Meet Me Half Way: Concerted Physical and Virtual World Manipulations for Effective Haptic Feedback in VR

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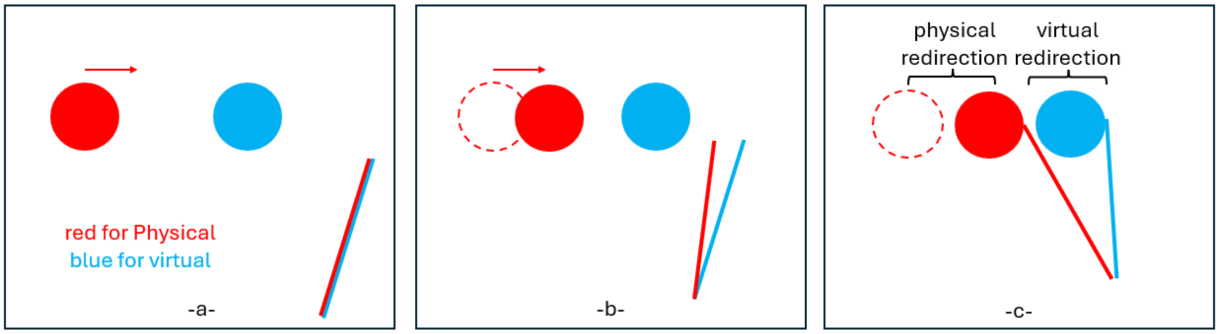

Figure 1: Combination of physical and virtual redirection to synchronize virtual and physical contacts for VR haptic feedback. *a*: the user is asked to tap a virtual disk (blue) with a handheld stick; an encountered-type haptic device (ETHD) carrying a physical disk of same size (red) starts moving towards the virtual object; initially, the virtual and physical sticks are aligned. *b*: the ETHD cannot align the physical disk to the virtual disk in time and virtual redirection of the virtual stick begins. *c*: the ETHD continues to move and virtual redirection adapts the position of the virtual stick gradually to synchronize the virtual and physical contacts; here half of the original gap (*a*) between the physical and virtual disks is bridged by the ETHD implementing a "physical redirection", and the other half is bridged by "virtual redirection".

Abstract

Passive haptic opportunities are scarce because they require the precise alignment of the virtual object with a physical object. Increasing the number of haptic opportunities can be done by moving the physical object to place it in alignment with the virtual object, i.e., through physical redirection. The physical object is moved with a robot called an encountered-type haptic device, or ETHD. Another option is virtual redirection, which manipulates the virtual object with which the user interacts with the virtual environment in a way that indirectly changes the user's physical motion to synchronize the physical and virtual contacts. This paper demonstrates that virtual and physical redirection can complement each other effectively. Indeed, the ETHD can reduce the physical to virtual gap that virtual redirection has to bridge, making the virtual redirection less noticeable. Conversely, virtual redirection can help synchronize the virtual and physical contacts when the ETHD fails to arrive at the needed position. A user study (N = 8), in which participants were asked to tap a virtual disk using a handheld stick, recorded the amount of physical and virtual redirection needed to synchronize the physical and virtual contacts. The results confirm that the faster the ETHD, the larger the physical redirection, and the smaller the virtual redirection needed. Furthermore, the ETHD provided sufficient reduction of the initial physical to virtual gap for the virtual redirection distance to remain below detectable thresholds that were measured by prior work.

Keywords: Passive haptics, redirection, virtual reality, ETHD.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Interaction devices—Haptic devices;

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1 Introduction

Virtual Reality (VR) holds the promise of delivering users an immersive 3D virtual experience. Despite the user's ability to see a vibrant virtual world and to interact with virtual objects using virtual laser pointer, virtual prop, or virtual hand metaphors, the absence of haptic feedback diminishes the believability of the experience. One approach for providing haptic feedback is to rely on *active* haptic devices such as VR gloves or suits. The advantage is that users take these devices with them as they move through the virtual environment so the user can benefit from haptic feedback anywhere in the virtual world. However, these devices can be bulky and uncomfortable. Furthermore, a haptic glove cannot provide realistic haptic feedback, for example, when the user touches a virtual wall and the user's hand has to stop from progressing forward upon contact. Another approach is to provide *passive* haptic feedback through stationary physical objects that are precisely aligned with the virtual object with which the user makes contact. However, this one-to-one mapping restricts reusability of the same physical object to provide haptic feedback for multiple virtual objects. This constrains the creative freedom of virtual scene designers who have to align all potential of contact in the virtual world with the physical objects in the user's surroundings.

