Sparse Haptic Proxy: Touch Feedback in Virtual Environments Using a General Passive Prop

Lung-Pan Cheng[1,2], Eyal Ofek[1], Christian Holz[1], Hrvoje Benko[1], Andrew D. Wilson[1]

[1]Microsoft Research
Redmond, WA, USA
{eyalofek, cholz, benko, awilson}@microsoft.com

[2]Hasso Plattner Institute
Potsdam, Germany
lung-pan.cheng@hpi.de

Figure 1. (a) Our hemispherical prop is an example of a *Sparse Haptic Proxy*. It simulates both, (b) a room and (c) a cockpit scene to provide physical touch feedback during interaction. (White lines on the prop added for visibility on the black background).

ABSTRACT

We propose a class of passive haptics that we call *Sparse Haptic Proxy*: a set of geometric primitives that simulate touch feedback in elaborate virtual reality scenes. Unlike previous passive haptics that *replicate* the virtual environment in physical space, a Sparse Haptic Proxy *simulates* a scene's detailed geometry by redirecting the user's hand to a matching primitive of the proxy. To bridge the divergence of the scene from the proxy, we augment an existing Haptic Retargeting technique with an *on-the-fly* target remapping: We predict users' intentions during interaction in the virtual space by analyzing their gaze and hand motions, and consequently redirect their hand to a matching part of the proxy.

We conducted three user studies on our haptic retargeting technique and implemented a system from the three main results: 1) The maximum angle participants found acceptable for retargeting their hand is 40°, rated 4.6 out of 5 on average. 2) Tracking participants' eye gaze reliably predicts their touch intentions (97.5%), even while simultaneously manipulating the user's hand-eye coordination for retargeting. 3) Participants preferred minimized retargeting distances over better-matching surfaces of our Sparse Haptic Proxy when receiving haptic feedback for single-finger touch input.

We demonstrate our system with two virtual scenes: a flight cockpit and a room quest game. While their scene geometries differ substantially, both use the *same* sparse haptic proxy to provide haptic feedback to the user during task completion.

Author Keywords

Virtual reality; passive haptics; perception; retargeting;

ACM Classification Keywords

H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems-Artificial, Augmented, and Virtual Realities; H.5.2 [User Interfaces]: Haptic I/O.

INTRODUCTION

Since the conception of the ultimate display in 1965 [17], researchers have sought to better convey the physicality of virtual worlds and reality (VR) to enhance immersion using active and passive haptics. Active haptics dynamically match the location of virtual shapes through active components, such as robotic arms [23,35,36] or human actors that adjust props on-the-fly [7]. Passive haptics are statically-positioned physical replica that match the virtual environment [14].

While passive haptics are easier to set up, their need for *static* positions limits their capability to represent virtual environments with complex geometries, large dimensions, or dynamic objects. Researchers have thus examined reversing this approach and fitting the virtual scene to the geometry of existing physical objects [13,30].

CHI 2017, May 06 - 11, 2017, Denver, CO, USA

ACM 978-1-4503-4655-9/17/05…$15.00
DOI: http://dx.doi.org/10.1145/3025453.3025753

In this paper, we present *Sparse Haptic Proxy (SHP)*, a class of passive haptics [14] that simulates touch feedback for a variety of *different* virtual environments. Unlike traditional passive haptics, which replicate virtual scenes with high fidelity, SHP's geometry comprises a sparse set of primitives that simulates virtual environments with geometries that may vary largely in sizes and shapes.

We bridge the difference between a Sparse Haptic Proxy and the simulated virtual geometries with Haptic Retargeting [1]. That is, we manipulate the user's hand-eye coordination to redirect their hand to a physical proxy *while* they are approaching a target in the virtual environment.

To preserve *unscripted* and *natural* properties of passive haptics while using Haptic Retargeting, we contribute the following necessary enhancements:

1) We evaluate haptic retargeting in a user study to inform the limits of retargeting that users still rate as tolerable. The further the virtual geometry can stray from a given SHP while still being well represented, the larger the range of scenes that proxy can simulate.
2) We predict the user's touch intention to make use of Haptic Retargeting in unscripted scenarios. We found that a combination of the user's gaze fixation and hand motion is an accurate predictor for touch targets and we evaluate the accuracy of our prediction algorithm in a user study.
3) We investigate and evaluate three mappings between the virtual object and a target location on the SHP, ranging from a technique that minimizes hand travel to a technique that better matches virtual and physical geometries.

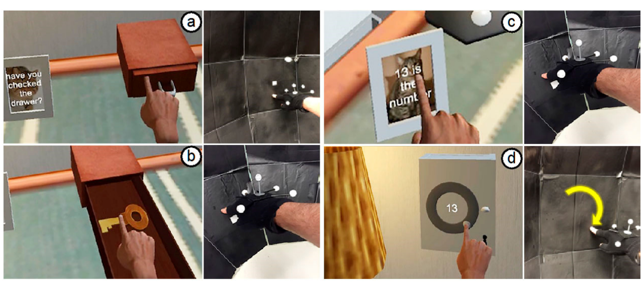

Figure 2. Our Sparse Haptic Proxy provides touch feedback for touch and drag interactions on these virtual objects.

Example Scenarios for Sparse Haptic Proxies

To demonstrate our system, we constructed a SHP made of planar plates of different orientations (Figure 1a) and created two substantially different virtual scenes: a room scene (Figure 1b) and a flight cockpit scene (Figure 1c). The same sparse haptic proxy provides touch feedback for *both* worlds.

As shown in Figure 2, the user in our virtual room scene turns on the light by touching the switch on the lamp, opens the drawer, grabs the key, and reveals a secret message by touching the picture frame. The user finally opens the safe by turning its dial. Note that the user can touch all features of the virtual scene in any order while their physical hand is continuously redirected to touch the physical prop. In our cockpit scene, the user operates the spaceship by pushing buttons and turning a dial. Though the cockpit geometry does not match the proxy shape, reaching for a button allows the user to feel the physical feedback of a solid surface on the proxy.

