Adaptive Reset Techniques for Haptic Retargeted Interaction

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Abstract—This article presents a set of adaptive reset techniques for use with haptic retargeting systems focusing on interaction with hybrid virtual reality interfaces that align with a physical interface. Haptic retargeting between changing physical and virtual targets requires a reset where the physical and virtual hand positions are re-aligned. We present a modified Point technique to guide the user in the direction of their next interaction such that the remaining distance to the target is minimized upon completion of the reset. This, along with techniques drawn from existing work are further modified to consider the angular and translational gain of each redirection and identify the optimal position for the reset to take place. When the angular and translational gain is within an acceptable range, the reset can be entirely omitted. This enables continuous retargeting between targets removing interruptions from a sequence of retargeted interactions. These techniques were evaluated in a user study which showed that adaptive reset techniques can provide a significant decrease in task completion time, travel distance, and the number of user errors.

Index Terms—Haptic retargeting, redirection, interaction, perception, user interfaces, virtual reality

1 Introduction

Haptic retargeting leverages hand redirection enabling virtual reality interactions to employ physical passive haptics with a non-fixed mapping between the virtual and physical spaces. When interacting with a virtual object the user's hand position is imperceptibly manipulated, leveraging the visual dominance over proprioception to redirect the user's real hand to passive haptic approximations of the virtual object. We present a set of adaptive reset techniques to improve haptic retargeted interaction with passive haptics in Virtual Reality (VR).

The *reset action* is a necessary step in hand redirection systems that remap passive haptics to multiple virtual objects as it re-aligns the physical and virtual hands between interactions. This additional procedure interrupts the interaction flow of the user, adding additional movement and time between interactions. An ideal haptic retargeting system would not require these resets at all. The adaptive reset techniques presented aim to reduce the impact of, and where possible, entirely remove the need for the reset action.

VR enables users to experience high-resolution immersive environments in a diverse set of applications. These systems deliver visual experiences that are compelling and allow users to be immersed in synthetic worlds. Providing haptics in VR is recognized as a fundamental challenge [1] for which haptic retargeting is providing a potential solution as research matures [2], [3], [4], [5], [6]. Haptic feedback includes both tactile feedback, provided through receptors in the skin such as vibration and texture, and kinesthetic feedback, provided by the muscles, joints, and tendons, such as weight, stretch, and voluntary or involuntary movement [7]. Without kinesthetic feedback, the user's physical hands can pass through virtual objects which affect the synthetic world illusion. Passive haptics are passive objects that approximate virtual objects, providing kinesthetic [8], [9], [10] and/or tactile feedback [11], improving realism and providing an additional channel to communicate information [9].

Through the application of haptic retargeting, realistic haptic interaction with virtual objects can be enabled by reusing passive haptic proxies [2], [3], [5], [12]. This enables the creation of re-configurable user interfaces [6], [13], providing accurate haptic feedback of pressing any virtual button on a dynamic interface using a small set of real physical buttons. The performance of interface manipulation tasks was shown to significantly improve when passive haptic feedback such as a handheld paddle [14] or the user's non-dominant hand [15] is introduced. Alternatively, the virtual hand may collide with the interface while allowing the physical hand to pass through. This provides a pseudo-haptic effect [16] but cannot provide the real haptic feedback of a physical user interface. The tactile click of a button and the kinesthetic feedback as the button reaches its limit provides information about the actuation point and prevents the hand from penetrating the virtual interface which has been shown to result in poor task performance [17].

Three reset techniques are explored, Point, Threshold, and Touch. The techniques are extended with an Adaptive variant and compared through a user evaluation to their original Static variant. The Threshold and Touch techniques

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Manuscript received 14 Oct. 2020; revised 13 Aug. 2021; accepted 30 Sept. 2021. Date of publication 15 Oct. 2021; date of current version 30 Dec. 2022.
This work was supported by an Australian Government Research Training Program Scholarship, Department of Education, Skills and Employment.
(Corresponding author: Brandon J. Matthews.)
Recommended for acceptance by A. Lécuyer.
Digital Object Identifier no. 10.1109/TVCG.2021.3120410

are drawn from recent haptic retargeting research. The Touch technique involves 'touching' a virtual object that is spatially co-located with a physical approximation based on the reset method used by Matthews *et al.* [6]. In the Threshold technique, the user moves their hand beyond a given threshold in space between themselves and the targets. This is drawn from previous work [3] and adapted for this research to support haptic retargeted interaction with user interfaces. Finally, we introduce the Point technique, a modification of a single point reset employed by Azmandian *et al.* [2]. The technique is modified by placing the location of the reset between the current and next targets, creating a path that the user can follow toward their next interaction.

The magnitude of the hand redirection is defined by the angular gain (around the position at which the reset occurred) and a translational gain (in the direction of movement) as shown in Fig. 4. The Adaptive variant of these reset techniques aims to optimize these parameters. When the gain is below a given limit the reset can be entirely omitted, enabling continuous redirection between passive haptics, such as components on a physical user interface. This could improve the usability, flexibility, and functionality of coupled physical and virtual buttons used in virtual reality.

1.1 Contributions

This paper presents three primary contributions that advance hand redirection and haptic retargeted interaction with user interfaces in Virtual Reality applications:

- An optimized Point reset technique using a point in space bisecting the interactions, creating a path along which the hand travels to complete the reset.
- Adaptive versions of three reset techniques that can optimize or remove reset tasks for haptic retargeting.
- A user study evaluation of the performance of the three reset techniques (Point, Threshold, Touch), and their Adaptive variants.

We present a summary of related work in which we draw on previous hand redirection research to support our system design. Building on this, we present our adaptive reset techniques and design parameters to support a generalized and targeted implementation for user interface interactions. We present an evaluation of the Adaptive and Static variants of each reset technique (Point, Threshold and Touch) to determine their relative performance in an interface operation task. Finishing with an analysis, results, highlighting the benefits and drawbacks of the techniques and future directions.

2 Related Work

This section provides an overview of related work in the areas of hand redirection, haptic retargeting, and prior examples of reset techniques for hand redirection systems.

2.1 Hand Redirection and Haptic Retargeting

Desktop scale hand redirection is a type of visuo-haptic illusion which leverages the dominance of visual perception over proprioception and haptic perception. When a conflict between the senses of vision and touch is introduced it has been reported that an observer will be more likely to perceive the visual shape rather than the tactile shape [18]. This also applies to discrepancies between vision and proprioception. Proprioception provides an understanding of limb position even when a human's eyes are closed. When visually altered, a person is likely to perceive their limb where they visually see it, overriding their proprioception [19]. A physical interface with redirection would be preferable to a virtual interface which the hand can pass through as users are less sensitive to the discrepancies in hand position than they are to visual interpenetration [20] and visuotactile mismatches in general [21].

In VR, this is achieved by warping the virtual space and applying a translation or rotation gain to a virtual hand that mimics the user's physical hand. Previous work has explored applications of these illusions for warping 3D surfaces [22], re-using passive haptics [2], [5], exploring a virtual environment using a haptic proxy [3], ergonomic optimization of virtual environments [23] and improving the performance of shape displays [4]. We leverage this premise to support interaction with user interfaces in VR.

