Desktop VR using a Mirror Metaphor for Natural User Interface

Santawat Thanyadit
Hong Kong University of Science & Technology
Hong Kong
sthanyadit@connect.ust.hk

Ting-Chuen Pong
Hong Kong University of Science & Technology
Hong Kong
tcpong@ust.hk

ABSTRACT
The main objective of this research work is to create a desktop VR environment which enables users to interact naturally with virtual objects positioned both in front and behind the screen. We propose a mirror metaphor that simulates a physical stereoscopic screen with the properties of a mirror. In addition to allowing users to interact with virtual objects positioned in front of the stereoscopic screen using their virtual hands, the virtual hands can be transferred inside the virtual mirror to interact with objects behind the screen. When the virtual hands are operating inside the virtual mirror, they are transformed like the reflection in a real mirror. This effectively doubles the interactable space and creates an interactive space that could facilitate collaborative tasks. Our user study shows that users could interact through the mirror approach as effectively as similar interaction techniques, hence demonstrating that the mirror technique is a viable interface in certain VR setups.

ACM Classification Keywords
H.5.2. User Interfaces: Interaction styles (e.g., commands, menus, forms, direct manipulation)

Author Keywords
Natural User Interfaces; Direct Interaction; Leap sensor; Stereoscopic Display; Desktop VR

INTRODUCTION
Desktop VR (aka Fish Tank VR [14]) is a kind of human-computer interface system that combines a stereoscopic display with head tracking. The system generates a 3D interactive environment based on the user's head position, creating the illusion that the user is peering into a fish tank. Desktop VR can be well integrated into office environments, is relatively low cost, and easy to deploy. However, it has a lower level of immersion when compared to other types of virtual reality setups. It also has a smaller interactive space which is often limited to the front of the physical screen. Thus, a realistic interactive experience in existing desktop VR systems is hard to achieve. For instance, if we want to create a system that positions virtual hands to co-locate with a user's physical hands, the virtual hands could only be positioned in front of the screen. Meaning they could only interact with objects that protrude out of the screen, since the user's hands could not physically reach through the stereoscopic screen.

In this paper, we approach the desktop VR from a different perspective. We assume that the stereoscopic display possesses the property of a mirror which divides the virtual world into a "normal virtual world" and a "mirror virtual world". The main difference between the mirror virtual world and an actual physical mirror is that only the mirror image of the physical hands is created through reflection but not the virtual objects. Instances of virtual objects can be created and displayed in either the normal virtual world or the mirror virtual world. In the normal virtual world, virtual hands are aligned with the user's physical hands and the user can interact with virtual objects in the normal way. In the mirror world, the virtual hands can be translated and oriented as if the virtual hands are the reflection of the physical hands in a real mirror. The user could perform a "hand transfer" to move the virtual hands in and out of the mirror world. The system tracks the two hands individually, hence it is possible to have one hand in the mirror world and the other hand outside of it, which would allow the two hands to perform different tasks at the same time. In our user study, we are able to demonstrate the benefits of the mirror metaphor when compared to similar techniques.

We have organized the paper as follows. First, a summary of related work is provided. Next, the apparatus and implementation are described in detail. A formal user study was conducted to examine the advantages and disadvantages of mirror techniques. Finally, concluding remarks and future research possibilities are discussed.

RELATED WORK

Mirror
Humans started to use mirrors thousands of years ago. Mirrors are used daily, from everyday tasks such as combing our hair, doing makeup, monitoring traffic while driving, to highly skilled tasks such as the use of dental mirrors for checking teeth inside a patient's mouth. For most of these tasks, the mirror is used to provide information that is obscured from the user's point of view. In virtual reality and augmented reality, the virtual mirror can be used to simulate certain situations in the real world. For example, clothing

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stores use commercialized augmented reality systems to encourage users to choose their products. Users could virtually try on clothes and see a product on their body through a virtual reflection. Blum et al. [3] use a similar concept as in clothing stores for anatomic education. Bichlmeier et al. [2] use the virtual mirror in the form of a handheld tool similar to a dentist's mirror in mixed reality surgery simulation. This grants surgeons visual access to crucial information without having to move around the operating table or changing the patient's position. The main drawback with the mirror approach is that left/right confusion may occur which requires time for adjustment. Henneckea et al. [6] try to address this issue in remote collaboration tasks using a double mirror to match coordinates. While there are many research works that use virtual mirrors, they focus on using them for presenting information. Some works use them as an interactive tool such as, Hosoya et al. [7], who use a 2D mirror effect to select remote objects by overlaying user's hand with the objects. Another recent work, Woodworth et al. [15] use 3D virtual pointing with a virtual mirror for a remote guidance system. In their system, a guide conducts a tour for remote visitors and students standing in front of a Microsoft Kinect and a large 2D display. The display shows the mirror view of the guide in the virtual environment. The Kinect captures the guide's body gesture for 3D virtual pointing in the virtual environment. Multiple visual pointing cues are studied to encourage the guide to point at the correct depth since the guide does not have a depth cue. In our work, we focus on 3D manipulation using virtual hands in a virtual mirror.

