VR Grabbers: Ungrounded Haptic Retargeting for Precision Grabbing Tools

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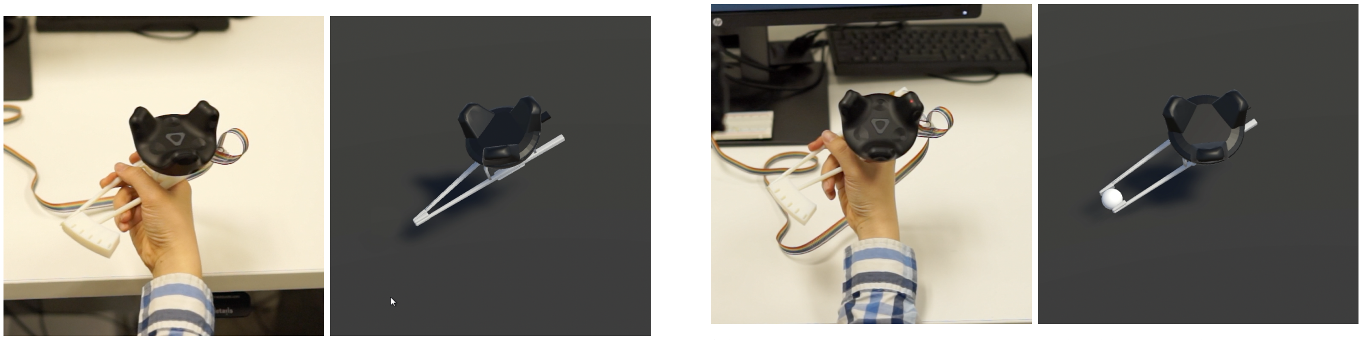

(a) Physical grabber controller (Left) and virtual grabbers (right) when closing the grabbers with no virtual object in between. Note that the physical grabbers close in conjunction with the virtual chopsticks as expected.

(b) Physical grabber controller (Left) and virtual grabbers (right) when closing the chopsticks on a virtual object. Note that the physical grabbers close in conjunction with the virtual grabbers grabbing onto the virtual object to provide the expected force feedback.

Figure 1. *Ungrounded Haptic Retargeting* with *VR Grabbers* Controller. The angle of the virtual chopsticks is retargeted to provide haptic feedback when grabbing virtual objects.

ABSTRACT

Haptic feedback in VR is important for realistic simulation in virtual reality. However, recreating the haptic experience for hand tools in VR traditionally requires hardware with precise actuators, adding complexity to the system. We propose *Ungrounded Haptic Retargeting*, an interaction technique that provides a realistic haptic experience for grabbing tools using only passive mechanisms. This technique leverages the ungrounded feedback inherent in grabbing tools combined with dynamic visual adjustments of their position in virtual reality to create an illusion of physical presence for virtual objects. To demonstrate the capabilities of this technique, we created *VR Grabbers*, an exemplary passive VR controller, similar to training chopsticks, with haptic feedback for precise object selection and manipulation.

We conducted two user studies based on *VR Grabbers*. The first study probed the perceptual limits of the illusion; we found that the maximum position difference between the virtual and physical world acceptable to the user is $(-1.48, 1.95)$ cm. The second study showed that task performance of the *VR Grabbers* controller with *Ungrounded Haptic Retargeting* enabled outperforms the same controller with *Ungrounded Haptic Retargeting* disabled.

Author Keywords

Virtual reality; Passive haptics; Haptic Illusions; Grabbing tools

INTRODUCTION

The pace of advancement in the virtual reality (VR) technology space has accelerated its use as a platform for training and simulation. However, simulation realism tends to break down for tasks that rely on skilled handwork. Precision handwork in the real world often requires specialized tools, making the use of generic controllers in VR an unacceptable substitute for realistic task simulation. Additionally, lack of haptic feedback can impair a sense of immersion and presence in virtual reality [24]. With this work, we want to enable professionals to bring the tools required for real world tasks into VR simulation and training with realistic haptic responses.

In this paper, we present *Ungrounded Haptic Retargeting*, a novel virtual reality interaction technique that allows grabbing tools to support haptic feedback with only passive components.

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The technique retargets the opening angle of the handheld grabbing tool to create a haptic illusion. Users are led to believe they can feel the presence of virtual objects that are not physically present; the reaction force people attribute to a virtual object is actually created from the internal mechanism of the handheld grabbing tool. To validate the proposed technique and algorithm, we created an exemplary handheld grabbing tool, *VR Grabbers*, a passive VR controller similar to training chopsticks for precise object selection and manipulation. Through our evaluation of *VR Grabbers*, we demonstrate how using *Ungrounded Haptic Retargeting* improves task completion time and subjectively improves realism over similar techniques with no haptic feedback.

RELATED WORK

Haptic feedback mechanisms can generally be classified as grounded or ungrounded. Grounded haptic feedback uses reaction forces that are directed through a static reference frame like a desktop or a floor. Ungrounded haptic feedback mechanisms apply their reaction force to a part of the user's body or internal to the haptic device [23]. *Ungrounded Haptic Retargeting* is unique in that it provides a way to generate ungrounded haptic feedback for handheld grabbing tools with only passive haptic mechanisms.

Ungrounded passive haptic systems

Hummel et al.'s work [11] explores two ways to represent the weight of a virtual object: the distance between tracked fingers and thumb and the strength of pinching fingers and thumb. Ban et al.'s [8] work shows a way to provide haptic sensation of touching AR objects from the user's finger touching each other by distorting user's camera footage. Matsumoto's work [20] focuses on using a controller with nonlinear spring to simulate variable stiffness while Achibet's work [3] shows a multi-finger haptic device with passive strings attached to all fingers and stimulate stiffness by changing *Control/Display* ratio.