Kohli *et al.* found that, when trained, users will adapt to hand redirection with throughput and task completion time no worse than without redirection [22]. The rate of task errors was also shown to be no worse with the illusion than without any illusion [24]. Path analysis in hand redirection systems has shown the user sometimes overshoots the target then later corrects [2]. It has also been shown that the illusion can remain undetectable with small angular and translational gains. Zenner and Krüqer found that horizontal or vertical angular gain can remain undetectable up to approximately 4.5° in either direction while a translational gain in the same direction as the hand is moving remains undetectable between 0.88 and 1.07 [25]. The avatar appearance has been shown to increase these detection thresholds for hand redirection by 31.3% [26]. A fixed offset between the physical and virtual hands can also remain undetectable between 7.8 cm and 13.4 cm depending on direction [27].

Kohli *et al.* calculated their spatial warp using a 3D Principal Warp method which does not require a reset to support mapping between planes with an angular offset [28]. Zhao *et al.* developed a method of functionally optimizing continuous hand redirection that does not require a reset step [29]. This method can map passive haptics to virtual objects with a different shape, also allowing continuous redirection between two virtual objects if each has a physical counterpart. This continuous warping does not apply to situations where a physical object is reused for multiple virtual objects. ErgO which aims to improve interaction ergonomics in VR also does not require a reset as the distortion is solely based on the hand's spatial position with no fixed physical target [23].

2.2 Hand Redirection Reset Techniques

In past hand redirection research for the reuse of passive haptics, a reset step is typically required to support the hand redirection between multiple physical targets, especially when virtual targets share the same physical targets. This reset step re-aligns the physical and virtual hand enabling redirection to a new target. In previous hand redirection systems, the reset has been in a fixed position and is required between every interaction.

To reset the user's hand in their Haptic Retargeting system, Azmandian *et al.* [2] utilize a virtual button that is co-located with a Griffin PowerMate knob close to the user. This button is then pressed by the user between each step of their construction task. The user must also read instructions positioned in such a way as to require them to rotate their head for their World Warp implementation to function. Similarly, Lohse *et al.* require the user to rotate their head, leveraging change blindness during this movement to remap a physical prop to multiple virtual props [30]. In both these cases, the rotation is analogous to a reset step and is required for the remapping to take place but neither requires any additional hand movement. Suhail *et al.* use a fade-to-black method in which the user's vision fades to black and the coordinate space is adjusted to align a virtual object with a physical prop when the user moves close to it [31]. This changes the direction the user is facing, thus requiring them to turn and face the object, but not introducing any additional hand movements.

For interactions with the Sparse Haptic Proxy, Cheng *et al.* use a threshold fixed in place just in front of the user that they must return their hand behind after each touch [3]. This requires the user to move their hand back to themselves before they can touch another part of the haptic proxy however it allows the reset to take place anywhere near the user. Han *et al.* use a circular boundary within which the redirection takes place surrounding the physical target [5]. The physical and virtual hands return to alignment as the hand exits the boundary. The radius of the boundary is based on the initial distance between the hand and target meaning the resulting redirection angle and translation could be beyond the tolerable limits.

Between each retargeted interaction, Matthews *et al.* required users to press a physical button positioned at the bottom of their remapped physical-virtual interface [6]. This doubles the number of button presses required to perform the task and breaks up the sequence of the user's interaction however the user does not need to move their hand far from the interface. Matthews and Smith reduce the need for a reset in hand redirection systems by preventing the user from selecting targets with head gaze while they are within a fixed distance of the targets [13], then applying On-The-Fly retargeting [3].

We propose that the reset can be optimized to minimize hand motion by considering the interactions that come before and after and calculating the position and direction of the reset based on these factors.

3 Adaptive Reset Techniques

We outline three reset techniques for haptic retargeted interaction with user interfaces, Point, Threshold, and Touch, each of which has a Static and Adaptive variant. These techniques support the mapping of physical targets (physical buttons in our application), to virtual targets (virtual buttons in our application). An *interaction sequence* consists of a *previous* target pair, a *current* target pair, and the reset that separates interactions with these targets. These target pairs consist of a virtual target it's the nearest physical target.

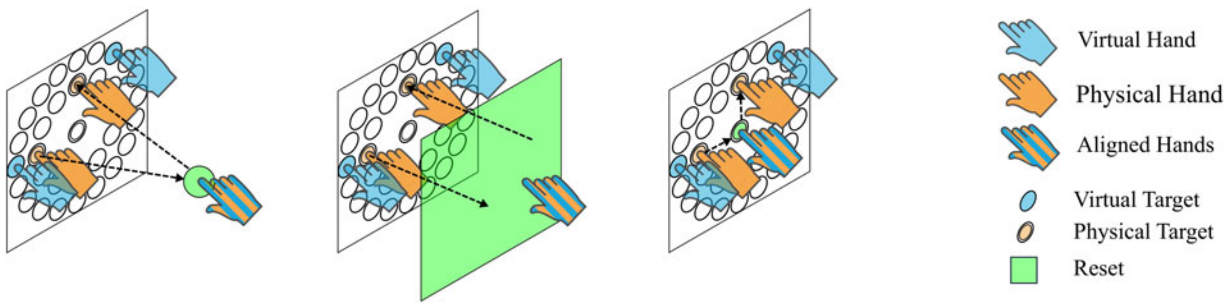
In their Static forms, the distance of the reset from the interface (Point and Threshold) or the target (Touch) is always the same for all unique interaction sequences. The Adaptive variants of each technique aim to keep the angular and translational gain (calculated in Section 4.2) at or below a defined limit, and where possible, omit the reset.

Preferably the angular and translational gain would be less than the detection limit of 4.5° and 0.88 to 1.07 respectively [25]. However, depending on the layout of the virtual and physical targets, this may be unachievable without requiring extreme movements. Angular gain up to 40° is tolerable by users but not undetectable [3]. The adaptive reset system can be configured with a previously determined threshold or another target threshold based on the application. The system aims constrain the redirection gain by dynamically introducing resets where necessary. In our evaluation we configured the system with the average angular and translational gain experienced when operating the interface.

When the same physical target is shared between both target pairs in an interaction sequence, a reset is necessary. This prevents the virtual finger from snapping to the new target and breaking the illusion as the physical finger is already in the target position. When each target pair in an interaction sequence is assigned a different physical target, a reset is only necessary if the angular and/or translational gains exceed the acceptable limit. As a result, there are some interaction sequences in which a reset is not required at all. When a reset is necessary, the position of the reset can be optimized to minimize the movement required to complete the reset while remaining within acceptable limits for translational and angular gain.

3.1 Point Reset

The Point reset technique is a novel technique inspired by Azmandian *et al.* [2] in which users move their hand to a location in space defined as a position and a radius. This position of this region is always a given distance along a vector extending from the midpoint between the previous target and the current target, toward the user (Fig. 1a). This



(a) Point Reset (b) Threshold Reset (c) Touch Reset

Fig. 1. Example of each reset (green), showing the path taken by the Physical (yellow) and Virtual (blue) hands to move from the previous target pair in the interaction sequence, through the reset task, to the current target pair in the sequence.

