Give Me a Hand: Exploring Bidirectional Mutual Embodied Tangible Interaction in Virtual Reality

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***Abstract*—Virtual reality (VR) systems have been increasingly used in recent years in various domains, such as education and training. Presence, which can be described as 'the sense of being there' is one of the most important user experience aspects in VR. There are several components, which may affect the level of presence, such as interaction, visual fidelity, and auditory cues. In recent years, a significant effort has been put into increasing the sense of presence in VR. This study focuses on improving user experience in VR by increasing presence through increased interaction fidelity and enhanced illusions. Interaction in real life includes mutual and bidirectional encounters between two or more individuals through shared tangible objects. However, the majority of VR interaction to date has been unidirectional. This research aims to bridge this gap by enabling bidirectional mutual tangible embodied interactions between human users and virtual characters in world-fixed VR through real-virtual shared objects that extend from virtual world into the real world. I hypothesize that the proposed novel interaction will shrink the boundary between the real and virtual worlds (through virtual characters that affect the physical world), increase the seamlessness of the VR system (enhance the illusion) and the fidelity of interaction, and increase the level of presence and social presence, enjoyment and engagement. This paper includes the motivation, design and development details of the proposed novel world-fixed VR system along with future directions.**

Keywords*— *Virtual reality; bidirectional mutual tangible interaction; social interaction; collaboration with virtual humans.

I. Introduction and Background

Virtual reality (VR) has been widely used in several domains, such as education, rehabilitation and training. VR had been shown to provide effective training and learning, along with several other benefits. Several aspects in VR contribute to user experience, such as interaction, visual and auditory fidelity.

In various previous studies, it was suggested that increased similarity to real-life encounters (e.g., one to one directly mapped interactions) increased the benefits gained from VR training [2, 9, 11, 22]. In real life, mutual interactions take place between humans. Mutual interactions can be described as interactions between two entities (e.g., human vs. human, human vs. virtual character) through a common shared object (virtual or real) that can be manipulated by the either party. The benefits of mutual interactions can be described with the Activity Theory, which states that when social actors (i.e., humans) take part in activities that include shared goals, task comprehension and engagement improve [34]. Shared activities are known to enhance learning by using context for generalizing and understanding acts in a systematic and relational way, which also translates to VR systems [28]. In real-world, humans most often engage in direct mutual interactions while collaborating, which can be described as explicit and overt interactions that are mediated by bidirectional movements of a shared object (e.g., a tennis ball). An example of a mutual direct interaction in VR between a human user and a virtual character can be given as a shared virtual thermostat knob that can be rotated by either party.

Embodied interaction can be described as the natural physical way in which humans interact with their environments in their daily lives [13]. Tangible interaction in computer-human context encompasses interaction that emphasize tangibility and materiality of the interface while offering physical embodiment. An abundance of studies evaluated tangible interaction in various contexts, such as learning and training in VR, computer controlling interfaces and cognitive tasks in virtual environments [7, 8, 18, 26, 31, 32]. It is now a commonly accepted best practice in computer-human interaction that tangibility improves user experience in various settings, such as training, mainly because it leverages natural motor and body skills, acute spatial awareness, perceptual processes that affect motor and semantic memory and maintaining the sense of proprioception. Tangible objects that are close to their real-life encounters (in their form or context in use) are linked to increased spatial cognition and skills [12, 24, 25], more benefits in learning through psychophysical kinesthetic figural after effects [1], improved and more natural interaction with no prior training [17], and more intuitive, natural and familiar user experiences [16]. Moreover, haptic feedback on shared virtual objects is known to increase presence in remote participants who are in separate physical spaces [4, 30]. Benefits of tangible interaction with familiar everyday objects that match their virtual representation and daily-life use can also be described with the Activity Theory, which states that interaction of humans with the real-world takes place in a context that includes individuals and artifacts. In their early previous work, Bannon and Bodker emphasized the importance of incorporating tangible artifacts into computer-human systems in meaningful contexts that are familiar from the real-world interactions and environments would result in better usability [10]. Tangible interaction through common and familiar objects whose representations in the real and virtual worlds match facilitates enhanced learning through direct relationships of content and actions, and contextual reasoning.