Although those scholars describe methods to create haptic illusions for ungrounded haptic feedback, those projects focus on techniques that simulate grasping directly with the hand, whereas we focus on haptic feedback for grasping objects indirectly through a tool. The above techniques also cannot simulate the sudden increase of force when the controller comes in contact with a virtual object; most of those techniques can only support soft objects [20, 3].

Grounded passive haptic systems

Pseudo-haptic feedback [18] uses visual feedback to change the perceived stiffness of an isometric controller. Redirected touching [14, 15, 16] warps the visual space so that one physical haptic prop can simulate surfaces of different objects for one finger touching in virtual reality. This technique also shows that users can adapt to warped space and can perform tasks as efficiently as in un-warped space. Ogawa et al.'s[22] work explores how to change the perception of sizes of virtual objects by scaling the size of user's body. Ban et al.[7]'s work shows how to change the perceived shaped dynamically by warping the space around the object with a see-through camera. Haptic Retargeting[6] further expands this idea for space warping across multiple dimensions and allows representing the full body of the object for more interaction than just one-finger touching. Notably, although that system also provides some ungrounded haptic feedback, it must have a matched physical prop for each shape of the virtual objects, a significant limitation even when ported to grabbing tools.

All the systems above require the user to interact with the environment when following predefined steps so that the system does not have to adapt to the user's intention. Sparse Haptic Proxy [9] further augments these ideas with on-the-fly target remapping so that the system can predict user's intention during user's interaction with the environment. Without the use of a physical haptic prop, Virtual Mitten [4] uses the grasp force feedback from a hand exerciser and various visual illusions to simulate force and torque feedback received from the virtual environment.

Active Haptic Feedback

Active haptic feedback techniques can be divided into three categories: 1. non-grounded such as [31, 29]. They both use angular momentum of one or a few spinning disks to generate feedback forces. 2. grounded on body parts that should receive force feedback, including [10, 32, 12]. 3. grounded on body parts that should not receive force feedback. For example, CyberGrasp [19] is grounded on the wrist and Multi-fingered exoskeleton [17] is grounded on the back of the hands. In our work, we explored a new approach to provide ungrounded force feedback in a more compact and affordable way by leveraging a haptic illusion to simulate haptic feedback using only passive haptic devices and visual cues.

Handheld grabbing tools in VR

Virtual Chopsticks [13] demonstrates virtual object manipulation using virtually rendered chopsticks. However, their implementation uses exclusively 1:1 motion mapping between virtual and physical so that object will be picked up when there is a corresponding gap between user's finger, thus lacks any haptic feedback mechanism. Daichi's artworking [27], MAI Painting brush ++ [26], and ToolDevices [5] take the concept of tools in VR further by having a physical representation resembling the corresponding virtual tools plus actuated parts on one of their controllers, TweezersDevice [28], for ungrounded haptic feedback. HapSticks [12] also creates a chopsticks-shaped active controller with motors to render gripping force and gravity force. However, those actuation mechanisms add extra cost and fabrication complexity.

SYSTEM OVERVIEW

In this section, we introduce the design of the *Ungrounded Haptic Retargeting* framework and the system implementation of the *VR Grabbers* controller.

Ungrounded Haptic Retargeting

Before we discuss the detailed implementation of this algorithm, we will describe a general representation of a grabbing tool. As shown in Figure 2, a generic grabbing tool (simplified for illustration) consists of two opposing arms where arms converge to grab any objects that the user wants to manipulate. When the grabbing tool is used to hold a physical object, the

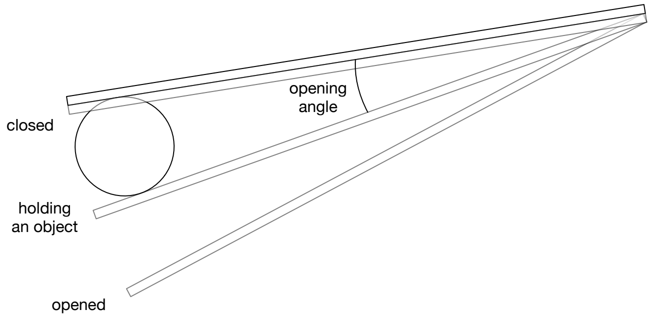


Figure 2. A simplified model of a general grabbing tool.

user will feel the force feedback generated by the arms touching the object. Similarly, when the grabbing tool is closed entirely, the user will feel the force feedback generated by the arm touching the surface of the other arm.

Ungrounded Haptic Retargeting leverages the dominance of visual perception to change the way the brain interprets haptic feedback, creating a haptic illusion. Because virtual objects do not physically exist, no force feedback can be generated when users "hold" virtual objects in VR. However, *Ungrounded Haptic Retargeting* changes the rate at which the virtual grabbing tool converges so that at the moment the user visually perceives the virtual grabbing tool converging on the virtual object, in physical reality the physical grabbing tool tips converge together. This design emulates the feelings of force feedback that occurs when there is an actual object between the opposing arms of a grabbing tool. The force feedback is not grounded on an external object; therefore, this technique is "ungrounded."

The key challenge in implementing this haptic illusion is that the amount of retargeting depends on whether a virtual object is being targeted and the size of the virtual object the grabbing tool is converging upon. Importantly, the controller should be able to fluidly adapt to user's change of intents among converging around a virtual object, shifting their hand position away to a different object and no longer targeting any objects to converge upon.

Remapping all these states of the tool is different from remapping the spatial location as in other haptic retargeting algorithms [6]. Although the class of grabbing tools we are considering only has one degree of freedom, the tool is expected to reach different virtual states as displayed to the user at the same physical position on that axis according to its environment. Specifically, the grabbing tool should be closed if there is an object in between while it should still be open if there isn't any object.