A single prop provides touch feedback to two scenes that are different in geometries, size, and appearance. Whenever a user is moving the virtual hand towards a virtual target, the physical hand is redirected to touch a plane of the proxy.

RELATED WORK

This paper builds upon the research fields of simulating touch feedback in virtual reality, including active haptics, passive haptics and haptic retargeting.

Active Haptics

Simulating touch feedback using active machinery has been researched for decades since Goertz and Thompson in 1954 proposed a robotic arm for tele-operation that transmitted the force feedback on the end effector to users [11]. Project GROPE [6] in 1967 then used the robotic arm to provide force feedback when users were operating the arm to touch and grasp virtual objects in virtual reality.

Exoskeletons have been used to directly apply the force feedback to users' body instead of through a controlling interface [2]. Robotic Graphics [36] used a robotic arm to move a board to where users were about to touch, which physically "rendered" the entire geometry of the virtual world. Iwata et al. used shape displays [16] to render geometries and provide touch feedback.

While able to represent a large variety of scenes, these machineries have high cost, large size and safety concerns limits most of them to stay in professional labs. Thus, TurkDeck [7] implements this using a series of human actors that move and deform the geometry using a set of primitives, such as wall parts to fit the on-line geometry in the virtual world.

Passive Haptics

Hinckley et al. [14] pioneered the concept of using passive props to as haptic feedback when controlling 3D virtual models followed by [5,8,10]. Low et al. project augmented reality experiences onto Styrofoam walls [22], allowing users to experience different virtual worlds in the same physical room. Similarly, Mixed Reality for military operations in urban terrain [15] uses passive haptics to create a haptic sense of objects, terrain, and walls in the virtual world.

FlatWorld integrated large props into a physical world; between experiences these props can be rearranged to match the next virtual world [26]. Similarly, the Personal Interaction Panel used a pen and a pad to manipulate objects in see-through augmented reality [34]. Sheng et al. used a sponge-like prop to create a range of interaction techniques [29]. Corston et al. [9] provide the ability to recognize and track these physical props using Kinect. However, they used a fixed one-to-one mapping of the physical controls to the virtual world. All these approaches require the physical objects that match virtual geometries to align prior to interaction.

Opportunistic controls for Augmented Reality [12] connect the displayed environment to physical surfaces that are repurposed to provide haptic responses to specific widget-like digital controls, such as sliders and buttons. Annexing reality [13] analyzes the environment and opportunistically assigns objects as passive proxies, but a given physical environment may not support all the application needs, and the virtual geometry has to deform to fit existing geometries. Substitutional reality [30] investigated the limits of mismatches between physical and virtual objects.

Haptic Retargeting

Redirected touching was suggested by [18] as a mean to use manipulation of the virtual hand-eye coordination. This results in discrepancies between a person's real and virtual hand motions, so that they reach the real and virtual objects simultaneously.

Haptic Retargeting [1] redirects the user's hand when touching any one virtual cube on the table to touch a single physical cube prop. However, [1] assumed a-priori-known targets and scripted interaction. Our work extends their technique to support natural unscripted interaction. The amount of possible retargeting effects the range of geometries that can be represented by a single passive proxy. We explore the range in which haptic retargeting can be applied under 1) change of retargeting distance, 2) effect on hand eye coordination, and 3) change of surface normal. All of them are essential to design a practical system.

Studies have shown that people adapt to spatial warping [21] and perform tasks as effectively as they do under non-warped conditions [20]. In the context of walking, a single physical prop can be used to provide haptics for multiple virtual objects [19]. This is achieved by using redirected walking [28], a technique that injects additional translations and rotations to the user's head movements. This causes users to walk on a physical path that is different from the perceived virtual path. By having the user walk back to the same physical object when moving from one virtual target to the next, the object provides haptic feedback for multiple virtual targets, but imperceptible redirections require large tracking spaces [33].

Spillmann et al. [32] proposed adaptive space warping to warp different organ geometries onto one physical mock-up. We are inspired from their work and extend the idea to a more general scenario where one general passive object provides touch feedback for many other objects in virtual environments.

REALIZING SPARSE HAPTIC PROXY

Whenever the user touches a virtual geometry, their hand is redirected using Haptic Retargeting to one of the SHP primitives. A Sparse Haptic Proxy's geometry should therefore be abstract enough to support multiple virtual environments. During interaction, users should be free to decide when and what they want to touch and be provided with touch feedback that matches their expectation based on their visual impression. The retargeted virtual hand movement should move smoothly and comfortably.

To achieve touch feedback, the system needs to map a suitable primitive of the proxy that will provide adequate feedback. To achieve comfortable hand motion, retargeting should be limited to a tolerable range, thus limiting the range in which such a primitive can be found. Natural, unscripted interaction requires the ability to predict users' touch intentions on-the-fly, so that retargeting can be applied.

We now investigate how to achieve and balance these needs by implementing and evaluating a system through studies.

SYSTEM IMPLEMENTATION

To investigate the different aspects of realizing Sparse Haptic Proxy, we implemented our VR system with an Oculus Rift DK2 headset that incorporated an SMI eye-tracker at 60 Hz. The headset is tracked by the Oculus camera in combination with an overhead OptiTrack V120:Trio tracking system. Depending on the specific virtual reality application, the user sits or stands in front of our sparse haptic proxy.

For the support of single-finger interaction across the physical surface, we assembled the SHP with a set of 25 solid planar surfaces, at orientations ranging from -60° to +60° in horizontal and vertical directions as shown in Figure 3.

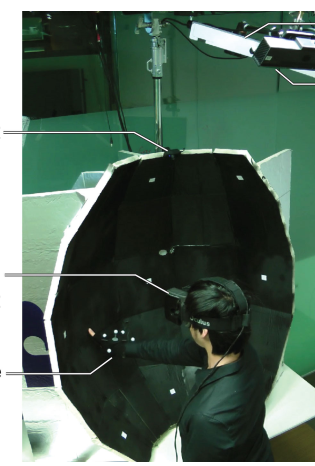

Figure 3. Left: Our system set-up. Right: The glove & Oculus DK2 HMD modified by SMI to include eye tracking.