Virtual Hand

A virtual hand can be generated by using a human hand to move a hand avatar in the virtual world. This representation is more realistic than virtual pointing (e.g., the ray casting method) since the virtual hand and real hand are co-located. Moreover, the user could rotate an object with the hand as a center of rotation, which more resembles real hand-object interaction than virtual pointing that rotates an object around the ray or object center. However, the physical hand can only select and manipulate objects around the user due to the limited extent of the user's reach. Providing a navigation mechanism to a remote object is an option, but can be inconvenient under many circumstances. Therefore, many researchers propose techniques to extend beyond the user's reach for interacting with objects far away. The world in miniature (WIM) by Stoakly et al. [12] provides a miniature world inside a virtual world. The user could interact with both the virtual world and the miniature world. Go-go technique [10, 11] extends virtual hands non-linearly beyond the user's reach. HOMER [5] uses ray-cast to first select an object and then transfer the virtual hand to the object's position. Voodoo doll [9] allows the user to create a remote-control doll from distance using two hands. The doll's movements are replicated onto the corresponding virtual objects, so the remote virtual objects act like they are under the effect of the Voodoo magic. A comprehensive discussion of virtual object selection techniques can be found in the survey by Argelaguet and Andujar [1].

Our technique is similar to the go-go techniques, which remap the position of the virtual hand to interact with objects beyond the user's reach. Other techniques may work in different setups, but may not be suitable for desktop VR. HOMER uses ray-casting that places virtual objects in the line-of-sight of the user, this could create a problem when the virtual objects are clustered in the center of the display on a desktop VR. WIM and Voodoo create another instance of the object, which could block target objects, owing to the desktop VR's limited space.

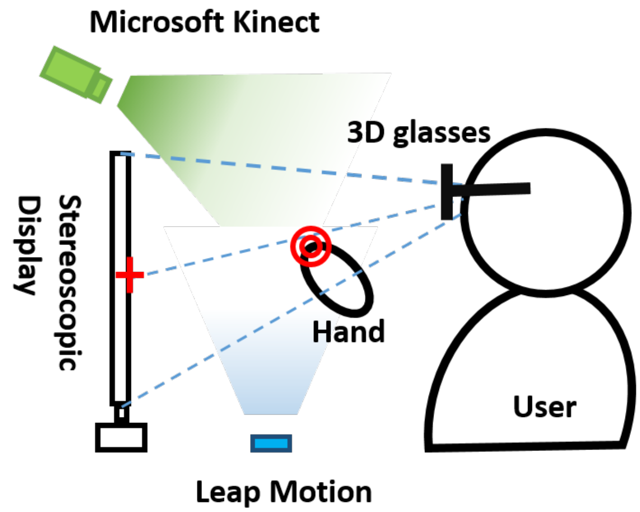

Figure 1. Physical setup of the system

SYSTEM OVERVIEW

Our system's physical configuration is illustrated in Figure 1. The shutter-glasses stereoscopic display (NVIDIA's 3D vision 2) is used to generate a 3D illusion for the user. The 3D display (Asus VG278HE) is combined with a head tracking system using Microsoft's Kinect to track a color marker on the 3D glasses to gain the 3D position of the head. We assume that the users keep their eyes horizontal to the screen. Since the tracked head movement is limited to the space in front of the screen, the effect from head tilting is minimum. Hand detection and tracking are handled by the Leap Motion sensor. The system transforms hand and head positions into a single coordinate system, such that the virtual hand and the user's physical hand align correctly from the user's perspective. The environment is simulated with NVIDIA's PhysX physical simulation system. The interaction between the virtual hands and virtual objects can be implemented using simple approaches such as attaching a virtual object to the virtual hand position or more complicated approaches with a higher degree of realism by using a spring model as introduced by Borst and Indugula [4]. In the scenario of the spring model, a virtual hand follows the user's physical hand as if there are springs attached between the two hands. The spring model allows the user to interact with virtual objects without interpenetration issues. The simple approach is used in our experiment and the spring model is used in our application scenario.