We developed a general *Key State Mapping* algorithm to allow designers to create other tool-inspired controllers using *Ungrounded Haptic Retargeting* for haptic feedback.

State is the core concept in *Key State Mapping*. State means the status of the tool at a precise moment. Each state contains both the physical status and what appears to the user in the VR. There are 2 kinds of state: key state and transfer state. Key states are a few states that are necessary to maintain the haptic illusion and are specified by the tool designer while creating the tools. Transfer states are all the other states other than key states. They are generated automatically by *Key State Mapping* by interpolating other states to keep the entire interaction smooth. To generate all the transfer states, an algorithm also needs to be specified to determine which key state transfer the controller is currently going through, as well as the progress of that transfer.

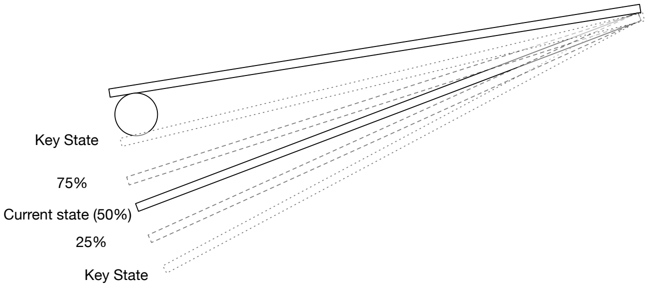
For example, for the simplified model, three key states can be defined: closed, (completely) open, and holding an object. When the grabbing tool is closed or holding an object, the grabbing tool should be physically closed to give the appropriate amount of haptic feedback; when the grabbing tool is open, it should appear to be at the same maximum opening angle. All the other states (the transfer states) can all be defined as between open and closed or between open and holding an object. We can use the presence of an object between the ends of the grabbing tool to determine whether the transfer is currently between holding an object and open or between closed and open, and the physical opening angle as the progress between the transfer. However, users may start closing their grabbing tool with one object in the middle but end up moving the grabbing tool beyond the grasp of an object. In a general sense, the algorithm used to predict the user's intention (which state transfer the controller is going through) may not be accurate, so we need to make sure that even when misprediction occurs, the transition between states remains smooth in consequent frames.

In *Key State Mapping*, we always use the state of the last frame and the key state the user is moving towards in this frame as a reference. If the user physically moves towards a specific key state, the visual representation will move proportionally to the progress that the user has made in this frame towards that key state. Equation 1 shows the mathematical form of *Key State Mapping*.

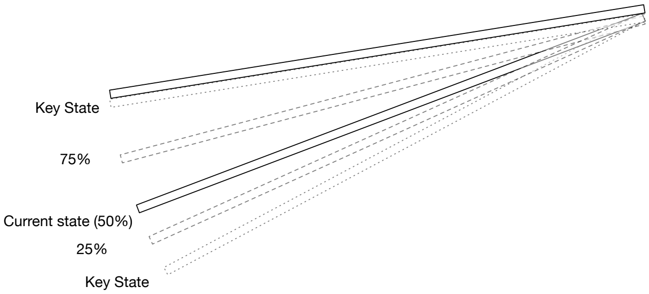
$$S_{i+1} = \begin{cases} Lerp(S_i, K_B, \frac{p_{i+1}^{A\to B} - p_i^{A\to B}}{1 - p_i^{A\to B}}) & p_{i+1}^{A\to B} >= p_i^{A\to B} \\ Lerp(S_i, K_A, \frac{p_i^{A\to B} - p_{i+1}^{A\to B}}{p_i^{A\to B}}) & p_{i+1}^{A\to B} < p_i^{A\to B} \end{cases}$$

Equation 1. *Key State Mapping*: S_i means state at the ith frame. K_A, K_B are two key states A and B. $p_i^{A\to B}$ means progress between two key states at the ith frame. $Lerp(a,b,t)$ is a given interpolation function to generate a state between a and b by the interpolant t. This equation shows how the state of the tool in the next frame is calculated given the state of the current frame and the transfer between two key states that the tool is currently undergoing.

For example, if the user first closes the grabbing tool with an object in between and reaches progress of 50% (Figure 3a). The system would treat (completely) open and holding an object as two key states and move the user's grabbing tool halfway between those key states. If the user chooses to further close the grabbing tool to a progress of 75% or otherwise open the grabbing tool to a progress 25%, the system will interpolate between the current state and the key state that the user is moving towards, which creates a smooth transition. If the



(a) User closes the grabbing tool with an object in between



(b) User then moves the grabbing tool so there is no longer an object in between

Figure 3. *Key State Mapping* for grabbing tool (visual status shown in the figure)

user's actual intention is to close the grabbing tool completely, and move the grabbing tool away from the object at this point, the system would change the prediction and determine that the controller is actually undergoing a different transition, which is between (completely) open and closed. However, because the progress of the transition has not changed yet, the visual status of the grabbing tool will not change, which fits the user's expectation. At this point, if the user chooses to open the grabbing tool, the transition would still be the same as before. But if the user chooses to close the grabbing tool to a progress of 75%, because the key state the user is moving towards has changed, the grabbing tool will move a bit faster, so that when the user closes the grabbing tool physically, the grabbing tool will also be closed visually.

To summarize, with *Key State Mapping*, we make implementing a new tool with *Ungrounded Haptic Retargeting* as easy as providing a few key states, a script to identify the state transfer, and a script for measuring the progress of each state transfer. The refined algorithm for *Key State Mapping* makes sure the transition between states is smooth and also keeps the entire *Ungrounded Haptic Retargeting* unnoticeable. This *Key State Mapping* conceptually allows the *Ungrounded Haptic Retargeting* technique to be extended to other grabbing tools with opposing arm mechanisms such as pliers, tweezers, or even a pair of scissors.