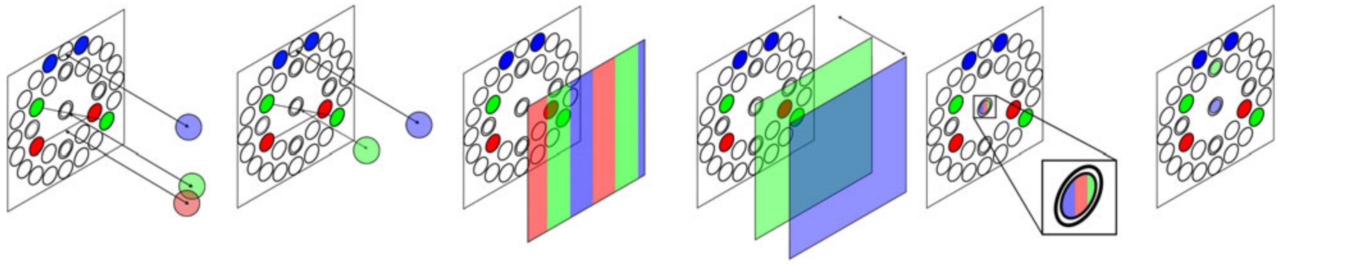


Fig. 2. Variations of each reset. Blue: from a virtual target to another virtual target with the same physical target. Green: from a virtual target to another which uses a different physical target with an angle or translation beyond the acceptable range. Red: from a virtual target to another which uses a different physical target but the angle and translation are within the acceptable range. Note that the red reset does not appear in the Adaptive variants as a reset is not necessary for this interaction sequence.

means the user has already begun moving in the direction of their next interaction. The reset region is a sphere of radius 2 cm within which the physical and virtual hands are aligned.

Static Variant. The distance along the reset direction vector at which the reset is positioned is the same for all interaction sequences. This distance is defined, in this system, as the largest optimal reset distance found when applying the algorithm described in Section 4.3 to all possible interaction sequences for the interface layout (Fig. 2a).

Adaptive Variant. The distance along the reset direction vector is based on the current interaction sequence the reset is part of. If the angular and/or translational gain for the interaction sequence is below the acceptable limit a reset is not required (Fig. 2b), otherwise the reset position is calculated as described in Section 4.3.

3.2 Threshold Reset

The Threshold reset technique is based on the reset methods used by Cheng *et al.* [3] and Han *et al.* [5]. In this technique, the warp origin is not a single position but a plane between the user and the interaction targets placed a given distance from the midpoint between the previous and current targets (Fig. 1b). The reset is completed when the fingertip is moved toward the user and passes beyond the plane. To compute the distance from the threshold we use a signed distance field (SDF) of an infinite plane. A plane was chosen over a spherical threshold in this application as the interface is flat and this guarantees the hand will be a minimum distance away upon completion of the reset. In some cases, such as touching individual objects a spherical threshold, such as that used by Han *et al.* [5] may be preferable. The distance calculated for this technique could then be used to determine a radius for a spherical threshold. For more complex target layouts, multiple SDFs (either planes or other shapes) can be combined to create a Threshold that conforms around the targets.

Static Variant. The distance between the plane and the targets is the same for all interaction sequences. This distance is defined, in this system, as the largest optimal reset distance found when applying the algorithm described in Section 4.3 to all possible interaction sequences for the interface layout (Fig. 2c).

Adaptive Variant. The distance between the plane and the targets is based on the current interaction sequence the reset is part of. If the angular and/or translational gain for the interaction sequence is below the acceptable limit a reset is not required (Fig. 2d), otherwise the reset position is calculated as described in Section 4.3.

3.3 Touch Reset

The Touch reset technique is based on the reset used by Matthews *et al.* [6]. In this technique, a reset is completed by interacting with a target pair in which the virtual target is spatially co-located with its physical counterpart (Fig. 1c). This technique utilizes the same targets as the user's other interactions, in other applications such as the cube task employed by Azmandian *et al.* this could be a second physical cube with a co-located virtual cube. It does not require the user to move their hand far away from the objects they are interacting with to complete the reset however it does introduce an additional interaction for the user to complete and requires at least one pair of co-located physical and virtual targets.

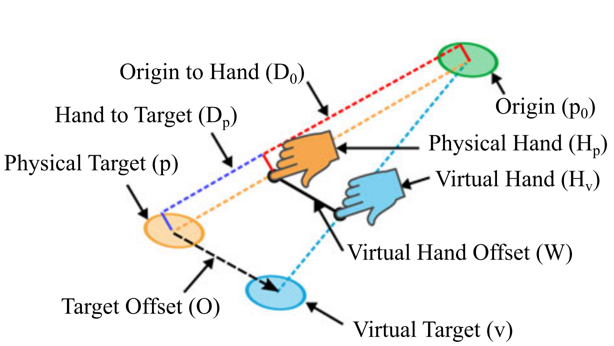
Static Variant. The target pair used to complete the Touch reset is always the same for all interaction sequences (Fig. 2e). In this application, the reset target is a physical button that shares the same spatial position on the interface as one of the virtual buttons. In other applications, such as reusing passive haptic props [2], [5] this could be a virtual representation, co-located with a physical prop.

Adaptive Variant. All target pairs in which the physical and virtual targets are in the same spatial position are considered as potential Touch resets. If the angular and/or translational gain for the interaction sequence is below the acceptable limit a reset is not required (Fig. 2f). Otherwise, the angular and translational gains are calculated for all co-located physical and virtual targets excluding the target used in the previous interaction. The physical-virtual target that provides the lowest angular and translational gain is selected as the reset.

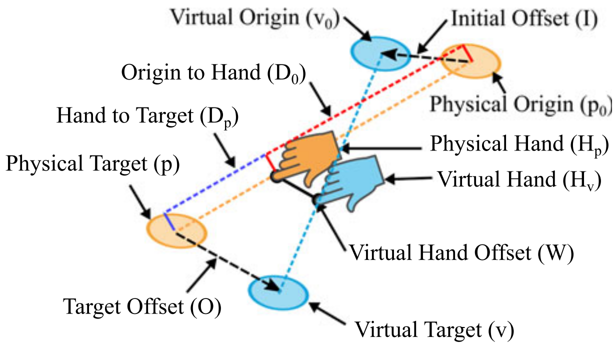
4 Implementation

To achieve haptic retargeting the virtual hand position is offset from the physical hand position.

The algorithm used to compute the virtual hand position is derived from the On-The-Fly retargeting [3] that enables



(a) Single Origin Retargeting



(b) On-The-Fly Retargeting

Fig. 3. The virtual hand offset is computed differently for On-The-Fly retargeting, introducing a physical and virtual origin, as compared to retargeting with a single origin position.

target switching part-way through a retargeted movement. This can be leveraged to enable the user to move directly from one physical-virtual target pair to another distinct physical-virtual target pair [13]. The adaptive reset algorithm then dynamically introduces a reset when the angular and translational gain exceed a predefined threshold. This section outlines the method used to compute the virtual hand offset and retargeting gain, as well as the algorithm used to compute the adaptive Reset position for the Point and Threshold techniques.