SYSTEM IMPLEMENTATION

Creating interactive space

The physical simulation is done via NVIDIA's PhysX and the rendering of the objects is implemented using Microsoft's DirectX. The primary drawback with existing desktop VR systems is that the user cannot easily reach behind the physical screen. Thus, the interactive space is limited to the space in front of the screen. The effective interactable space extends approximately from the surface of the screen to 60cm outward from the screen and 40cm upward due to the range limitation of the Leap Motion sensor. The width of the interactive space is limited by the size of the screen. In our experiment, the width of the screen is 60cm and the interactive space is raised by 1/3 of the screen's height. This allows more objects to be displayed, especially those positioned close to the user's body. At the 0 depth value, which corresponds to the physical screen depth position, the red reference frame is displayed to mark the start of the mirror world. This frame is the same size as the physical screen space and is shown in Figure 2. The perspective matrix is computed using *Generalized Perspective Projection* by Kooima [8] so that this frame is always aligned with the physical screen. The matrix is updated based on the user's head position. We make a reasonable assumption that the user gazes at the center of the screen when using the system. A smoothing function is applied to the values generated by the head tracker to avoid sudden changes that may lead to dizziness/cybersickness. At runtime, we calculate the user's head distance from the display and adjust the eye-convergence value accordingly. This should match the actual display plane and determine the virtual objects' parallax value.

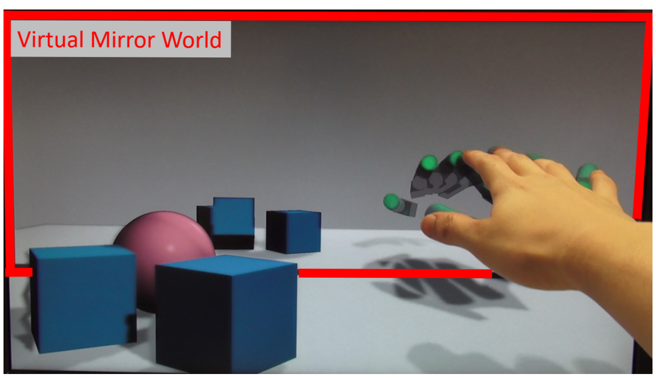

Figure 2. The mirror virtual world marked by a red square and the "hand transfer" process that moves the virtual hand into mirror and vise-versa

Virtual Mirror

A user could transfer the virtual hand into the mirror by putting the hand within a pre-determined distance from the screen. This would create another virtual hand based on the mirror position and orientation of the original virtual hand as shown in Figure 2. That is, a mirror image of the physical hand is created. A small time delay is used as a confirmation mechanism to prevent the user from accidentally making a "hand transfer". According to our informal pilot study, we determine that a distance of 10cm from the screen to the center of the palm and a 0.8s transfer time is a comfortable range for the user. These values are used in all of our experiment. If the transferred hand is grasping or pinching an object after the "hand transfer" is completed the object will also be transferred to its mirrored position and orientation as displayed in Figure 3. The system keeps track of the two hands separately, thus different hands could perform different tasks in the normal virtual world and the virtual mirror world at the same time (Figure 4). According to our pilot study, most users would be able to understand the mirror metaphor and "hand transfer" process after brief instructions. Moreover, users could adapt to mirror positioning well, but may experience some difficulty in adapting to mirror orientation. This issue is examined further in our formal user study.

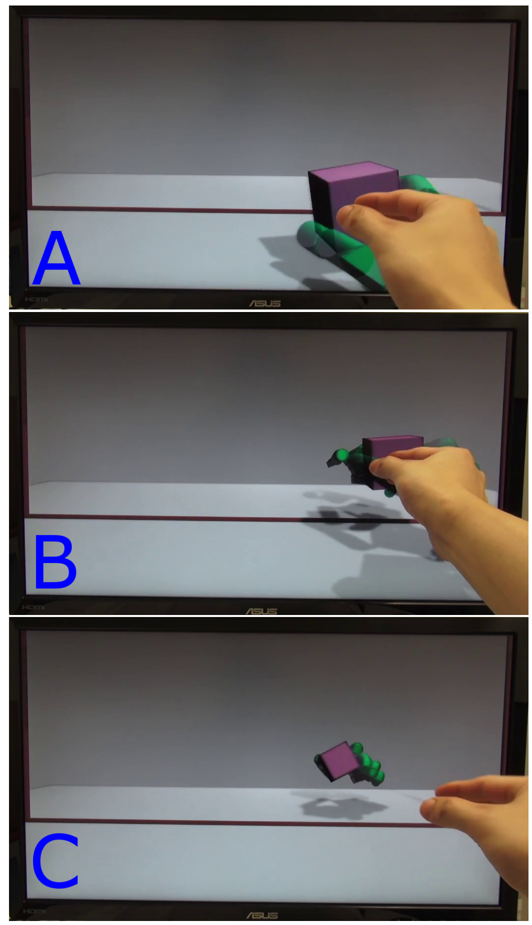

Figure 3. A: The user grabs the virtual object in the normal virtual world. B: The user moves his/her hand closer to the screen to initiate the "hand transfer". C: The user's virtual hand and the grabbed object are transferred into the mirror virtual world after the "hand transfer" is completed