Presence, in general, can be described as a sense of non-mediation [23]. A simpler description of presence can be given as 'the feeling of being there in the virtual world'. Social presence (copresence) is a subtype of presence, which is related to a sensation of perceiving one's self as in an interpersonal environment "in the presence of, and dynamically interacting with, other veritable human beings" [5, 6] (i.e., social connectedness and togetherness). It is known that sense of presence is generally linked to more benefits gained from VR systems, such as more effective training, learning and engagement, and also better translation of the learned tasks to real-world [20]. Previous studies showed that virtual interactions that are closer to real-life provide a higher degree of presence [27].

In real world interactions that take place in shared spaces, when an object is moved the effect can be observed by the other people in that space as a change in the space caused by the movement of that object (i.e., the object's location changes because of that movement). If another person is touching an object while it is being moved by another person, the movement is transferred through the object and can be felt as a force exerted on the touching person (e.g., a person sliding a book while another person is touching the book).

The believability of illusion is an important aspect that contributes to the level of presence. Seamlessly merging virtual imagery into the physical world is strived for to improve user experience in augmented and world-fixed virtual reality [37]. Even when high fidelity visuals are included in the virtual world and seamlessly blended into the real (physical) world, the believability of the created illusion would be limited by the responsiveness of the virtual entities to the physical entities. It is believed that if virtual characters perceive and respond to the physical world (i.e., actuate items), the illusion of virtual and physical content existing side by side in the real world is enhanced [38]. Although significant advancements have been made in recent years in VR, bidirectional mutual embodied tangible interaction with virtual characters through shared real-virtual objects that extend from the real-world into virtual worlds (and vice versa) is still an unexplored area. I believe enabling a form of interaction in VR, where a shared real-virtual object that crosses the physical-virtual boundary (extends from the virtual world into the real world and vice versa) can be moved bidirectionally both by the human user and the virtual character, and where the effects of the movement can be immediately observed in the opposite world (i.e., real or virtual), will improve user experience.

However, VR poses challenges in incorporating real-life like tangible interactions, such as making the mutually shared tangible objects move based on both the human user's and the virtual character's actions through custom-built hardware systems, adjustment of software system parameters in real-time to synchronize the movements of the physical and virtual parts of the shared object that crosses the physical-virtual boundary, providing seamless projection of the virtual world on a display which includes the shared tangible object. The aimed overall increased believability of the illusion would only be achieved when all of these challenges are overcome. In this paper, I propose a custom novel prototype that tackles these challenges and incorporates shared tangible objects (i.e., a steering wheel and a block) into a world-fixed VR system to enable bidirectional mutual embodied direct tangible interaction in an effort to increase the verisimilitude of interaction and improve user experience in terms of presence, social presence, engagement and enjoyment by decreasing the boundary between the physical and virtual worlds.

Even though several previous studies explored mutual, embodied or tangible interaction separately in VR, only three previous studies to the author's knowledge investigated these collectively as a single form of interaction. Willis et al. developed a prototype system for an interaction metaphor named MotionBeam that included handheld projectors with the aim of creating unified interactions where the input and output are coupled [38]. In the MotionBeam, the user controlled and interacted with the projected imagery by moving the handheld projector. The virtual characters were aware of the physical world (e.g., a virtual character gliding on the floor) and in some scenarios reacted to physical objects as well as pushing back on the physical world to affect physical objects (e.g., a virtual car tilting a physical picture frame when dropped from a height and landed on top of it). Although the mentioned study proposed example uses of augmenting physical and virtual objects within the context of using a handheld projector as a display device, little insight was shared on the effects of the physical-virtual interaction on user experience. A preliminary user study was performed but it served as a validation of the usability of the interaction itself (manipulating the handheld controller to move virtual characters), and not the physical-virtual interaction. Yao et al. [36] developed gesture-controlled games (single player or remotely located multiplayer) with a tangible rope. The system enhanced user experience through a remotely shared game space and tangible interaction with everyday objects. However, the interaction was not bidirectional (the manipulation of one side didn't make an observable effect in the other space). Lee et al. [19] developed a VR system that included a real-virtual wobbly table with physical and virtual representations. The table was moved incidentally based on the weight the human user and the virtual character put on the table with their arms. The researchers found out that the proposed interaction increased presence. As a differentiating point from this proposed study, the interaction was incidental and indirect (the table wasn't interactive, human user or the virtual character could not interact with it or control any event/action with it, but it rather acted as a prop that was moved incidentally and provide indirect interaction).