4.1 Computing Virtual Hand Offset

As shown in Fig. 3a, the virtual hand position H_v is offset relative to the physical hand position H_p to achieve the retargeting illusion. Let v represent the virtual target and p represent the physical target. The target offset O is the vector from p to v: $O = v - p$. The warp ratio r is the ratio of the distance (D_0) from the warp origin p_0 to the H_p, and (D_p) from H_p to p. The virtual hand offset (W) is then the target offset multiplied by the ratio

$$D_0 = |H_p - H_0|, D_p = |H_p - P_p| \tag{1}$$

$$W = rO, r = \left(\frac{D_0}{D_0 + D_p}\right). \tag{2}$$

On-The-Fly retargeting shown in Fig. 3b extends this by introducing an initial offset (I) from p_0 to a new virtual origin v_0: $I = v_0 - p_0$. Whenever the physical and virtual target changes p_0 is moved to H_p and v_0 is moved to H_v. W then becomes the linear interpolation from I to O by the warp ratio r

$$W = rO + (1 - r)I. \tag{3}$$

4.2 Computing Retargeting Gain

As shown in Fig. 4, the angular gain G_A is computed using the relative angle between the physical and virtual path vectors: $U_p = p - p_0$ and $U_v = v - v_0$. The translational gain G_T is then the ratio between the lengths of U_v and U_p

$$G_A = arccos\left(\frac{U_v \cdot U_p}{||U_v|| \, ||U_p||}\right)\left(\frac{180}{\pi}\right), G_T = \frac{||U_p||}{||U_v||}. \tag{4}$$

Where p and p_0 are the same as in the case shown in Fig. 5b, the angular and translational gains cannot be defined as the magnitude of U_p becomes zero. Thus a reset is always required to prevent the virtual hand from jumping to the new virtual target which would break the retargeting illusion.

4.3 Adaptive Reset System

The angular and translational gain of a redirection can be reduced by introducing a reset between the initial positions (p_0, v_0) and target positions (p, v). Algorithm 1 outlines the procedure to compute the adaptive reset position. The angle reset distance d_A and translation reset distance d_T are computed independently for the respective angular threshold A and translational threshold T provided to the system. If v_m is the midpoint between the virtual targets and R is a vector from v_m toward the user normalized by its length. d_A and d_T are computed as outlined in Algorithm 2, a binary search is performed along R that searches for a point at which the angular or translational gain $X_{[A,T]}$ are approximately equal to the provided threshold. We employ a tolerance of 0.1 degrees of angular gain and 0.01 translational gain to ensure the binary search converges on a solution.

The final distance d along R of the virtual reset position (v_R) is the larger of d_A and d_T. The visual representation of the Point reset is placed at v_R, and the Threshold reset is placed d away from the interface in the application presented in this paper. In the Point reset technique, the physical reset position (p_R) is placed along R, but extending from p_m. This allows some discrepancy to remain between the hands,

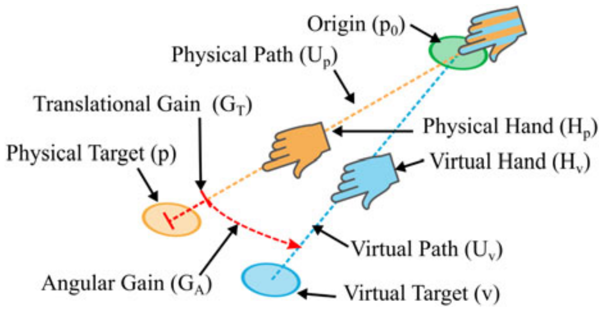
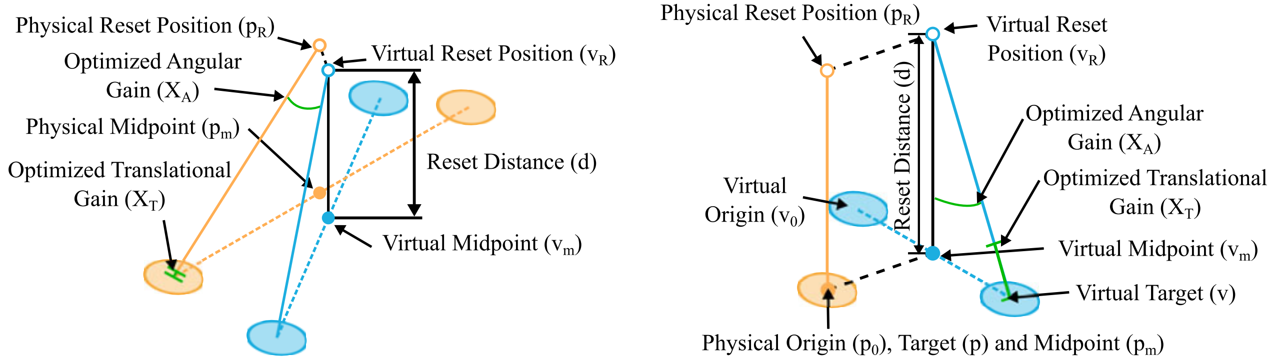


Fig. 4. Angular and translational gain describe the discrepancy between the physical hand and the virtual hand positions around the origin. They are calculated as the angle and ratio of magnitudes between the physical and virtual paths.



(a) Different Physical Target (b) Shared Physical Target

Fig. 5. The angular and translational gain can be modified by adjusting the distance of the reset from the midpoint between the targets.

enabling the virtual and physical hands to follow a more direct route through the reset to their respective targets.

Algorithm 1. Adaptive Reset Algorithm, Determines the Position of the Point Reset, and Distance of the Threshold Reset

Input

p_0, v_0 virtual and physical origins
p, v virtual and physical targets
A angle gain threshold
T translation gain threshold
R normalized direction of the reset
t tolerance value

Output

distance and position of the physical and virtual reset

```
procedure CALCRESETPOS
    get physical and virtual path midpoints
    p_m ← MIDPOINT(p_0, p)
    v_m ← MIDPOINT(v_0, v)
    search for target reset distance if required
    if ANGLEGAIN(U_p, U_v) > A then
        d_A ← BINARYSEARCHANGLE
    if TRANSLATIONGAIN(U_p, U_v) > T then
        d_T ← BINARYSEARCHTRANSLATION
    get reset distance and positions
    d ← max(|d_A|, |d_T|)
    p_R ← p_m + (R · d)
    v_R ← v_m + (R · d)
    return d, p_R, v_R
```

5 Evaluation

A user study was conducted to evaluate the three reset techniques and the Static and Adaptive variants using a two (Static, Adaptive) by three (Touch, Point, Threshold) within-participants design. We recruited 30 participants who all completed the study (7 female, 23 male) with a randomized condition order for each participant. Participants completed a demographics questionnaire, all participants were between the ages of 18 and 45 (mean = 25.3, sd = 4.92) and had normal or corrected to normal vision. Participants reported their approximate experience with virtual or augmented reality systems never used: 5, once or more per: day: 4, week: 7, month: 4, year: 10 and selected their dominant hand 3 left, 27 right. During the study, participants wore an HTC Vive Pro Head Mounted Display with a Leap Motion affixed to the front. The software was developed in Unity version 2019.1.8f1 using the Leap Motion Orion 4.0.0 SDK designed for head-mounted hand tracking, running on a desktop PC with an Intel i5-6500 CPU and an NVIDIA GTX 1070 Ti GPU. The participant's avatar was a realistically modelled hand and forearm with a generic blue color.