USER STUDY

In this user study, we want to evaluate the accuracy of user interactions with virtual objects through the mirror technique when compared to other existing techniques. We performed this evaluation by comparing the mirror technique with the

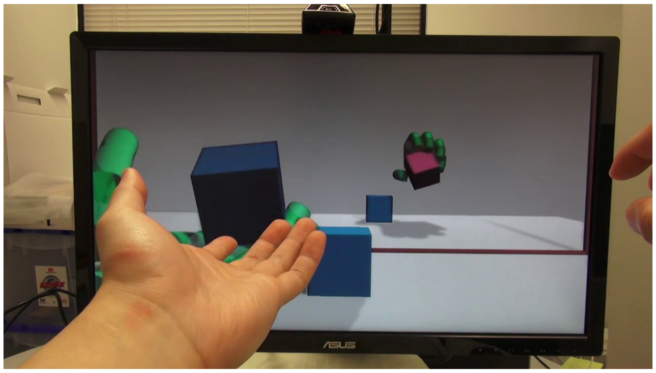

Figure 4. The system keeps track of the two hands separately, thus different hands could perform different tasks in the normal virtual world and the mirror virtual world at the same time

classic go-go technique. We selected the go-go technique introduced by Poupyrev et al. [10, 11] as a baseline, owing to two reasons. First, it integrates well into the desktop VR and the virtual hand environment. Second, it is designed to interact with virtual objects beyond user's reach, which is similar to the mirror technique. We implemented the go-go technique based on the original equations described in [10]:

$$R_V = F(R_r) = \begin{cases} R_r & if\ R_r < D \\ R_r + k(R_r - D)^2 & otherwise \end{cases}$$

where R_V is the distance of the virtual hand to the user's chest, R_r is the distance of the user's physical hand to the user's chest, D = 2/3 of arm length and k = 1/6. We assume that the average arm length from the shoulder to the wrist is approximately 60 cm, thus the user's physical hand and the virtual hand are aligned up to a distance D (or around 40 cm) in front of the user and the arm would be extended beyond D. The fully extended go-go arm could reach around 127 cm, which is similar to the mirror technique that extends spaces twice their original length. However, in go-go, we cannot set the position of a virtual hand to align with a physical hand from the users' perspective because that would lead to occlusion between the physical hand and the virtual hand. This problem does not exist in the mirror technique since the user knows that the virtual and physical hands are aligned in the normal virtual world. In the mirror virtual world, the virtual and physical hands are far apart and do not occlude each other. In our pilot study on go-go, the users prefer virtual hands that are not aligned with the user's perspective. Thus, in our experiment on go-go, the virtual hands are computed by forming a vector from the user's chest and the physical hand as in the original implementation.

In addition, we had considered different variations of the go-go technique including the fast go-go and stretch go-go [5] which use different mapping functions. The fast go-go removes the local area defined by the threshold (D), where the virtual hand matches the physical hand. The stretch go-go divides the arm length into three areas. When the user's hand is positioned in the outermost area, the virtual hand extends out indefinitely at a constant speed. If the user's hand is in the innermost area, the virtual hand retracts at the same speed. However, the virtual arm length remains the same in the middle area. The stretch go-go determines the virtual hand's velocity based on the position of the physical hand, which is different from the original go-go and the mirror technique. We decided to use the original go-go because these variations do not provide a better comparison to the mirror technique.

Experiment

The experiment was designed to test the following hypothesis:

H1 *The accuracy of the mirror technique is at least as good as the go-go technique in virtual object manipulation.*

We anticipated that with the mirror technique, users could attain higher accuracy in positioning virtual objects, but may take a longer time to complete the tasks because extra time is required to perform the "hand transfers".

To verify our hypothesis, we performed a 2x1 within the subjects user study on two techniques 1) go-go technique (**GG**) and 2) Mirror technique (**MR**). In all scenarios, the participants were required to wear the 3D glasses with a marker for head tracking, and the screen resolution was 1920x1080. The head tracking was activated in all cases for providing a correct perspective point of view from the user's head position.