VR Grabber controller

VR Grabbers controller is an example handheld grabbing tool created to demonstrate the capability of *Ungrounded Haptic Retargeting* and *Key State Mapping*. We wanted to recreate the experience of using a pair of training chopsticks in real life by leveraging a chopsticks-like shape and appropriate force feedback from the *Ungrounded Haptic Retargeting*.

The hardware of the *VR Grabbers* controller (shown in Figure 4) consists of two chopsticks-shaped handles with a haptic prop block fixed on the bottom handle, an HTC Vive [2] VR Tracker for tracking position and orientation, a potentiometer for opening angle, and a joint and spring between two handles. A micro-controller reads the value of the potentiometer and transmits the value back to the Tracker. Note that the haptic block will not be rendered in VR: The block is only there to enhance the acceptable range of *Ungrounded Haptic Retargeting* and will be discussed in Section 4.1.4. To complete the VR setup, we used an HTC Vive [2] headset incorporated with two lighthouses for tracking both the Chopsticks VR controller and the user's viewport.

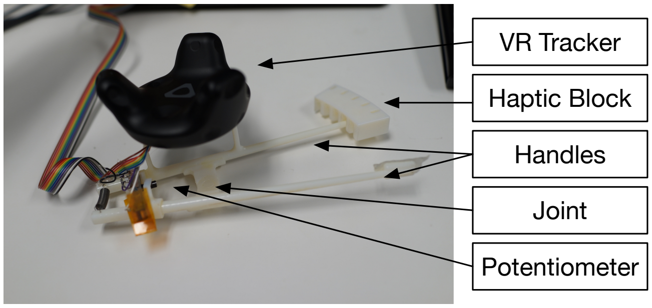


Figure 4. Components of *VR Grabbers* Controller

The physical parameters of the controller are shown in Figure 5. This figure illustrates how the simplified model from Figures 2 and 3 maps to this specific instance of a handheld grabbing tool to facilitate the use of the *Key State Mapping* algorithm. The maximum opening angle of the chopsticks is 30°. The length from the chopsticks tip to the hinge is 114 mm. For the haptic block, each slot is 5° or 10 mm in distance. The haptic block has a total of 5 slots. The weight of the *VR Grabbers* controller is 141 grams. The chopsticks body, passive haptic block, and the HTC Vive tracker has a weight of 42, 14, and 85 grams respectively.

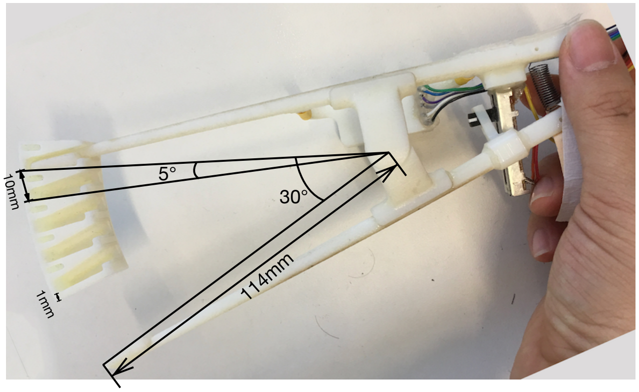


Figure 5. Dimensions of *VR Grabbers* Controller

To provide force feedback as a haptic illusion, the visual properties of the *VR Grabbers* Controller to retarget must be defined first. One possible implementation is to only retarget the opening angle (as shown in Figure 2). However, with this implementation, it is very likely that during the closing process one stick will touch the object first and the user will expect a force feedback that is grounded but that cannot be fulfilled. To create a smooth experience with only *Ungrounded Haptic Retargeting*, we retarget two parameters: the rotations for the top part and the bottom part. With this implementation, we can make both of the chopsticks touch the object at the same time; therefore, no grounded force will be expected from the system.

The key states for the *VR Grabbers* controller includes open, closed, and holding an object. While the chopsticks are open, both of the chopsticks are in the same orientation as in the real world. When the chopsticks are closed, both of the chopsticks appear to be touching each other while they are physically stopped by the block with some distance in between. When the chopsticks are holding an object, the virtual chopsticks look as though they are touching the surface of the closest object (in terms of the sum of angular distance between two chopsticks) between the chopsticks, while the physical chopsticks are stopped by the haptic block. The haptic block is used to maximize the largest size of the object that can be accommodated in VR while still ensuring an acceptable experience (detailed discussed in Section 4.1.4).

We then use *Ungrounded Haptic Retargeting* to calculate the transfer state and render the virtual model of the chopsticks accordingly. We also implemented a script to move the virtual object in between the chopsticks when the controller reaches the "holding an object" key state and a script to calculate the release translational and rotational velocity of the object when released. This gives the *VR Grabbers* controller the ability to pick up and release objects. Our system and application are implemented with Unity game engine 2017.1.

EXPERIMENT

We have conducted two empirical user studies to evaluate the *VR Grabbers* controller with *Ungrounded Haptic Retargeting*. The first study explored the limitations of the illusion from the *Ungrounded Haptic Retargeting*. The second study compared the task performance and sense of presence while using *VR Grabbers* between when *Ungrounded Haptic Retargeting* is enabled and disabled.

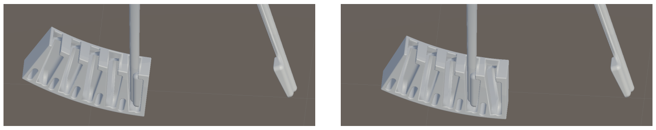
Study 1: Exploring the Limits of the Illusion

As *Ungrounded Haptic Retargeting* adjusts the visual state of the virtual grabbing tool and the Control/Display ratio of user's movement, the user may feel some uneasiness due to the conflict between visual and haptic senses. We designed and conducted a user study to find the maximum redirection parameters that users still find acceptable. We used the results of this study to inform the final design of the *VR Grabbers* controller.