Algorithm 2. Binary Search Operation to Find Reset Position

Input

p, v physical and virtual targets
p_m, v_m midpoint of physical and virtual paths
R normalized direction of the reset
M target angle/translation threshold
$maxD$ maximum search distance

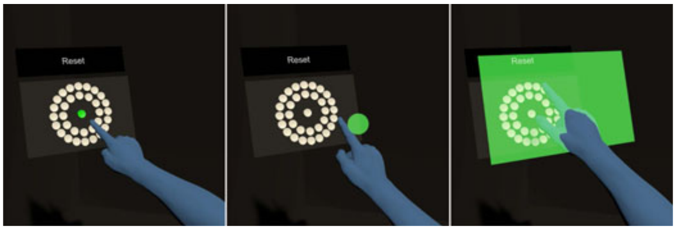
Output

distance along R that the angular or translational gain are approximately M

```
procedure BINARYSEARCH[ANGLE/TRANSLATION]
    low = 0
    high = maxD
    while low < high do
        mid ← (low + high)/2
        offset search positions p_s and v_s by 'mid' distance along R
        from the respective midpoints
        p_s ← p_m + (R * mid)
        v_s ← v_m + (R * mid)
        get adjusted physical and virtual paths using search
        positions
        S_p ← p − p_s
        S_v ← v − v_s
        X ← [ANGLE/TRANSLATION]GAIN(S_p, S_v)
        if X ≈ M then
    gain is within the allowed tolerance of the target threshold
            return mid
        else
    update binary search parameters
            if X < U then
                low ← mid
            else
                high ← mid
```

5.1 Design

We decompose task performance into three quantitative measures; the task completion time, the accumulated travel of the fingertip and the proportion of tasks in which the



(a) Touch (b) Point (c) Threshold

Fig. 6. The virtual study environment with the three different reset visualizations, the participant's avatar and the layout of virtual buttons used for the study.

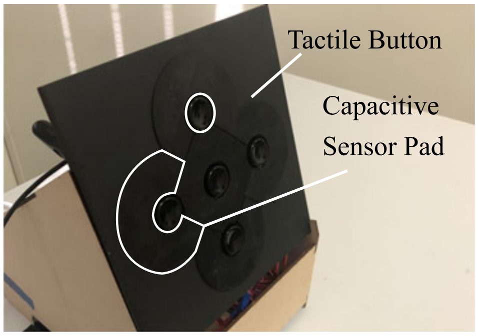


Fig. 7. The physical interface with 5 tactile buttons and 5 capacitive touch sensing pads surrounding them.

participant overshoots and misses the button. Task completion time and accumulated travel of the fingertip are measured from the previous task completion to the current task completion, including the reset. System Usability was collected using the System Usability Scale [32], and the perceived discrepancy in hand position and movement through a post-condition questionnaire.

The physical interface shown in Fig. 7 was mounted a desk and consisted of 5 physical arcade machine-style tactile buttons with a diameter of 22 mm. This diameter is above the average accuracy of the Leap Motion controller of 17.3 mm [33] allowing for some error in the hand tracking. Fig. 6 shows the layout of the physical and virtual buttons used for the evaluation with an inner ring of 12 buttons with a 5 cm radius and an outer ring of 20 buttons with a 7.5 cm radius. The center, top, left, bottom, and right buttons on the inner ring align with the physical buttons on the physical interface.

The transient closure of every button on the virtual interface shown in Fig. 6 used for the study results in 496 unique paths from any one virtual button to any other virtual button. For each of these paths we apply the redirection gain calculation to determine the angular and translational gain resulting in a movement directly from the starting virtual (and corresponding physical) button to next virtual (and corresponding physical) button. From the resulting angular and translational gains of all pairs in the transient closure, the average angular gain: $12.5°$ and the average translational gain: 1 ± 0.28 are used as the target for the adaptive reset algorithm. These values are above the detectable thresholds identified in in previous literature [25] but below the tolerable thresholds [3].

Of the unique paths in the transient closure, 112 (22.5%) paths required a reset as the virtual targets shared a common a physical target. 92 (18.5%) paths exclusively exceeded the angular gain threshold, 102 (20.5%) paths exclusively exceeded the translational gain threshold, and 104 (20.9%) pairs exceeded both the angular and translational gain thresholds. 86 paths (17.3%) did not require a reset, enabling the participant to move directly to their next target.

The binary search element of the adaptive reset algorithm was configured with an upper limit of 500 mm and lower limit of 40 mm to prevent the reset appearing behind the user or extremely close to the interface. For both the Static Point and Static Threshold resets, the distance at which the reset is placed were identified by calculating all adaptive reset positions for the transient closure. This produced a maximum distance from the interface of 198 mm. To ensure all the Static resets were below the specified angular and translational gain limits 198 mm was the distance at which the Static Point and Static Threshold resets were placed. The Static Touch condition used the center physical button for all reset actions, while the Adaptive Touch condition could use any of the 5 co-located physical and virtual buttons when a reset action is necessary.

5.2 Procedure

Participants were seated in front of a desk with the physical interface shown in Fig. 7. The system was calibrated by the participant by aligning the center button with their index fingertip before each condition. This ensured the system understood the position of the interface with respect to the Leap Motion and HTC Vive tracking spaces and the participant's hand. Prior to beginning any conditions the reset techniques and task procedure were described to the user. Each condition in the study also included a short practice sequence consisting of 10 tasks to ensure they were familiar with how the reset operated. This was followed by three trials consisting of 32 tasks each. Each task consisted of a single reset followed by a button press unless a reset was not required. Tasks were generated in a pseudo-random order until all buttons were pressed. As shown in Fig. 6, the button to press (and reset button) are highlighted green. The Point and Threshold resets are represented using a green sphere, or green filled rectangle respectively. Participants were required to press buttons using the index finger of their dominant hand and the reset was considered complete when the index fingertip passes into the Sphere or beyond the Plane in the Point and Threshold resets, or when the reset button was pressed in the Touch condition.

Between each condition and each sequence within the conditions, participants were allowed to rest. After each condition participants completed a System Usability Scale questionnaire with two additional questions regarding the perceived difference in hand position and movement. These questions were answered on a 5-point Likert scale from "Not at all" to "Perfectly"

- Did the position of your hand in the virtual environment match the position of your real hand?
- Did the movement of your hand in the virtual environment match the movement of your real hand?

To understand how often participants missed the button and required correction, the physical buttons were surrounded by five capacitive touch sensors. These sensors were 3D printed black conductive filament pads (outlined in Fig. 7) to ensure they would not interfere with the Infrared tracking of the Leap Motion. In preliminary testing, it was found that pressing the edge of a button could result in contact with the capacitive sensors. To filter out these edge presses, we only considered touch to be a miss if the participant touches the interface and does not press the target button within 300ms. The interface reported its state 50 times per second over serial communication with the desktop computer and the hand position data was also logged at the same rate.