In order to increase the applicability of haptic feedback, one has to make do with physical/virtual object pairs that are not in perfect alignment. At a fundamental level, this can be done with one one of two strategies: either modify the virtual world to place the virtual object in alignment with the physical object, which we call "virtual redirection", or modify the physical world to place the physical object in alignment with the virtual object, which we call "physical redirection".

Virtual haptic redirection. When the user makes contact with the virtual environment, the user acts with a virtual object A upon a target virtual object. Object A can be a virtual replica of the user's hand, or a virtual prop, such as a virtual screw driver or a virtual golf club. Object A has a physical counterpart that is aligned at the beginning of the VR session through calibration. The target object does not have a perfectly aligned physical counterpart and virtual redirection is called upon to provide haptic feedback using a nearby physical target object. Virtual redirection has two options. One option is to move the virtual target object to the location of the physical target object. As the user approaches to make contact with the virtual object, the virtual object moves as if it were trying to evade the user. This option is unsatisfactory because the user is likely to notice this spurious motion, as the user focuses on the virtual target object. A second option is for virtual redirection to manipulate the virtual object A with which the user attempts to make contact, which is less noticeable by the user. As the user approaches the virtual target object, the position and orientation of the virtual hand or prop is modified gradually to bridge the gap between the physical and virtual target objects, ensuring a synchronized contact. This means that the virtual contact between the virtual hand (or prop) and the virtual target and the physical contact between the physical hand (or prop) and target occur simultaneously. However, virtual direction cannot bridge large gaps between virtual and physical target objects without the user noticing.

Physical haptic redirection. An alternative approach is to move the physical target object with the help of a robot to place it in alignment with the virtual target. A robot used for haptic feedback is commonly known as an Encountered-Type Haptic Device (ETHD). The ETHD is not rendered in the virtual environment and is therefore not visible to the user, who has the illusion that the virtual object has tangible properties. Just like for virtual redirection, ETHD's cannot bridge large gaps between virtual and physical target objects due to their limited speed. When the gap is too large, the ETHD fails to arrive at the virtual target location and the user moves the virtual hand or prop through the virtual object that does not provide resistance. In other words, the physical contact felt by the user is delayed with respect to the virtual contact that the user sees.

The ultimate goal of providing passive haptic feedback in VR is indeed to act directly on the user's hand or body. However, for now, using a handheld prop with which the user probes the virtual environment offers the advantage of diminishing the user's tactile perception. Paradoxically, this enhances the credibility of the haptic feedback compared to delivering the haptic feedback directly through the user's fingers that can perceive tactile properties of the physical object such as texture and temperature. Any deviation from the expected properties of the virtual object may compromise the effectiveness of haptic feedback. Furthermore, using a prop reduces the user's awareness of the position of the prop compared to that of their fingers, broadening the design possibilities and potential applications of virtual haptic redirection. Finally, considering the prevalence of virtual reality applications involving user interaction through handheld tools, the study of haptic feedback via the handheld stick holds direct relevance.

In this paper we demonstrate that virtual and physical redirection can complement each other effectively, extending the physical to virtual gap that each can address individually. Indeed, the ETHD can reduce the physical to virtual gap that virtual redirection has to bridge, making the virtual redirection less noticeable. Conversely, virtual redirection can help synchronize the virtual and physical contacts when the ETHD fails to arrive at the needed position. To this effect we have conducted a user study (N = 8) with the approval of our Institutional Review Board (IRB) in which participants were asked to tap a virtual disk using a handheld stick. Physical redirection was provided by an ETHD implemented with a Cartesian robot that moved a physical disk to place it in alignment with the virtual disk. When the physical disk failed to arrive at the location of the virtual disk, virtual redirection bridged the gap to synchronize the virtual and physical contacts.