This proposed study differs from the mentioned previous interactions by merging the following aspects into a novel interaction method for world-fixed VR: (1) mutual (including interaction exchanges between a human user and a virtual character), (2) direct (including explicit, intentional and overt changes on a common shared object, which can be caused by both parties), (3) embodied (being close to real-life interaction encounters to a high degree, both in motion and tools), (4) bidirectional and crossing the physical-virtual boundary (both the human user and the virtual character can manipulate the shared tangible object, creating an immediately observable effect on the other side since the physical and virtual forms of the shared object are synchronized through being electromechanically linked).

II. Design and Development

In this proposed system, shared objects span physical and virtual spaces (i.e., the objects are represented in two complementary forms -physical and virtual- that are synchronized through electromechanical linking such that when the physical representation moves, the virtual representation also moves accordingly, and vice versa). The extension of the shared objects from the virtual world into the real world (and vice versa) are achieved through a custom altered projection curtain and custom-developed mechanical systems (Figure 1). A projection curtain is used as an intermediary display. The human user can view the virtual world through this display on which projections are made. The projection surface was modified (a hole was cut out) so that only a portion of the physical object is visible to the human user at all times, while the remaining complementary portion of the object is rendered on the curtain digitally (Figures 2 and 3). The mechanical systems include physical object parts, 3D printed attachments, microprocessors, actuators, and motion sensors (Figures 4 and 5). These mechanical systems are employed for electromechanically synchronizing the movements of the physical objects and their virtual counterparts in real time in terms of visual-motor. As one of the agents (human or virtual) affects the corresponding form (physical or virtual) of the shared object (e.g., by moving or rotating it), the effect is immediately observable on the other form of the object.

Two modes of interaction/tools were designed and implemented: (1) Rotation motion with a horizontal steering controller, (2) Translation motion with a rectangular block. The linear or rotational movements in this proposed system are achieved with the use of a stepper motor and a microstep stepper motor driver. After it completes the desired motion representing the movement induced by the virtual human, the motor is deactivated to enable the human user to manipulate the tangible object. The motion of the tangible object is tracked with a rotary encoder. An Arduino Uno microcontroller [3] is used to control the system and communicate with the main VR computer. The position data from the microcontroller is sent to the computer software for the real-time rendering of the digital representation of the tangible objects. The virtual human's actions are sent from the computer software to the microcontroller to create a physical movement on the tangible object (the illusion of virtual character physically moving the object in the real world). Each interaction tool was attached onto a modular cube, which will placed on a table behind the projection curtain such that the tangible object extends into the front of the curtain. The cubes will be changed for each interaction mode such that different shared objects can be used in different scenarios. The dimensions of the tangible objects were designed similarly such that a single hole on the curtain accommodates either one of the tangible interaction tools. The diameter of the steering controller is 30cm.

In the proof-of-concept prototype, foam boards were used as the representative projection surfaces. In the actual high-fidelity prototype, a tension projection curtain (diagonal 100-inch) will be used as the world-fixed VR display. A short throw laser projector with 1920 x 1200 resolution and 0.27 – 0.37 throw ratio range (Epson PowerLite 700U WUXGA [14]) will be mounted onto the ceiling to project the virtual world onto the curtain. The human user's head movements will be tracked via an infrared-based head tracker and the rendering of the virtual world will be updated in real time according to their viewing angle.

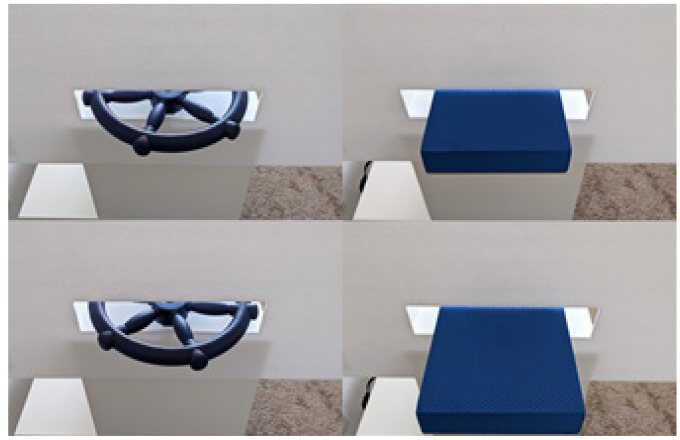

Fig. 1. Front views of the proof-of-concept prototypes of the proposed novel interaction forms. There will be a projection curtain (diagonally 100" sized) in the actual prototype instead of the foam board, on which the virtual world will be displayed. Left: Rotation. Right: Translation.