5.3 Hypotheses

We define a set of hypotheses based on pilot testing of the reset techniques related to the overall task performance, the usability of the system, and perceived position and movement discrepancy of the participant's hands.

5.3.1 Task Completion Time

It is hypothesized that the Threshold technique will provide significantly reduced task completion times between button presses as compared to the Point and Touch techniques (*H1*). Users can retract their hands until the reset is complete without considering the specific location of the reset. Additionally, due to the reduced direct distance between the task and the resets and the removal of unnecessary resets, it is hypothesized that the Adaptive variant will also provide reduced task completion times as compared to the Static variant (*H2*).

5.3.2 Misses

It is hypothesized that due to the larger redirection angles and translation in both the Static Touch and Adaptive Touch resets for the interface used in the evaluation, the presses in which the participants miss or over-shoot the button will be significantly higher for the Touch reset technique as compared to the Point and Threshold techniques (*H3*).

5.3.3 Accumulated Travel

Due to the nature of both the Point and Threshold reset techniques, it is hypothesized that the accumulated travel of the hand will be significantly higher for these techniques as compared to the Touch techniques (*H4*). Additionally, the Adaptive versions are hypothesized to significantly reduce the accumulated travel for the Point and Threshold resets as compared to the Static counterparts while increasing it for the Touch technique in which the Adaptive selection process typically selects a reset target that is further from the subsequent target (*H5*).

5.3.4 Perceived Hand Discrepancy

As mentioned in H3, the Touch reset technique generally results in larger redirection angles and translation. As a result, it is hypothesized that the perceived difference between the physical and virtual hand position and movement will be significantly higher for the Touch reset technique as compared to the Point and Threshold techniques (*H6*).

In this evaluation, the acceptable limit for angular and translational gain are above the previously determined detection thresholds [25] yet below the tolerable thresholds [3]. Additionally, tasks in the Adaptive conditions had an angular and translational gain greater than or equal to their Static equivalents that were placed at the maximum distance found in Section 5.1 of 198 mm. Thus it is hypothesized that the discrepancies will be more perceivable for the Adaptive variant as compared to the Static variant (*H7*).

5.3.5 System Usability

The Touch reset does not require large hand movements to complete and integrates the reset into the normal sequence. It is hypothesized that, while it results in larger angular gains and translation, the Touch reset will be more usable than the other reset techniques (*H8*).

6 Results

To examine task completion time, misses, and travel distance between reset variants (Static, Adaptive) and reset techniques (Point, Threshold, Touch), linear mixed-effects models were conducted using the lme4 package in R. The models were specified with fixed effects of reset technique and reset variant including an interaction effect between them, with a random effect of the participant on the intercept. Significance values were extracted using Type II Wald chi-square tests, and where appropriate, pairwise post-hoc comparisons were conducted using Tukey's HSD for multiple comparisons. The first task in each trial was removed as they are not preceded by a reset, giving $N = 30 \times 3 \times 6 = 540$ trials and $N = 540 \times 31 = 16740$ individual task completions.

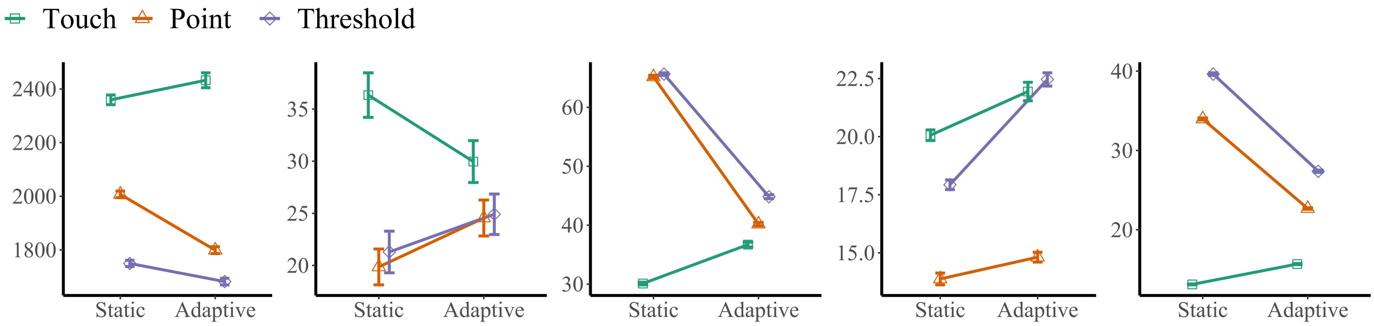
6.1 Task Completion Times

Task completion time is measured from the completion of one task to the completion of the next task (Fig. 8a). The model showed significant fixed effects of the reset technique (Point, Threshold, Touch) $\chi^2(2, N = 16740) = 2003.977, p < 0.001$ and reset variant (Static, Adaptive) $\chi^2(1, N = 16740) = 27.779, p < 0.001$ in addition to a significant interaction effect between reset technique × reset variant $\chi^2(2, N = 16740) = 80.079, p < 0.001$.

Pairwise comparisons showed task completion time in both Adaptive Point and Adaptive Threshold were significantly shorter than their Static counterparts (Adaptive Threshold - Static Threshold: $p = 0.0283$, Adaptive Point - Static Point: $p < 0.001$). Adaptive Threshold completion times were significantly shorter than all other resets ($p < 0.001$). The Adaptive Touch condition was significantly longer than its Static counterpart ($p = 0.0131$).

6.2 Misses

To examine the miss results between reset variant and techniques, the miss data was converted from binary True/False data to the percentage of presses for each sequence that resulted in the user overshooting and missing the target (Fig. 8b). The model showed a significant fixed effect of the reset technique (Point, Threshold, Touch) $\chi^2(2, N = 540) = 94.5389, p < 0.001$ and a significant interaction effect of reset technique × reset variant $\chi^2(2, N = 540) = 23.8519, p < 0.001$. The model did not show a significant fixed effect of reset variant (Static, Adaptive) $\chi^2(1, N = 540) = 0.3992$, $p = 0.5275$.



(a) Task Completion Time (ms) (b) Miss Percent (%) (c) Accumulated Travel (cm) (d) Excess Travel (cm) (e) Movement Speed (cm/s)

Fig. 8. Mean task completion time, percentage of tasks in which misses occurred, accumulated travel, speed and excess travel. Error bars indicate ± standard error.

Pairwise comparisons showed the percentage of tasks in which participants missed was significantly higher for Static Touch than all other conditions (Static Touch - Adaptive Touch, p = 0.0049, other pairs: p < 0.001). Adaptive Touch resulted in significantly more misses than Adaptive Point (p = 0.0293), Static Point (p < 0.001), and Static Threshold (p < 0.001). Other comparisons did not show any significant differences.