Participants: There were 18 participants (15 males, 3 females) in our experiment. The participants are daily computer users between the ages 21-49, and 13 of them wear optical glasses. Half of the participants have prior experience in virtual reality, augmented reality or mixed reality. 5 of the participants are familiar with Kinect or Leap motion sensor.

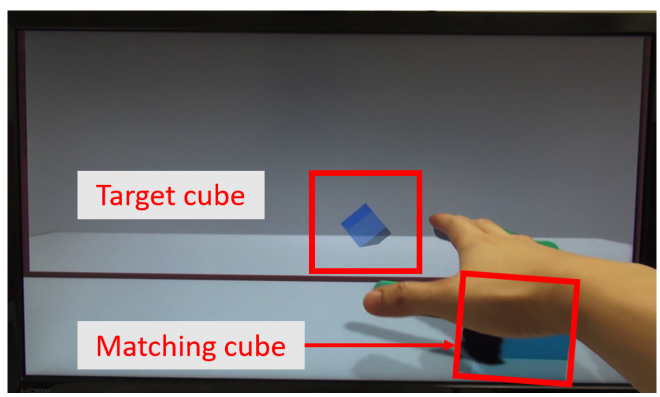

Figure 5. Participants were instructed to align a cube (matching cube) attached to their hand accurately with the target cube

Task: We designed the following task to validate the accuracy of interaction for each technique. Participants were given a target cube, which is displayed as a semi-transparent cube as shown in Figure 5. Participants were instructed to align a cube attached to their hand (referred to as matching cube) as accurately as possible. There were no constraints on which face of the matching cube was to match the target cube. In both techniques, the matching cube was attached to the user's hand and rotated according to the hand orientation. Participants could use a CTRL key on the keyboard to lock the cube orientation and then re-adjust their hands to avoid awkward hand positions. This is similar to releasing and re-grabbing a screw driver when the hand is rotated too far. The participants could use either hand to align the cube and another hand to press the CTRL key. The participants could switch hands depending on the position of each cube. The participants were instructed to press a confirmation key on the keyboard when they decided that the cubes were aligned. When the system received the confirmation command, the next target cube was displayed. The participants had to align 5 cubes per session. The target cubes' positions were programmed to alternate between the normal virtual world and the mirror virtual world. This was designed to examine the effect of "hand transfer" and the participants' adaptability to the mirror technique. The target cube always starts in the mirror virtual world, so that three virtual mirror world cases and two normal virtual world cases were tested. 10 pre-determined sets of target cube positions and orientations were generated and recorded before the experiment so that every set has the same translation distance. In each session, one of the 10 pre-determined sets was randomly selected.

Note: We settled for simply attaching the cube to the hand position and orientation because of two reasons. First, grasping through a physically accurate method such as the spring model [4] requires further practice time, which would further increase the length of an already long session. Second, our pilot study shows that the spring model is incompatible with the go-go technique. When the virtual hand reaches beyond a certain range and the virtual hand maps nonlinearly to the user's physical hand position, the virtual hand often moves faster than what the user expects and causes the grasped virtual objects to slip out of the user's hand. This is due to the property of the spring, which takes the velocity of the hand into consideration. While there might be an approach for the go-go technique and the spring model to work together, it is not within the scope of our work and is left for future research work.

While our proposed system did not aim to solve the fatigue issue in mid-air interaction, we took the following precautions to mitigate the fatigue factor in our experiment. First, we instructed the participant to move closer to the screen to reduce instances of fully extended arm gestures. We raised the screen to match the average users' head level using a platform and this platform could be used as a resting space for the user's hands. There was also a space in front of the platform for the users to rest their elbows. We notified the participants that they could use different hand gestures to match the cube, for instance, the hand pointing sideways required less arm lifting than hand pointing down.

Procedures

The independent variable of this experiment is the type of interaction techniques implemented: MR and GG. The dependent variables are the time to align each cube, translation error, rotation error and transform error as described in Table1. To avoid learning effects, the experiment was counterbalanced using the Latin Square design. At the start of each scenario, the participants were guided through both interaction techniques and command keys. For each scenario, the participants had to go through a training session before performing a real session. The training sessions followed the same procedure and interaction techniques as a real session. A 30 seconds rest interval was administered following each session to mitigate the fatigue effect. Participants were asked to perform the task as best as they could. The entire experiment was observed at all times.

Measurement	**Recording Method**
Time to align each cube (s)	The difference between the time when the target cube appears and the time when the user presses the confirm button on current cube
Translation error (cm)	The Euclidean distance between the centers of the target cube and matching cube
Rotation error (cm)	The Euclidean distance between the closest pair of corners of the target cube and the matching cube after applying the rotation transform, i.e, both cubes have the same center point
Transformation error (cm)	The Euclidean distance between the corners of the rotational pair of target cubes and the matching cube after applying both translation and rotation transforms.