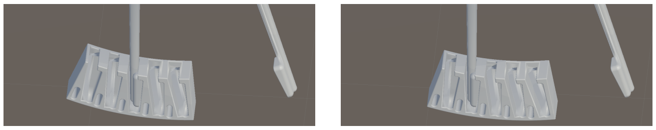
Participants

We recruited 12 right-handed participants (7 female, 5 male), aged 22 to 28 (M=24.5). Five of the participants had used VR more than 5 times, while the remaining participants had never used VR or only used it less than 5 times. Eight of them had used actual chopsticks for more than 20 times in the last 6 months, while the remaining participants used chopsticks less than 20 times or never used chopsticks in the last 6 months. Participants received a dessert as compensation for their time.

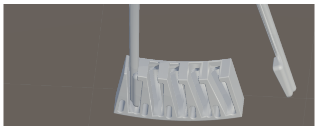
Task



(a) Position 1 **(b) Position 2**



(c) Position 3 **(d) Position 4**



(e) Position 5

Figure 6. Haptic block at different position

In this study, participants were asked to operate the controller with different configurations. For each configuration, the fixed haptic block was positioned in a particular slot (as shown in Figure 6), while in VR the haptic block was rendered in another specific slot. Participants were asked to close their chopsticks a few times and note whether they could detect any mismatch between their visual and haptic sensations. We modeled the study design after prior work examining tolerance of visual feedback distortions in virtual environments [21]. For each configuration, we asked each participant whether they noticed any retargeting and how confident they felt about their answer using a 5-point Likert-type scale. We defined '1' as 'not confident at all' and '5' as 'very confident.' Each participant tried the combination of 25 different virtual and physical slots in a random order. We did not disclose how we selected those configurations so the participants would not rule out one combination because they thought they had already tried it.

Results

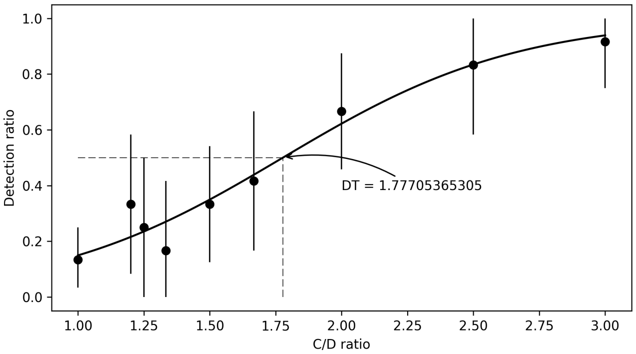
Based on the measurement in Figure 5, the travel distance of the tip of the chopsticks from completely open to completely closed should range from 2 cm to 6 cm according to the position of the haptic block. From that, we grouped the different trials that we performed on each user by different C/D ratio or absolute difference between travel distance in physical world and virtual environment.

We defined the detection ratio in each group for each participant as the number of times they detected the retargeting (first question) divided by the number of trial in that group. We then averaged the detection ratios across participants for each group and fitted psychometric function of the form:

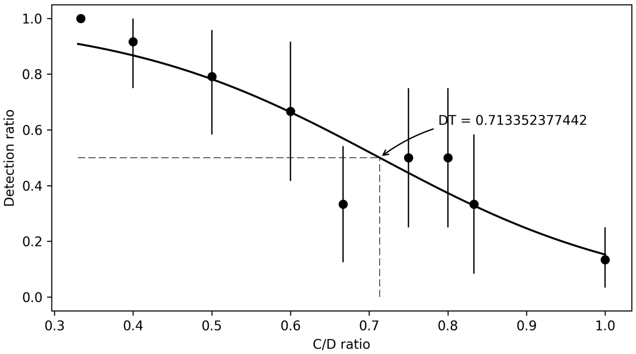
$$f(x) = \frac{1}{1+e^{ax+b}}$$

with real numbers a and b [25].

As stated in Steinicke et al.'s work [25], psychophysical experiments usually choose the point at which the curve reaches the middle between the chance level and 100 percent as the threshold. With a similar rationale, we chose the middle between 0% and 100%, 50% as our Detection Threshold (DT). The error bar of all the graphs in this subsection were generated according to the 95% bootstrap confidence intervals.



(a) C/D ratio ≥ 0

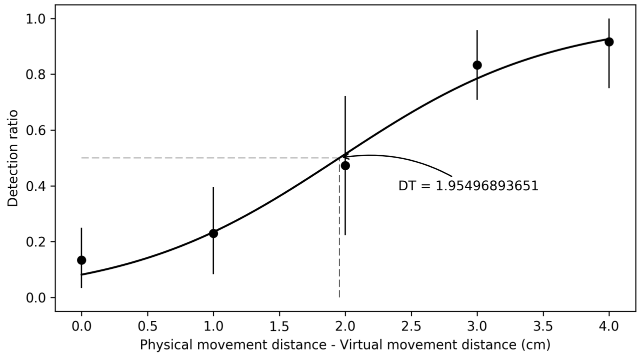


(b) C/D ratio ≤ 0

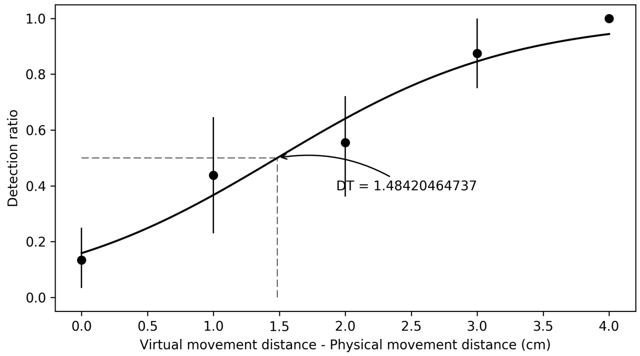
Figure 7. Detection threshold by C/D ratio

Figure 7a and Figure 7b shows the average of the participants' detection ratios grouped by Control/Display ratio. The psychometric fit in those Figures is $a = -2.2385, b = 3.9781$ and $a = 5.9874, b = -4.2711$. The result shows that the detection threshold of *Ungrounded Haptic Retargeting* for *VR Grabbers* should be $(0.71, 1.77)$ in terms of C/D ratio.