The tapping task is illustrated in Fig.1. In panel *a* a virtual disk (blue) appears and the user has to tap it with the handheld stick. The ETHD starts moving its carried physical disk (red) towards the position of the virtual disk. The virtual (blue) and physical (red) sticks are aligned. Note that the physical disk and stick are shown here for explanatory purposes and they are *not* visible to the user. When the VR system realizes that the ETHD will not get the physical disk to the desired position on time, virtual redirection begins, and the alignment of the virtual and real sticks is broken (panel *b*). The virtual stick undergoes continuous redirection, that ends with the synchronization of virtual and physical contacts (panel *c*). We also refer the reader to the accompanying video that provides further illustration of the tapping task.

A participant was asked to tap multiple virtual disks in succession, and for different ETHD speeds. We recorded the amount of physical and virtual redirection needed to synchronize the physical and virtual contact (Fig. 1*c*). Physical redirection is quantified as the distance traveled by the ETHD from when the virtual object appeared and when contact was made. Virtual redirection is quantified as the gap between the virtual and physical disks when contact is made. The results confirm that the faster the ETHD, the larger the physical redirection, and the smaller the virtual redirection. Furthermore, the ETHD provided sufficient reduction of the initial physical to virtual gap for the virtual redirection distance to remain below detectable thresholds that were measured by prior work.

2 Related Work

VR headset users can feel haptic feedback from different sources, categorized as either indirect or direct forces on their body. An example of indirect feedback is delivering mid-air tactile sensations to the user's bare hand using ultrasound technology [12]. This involves emitting ultrasound waves through a transducer array, creating sensations like moving through the air or interacting with floating objects.

On the other hand, direct haptic feedback involves applying forces through physical contact, offering a cost advantage. These direct methods are further divided into *active* and *passive* categories.

Wearing a haptic display, like haptic gloves [1], is an example of devices providing active haptic feedback by exerting pressure on their hands upon interacting with virtual objects. This active haptics method offers the advantage of users carrying the haptic display with them throughout the virtual world, ensuring haptic feedback is accessible wherever they navigate. However, drawbacks include a continuous awareness of the haptic glove's presence, not just during virtual interactions, and limitations in the intensity range and realism of the provided haptic feedback. Some researchers have explored a solution involving a backpack-mounted robot arm that restricts the user's hand movement when in contact with virtual objects [11], but this exacerbates the encumbrance issue.

Passive haptic devices operate without an external power source, relying on the user's actions to generate necessary force. Essentially, haptic feedback is produced through the reactionary force when the user interacts with a physical object unattached to their body [6]. This approach closely emulates the haptic feedback experienced in the real world, offering greater potential for realism. For instance, when touching a virtual table, aligning a physical object anchored to the floor with the virtual table creates a realistic haptic sensation, avoiding any pinch-like feel.

Although passive haptic feedback is realistic and doesn't strain the user's body, it becomes impractical when trying to match a physical object with various virtual objects that differ in position, size, shape, orientation, and surface properties like texture and roughness. Additionally, it's not ideal to create a unique physical setup for each virtual environment. To address this, one can either create illusions in the virtual world to diminish the user's visual perception (Sec. 2.1) or adjust the physical environment to align with the virtual world, making the physical setup more reusable (Sec. 2.2).

2.1 Virtual Redirection

Virtual redirection methods change the virtual world, like the user's virtual body or environment, to match the physical world. Since people usually trust what they see more than what they feel, even a slight difference between the virtual and physical worlds might go unnoticed [7]. Redirection has been explored in the realm of VR locomotion, where users move on a different path in VR without realizing it compared to their movement in the physical world [19].

In the realm of haptic feedback, redirection has proven effective in interacting with stationary objects [5]. Modifying a physical object's characteristic is possible by visually obstructing or transforming hand movements. For instance, when turning a physical knob, limiting the virtual rotation speed can make users feel like the knob has more resistance than it truly possesses [9]. It not only helps in tolerating differences between real and virtual objects but also creates the impression of stiffness [18] or alterations in shape [3].