6.3 Accumulated Travel

The accumulated travel is the sum of the distances traveled by the fingertip (Fig. 8c). The linear mixed-effects model showed significant fixed effects of the reset technique (Point, Threshold, Touch) $\chi^2(2, N = 16740) = 7210.8, p < 0.001$ and reset variant (Adaptive, Static) $\chi^2(1, N = 16740) = 3239.6, p < 0.001$ in addition to a significant interaction effect between reset technique × reset variant $\chi^2(2, N = 16740) = 3724.7, p < 0.001$.

Pairwise comparisons showed the Static Touch condition had significantly lower accumulated distance than all other conditions (p < 0.001). Adaptive Point and Adaptive Threshold each had significantly lower accumulated travel than their Static counterparts (p < 0.001) and Adaptive Point was significantly lower than Adaptive Threshold. A statistically significant difference was not found between Static Point and Static Threshold (p = 0.8519).

Additional post-hoc analysis was performed to understand the difference between the optimal travel distance and the actual travel distance herein referred to as excess travel (Fig. 8d). A mixed-effect model was conducted as specified above that showed significant fixed effects of the reset technique (Point, Threshold, Touch) $\chi^2(2, N = 16740) = 781.9, p < 0.001$ and reset variant (Adaptive, Static) $\chi^2(1, N = 16740) = 133.3, p < 0.001$ in addition to a significant interaction effect between reset technique × reset variant $\chi^2(2, N = 16740) = 51.4, p < 0.001$.

Pairwise comparisons of the individual conditions showed the Static Point and Adaptive Point conditions resulted in significantly less excess travel than all other conditions (p < 0.001) excluding between each other (p = 0.1100). Excess travel for Adaptive Threshold and Adaptive Touch was significantly higher than all other conditions (p < 0.001) excluding between each other (p = 0.7183). Excess travel for Static Threshold was significantly lower than Static Touch (p < 0.001).

6.4 Movement Speed

Further post-hoc analysis was performed to understand the relationship between travel distance and task completion time in a joint metric 'movement speed' (Fig. 8e). A mixed-effect model was conducted as specified above that showed significant fixed effects of the reset technique (Point, Threshold, Touch) $\chi^2(2, N = 16740) = 38735.7, p < 0.001$ and reset variant (Adaptive, Static) $\chi^2(1, N = 16740) = 7276.3, p < 0.001$ in addition to a significant interaction effect between reset technique × reset variant $\chi^2(2, N = 16740) = 6816.8, p < 0.001$.

Pairwise comparisons showed significant differences between all pairs p < 0.001. Both Touch conditions resulted in significantly slower movement speed than the Threshold and Point conditions (p < 0.001) and Adaptive Touch resulted in faster movement speed than Static Touch (p < 0.001). Participants moved significantly faster in the Static Threshold, and Static Point conditions than their Adaptive counterparts (p < 0.001).

6.5 Qualitative Measures

The qualitative metrics, perceived accuracy of the hand position and movement and system usability were examined using Friedman's Anova on the reset variants (Static, Adaptive) and reset techniques (Point, Threshold, Touch) separately. Where appropriate, pairwise comparisons were conducted using the Nemenyi multiple comparison test. Nemenyi comparisons were also performed between all six conditions to look for potential interaction between reset techniques and reset variants as Friedman's Anova is unsuitable and analysis of the quantitative metrics identified interaction effects.

The perceived hand movement accuracy (Fig. 9) was significantly different between the three reset techniques, $\chi^2(1) = 15.136, p < 0.001$. Post-hoc Nemenyi pairwise comparisons showed hand movement was perceived to be significantly less accurate for the Touch technique than the Point technique (p = 0.0068) and Threshold technique (p = 0.0446) with no significant difference between Point and Threshold (p = 0.038). The perceived accuracy in hand movement did not significantly differ between the two reset variants, $\chi^2(1) = 0.4737, p = 0.4913$. No statistically significant differences were found between individual conditions.

The perceived accuracy of hand position (Fig. 9) was significantly different between the three reset techniques, $\chi^2(2) =$

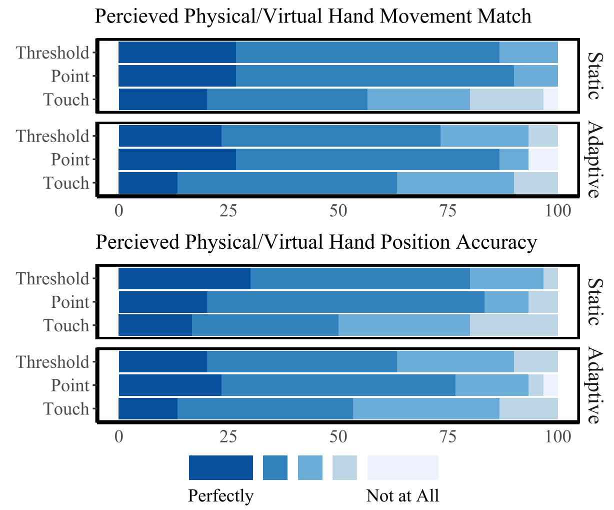


Fig. 9. Perceived accuracy between the movement and position of the physical and virtual hands.

$11.873, p = 0.0026$. Post-hoc Nemenyi pairwise comparisons showed hand position was perceived to be significantly less accurate for the Touch technique than the Threshold (p = 0.038) and Point techniques (p = 0.045) with no significant difference between Point and Threshold (p = 0.7949). The perceived accuracy in hand position did not significantly differ between the two reset variants, $\chi^2(1) = 1.3158, p = 0.2513$. No statistically significant differences were found between individual conditions.

The System Usability Scale scores were calculated as per the scoring process defined by Brooke *et al*. [34] (Fig. 10). The scores were found to be significantly different between the three reset techniques, $\chi^2(2) = 7.386, p = 0.0249$. Post-hoc Nemenyi pairwise comparisons indicate a significant improvement in System Usability Scale scores of the Threshold technique over the Touch technique (p = 0.022) with no other significant differences found (Touch - Point: p = 0.330, Threshold - Point: p = 0.437). The System Usability Scale score was not shown to significantly differ between the two reset variants, $\chi^2(1) = 0.36, p = 0.5485$. No statistically significant differences were found between individual conditions.

7 Discussion

In the evaluation, both the Static and Adaptive Threshold resets produced shorter task completion times than all other resets supporting H1. Both Adaptive Point and Adaptive Threshold were significantly faster than their Static counterparts supporting H2 while Adaptive Touch was slower than its Static Counterpart which does not support H2. The Adaptive Threshold reset provided the lowest completion time overall. H3 was supported as both Static and Adaptive touch resulted in a percentage of tasks in which the participant overshot and missed the physical target. The Point and Threshold techniques produced the least misses with a similar increase in misses for their Adaptive variants as compared to their Static variants.