Figure 8a and Figure 8b shows the average of the participants' detection ratios grouped by difference in moving distance. The psychometric fit in those figures is $a = -1.2392, b = 2.4227$ and $a = -1.1246, b = 1.6692$. The result shows that the detection threshold of *Ungrounded Haptic Retargeting* for *VR Grabbers* should be $(-1.48, 1.95)$ cm in terms of difference in moving distance.



(a) Physical moving distance - virtual moving distance ≥ 0



(b) Physical moving distance - virtual moving distance ≤ 0

Figure 8. Detection threshold by difference in moving distance

Discussion

To sum up, we learned from this study that for *VR Grabbers* the traveling distance difference between the visual chopsticks and the physical chopsticks needs to be in the range of $(-1.48, 1.95)$ cm and the Control/Display ratio needs to be between 0.71 and 1.77.

With these results, we can determine the optimal position of the passive haptic block to maximize the size of the virtual object that our chopsticks can realistically emulate using *Ungrounded Haptic Retargeting*. The optimal slot of the block should be able to accommodate the largest object as well as properly simulate fully-closed chopsticks. According to the measurement of the chopsticks (See Figure 5) position 1-5 can provide a travel distance of 6 cm, 5 cm, 4 cm, 3 cm, 2 cm respectively (we ignored the 1mm thickness of the block in position 1). Position 2 would be the best choice as it can simulate a larger object than position 1. Any greater position would not be able to realistically simulate fully-closed chopsticks. At this position, the *VR Grabbers* can accommodate objects from 0 cm to 2.95 cm in diameter. Note that in this position, the chopsticks would travel 5 cm physically from fully open to fully closed, which means that by adjusting the Control/Display ratio the maximum range of travel distance that we can simulate visually is $(2.82, 7.04)$ cm. This distance covers virtual object sizes of $(0, 2.95)$ cm.

Study 2: Task performance comparison and user feedback on VR Grabbers

In this study, we evaluated the task performance difference of the *VR Grabbers* controller with and without *Ungrounded Haptic Retargeting*, and we gathered qualitative feedback with these two configurations to evaluate the impact on immersiveness and performance of the *Ungrounded Haptic Retargeting* technique for *VR Grabbers*.

Experimental Setup

For the control condition without *Ungrounded Haptic Retargeting*, we adopted an interaction similar to Virtual Chopsticks [13]. This method stops the chopsticks visually at the point when they both collide with the object in between, while the chopsticks' tips can still physically move inside the boundary of the virtual object. This technique is a common approach in modern VR frameworks (e.g. [1]).

The haptic prop block is removed in this design so that participants could fully closed their chopsticks both visually and physically.

Participants

We recruited 12 right-handed participants (8 male, 4 female), aged 22 to 59 (M=28.75). Ten participants had some experience with VR, while 2 had no experience with VR. Participants received a dessert as compensation for their time.

Task

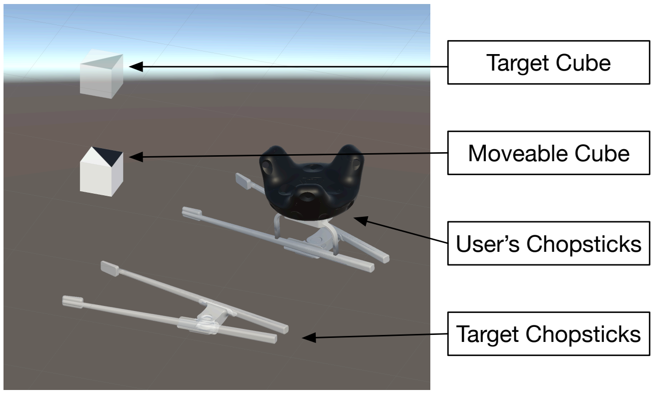


Figure 9. Setup of Study 2

The task (as shown in Figure 9) is a precise object manipulation task that consists of grabbing a different-sized object, moving it in a specific direction, and aligning the rotation with the target object. This task has a similar design the to *Precise Object Alignment* task described in the Virtual Chopsticks [13] paper.

For this task, participants first saw a 50% transparent chopsticks model along with the chopsticks they were physically holding. They were instructed to overlap their chopsticks with the transparent chopsticks model to start the task. This task was designed so that participants would always start the task with their chopsticks at the same position to avoid interference between each task. Once participants aligned their visual (virtual) chopsticks with the model within a certain threshold, the model disappeared and two white cubes were shown, each marked with a black triangle on one surface to distinguish orientation. Similarly, one of the cubes was 50% transparent to signify it as a target. The target cube had a fixed position and the participants could not pick it up, while the opaque cube was movable and available to be picked up. Participants were instructed to pick up the opaque cube with their chopsticks and move the cube so that it aligned with the target cube in both position and orientation. Once the system determined that the two cubes were aligned, the system rendered the target cube green to show that participants should now release their chopsticks. Once participants released their chopsticks with the opaque cube still in the target area, the task was considered completed.