When the user touches the virtual object with a handheld prop, the prop can cover up the surface details and open up new ways to interact with virtual objects. For example, redirection has been employed to make tool-based interactions feel more real in a virtual workspace. This helps in giving a sense of touch feedback that mimics the impact and resistance experienced when using tools such as a hammer, saw, or screwdriver [15]. The handheld prop can make the user less alert, which in turn raises the detection threshold for redirection. This provides designers with extra room for potential applications [20].

2.2 Physical Redirection (ETHDs)

In addition to using virtual methods to sync final contacts, you can also make the physical world match the virtual object by using mechanical positioning systems. One example is an ungrounded device like a drone (source: [4]). Ungrounded devices, unlike those with support structures, don't have lifting limitations, allowing them to cover a larger volume. However, compared to popular grounded devices like a robot arm (source: [17]) or a table-top robot (source: [10]), ungrounded systems may have drawbacks in precision, latency, and payload capacity.

According to a recent survey [14], robot arms are widely used in ETHD for moving objects. The main advantage of robot arms is their flexibility and space-efficiency. These arms, typically equipped with three to four joints, can perform various tasks like repositioning, grasping objects, manipulating tools, and making precise movements with improved dexterity. The end effector of a robot arm can be easily replaced with specialized hardware for continuous sensing of surfaces [13].

In the discussed paper, the authors swapped the end effector of their robot arm with a rolling cylinder. This cylinder, rotating and moving along with the user's hand, was used in a virtual environment. As the user rubbed their finger on a surface, the robot arm synchronized its movement with the user's hand. The rolling cylinder rotated in the opposite direction, ensuring that the user's finger felt the simulated movement on the surface. The tactile sensation of rubbing came from the relative movement of the rolling end effector, not the actual touch of the user's hand.

Even though a robot arm offers flexibility, its cost rises significantly based on its reachability and payload capacity. In practical terms, it becomes economically impractical to extend a robot arm to cover the entire user-reachable space. To address this issue, one viable solution involves mounting the robot arm on carts or utilizing an inexpensive navigation robot, as suggested by Dai et al. in their work on RoboHapalytics [8]. Another cost-effective alternative is the utilization of a Cartesian robot, which is the approach adopted in this paper.

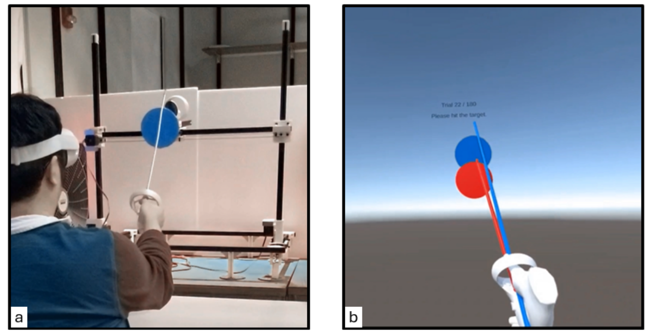

Figure 2: The ETHD setup (left) and the user view (right). The red disk and stick are shown for illustration and the user cannot see them.

Researchers have begun examining the benefits of combining ETHDs with redirection. One prior study employed a robot that could move on a planar surface, similar to a robotic floor sweeper, to provide feedback to a user touching stationary virtual objects on a table in front of them [10]. The study investigated how frequently the robot can get within 2cm of the virtual object the user intends to touch, for various robot speeds (i.e., 20, 25, 30 and 35cm/s). The results show that the faster robot has a rate of on-time arrival to the point of contact that is up to 25% higher than the slower robot.

In this paper, we aim to showcase the efficacy of integrating virtual and physical redirection methods. Specifically, we explore the synergy between software and hardware-based approaches within a voluminous 3D space. The objective is to illustrate how these methods can collaborate to address respective limitations.

3 User Study

We conducted a user study with the approval of our Institutional Review Board. The goal of the study is to investigate how much virtual redirection can improve the ability of an ETHD to provide haptic feedback in a virtual disk hitting task. The user is asked to tap several disks in succession, which doesn't give the ETHD enough time to align the virtual and physical disks.