Our system tracks the user's finger using a worn glove and the OptiTrack system. A Kinect V2.0 depth camera is used at a calibration stage to measure the physical proxy location. The displayed hand in the virtual world is a generic hand. The offset of the user's fingertip to the tracked marker, is found by a short calibration routine where each user touches proxy plates. Our system and applications are implemented using Unity game engine 5.2.3.

MAKING HAPTIC RETARGETING WORK DYNAMICALLY

Figure 4 illustrates how Haptic Retargeting redirects the user's hand to a physical location different than the virtual target location [1]. The virtual hand (skin color) and the physical hand (blue color) are initially at the same position. As the users' hand moves towards to the virtual target, the virtual hand position is gradually deviating in a direction away from the haptic proxy, causing the user to correct the trajectory toward the virtual target. Thus, the physical hand is gradually moved toward the haptic proxy.

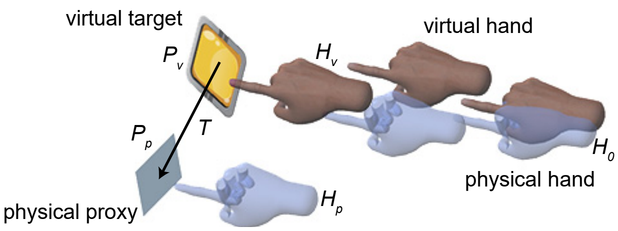

Figure 4. The virtual hand (skin color) shifts from its true physical location (semi-transparent blue color), inducing the user to correct the hand movement to touch the physical prop.

To perform haptic retargeting in a gradual manner along the hand path, the system needs to be supplied with the hand the starting point, the location of the virtual target that will be touched, and the location of the corresponding physical target. The retargeting is described as follows:

Let H_p be the physical position of the user hand, and H_v be the position in which the virtual hand is rendered to the user. Assume that a virtual scene point P_v should be mapped to a physical proxy point P_p.

$$T = (P_v - P_p)$$

This offset between the real and virtual hand position is gradually added to the position of the virtual hand as the user's hand starts moving from initial position H_0 toward P_v:

$$W = \alpha T,\ \alpha = \left(\frac{D_s}{D_s + D_p}\right).$$

Where α is the shift ratio, ranging between 0 and 1 from the beginning of the motion to a full offset T when the virtual hand touches P_v, and the physical hand touches P_p, $D_s = |H_p - H_0|$ and $D_p = |H_p - P_p|$.

Extension 1: Changing Retargeting On-the-Fly

Azmandian et al. [1] looked at a motion of user's hand from a fixed point, H_0, (near the body) to the targets arranged in front of the user. However, during natural interaction, a decision on a new touch target can be made while the user's hand has already been moving under some other retargeting amount to a prior target. To maintain a smooth movement of the virtual hand, we modify the original Haptic Retargeting offset to interpolate between the current retargeting and the updated retargeting to the new target:

$$W = \alpha T + (1 - \alpha)T_0\ ,\ \alpha = \left(\frac{D_s}{D_s + D_p}\right)$$

Where $D_s = |H_p - H_0|$, and $H_0 = H_p$ at the frame where a new touch target is acquired.

This general retargeting should be reduced to zero whenever the users retract their hand close to the body. This is done to avoid visible position difference between the physical hand and its rendering closer than 20 cm to the body as shown in Figure 5. Virtual hand retargeting starts only when the user's hand crosses the line and D_s in the previous equation is now defined as the distance between the line and the physical hand.

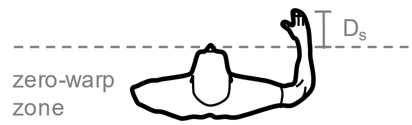

Figure 5. A zero-warp zone to help users reset their virtual hand position when retracting it.

Study 1: Maximum Tolerable retargeting

As the distance between the user's physical hand and the place it is rendered at grows, it can generate uneasiness due to conflict of the user senses. The goal of the first study is to map the limit of comfortable retargeting distance. [1] showed useful redirection beyond noticeable difference JND found by [24]. To explore the useful range of redirection we look at the user's tolerance which is a combination of touch feedback and hand redirection.

Participants

We recruited 12 right-handed participants (4 female) from our institution, ages 21 to 30 (M=27.0). 6 participants had experience with head-mounted VR. Participants received a small gratuity for their time.

Task

The task was a target-acquisition task. The participant saw a virtual bullseye target whose location was mapped to our physical proxy with a controlled offset. The participant then touched the virtual target with their right hand while our system redirected their hand to touch the physical prop. Hitting the virtual target completed a trial (the virtual finger collides with the virtual target). The participant then rated the acceptance of the experience on a 5-point Likert scale. We assigned a tolerability of '5' to 'no redirection', representing the base condition (and demonstrated to participants prior to the study). '1' represents intolerable redirection, i.e., the participant struggled to reach the target. We chose '3' as our threshold, balancing easy reach with distance of redirection.

Procedure

After a brief introduction to our system, participants sat down one at a time and put on the HMD and the marker glove and familiarized themselves with moving their hand in VR.

To sample the proxy space, we used 9 different locations on the proxy (Figure 6 left). For each proxy location, 33 virtual target locations were generated with 0, 15, 30, 45, 60° offset in 8 different directions as shown in Figure 6 right. We shuffled all possible conditions and used one condition for each trial. Whenever a virtual target fell outside the proxy (such as in the case of a left-wise virtual target of the left most location on the proxy), it was removed from the experiment to prevent extreme rotations of the participants.

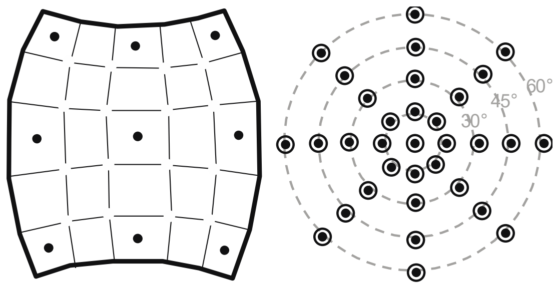

Figure 6. The 9 physical locations on the physical proxy (left) and all possible 33 offsets of a vertical target (right). The middle location is the physical location (zero retargeting).