We calculate the completion time starting from when participants aligned the chopsticks controller with the chopsticks model and ending when participants released the cube within the target area. For the alignment of the chopsticks, we used 50mm and 0.1 radians as the thresholds for translation and rotation difference. For the alignment of the cubes, we used 5mm and 0.1 radians as the thresholds.

Procedure

We first asked participants to fill in a demographics questionnaire and introduced them to the study procedures. The study consisted of two parts. The first part was a quantitative measurement of task performance and immersiveness, while the second part was a qualitative study of participants' feedback about the system. We instructed participants to evaluate two design of the chopsticks without telling them that one design was with *Ungrounded Haptic Retargeting* while the other one had no *Ungrounded Haptic Retargeting*. For both parts of the study, we randomly designated one design of the chopsticks as "chopsticks A" and the other as "chopsticks B." Participants first tried "chopsticks A" in a free-form virtual environment with a bowl and a few spheres and cubes available for pickup so they could get used to the design of the chopsticks. Participants were then asked to do the performance task under different combinations of configurations. Next, participants filled out the Witmer 21-question presence questionnaire[30] to evaluate the immersiveness of the variant of chopsticks they just tried. We conducted the same protocol for "chopsticks B."

After timed tasks for both chopsticks were complete, participants were allowed to revisit the free-form environment with each of the designs of the chopsticks. As they did so, we asked them to provide qualitative comments about the system. We allowed participants to go back and forth between the two designs so they could compare the differences.

We carefully designed the study so that half of the participants tried chopsticks with no haptic retargeting as "chopsticks A" while the rest of the users tried chopsticks with *Ungrounded Haptic Retargeting* as "chopsticks A" to counteract the effect of fatigue and adaptation to the controller. For the 36 trial, we used a combination of 3 different-sized blocks (10 mm, 15mm, and 20 mm), three different movement directions (up, right, and front), and four different rotations (90° in up, right, and front and 180° in front). The combinations were arranged in a randomized order for each participant, and they had the same order of combinations for both of the chopsticks. As the only difference in physical design between the chopsticks with *Ungrounded Haptic Retargeting* and with no *Ungrounded Haptic Retargeting* was the removable haptic prop block, we used the same *VR Grabbers* controller throughout the experiment to avoid the effect of manufacturing differences between controllers. We carefully hid the physical haptic prop and only put it on the chopsticks while participants had their eyes covered with the VR head-mounted display so that the *VR Grabbers* looked exactly the same in both study conditions.

Result

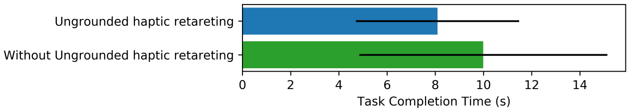


Figure 10. Average task completion time in study 2

As shown in Figure 10, the average task completion time in study 2 for chopsticks with *Ungrounded Haptic Retargeting* was statistically significantly lower than those for chopsticks without($t = -2.75, p = 0.006$).

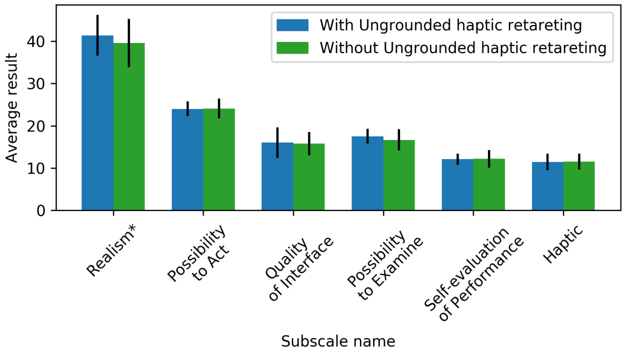


Figure 11. Average result of Presence Questionnaire (The larger the better except "Quality of Interface") *: Two sets of data are significantly different from each other with 95% confidence

Figure 11 shows the result of the 21-question presence questionnaire [30] aggregated by the scores of questions grouped by subscale. A paired t-test indicated that on the category of 'realism', chopsticks with *Ungrounded Haptic Retargeting* had a significant advantage over the chopsticks without ($t = 2.28, p = 0.04$). Per question analysis did not yield statistically significant results at the individual question level.

In the qualitative study, eight users suggested that the *VR Grabbers* with *Ungrounded Haptic Retargeting* were "better", three thought that there was "no noticeable difference", and one thought the chopsticks with no feedback are "slightly better". The most common feedback included that the *VR Grabbers* with *Ungrounded Haptic Retargeting* gave them "more control" (P4, P7, P10, P12), made them "easier to grab the object" (P2, P10, P12), and "feel more natural" (P4, P7, P10). Two participants also suggested the *VR Grabbers* with *Ungrounded Haptic Retargeting* have "higher accuracy" when grabbing the object (P6, P10).

Feedback about the *VR Grabbers* without *Ungrounded Haptic Retargeting* included that it made the object feel "softer" (P2, P6) and had a longer "delay" (P2, P6), especially when releasing the object (P6). P4 also thought that the chopsticks without *VR Grabbers* were "sticky", possibly due to the fact that the object in hold would not be released instantly after enlarging the opening angle, as in this design the physical angle had to be larger than the visual angle in order to release the object. P4, P6, and P9 complained that the chopsticks without *Ungrounded Haptic Retargeting* had no feedback when the chopsticks touched the surface of an object.