Participants. We recruited N = 8 participants with an average age of 27.6, 5 men and 3 women, 6 of whom used VR headset occasionally, and 2 frequently. All participants were right-hand dominant. The participants completed the experiment on average in 19.1 minutes.

Implementation and setup. The participant wore a Meta Quest 2 VR headset [2] and held the controller in their right hand, with a 55 cm Aluminum interaction stick attached to the controller. The participant was positioned in front of a 50 cm wide empty table, so the participant couldn't reach the ETHD with their hand. The VR application was developed using Unity 3D, version 2022.3.4.

The ETHD was implemented with a Cartesian robot capable of accessing any point within a 50cm $\times$ 50cm $\times$ 30cm volume. The ETHD speed ranged from 10 cm/s to 22 cm/s along the x axis, 10 cm/s to 16 cm/s along y axis and from 3 cm/s to 5 cm/s along the z-axis. Control of the ETHD was managed by the headset through a server (a laptop). The server established a wired serial connection with the ETHD and a wireless TCP connection with the headset. The ETHD coordinate system was calibrated to the headset coordinate system through a calibration process involving touching the disk with the stick at various ETHD positions. Fig. 2(left) shows the ETHD setup.

The carried object was a thin 3D-printed PLA disk with a diameter of 14cm, serving as a physical replica of a virtual disk of the same radius. The use of identical disks minimized the impact of shape variations for different impact directions. The virtual contact between the virtual stick and the virtual disk was synchronized with the physical contact between the physical stick and the physical disk through a prior art redirection algorithm that continually predicts the two physical and the two virtual contact points [20].

Task. A series of virtual disks appear in front of the user, one at the time. The user is asked to tap each disk with the stick. The virtual disks appear at random locations within the volume of the ETHD. Once it appears, a virtual disk remains stationary. Once the virtual disk appears, the ETHD starts moving its physical disk toward the virtual disk's position. The user swings the stick towards the virtual disk to make contact. Once the stick approaches within 10cm of the physical disk, if the ETHD still moves, the ETHD stops for safety. This further increases the demands on the ETHD speed, which has to reach the position of the virtual disk before the stick gets within 10 cm of it. Due to the limited speed of the ETHD, the physical disk might not reach the position of the virtual disk. In the best case scenario, the user begins swinging after the ETHD arrives, and the physical and virtual disks are perfectly aligned, preventing any virtual redirection. On the other hand, if the user starts swinging as soon as the virtual object appears, moves at a speed of 12 cm/s, and comes to a halt in 1 second, the ETHD will not reach the position of the virtual object. As a result, virtual redirection will be 8 cm. Virtual redirection is applied to the virtual stick, to bridge any remaining gap between the virtual and physical disks, synchronizing the physical and virtual contacts. When the virtual stick touches (visually) the virtual disk, the physical stick makes contact with the physical disk, imparting haptic feedback to the user. After contact is made, the virtual disk disappears and, after a brief delay, a new one appears at a different position. Fig. 2(right) shows the user view during the experiment. The red stick and disk are shown for illustration, and the user cannot see them.

Independent variables. The experiment examines two factors that influence the amount of redirection needed to synchronize the virtual and physical contacts: the speed of the ETHD, and the time gap between consecutive virtual disks. The ETHD speed is investigated at three levels: stationary (0 cm/s), slow (12 cm/s), and moderate (16 cm/s). When the ETHD is stationary, only virtual redirection is applied, while at slow and moderate speeds, both virtual and physical redirection occur. The time gap is investigated at four levels: 1, 2, 3, or 4 seconds. A disk always disappears one second after being tapped. Participants are instructed to retract the stick after contact is made, and no new disk is spawned if the stick is within 50 cm of the ETHD. Different time gaps may affect the user's response time. If a sphere appears as soon as the previous one disappears, the user needs to immediately reach for it after retracting their stick. If the sphere appears 4 seconds later, the user has to wait a little before aiming for the target. This behavior may result in discrepancies at last. In total, the experiment collected data for 12 combinations of independent variables: 3 speeds $\times$ 4 time gap values.