Before the study, participants practiced 10 trials with increasing offset up to 60°. We did not include these practice trials in our analysis. Throughout all trials, we logged participants' gaze, hand, and head motion for offline analysis. After each task, participants filled out a questionnaire. Each participant completed all 169 trials in about 30 minutes.

Results

Figure 7 shows the overall distribution of participants' ratings and the time spent with all tested offsets and directions. We used one-way ANOVA, but found no significant difference in the rating and time spent between different physical locations, different directions within the same offset ($F_{7,40}$=0.111, 0.298, 0.408, 0.421 for the rating, $F_{7,40}$=0.465, 2.014, 0.932, 3.446 for the time spend within 15°, 30°, 45°, 60° respectively, all p>.05).

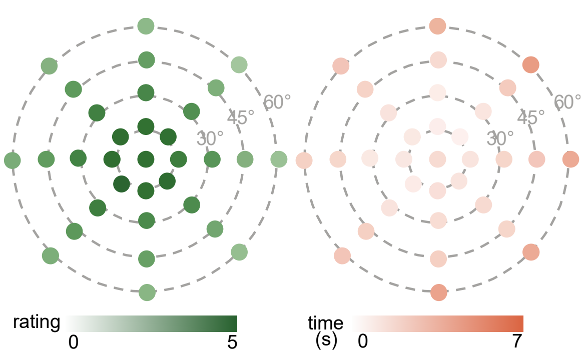

Figure 7. The distribution of user tolerance and time spent with 15°, 30°, 45°, 60° offset in 8 directions.

The average time spent on each task without offset was 1.81 seconds (SD=1.85). With 15° offset it was 1.80 seconds (SD=1.71), 2.07 seconds (SD=1.66) with 30° offset, 2.84 seconds (SD=2.13) with 45° offset, and 4.03 seconds (SD=3.35) with 60° offset. The time for reaching targets had positive correlation (r= 0.91) with the distance of redirection.

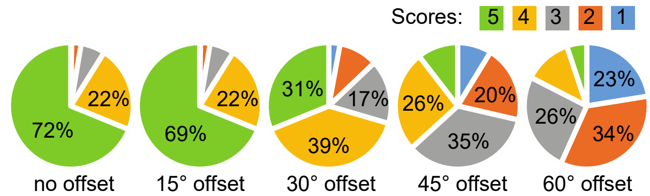

Figure 8. The rating population for each offset.

Figure 8 shows the rating population for each offset. Retargeting of up to 15° generated similar rating to no retargeting. Retargeting up to 45°, received lower but above natural ratings. Beyond 45° the average and the standard deviation of time spent increased dramatically, perhaps because the retargeting is more prominent and less natural to the user.

Following this experiment, the following experiment and the final system were limited to retargeting distances of up to 40°.

Extension 2: Predicting the User's Intention

In the original implementation of haptic retargeting, user was always directed towards a known target. In order to enable the user to freely interact with any object in the scene, our system predicts the user intended target in the virtual space. Following [31], we used both the user's gaze fixation and the user's hand movement to predict touch targets.

We detect gaze fixation using Binsted et al.'s approach [4], using a moving window of 0.6 seconds and check whether the standard deviation of the angle of gaze samples within this temporal window falls beneath 1°.

We use the state machine shown in Figure 9 to predict the user's intention and to determine the touch target. The three states represent the user's current activity: (a) Seeking a new target – the user gaze scans the scene, (b) looking at a target for more than a minimal time (fixation) and finally reaching for it. We used a significant hand velocity V_{hand} to detect that the user started to move her hand toward the target, and report a possible touch event. The threshold of 3 cm/s was found empirically from our pilot study

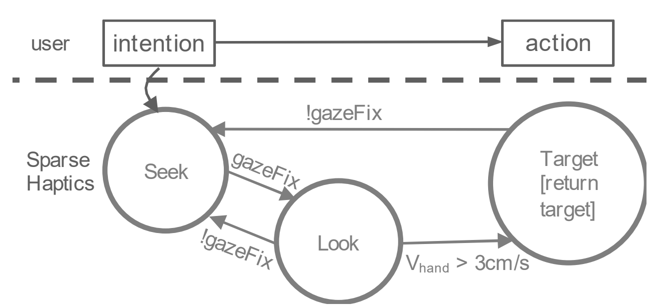

Figure 9. Our target prediction state machine.

Study 2: Predicting User Touch Targets

Our system introduces haptic retargeting and manipulate the hand-eye coordination. The goal of this study was to evaluate any effect of retargeting on the performance of the touch events prediction. This study focused only on prediction accuracy and participants touched virtual targets with no haptic feedback.

Participants

We recruited a fresh group of 12 right-handed participants (7 females, ages 24-30, M=27.6). 8 participants had previous experience with head-mounted VR. Participants received a small gratuity for their time.

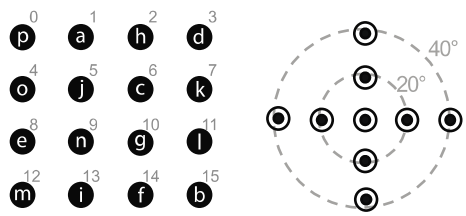

Figure 10. Left: The testing scene for target selection. The letters on the balls were shuffled for every trial. Numbers were not displayed, and are used for correspondence to Figure 11 only. Right: Possible retargeting distances and direction used.

Task

We showed a 4x4 grid of virtual balls with letters to participants as shown in Figure 10, left. For each trial, our system read a letter out loud. Participants then searched and touched the corresponding target, completing the trial upon contact. A new trial is started by pushing a 'next' button. Each trial has a different arrangement of letters on the balls. Since this study focused on our prediction, no physical prop was used.

