kiyokawa, and Haruo Takemura. 2016. A Non-grounded and Encountered-type Haptic Display Using a Drone. In *Proceedings of the 2016 Symposium on Spatial User Interaction*. ACM, 43–46.

[54] Andre Zenner and Antonio Kruger. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 23, 4 (April 2017), 1285–1294. https://doi.org/10.1109/TVCG.2017.2656978