Table 1. Dependent variable measures and their recording methods

RESULTS

During the experiment, there were four occurrences when the users unintentionally pressed the confirmation key without first aligning the cube. We filtered out those occurrences from the data analysis. Only the mirror virtual world cases (the target cube is in the mirror virtual world) were used in the data analysis in order to focus on the manipulating tasks that make use of the mirror metaphor.

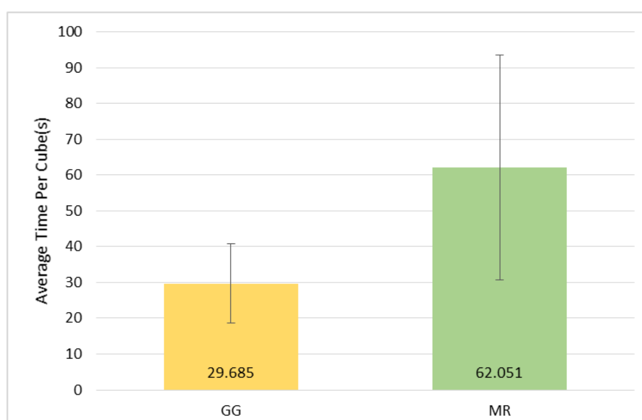

Figure 6. Average completion time per cube. The error bars represent +/- SD

Figure 6 shows that GG had a faster average completion time per cube (29.685s) than MR (62.051s). A within-subject

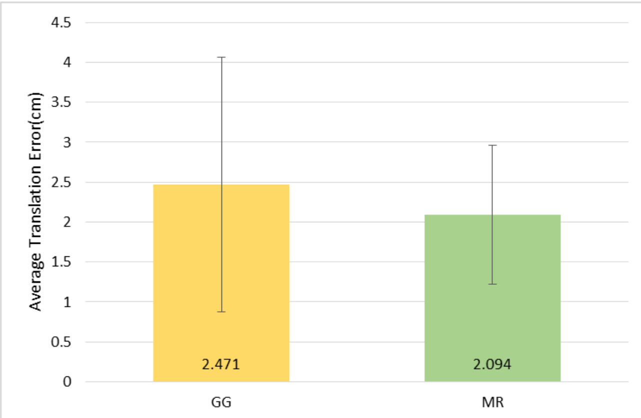

Figure 7. Average translation error. The error bars represent +/- SD

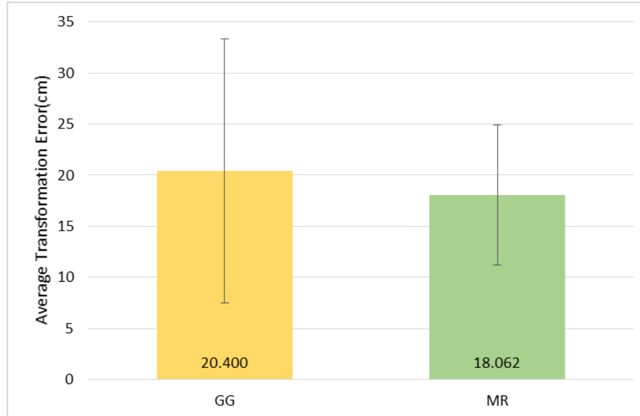

Figure 9. Average transform error. The error bars represent +/- SD

ANOVA showed a significant difference between the two variants ($F_{1,17}$ = 19.560, $p < 0.0005$, partial $\eta^2 = 0.574$). The extra time required by MR was most likely caused by the extra transfer time and the time to make an adjustment for orientation.

GG had an average translation error of 2.471cm which was more than MR with 2.094cm. However, a within-subject ANOVA showed no significant difference between the two variants ($F_{1,17}$ = 1.160, ns, partial $\eta^2 = 0.070$). This may be caused by the large standard deviation of GG as shown in Figure 7.

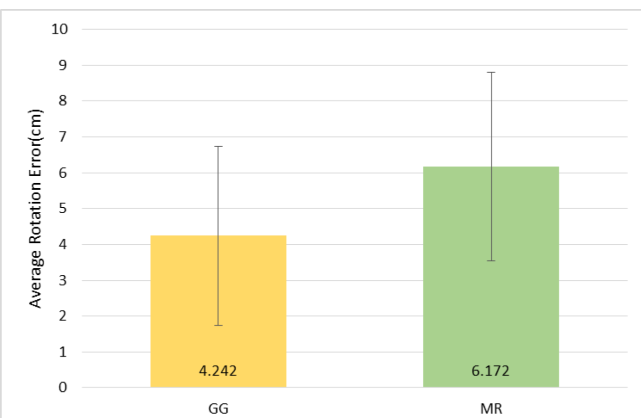

Figure 8. Average rotation error. The error bars represent +/- SD

MR had a rotation error of 6.172cm which was more than GG's 4.24cm. Nevertheless, a within-subject ANOVA showed no significant difference between the two variants ($F_{1,17}$ = 3.975, ns, partial $\eta^2 = 0.190$). Figure 8 shows large standard deviation values for both cases.