Procedure

We first calibrated the eye-tracking HMD for each participant. Participants then followed a similar procedure as in the first study. We simulated retargeting to distances of 0°, 20°, and 40° in 4 directions (up, down, left and right) from the touch target as shown in Figure 10. Each participant completed 16 targets x 9 retargeting = 144 trials in total.

Each participant trained with 10 trials without any offset to familiarize themselves with the system before the trial. Overall, each participant took about 30 minutes to finish.

Results

Figure 11 shows the confusion matrix for the results of our predictions. Each target was tested during 108 trials. Overall, our prediction was 97.5% accurate. On average, our system predicted the correct target 2.04 (SD=1.28) seconds before participants touched it with an average distance of 23.72 cm (SD=14.33) from touching the target.

To verify the hypothesis that retargeting affects hand-eye coordination and prediction accuracy, we compared for all offsets 1) the prediction accuracy, 2) the time between the prediction and the touch event, and 3) the distance from hand position to the touch point at the time of prediction. The mean accuracy without retargeting was 97.6%, 97.8% with 20° retargeting, and 97.1% with 40° retargeting.

	p0	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	p12	p13	p14	p15
a0	106	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
a1	0	108	0	0	0	0	0	0	0	0	0	0	0	0	0	0
a2	0	1	107	0	0	0	0	0	0	0	0	0	0	0	0	0
a3	0	0	0	108	0	0	0	0	0	0	0	0	0	0	0	0
a4	0	0	0	0	108	0	0	0	0	0	0	0	0	0	0	0
a5	0	0	0	0	0	107	0	1	0	0	0	0	0	0	0	0
a6	0	0	0	0	0	0	107	0	0	0	0	1	0	0	0	0
a7	0	0	0	0	0	1	0	106	0	0	0	0	0	0	0	1
a8	0	0	0	0	1	0	0	1	104	1	0	0	1	0	0	0
a9	0	0	0	0	0	0	0	0	0	107	0	0	0	0	0	1
a10	0	0	0	0	0	0	0	0	0	0	108	0	0	0	0	0
a11	0	0	0	0	0	0	0	0	0	0	1	106	0	1	0	0
a12	0	0	0	0	1	0	1	0	5	3	0	0	95	1	1	1
a13	0	0	0	0	0	0	0	0	1	2	1	0	0	104	0	0
a14	0	0	0	1	0	0	0	0	0	1	1	0	0	1	104	0
a15	0	1	0	0	0	0	1	0	0	1	1	1	1	0	2	100

Figure 11. The confusion matrix of our target prediction. ('a' = actual, 'p' = predicted)

From Figure 12, we used one-way ANOVA and found that the time from prediction to touch event and the distance from prediction point to touch point were affected by the offset ($F_{2,1004}$=12.424 and $F_{2,1004}$=62.9807 respectively, all p<.005). The mean last prediction time without retargeting was 2.88 seconds (SD=1.90), 2.11 seconds (SD=1.30) with 20° retargeting, and 1.88 seconds (SD=1.15) with 40° retargeting. The mean hand-to-target distance without retargeting was 28.7 cm (SD=14.90), 19.5 cm (SD=12.54) with 20° retargeting, and 15.2 cm (SD=4.01) with 40° retargeting.

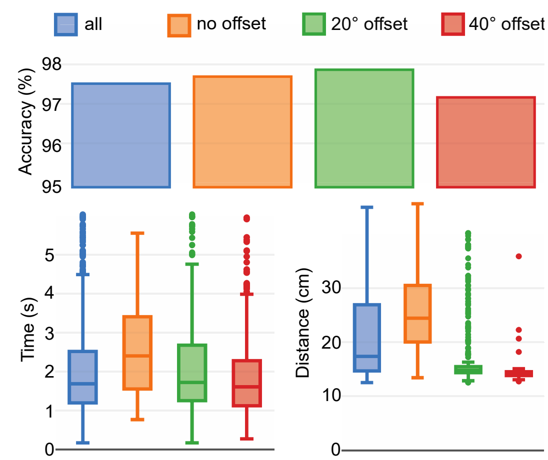

Figure 12. The accuracy, last target time and last target distance with different warping.

Discussion

The overall prediction accuracy was high (above 97%) and was not significantly affected by the introduction of retargeting. We do see some shortening of the time from prediction to touch: 73% and 66% for retargeting of 20° and 40°. This is caused by extra user gaze wandering preventing the system from making a prediction until later. This will increase the rate of retargeting needed, but since the prediction is successful, it did not hamper the system performance.

We did notice a lower accuracy (about 90°) at the lower side targets (12 and 15) due to the slightly lower reliability of the OptiTrack hand tracking around the corner targets.

Extension 3: Mapping Virtual Targets to the Physical Proxy

Mapping from the virtual geometry to the SHP can be optimized to achieve different goals. One can map the nearest physical primitive to minimize the retargeting distance. Another can fit the most similar primitive in order to enhance the range of possible haptic interaction. We present three mapping strategies that maps the predicted touch point to a single primitive on the Sparse Haptic Proxy.

One of the simplest interaction mode is a single finger touching the surface at a single point. Although simple, it enables a very versatile interaction: pressing a button, selecting or picking objects and more.

We investigated and implemented three approaches to remap the geometry touch point to a primitive of the Sparse Haptic Proxy as shown in Figure 13.

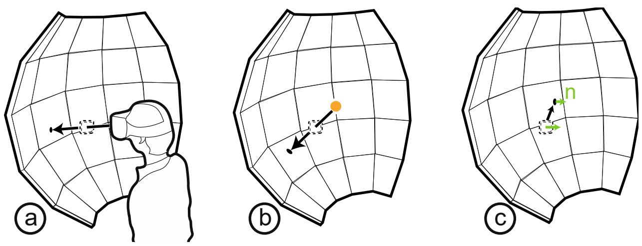

Figure 13. Remapping the trigger element using (a) line of sight, (b) closest point, (c) similar surface normal.