Dependent variables. The study quantifies the amount of physical and virtual redirection for each independent variable combination. The amount of physical redirection is given by the distance traveled by the ETHD from when the virtual disk appeared and when contact is made. The amount of virtual redirection is given by the distance between the virtual and physical disks when contact is made.

Research Hypothesis. The faster the ETHD, the smaller the amount of virtual redirection.

Procedure. A participant performed 180 counterbalanced virtual tapping trials: 12 independent variable value combinations $\times$ 15 repetitions. Before a disk appeared, i.e., after the previous disk disappeared, the participant was instructed to keep the stick close to their body, i.e. the stick tip more than 0.5m away from the ETHD. After each trial began, the virtual disk appeared and the ETHD moved towards it. The virtual disk always appeared randomly above, below, to the left, or to the right of the physical disk. Furthermore, the initial position of the virtual disk was always 20 cm away from the current physical disk position, and within the volume covered by the ETHD for the ETHD to be able to assume that position should it have time. Participants were allowed to tap the disk from any direction. The stick might move in the same, opposite, or perpendicular direction of the disk. When the physical stick was only 10 cm from the physical disk which was still moving, the ETHD would stop for safety concerns. If the physical disk reached the target position of the virtual disk, it stopped moving and waited for the participant to tap. In this case, the final virtual to physical discrepancy was 0 cm, so no virtual redirection was needed. In all trials, the ETHD moved for more than 1 second, providing the participant enough time to respond, giving them a chance to tap the physical disk before it arrived at the target position, engaging the virtual redirection process.

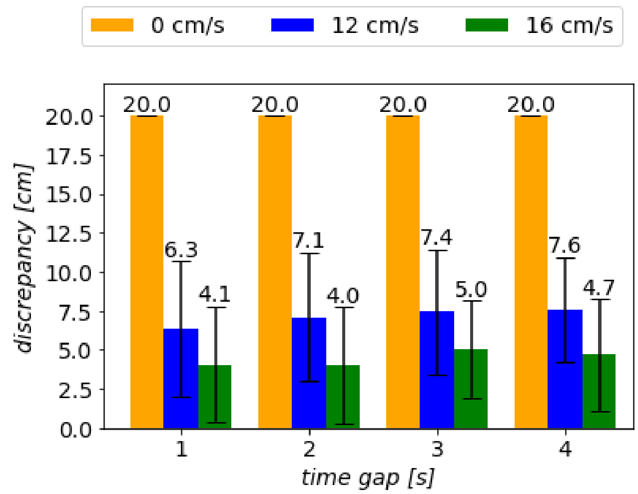

Figure 3: Final physical to virtual disk position discrepancy when contact is made, for various disk spawning time games and various ETHD speeds.

Data analysis. We analyze the impact of a variable involving three or four groups using the Friedman test. If the difference is significant, we apply a pairwise Wilcoxon test using a Bonferroni correction of $\times 3$ or $\times 6$ to account for the three or six pairs. We used the SciPy statistical package [16]. Our study not only records the final discrepancies under all conditions but also tracks the movement path of the virtual and physical sticks, as well as of the virtual and physical disks. These paths provide a better understanding of the user swing patterns and how they might affect the final findings.

Results. Fig. 3 shows the final discrepancies under different combinations of ETHD speeds and time gaps.

The final difference between virtual and physical objects is significantly reduced by the moving ETHD. When the ETHD doesn't move (0 cm/s), the final difference is always 20 cm, by definition. If the ETHD moves, the minimum average difference is 4.1 cm when the ETHD moves at 16 cm/s, and the time gap between the two consecutive disks is 1 s. For the same time gap, all pairwise comparisons between a stationary physical disk (0 cm/s) and a moving ETHD (12 cm/s or 16 cm/s) indicate a significant difference in terms of the final differences, with statistical factors p ¡ 0.001. The final difference of the stationary ETHD is larger than the detection threshold measured in prior work [20], while the moving ETHD can reduce the amount below the threshold, making it much harder to notice. Furthermore, the two speeds, 12 cm/s and 16 cm/s, also result in significant differences for all time gaps with significant values p ¡ 0.001. These results indicate that the moving ETHD can significantly help with the redirection detection threshold, and the faster an ETHD is, the more it helps.