Finally, GG had a transformation error of 20.40cm, which was more than 18.602cm for MR. A within-subject ANOVA showed no significant difference between the two variants ($F_{1,17}$ = 0.621, ns, partial $\eta^2 = 0.039$). Figure 9 shows a large standard deviation value for GG.

DISCUSSION

The main objective of the assigned tasks in the user study is to match the target and matching cubes as accurately as possible. Although there are no significant differences in terms of performance accuracy between the two techniques, the result reveals that the go-go technique has a high standard deviation (almost twice as high as a mirror) in translation and transformation errors, which can be interpreted as a high variation in adaptability to the technique among the participants. On the other hand, the mirror technique shows a lot more stable results.

From the results, the weakness of the mirror technique on rotation related tasks is also observed. From the observation, participants spent a longer time in the mirror virtual world which has an inverse rotation. The participants seem to have a harder time adjusting to rotation movement than translation, which is expected since translation in the mirror only inverses in the z-direction, while the inverse effect applies to all rotation directions. One of the participants commented that he had a hard time adjusting from the linear rotation (in the virtual world) to the inverse rotation (in the mirror virtual world). This issue is not present in the go-go technique since it has linear rotation throughout. We speculate that this problem is magnified since the experiment forced the participants to perform the "hand transfer" each time a cube is aligned, and the participants have to quickly adjust to different orientations. In real application scenarios, the user is usually not required to switch side as frequently as in the experiment.

Even though the participants spent a longer time adjusting to the rotation tasks in the mirror virtual world, they did not show sign of fatigue. However, some participants mentioned about fatigue during the go-go technique experiment. We speculate that due to mirror's interaction properties, the participants were not required to extend their hands to reach the target cube, only the lower arm was required to manipulate the matching cube while their elbows were tucked close to their body. Unlike in the go-go technique, the participants had to extend their arms to reach the target cube far away. However, based on our observations, further experiments are required to examine the relationship between arm fatigue and the interaction time of the two interaction techniques.

In exchange for the time and rotation cost, the mirror technique has other advantages over the go-go technique. Even though both techniques are using position control, that is, the position of the virtual hand (Γ) is equal to the function of gain (f_0) multiplied by the user's physical hand position (u). The go-go technique is a nonlinear position control (categorized by Sundin et al. [13], where the gain increases nonlinearly as the physical hand position increases, that is ($\Gamma = f_0(u) \cdot u$). While the mirror technique uses two separate linear gains, a normal virtual world gain (in this case, an identity matrix) and a mirror virtual world gain (diagonal matrix $(1, 1, -1)$), the mirror technique maintains linear position control with the user's physical hands in both virtual worlds, thus it is more compatible with physical-based object manipulation models such as the spring model [4] when interacting with virtual objects that are out of the user's reach. Second, multiple participants commented that in the go-go technique, their physical hands occluded the screen and virtual objects when they were extended. Although we were actively trying to avoid occlusion as described in the experiment session, a certain gesture such as the hand pointing downwards still occluded either the objects being manipulated or the virtual hands. In the mirror technique, the user's physical hand is aligned with the virtual hand in front of the screen and positioned far away from each other in the virtual mirror world, thus occlusion is unlikely to occur. We summarize the advantages and disadvantages of the mirror techniques as follows:

- Advantages
  1. Have consistent translation and transformation accuracy even the virtual objects are far away behind the screen and out of the user's reach.
  2. Have linear position control, hence work well with the physical-based models.
  3. Users' physical hands are unlikely to occlude the virtual objects.
- Disadvantages
  1. Required additional transition time.
  2. Users have a harder time adjusting to rotation tasks in the virtual mirror.

APPLICATION SCENARIO

We describe here one of the possible applications that could take advantage of the mirror technique. In this file browsing scenario, the user is working on organizing the files. The user has two separate work spaces, the mirror virtual world is designated as a storage space while the space in front of the screen is the working space. In the screenshot shown in Figure 10, there are two sets of folders, displayed in the form of file cabinet drawer. The user could scroll through the files using his/her fingers as in a real filing cabinet. The user then picks up the target file and performs "a hand transfer" to move the files into the workspace. Placing the file in a designated area in front of the scene would show a preview of the contents of the file (in this case, a note from Microsoft OneNote).