1) *Line-of-Sight* casts a ray to the virtual target and determine the intersection with the 3D model of the proxy as the remapping point. This mapping, dependent on the user's position, minimizes the angular offset between the touch point and the proxy, resulting in only back and forward redirection.
2) *Closest-Point.* The selected proxy point is the nearest point to the touch. This mapping, independent of the user's location, will minimize the retargeting distance, but can exhibit an angular offset between the proxy and the virtual geometry point.
3) *Similar-Normal* remaps the virtual target to the most similar direction surface normal in the Sparse Haptic Proxy, limited within a maximal angular deviation of 40° as found in Study 1. This lets the user feel a surface of similar direction, but can require larger retargeting distances.

Similar-Normal mapped primitive enables the user's hand slides along a larger area around the initial touch point, or use multiple fingers as touching the surface. Such operations can simulate dials, sliders, touch screen etc., such as the dial on the safe in our room scene in Figure 2.

Although we match an interaction surface to a similar primitive, there are still differences in surface orientation or shape between them. To enable the user to slide on the proxy surface, and is seen sliding on the virtual surface, we used Pseudo-haptic effect [2]. We project the virtual geometry onto the proxy interaction area so that each point touched by the virtual hand has a corresponding point on the physical proxy as shown in Figure 14.

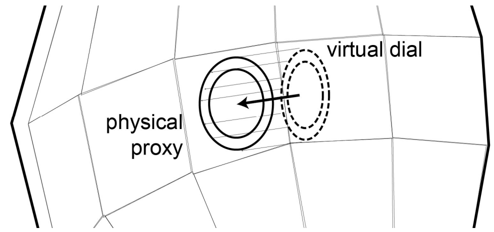

Figure 14. Remapping the virtual dial on the virtual safe to an area on the physical prop.

Study 3: Comparison of MAPPING strategies

The goal of our final study was to determine the mapping technique participants would prefer most.

Participants

We recruited 12 new right-handed participants (2 female), ages 26-47 (M=30.8). 5 participants had experience with head-mounted VR. Participants received a meal card as a gratuity for their time.

Task

The task in this study was similar to the task in Study 1. A trial began by showing the participant a virtual bullseye target and finished with the participant hitting the virtual target with their right hand.

The mapping to the physical proxy was determined by the chosen techniques (line-of-sight, closest-point and similar-normal). The virtual bullseye target was selected from two sets of nine orientations and locations as shown in Figure 15 to simulate both a simple virtual geometry and a complex one. The participants were instructed to move a step to the right to vary their location and perspective in the virtual and physical environment after they have done both sets of the targets.

Figure 15. Virtual bullseye targets in Study 3 were rendered in two set of different orientations and locations in the 3D scene.

Procedure

The procedure was similar to that in Study 2. Each participant completed 36 trials per technique (18 virtual targets x 2 points of view), resulting in 108 total trials. The order of techniques was counterbalanced across participants.

Between techniques, participants filled out a questionnaire. We asked 1) how smooth your hand could move and 2) how similar you feel the touch feedback as it should be in the virtual scene. Participants saw a text label for each presented strategy, but they were never told how a strategy works or what the label means: T0 (line-of-sight), T1 (closest-point) and T2 (similar-normal). Participants chose their preferred one among those labels after they had tried all three strategies. Overall the experiment took 20 minutes per participant.

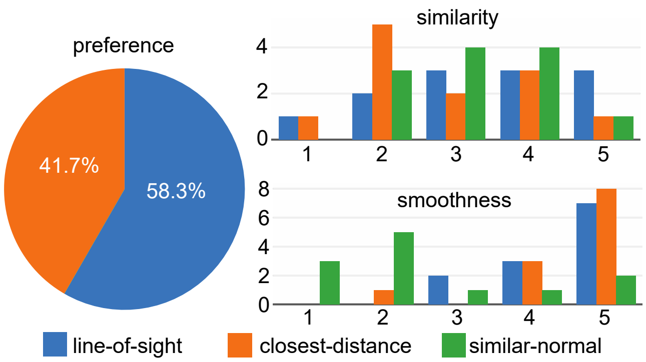

Figure 16. Participants' preference (left). Participants' rating histograms (Likert scale, 1= totally not) for the similarity of touch feedback (top right) and the smoothness of the hand movement (bottom right).

Results

As shown in Figure 16, no participant preferred Similar-Normal, which participants mostly rated low in smoothness. One user noted the difficulty to sense a surface normal from a single touch point. Another participant said the surface normal felt more correct under T2 but still preferred less redirection. One explanation could be that the haptic sensation for the single point touch is too limited to be a reward for that amount of redirection.

7 participants preferred the line-of-sight approach and 5 participants preferred the closest-point approach. We found no significant difference between both ratings (p>.05). The concave shape of the proxy and the limited motion possible for the users limited the differences between these mappings. It may be that a convex proxy will generate stronger differences when users move around it.

Since most participants preferred Line-of-Sight mapping, we used it as the mapping technique in our two demo applications. Line-of-sight always creates a 0° angle offset, such that retargeting only happens when a user is moving forward. This can result in having to stretch one's arm, similar to the GO-GO technique [27]. While the stretch is fixed in distance with GO-GO, it dynamically changes in our technique depending on the location of the target.

DISCUSSION AND FUTURE WORK

We have presented Sparse Haptic Proxy and its use to provide touch feedback to a variety of virtual applications of different geometry. The main idea of Sparse Haptic Proxy is the usage of a sparse set of physical primitives that can be mapped and reused for haptic simulation of mismatched virtual geometries (Figure 17).

Current commercial VR generates haptic feedback via hand held controllers, or wearables. The proposed approach has several major advantages, e.g., resistance felt by the user using a grounded sparse haptic proxy and hands-free interaction (no extra weight or limit to natural touch).