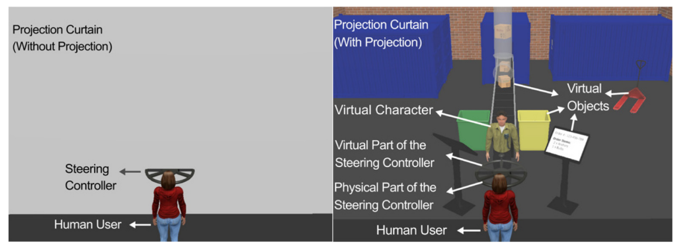

Fig. 2. Real-world view of the concept sketch of the proposed world-fixed VR system. Left: Tangible steering controller was placed inside a hole on the projection curtain (which will be cut out) so that the human user can always see the physical and the digital representations of the tangible object. Right: The human user is looking at the virtual world projection on the curtain. The human user sees half of the steering controller as physically represented while seeing the other half as digitally represented.

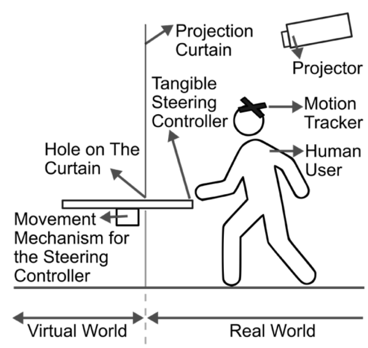

Fig. 3. Diagram of the proposed novel prototype (the rotation mode).

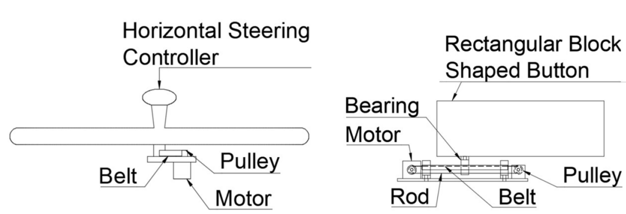

Fig. 4. Diagrams of the interaction modes (left: rotation, right: translation).

Task design is important for providing meaningful contexts in which the proposed form of interaction can be experienced. Hence, distinctive tasks were designed for each interaction mode/tool (rotation and movement). These tasks are currently being implemented in the Unity Game Engine [33]. Concept sketches of the rotation task can be seen in Figure 6. In the rotation task, the human user will perform sorting activities in collaboration with a virtual character in a virtual warehouse environment. They will rotate a shared horizontal steering controller in order to direct items that belong to the orders they were assigned into their corresponding bins. Both the human user's and the virtual character's orders will be displayed on their own virtual screens that are rotated towards them. A transparent pipe will feed items with different labels from the ceiling towards a central moving conveyor belt. If an incoming item belongs to the human user, they will intercept the direction of the pipe tip by rotating the shared steering controller. When the item falls into their bin, the human user will need to return the pipe tip's rotation towards the central conveyor belt by rotating the steering controller back in the opposite direction. The virtual character will also perform the same task with a separate bin and a different list of items for their orders. This way, the human user and the virtual character will share an object with two forms (i.e., tangible and virtual) and work towards the shared goal of fulfilling orders. As the virtual character rotates the virtual representation of the steering controller, the tangible representation of the steering controller will also rotate. In other words, the actions of the virtual character will affect the physical world through the shared object (the real-virtual steering controller will cross the physical-virtual boundary).