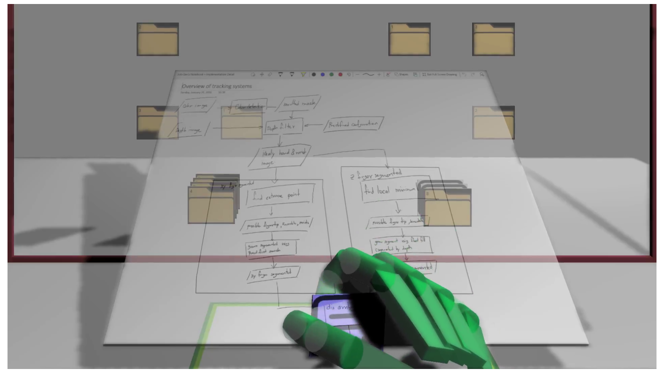

Figure 10. The user organizes the files using natural user interaction with the mirror technique.

The process can be reversed to close the file. The separated work spaces, with clear designated purposes, take advantage of the expanded space in the mirror technique, while a simple "hand transfer" provides a seamless mode changing mechanism. The consistent translation accuracy of the mirror technique allows the user to select objects beyond their reach, while preserving natural interaction.

CONCLUSION AND FUTURE RESEARCH

In this paper, we present an alternative technique that allows users to interact with virtual objects beyond their physical reach through the mirror metaphor. The user study shows that it has more consistent translation and transformation accuracy over existing methods.

Nevertheless, there are still unsolved issue with the mirror techniques. The user might feel awkward when interacting with the objects in the "hand transfer" zone, that is, the region close to the physical screen. In this zone, the user could not grab the virtual objects using a normal gesture. Multiple users accidentally tried to reach into the physical screen during our experiment. In addition, the "hand transfer" could finish before the user can complete the gesture. The current solution requires the user to poke the virtual objects out of that zone before interacting with the virtual objects. A more elegant solution is left for future research.

In practice or in a mobile platform, it is likely that a 3D display is not available. In our initial prototype, without a 3D display, many users could interact with virtual objects through a period of adjustment. However, such an interaction relies on the human capability to adjust through visual feedback, which may not be suitable for tasks that require accuracy. In addition, the users may have difficulty interacting with the virtual objects, since they would feel that the virtual and the physical hands are not aligned with each other. Additional visual cues to help users judge the depth cue is required to be able to use mirror techniques without the 3D display.

We strongly believe that the mirror technique could be applied to collaborative tasks especially in specific tasks where two users are required to manipulate virtual objects of their own and of others. The mirror virtual world could be used as a collaborative work space and the normal virtual world as a private work space using the mirror approach. The potential application of the mirror technique in collaborative tasks is being explored by our research team.

Another area of research based on the mirror technique is to improve realism using real-time color point clouds for representing the user's body. Therefore, the users could feel like they are looking into a real mirror. In our experiment, only geometric hand skeletons were shown, which leads to the question; "how much do the users actually feel that their hands are manipulating the object?" One possible approach to enhance the sense of hand ownership is by using the point cloud generated from Microsoft's Kinect as shown in Figure 11. From our preliminary study, 15 out of 18 users feel their interactions with virtual objects are more realistic when point clouds are presented. Questions such as how would point clouds improve the experience of users and how would they affect the performance, will be left for future research.

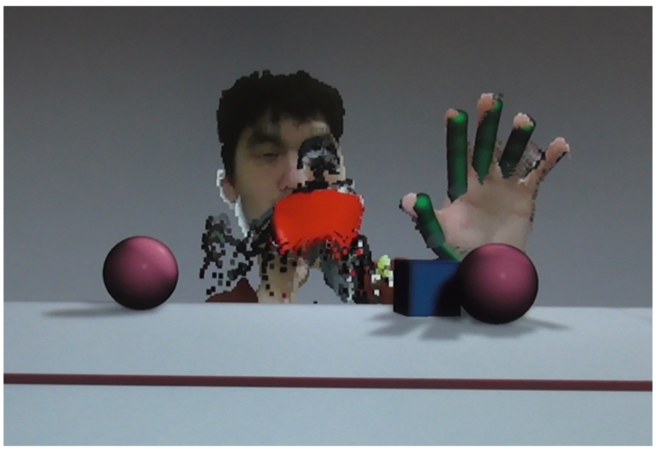

Figure 11. Point cloud generated from Kinect to replicate real world mirror and overlap with the virtual hand

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