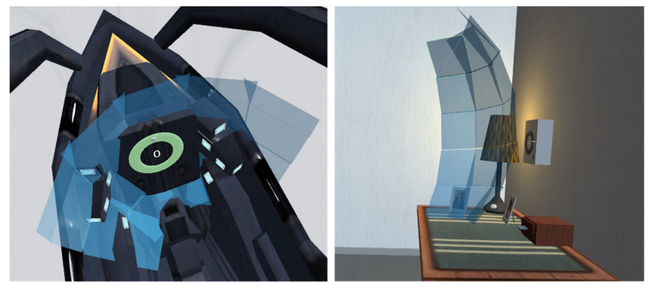

Figure 17. The mismatch between our proxy (blue overlay) and our cockpit and room scene.

One of our limitation is that each interaction with the virtual geometry is constrained to the span of the primitive. For example, when the user drags the finger over a planar primitive, it will eventually reach the end of the primitive where the mapping changes to another primitive, which can be at a different location. However, in many applications and games the common interactions are quite localized: open a lock, pick an object, push a door and so on. Such interactions are mapped well to a Sparse Haptic Proxy.

Direct motion between adjacent touch targets may not leave enough distance for redirection. This is future work. In our scenarios, the virtual objects are separated by at least 5 degrees, and we will look at ways to improve it in a future work.

Another limitation that raises from our use of planar primitives, is lack of representation of corner, edges and strong curvatures. Although planar or near planar surfaces are common in many geometries, there are many objects, such as handles, buttons, sliders and more, whose haptic representation will elevate the haptic experience. While even the simplest physical objects (e.g., boxes) can serve as Sparse Haptic Proxies for some scenes, more complex environments are better served by a Sparse Haptic Proxy that comprises a range of primitives. We see this as a future work.

Another dimension of variety could be the materials of which the primitives are made of. Some can represent soft materials while other can be hard. Textures and temperature may also be represented by different primitives.

The arrangement of the primitives should be derived from the range of applications to be supported. Our current arrangement of a hemisphere supports a symmetric set of primitives at arm reach. However, an analysis of VR applications may lead to a different arrangement.

The proxy we used for our experiments covers about 120° of view direction in front of the user at about arm's reach. There is no limit to build a proxy that will cover the complete directions around the user as long as the user can get in and out of the contraption. Another possibility is to actively rotate the proxy to face the user when turning. The speed of the rotation can be much slower than the rotation of the user hand, as the proxy covers about third of the full rotation. This allows for a slower and safer active operation.

Currently, we use a single proxy in front of which the user stands or sits. One can imagine a system that uses redirected walking to bring a user to multiple or one such proxies to simulate a larger environment.

CONCLUSION

We explored the possibilities and limitations of providing touch feedback for a variety of applications using a Sparse Haptic Proxy—a set of haptic primitives that is dynamically mapped and reused to fit virtual geometries.

We conducted a set of experiments that tested the performance of haptic retargeting and built on the results of each study to design the next one. Study 2 examined prediction accuracies under the maximum redirection we found in Study 1. Study 3 used the prediction system we evaluated in Study 2 and the redirection limit we found in Study 1.

We see Sparse Haptic Proxy as a "compressed" representation of the haptic feedback for a given scene. That is, Sparse Haptic Proxy uses fewer physical "bits" to represent the same amount of haptic information by removing repetitions. This simplifies the proxy and the space for passive haptics.

On the flipside, our approach to passive haptics using a Sparse Haptic Proxy is not a lossless compression. Proprioception and tactile sensation changes compared to the original representation. Nevertheless, Sparse Haptic Proxy enables users to perform a rich set of interactions that are common in different virtual reality experiences as we have shown in this paper, such as simulation, games and others.

ACKNOWLEDGMENTS

We thank our hardware lab for their insightful suggestions and thank all participants of our studies for their time.

REFERENCES

1. Azmandian, M., Hancock, M., Benko, H., Ofek, E., and Wilson, A. 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. DOI: http://dx.doi.org/10.1145/2858036.2858226
2. Ban, Y., Kajinami, T., Narumi, T., Tanikawa, T., and Hirose, M. (2012). Modifying an identified angle of edged shapes using pseudo-haptic effects. In *Proceedings of the International Conference on Haptics: Perception, Devices, Mobility, and Communication*, 25 of
3. Bergamasco M., Allotta B., Bosio L., Ferretti L., Parrini G., Prisco G.M., Salsedo F., Sartini G.. 1994. An arm exoskeleton system for teleoperation and virtual environments applications. In *Proceedings of IEEE International Conference on Robotics and Automation*. 2, 1449–1454. http://doi.org/10.1109/ROBOT.1994.351286
4. Binsted, G., Chua, R., Helsen, W., and Elliott, D. Eye-hand coordination in goal-directed aiming. *Human Movement Science 20*, 4–5 (2001), 563–585.
5. Burns, E., Razzaque, S., Whitton, M.C., and Brooks, F.P. 2007. MACBETH: The avatar which I see before me and its movement toward my hand. In *Proceedings of IEEE Virtual Reality Conference*, 295–296.
6. Frederick P. Brooks, Jr., Ming Ouh-Young, James J. Batter, and P. Jerome Kilpatrick. 1990. Project GROPEHaptic displays for scientific visualization. *SIGGRAPH Comput. Graph.* 24, 4 (September 1990), 177-185. DOI=http://dx.doi.org/10.1145/97880.97899
7. Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. 2015. TurkDeck: Physical Virtual Reality Based on People. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (UIST '15). ACM, New York, NY, USA, 417-426. DOI: http://dx.doi.org/10.1145/2807442.2807463
8. Conti, F. and Khatib, O. 2005. Spanning large workspaces using small haptic devices. In *Proceedings of First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 183–188.
9. Christian Corsten, Ignacio Avellino, Max Möllers, and Jan Borchers. 2013. Instant user interfaces: repurposing everyday objects as input devices. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces* (ITS '13). ACM, New York, NY, USA, 71-80. DOI=http://dx.doi.org/10.1145/2512349.2512799
10. George W. Fitzmaurice, Hiroshi Ishii, and William A. S. Buxton. 1995. Bricks: laying the foundations for graspable user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '95), Irvin R. Katz, Robert Mack, Linn Marks, Mary Beth Rosson, and Jakob Nielsen (Eds.). ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 442-449. DOI: http://dx.doi.org/10.1145/223904.223964
11. Goertz, R. and Thompson, R. 1954. Electronically controlled manipulator. *Nucleonics*, 12, 11, 46-47.
12. Steven J. Henderson and Steven Feiner. 2008. Opportunistic controls: leveraging natural affordances as tangible user interfaces for augmented reality. In *Proceedings of the 2008 ACM symposium on Virtual reality*

software and technology (VRST '08). ACM, New York, NY, USA, 211-218. DOI=http://dx.doi.org/10.1145/1450579.1450625