The goal of the adaptive reset system is to minimize the impact of resets by placing them closer to the interface or along the path to the next target. As such the reduced travel

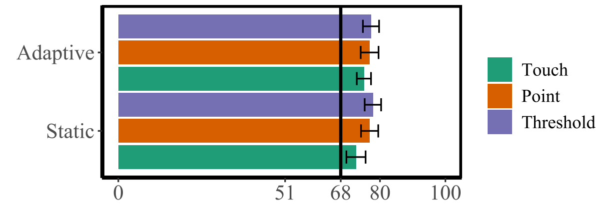


Fig. 10. Mean system usability scale results, the vertical line indicates the "Okay" level with all conditions sitting between 68 and 80 in the "Good" region. Error bars indicate ± standard deviation.

distance between Adaptive Point and Adaptive Threshold are expected as compared to their Static counterparts supporting H5. H4 was also supported with both variants of Point and Threshold producing increased travel distance compared to touch. The Static Touch reset showed the least accumulated travel overall. The post-hoc analysis of excess travel indicates that while the Adaptive Point and Threshold techniques result in significantly less overall movement than their Static counterparts, participants moved further than required in all conditions. In general, the Point technique showed the least excess travel likely due to the placement of the reset along a path between the targets.

Post-hoc analysis showed the hand movement speed was slowest for Touch techniques with the Threshold technique being significantly faster than other techniques. The Threshold technique has the largest region within which the reset is completed, thus it is believed participants tended to move their hand back quickly well beyond the threshold, predicting the reset will be complete if their hand is far enough from the interface. This correlates with the results for excess travel. Furthermore, the Static variants of both Threshold and Point showed increased movement speed than their Adaptive counterparts which could be due to their predictability.

H6 was supported as the Touch technique was perceived to result in less hand accuracy than Threshold and Point in terms of position and movement. H7 was not supported with no significant differences found between Static and Adaptive variants of each technique. Overall the System Usability Results suggested the system was usable, however, H8 is not supported as the Touch technique was the least usable of these resets, but only significantly less usable than Threshold.

The performance difference of the two Touch technique variants is the inverse of the variants for Point and Threshold. Where the Adaptive Point and Adaptive Threshold improve performance over their Static counterparts, the opposite is true for Touch. A possible cause of this discrepancy is the different movement required for the Touch technique (across the interface) as compared to the other techniques (away from the interface). Additionally, the requirement to press the reset button which would add to the task completion time.

Participants moved further than they needed to in all Adaptive variants as compared to their Static counterparts. They also moved slower for both Adaptive Point and Adaptive Threshold as compared to their Static counterparts. This could be attributed to the changing, unpredictable nature of the Adaptive variants. This unpredictability could present a challenge for a user's ability to learn a user interface as they may not know when a reset is going to occur.

Likewise, as the path between interactions is changed by each reset it could also be difficult to learn muscle memory.

Based on the findings from the evaluation the most optimal reset is likely dependent on the target application. The adaptive reset techniques can be applied in any haptic retargeting system, we focus on haptic retargeted user interface interactions which can extend physical interfaces with additional functionality and controls. Such a system could enable the creation of virtual reality simulators, context-aware control panels, and the design, and prototyping of physical interface layouts. For experiences in which task completion time and movement are important metrics, the Adaptive Threshold or Point are more suitable with the Threshold technique performing better than or equivalent to, the other techniques in most performance metrics. In experiences or tasks that involve learning such as interaction with an interface, the more consistent Static variants may be preferable.

7.1 Limitations and Future Work

Hand redirection for user interface interaction has the potential to enable the reconfiguration of physical controllers, such as an HTC Vive controller or flight simulator controls. This will enable a diverse set of configurations that change the layout of buttons on the controller and provide rich configurable 3D user interfaces for different applications. Further work is needed to integrate haptic retargeting with existing hardware and understand the potential for haptic retargeted interaction in real-world applications

In the evaluation, the acceptable angular, and translational gain are defined by the average gain of all target pairs instead of the previously determined detection thresholds [25]. Different layouts may provide a different distribution of reset positions and further work is needed to explore the effect of layout on the performance and usability of the presented adaptive reset techniques. With the layout tested, the Touch reset technique is unable to sufficiently reduce the magnitude of the angular and translational gain and this may have contributed to the increased chance of missing. Co-located physical and virtual targets placed further apart would allow for sufficient reduction in gain, which may improve the performance of this technique. The overall rate of misses could be attributed in part to the Leap Motion tracking accuracy [33]. Additionally, the Leap Motion has been shown to have a temporal delay of 40 ± 44 ms that could impact both rate of misses and perception of hand position and movement accuracy [34].

Some participants commented during the study that the retargeting was more noticeable when moving from two nearby targets that utilized different physical targets. This suggests further optimization is required to improve selection of the optimal physical-virtual target mappings such as the technique outlined by Matthews and Smith [13].

In the evaluation, participants did not select their own interaction targets and the adaptive reset system requires an understanding of which target a user will interact with next. Methods such as head [13] or eye gaze with target prediction [3] enable target selection for haptic retargeting, thus more work is required to explore the impact of target selection methods on both Static and Adaptive variants as they may have an impact on the results found in the evaluation. For example, in the Threshold technique, this issue could be overcome in future work using the method defined by Matthews and Smith [13]. As the user moves their hand away from the interface, targets would then become available for selection only when the hand has exceeded the threshold for that target as determined using the adaptive reset system. This presents other issues that require further investigation such as communicating what the user must to do make locked targets accessible and how usability is affected.

Further work is also required to understand the best indicator that a reset is required and visualization of the reset. Different cues could affect the cognitive load required to perform the tasks. Likewise, the signed distance warp origin used for the Threshold and Point techniques results in a change in hand direction as the retargeting starts, this could affect the detection of the retargeting illusion as the hand begins to change direction after passing the threshold.

Current haptic retargeting algorithms such as On-The-Fly retargeting [3] and Body Warping [2] rely on a single point definition for the hand (such as the fingertip or palm depending on the task) and the target (such as the position of a cube or button). For larger targets, the fingertip cannot reach the center of the target, or (in the case of other fingers) the fingertip used for computing the warp ratio is not touching the target. As a result, the retargeting is not operating optimally based on the shortest distance between the user's finger and the target's geometry. This creates a noticeable inaccuracy between the contact point on the physical and virtual targets. Further work is required to incorporate a geometric understanding of objects to improve current retargeting algorithms.

8 Conclusion

This paper presents a set of adaptive reset techniques which aim to optimize haptic retargeted interaction for user interfaces in Virtual Reality. We also present a modified Point reset technique in which the reset is a sphere placed between the current and previous virtual targets at a given distance from the interface creating a path to the user's next interaction. These resets use a novel algorithm for calculating the optimal position for the reset aspect of each interaction.

The resets were evaluated through a user study to evaluate which reset provides better task performance, system usability, and perceived discrepancy. It was found that when considering all metrics, the Threshold technique performed better than the other reset techniques, with the Adaptive variant performing better in terms of task completion time and accumulated distance and the Static counterpart producing fewer misses. The adaptive reset techniques presented can be applied to improve task completion time and accuracy of haptic retargeted interaction with user interfaces in VR, while reducing the amount of movement required to reset between tasks. Additionally, the adaptive reset system can reduce the number of resets required by identifying cases in which a reset is not necessary and eliminating it.

The use of hand redirection in Virtual Reality to support haptics for User Interfaces has a great potential to expand the function of existing devices such as handheld controllers, command and control consoles, and all configurations that use physical counterparts to enhance virtual reality realism with haptic sensations.

ACKNOWLEDGEMENTS

The authors would like to thank the participants for their time and feedback.

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