Other individual responses included the following: P2 thought the chopsticks with *Ungrounded Haptic Retargeting* were "slightly heavier", possibly due to the extra weight of the passive haptic block. When using the chopsticks with *Ungrounded Haptic Retargeting*, P4 reported that she felt that "the object is there". While using the same design of chopsticks, P7 thought she could "feel the boundary or the surfaces of the object". She also suggested that she felt no difference between closing the chopsticks with or without an object in between while using the chopsticks with no *Ungrounded Haptic Retargeting*. P10 and P11 indicated the chopsticks with *Ungrounded Haptic Retargeting* were more "responsive" and "quicker" respectively.

Feedback for the overall design of the system included the following comments: P6 and P10 thought the *VR Grabbers* controller was "too heavy", possibly due to the weight of the Vive Tracker. P5 thought the object should show deformation in some way when he applied force on the object.

DISCUSSION

Major findings and potential applications

The main findings of our evaluations are as follows:

- The detection threshold of *Ungrounded Haptic Retargeting* for *VR Grabbers* in terms of the Control/Display ratio is $(0.71, 1.77)$.
- Users think that with *Ungrounded Haptic Retargeting* on, *VR Grabbers* feels more realistic.
- Users have a better performance on precision task while using *VR Grabbers* controller with *Ungrounded Haptic Retargeting*.

Given these findings, we have demonstrated that *Ungrounded Haptic Retargeting* is a useful technique for the implementation of VR controllers with rich ungrounded haptic feedback. As we have shown in this paper, this technique is proven to work with positive effects on a user's sense of realism and task performance in VR. Chopsticks are only one example of a grabbing tool for precision tasks in VR. *Ungrounded Haptic Retargeting* can be applied to other controllers with opposing arm mechanisms. For example, controllers mimicking pliers or tweezers would have a very similar design as our chopsticks, and you would similarly treat the opening angle of the tool as the retargeting value. Alternatively, you could implement a glove-shaped passive haptic controller (similar to those described in Wolverine [10]) for grasping. In using *Key State Mapping* for gloves, you could treat the thumb and every other

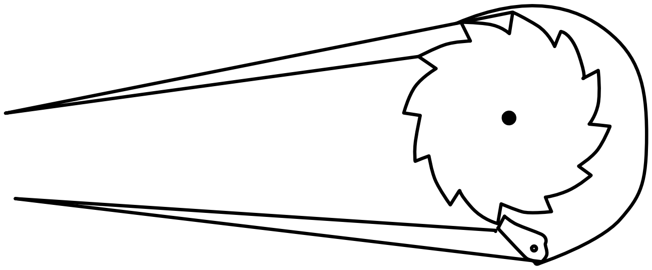


Figure 12. A tweezers with ratchet brake.

finger like a pair and retarget the opening angles of each pair of fingers.

Another potential application for *Ungrounded Haptic Retargeting* is to enhance the experience for some controllers with active haptic feedback. For example, the TweezersDevice Paper [28] shows two designs of the TweezersDevice. Both of them have a break to stop the two handles at a certain distance to provide ungrounded haptic feedback. One of the designs uses a ratchet brake while the other uses a drum brake. The ratchet brake (shown in Figure 12) has an advantage over the drum brake as it requires less power and can potentially provide more brake force. However, the ratchet cannot brake the tweezer between two teeth on its gear, which means that it can only stop the tweezers at discrete distances, limiting the size of the object that it can simulate. Combined with *Ungrounded Haptic Retargeting*, we could enable the tweezers to brake at the nearest distance from the actual size of the object and retarget the visual distance to match that exact size of the object, so that tweezers with a ratchet brake can support objects with a size in between those discrete distances.

Limitation and Future Work

The simplified model of a grabbing tool from Figure 2 is not necessarily an accurate model of the *VR Grabbers* controller. However, the user studies validate that this application of the simplified model through *Key State Mapping* is effective. The simplified model is also useful in providing designers an intuition for how the results of our study might scale to other devices of different sizes. For example, the range of object sizes within the detection threshold of needle-nose pliers will be smaller than that of our *VR Grabbers* due to its smaller arms. The simplified model cannot be used to accurately predict detection thresholds for other devices. We leave the characterization of detection thresholds of similar devices and the creation of an accurate predictive model to future work. The simplified model or the *Ungrounded Haptic Retargeting* interaction technique is also not likely to be useful for other training chopsticks tasks beyond grabbing, such as cutting, tearing, flaking, and peeling.

In the control group for study 1, we used chopsticks without any active haptic feedback. Although we adopted a common design used in today's VR applications as a reference, it might be interesting to compare the *Ungrounded Haptic Retargeting* with real ungrounded feedback such as chopsticks with a brake on the hinge. However, due to limited resources and complexity of actuation design, we have not yet implemented a chopsticks controller with active haptic feedback.

For user study 2, we observed the performance advantage for the group where *Ungrounded Haptic Retargeting* was used. As we stated in Section 1, training and simulating tasks are very common in VR. It might be interesting to know whether VR training with *Ungrounded Haptic Retargeting* can provide a significant increase in job performance in real life compared to training without any haptic feedback.

CONCLUSION

In this paper we present a system, *Ungrounded Haptic Retargeting*, for providing realistic haptic feedback in VR environment by remapping the physical and visual states of the *VR Grabbers* controller. We created a general algorithm, *Key State Mapping*, to simplify the implementation of other grabbing tools in VR. Taken together, these advances allow designers of VR environments a realistic haptic experience at a comparatively low cost. We explored the limits of *Ungrounded Haptic Retargeting* using *VR Grabbers* controller and refined the design of the controller based on study participant and other user feedback. We have also shown that *Ungrounded Haptic Retargeting* has a positive impact on task performance and sense of realism while operating *VR Grabbers* in virtual space. Using this technology as the foundation, future consumer VR experiences can go beyond direct hand interaction and incorporate handheld grabbing tools so that people can more effectively work within virtual reality.

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