13. 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. DOI: http://dx.doi.org/10.1145/2858036.2858134
14. 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), Beth Adelson, Susan Dumais, and Judith Olson (Eds.). ACM, New York, NY, USA, 452-458. DOI=http://dx.doi.org/10.1145/191666.191821
15. Hughes, C.E., Stapleton, C.B., Hughes, D.E., Smith, E.M. 2005. Mixed reality in education, entertainment, and training. *Computer Graphics and Applications*, 25, 6, 24-30.
16. Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: adding haptic surface to graphics. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (SIGGRAPH '01). ACM, New York, NY, USA, 469-476. DOI=http://dx.doi.org/10.1145/383259.383314
17. Ivan E. Sutherland. 1965. The ultimate display. In *Proceedings of the Congress of the International Federation of Information Processing (IFIP)*, 506–508. http://doi.org/10.1109/MC.2005.274
18. Kohli, L. 2010. Redirected touching: Warping space to remap passive haptics. In *Proceedings of IEEE Symposium on 3D User Interfaces (3DUI), 2010*, 129–130. http://doi.org/10.1109/3DUI.2010.5444703
19. Kohli, L., Burns, E., Miller, D., and Fuchs, H. 2005. Combining Passive Haptics with Redirected Walking. In *Proceedings of the 2005 International Conference on Augmented Tele-existence*, 253–254.
20. Kohli, L., Whitton, M.C., and Brooks, F.P. 2012. Redirected touching: The effect of warping space on task performance. *IEEE Symposium on 3D User Interfaces* (3DUI), 105–112.
21. Kohli, L., Whitton, M.C., and Brooks, F.P. 2013. Redirected Touching: Training and adaptation in warped virtual spaces. *IEEE Symposium on 3D User Interfaces* (3DUI), 79–86.
22. Kok-Lim Low, Greg Welch, Anselmo Lastra, and Henry Fuchs. 2001. Life-sized projector-based dioramas. In *Proceedings of the ACM symposium on Virtual reality software and technology* (VRST '01). ACM, New York, NY, USA, 93-101. DOI=http://dx.doi.org/10.1145/505008.505026
23. Massie, T.H. and Salisbury, J.K. 1994. The PHANTOM Haptic Interface: A Device for Probing Virtual Objects Three Enabling Observations Three Necessary Criteria for an Effective Interface. In *Proceedings HAPTICS '94, 55*, 1, 295–300.
24. Matsuoka, Y., Allin, S. J., & Klatzky, R. L. (2002). The tolerance for visual feedback distortions in a virtual environment. Physiology & behavior, 77(4), 651-655.
25. Patrick, N. 1990. Design, Construction, and Testing of a Fingertip Tactile Display for Interaction with Virtual and Remote Environments, Masters Thesis, Department of Mechanical Engineering, MIT, Boston, MA.
26. Pair, J., Neumann, U., Piepol, D., and Swartout, W.R. FlatWorld: Combining Hollywood Set-Design Techniques with VR. *IEEE Computer Graphics and Applications 23*, 1 (2003), 12–15.
27. Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. 1996. The go-go interaction technique: non-linear mapping for direct manipulation in VR. In *Proceedings of the 9th annual ACM symposium on User interface software and technology* (UIST '96). ACM, New York, NY, USA, 79-80. DOI=http://dx.doi.org/10.1145/237091.237102
28. Razzaque, S., Kohn, Z., and Whitton, M.C. 2001. Redirected Walking. In *Proceedings of EUROGRAPHICS*, 289–294.
29. Jia Sheng, Ravin Balakrishnan, and Karan Singh. 2006. An interface for virtual 3D sculpting via physical proxy. In *Proceedings of the 4th international conference on Computer graphics and interactive techniques in Australasia and Southeast Asia* (GRAPHITE '06). ACM, New York, NY, USA, 213-220. DOI=http://dx.doi.org/10.1145/1174429.1174467
30. Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). ACM, New York, NY, USA, 3307-3316. DOI: http://dx.doi.org/10.1145/2702123.2702389
31. Barton A. Smith, Janet Ho, Wendy Ark, and Shumin Zhai. 2000. Hand eye coordination patterns in target selection. In *Proceedings of the 2000 symposium on Eye tracking research & applications* (ETRA '00). ACM, New York, NY, USA, 117-122. DOI=http://dx.doi.org/10.1145/355017.355041
32. Spillmann, J., Tuchschmid, S., and Harders, M. (2013). Adaptive space warping to enhance passive haptics in an arthroscopy surgical simulator. *IEEE Transactions*

on Visualization and Computer Graphics, 19(4):626–633.

33. Steinicke, F., Bruder, G., Jerald, J., Frenz, H., and Lappe, M. 2010. Estimation of Detection Thresholds for Redirected Walking Techniques. *IEEE Transactions on Visualization and Computer Graphics* 16, 1, 17–27.
34. Szalavári, Z. and Gervautz, M. 2008. The Personal Interaction Panel - a Two-Handed Interface for Augmented Reality. *Computer Graphics Forum* 16, 3, 335–346.
35. Tachi, S., Maeda, T., Hirata, R., and Hoshino, H. A. 1994. Construction Method of Virtual Haptic Space. In *Proceedings of the 4th International Conference on Artificial Reality and Tele-Existence*, 131–138.
36. William A. McNeely. 1993. Robotic graphics: a new approach to force feedback for virtual reality. In *Proceedings of IEEE Virtual Reality Annual International Symposium, 1993*, 336–341. http://doi.org/10.1109/VRAIS.1993.380761