Time gap, on the other hand, does not have a clear impact. In pairwise comparisons, the pairs with a significant difference are (1 s, 2 s) and (1 s, 3 s) for 12 cm/s, as well as (1 s, 2 s) and (2 s, 3 s) for 16 cm/s. Out of 12 pairs, 4 show a significant difference, so it is unclear whether the time gap between two consecutive disks influences the final discrepancy.

If the ETHD is stationary, there is no physical redirection, and the entire physical to virtual discrepancy is covered by virtual redirection (Fig.4*a*). When the ETHD does move, even with the speed of 16 cm/s, te ETHD often could not cover the initial 20 cm difference between virtual and physical objects to reach the target position. Without virtual redirection, if the physical disk doesn't reach the target, the stick will move through the virtual disk (see Fig.4*b*). Virtual redirection always ensures a synchronized contact between the virtual and physical elements, as depicted in Fig.1*c*.

Conclusion Our study confirms our statement that the combination of virtual and physical redirection can significantly improve the performance of either redirection. Virtual redirection can help bridge the gap between the virtual and physical objects if the ETHD cannot reach the target position in time; on the other hand, physical redirection can significantly reduce the amount of discrepancy the virtual redirection has to bridge.

4 Conclusions, Limitations, and Future Work

We conducted a study that investigated how two redirection methods, virtual and physical redirection, can mutually enhance each other when used in tandem. Virtual redirection smoothly and gradually adjusts the virtual stick as the user approaches the target. Although the virtual and physical objects may not be perfectly aligned, virtual redirection bridges the gap between them, providing to the user believable tactile feedback. However, it is crucial to minimize the discrepancy between the positions of the virtual and physical objects because users can easily notice the redirection which negatively impacts the virtual reality experience. In this context, physical redirection in general, and ETHD redirection in particular, helps reduce the gap between the virtual and physical objects, making the virtual redirection less noticeable. On the other hand, there are instances where physical redirection alone cannot move the physical replica to the target virtual position in time due to speed limitations. In such cases, virtual redirection comes into play, ensuring the final synchronized virtual and physical contacts.

Our study has several limitations. Our ETHD has a relatively low maximum speed, preventing it from reaching the target position at a higher speed. If the ETHD could move faster, it would be able to cover a larger space, and the virtual redirection might not be necessary if the ETHD can quickly cover the entire volume. However, trade-offs are also apparent. Supporting a higher speed would require the robot to have more powerful motors and a more precise tracking system, leading to exponential cost increases. The higher speed also necessitates more stringent safety regulations to ensure that users are not injured by the ETHD. Future studies can investigate the balance between a faster ETHD and its trade-offs.

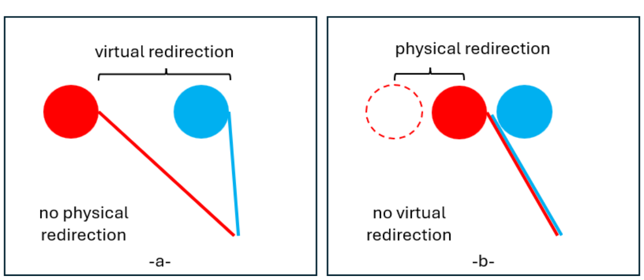

Figure 4: missing virtual or physical redirection

Specifically, what is the necessary and sufficient speed that an ETHD requires for potential applications without incurring high costs or severe safety concerns.

Another limitation is that our experiment only considers a single virtual object. Future work could test multiple virtual objects. The current ETHD design is not sufficient for supporting multiple virtual objects with which the user has to make contact in rapid succession. Future work should investigate the scene complexity limits that make haptic feedback possible with a given ETHD with known mechanical properties. Future work should also examine novel ETHD designs that can improve its overall versatility. Options include adding more contact points to a single ETHD, using multiple ETHDs together, or upgrading the ETHD hardware.

Providing haptics with versatility, safety, and realism will further advance the application of VR technology, including, for example, in the context of virtual laboratories that can be enhanced with haptic feedback.

Acknowledgments

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