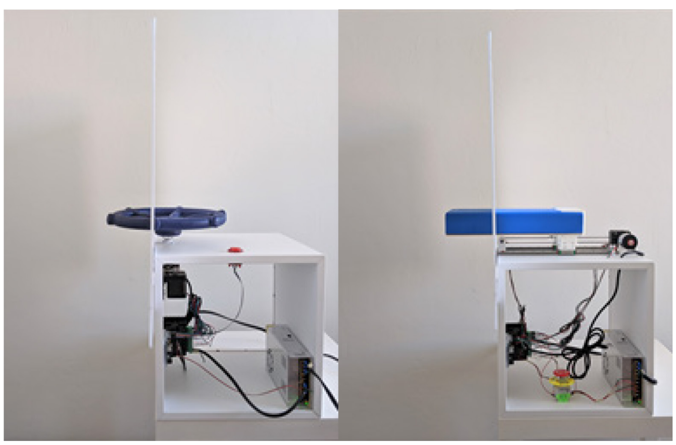

Fig. 5. Side views of the proof-of-concept prototypes of the proposed novel interaction forms. Left: Rotation. Right: Translation.

In the translation task, the human user will perform conveyor belt operation activities in collaboration with a virtual character in a virtual manufacturing environment. They will actuate a rectangular block to control the flow direction of a conveyor belt based on their assigned directions. There will be a two-sided shared assignment screen which displays the direction in which the conveyor belt needs to flow currently along with worker ID (either the human user or the virtual character). If a task is assigned to the human user, they will push or pull the tangible rectangular block in order to the bring the control panel to the desired configuration, so that the conveyor belt adheres to the given flow direction. If a similar task appears on the shared display for the virtual character, they will manipulate the block. As one of the characters (human user or virtual character) pushes or pulls the rectangular block, the corresponding effect will immediately be observed in the opposite world (real or virtual) in real time.

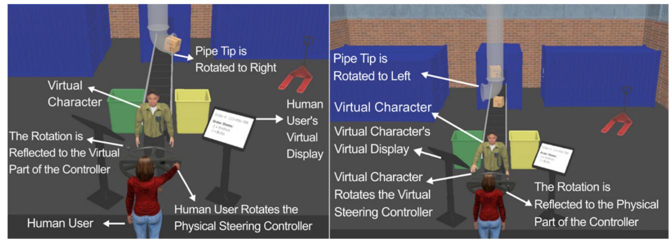

Fig. 6. The human user and a virtual character collaborate on a sorting task. Left: The human user rotates the tangible steering controller and can observe the immediate rotation effect on the virtual projection in real-time. The pipe tip in the virtual world is rotated based on the user's actions (the box will fall into the yellow bin). Right: The virtual character rotates the virtual representation of the steering controller. The rotation effect can be observed on the tangible representation of the real-virtual object in real time.

III. Discussion and Future Work

The focus of this study is exploring whether direct movements of real-virtual objects (i.e., objects that cross the physical-virtual boundary through real-time synchronized physical and virtual dynamic representations) will increase sense of presence, social presence, level of engagement and enjoyment in world-fixed VR. A custom system prototype was developed, and distinctive tasks were designed for two interaction modes: rotation and translation. To investigate the effects of the proposed interaction on user experience, the following data will be collected in the near future: (1) Automated data: performance and accuracy in terms of correct actions and task completion time, and level of engagement which will be measured with a Muse headband [29] that collects electroencephalographic (EEG) data. (2) Questionnaire-based data: Presence, social presence and enjoyment will be measured with the following well-accepted questionnaires in the literature: Witmer and Singer's presence questionnaire [35], Harms and Biocca's social presence questionnaire [15], and Loewenthal's core elements of the gaming experience questionnaire [21]. To compare the effects of the proposed novel interaction, a control version will also be developed where the tangible objects do not extend from/to physical/virtual worlds. In the control version, no virtual representation of the tangible object will be rendered. The virtual human will have their own controllers in the virtual world. A between-subjects design will be employed for the planned experiment. The hypotheses that will be evaluated are as follows: (1) Participants in the experiment group will report higher presence. (2) Participants in the experiment group will report higher social presence. (3) Participants in the experiment group will show higher engagement. (4) Participants in the experiment group will report higher enjoyment.

The limitations of this proposed study can be summarized as follows: being task dependent; allowing for the use of a single shared real-virtual object at a time; relying on a stationary setup; being dependent on the environmental lighting conditions.

The future plans include the completion of the software for the experiment and the control versions and conducting user studies to examine the effects of the proposed novel interaction on user experience in VR. I believe that this descriptive paper will help researchers who are interested in building similar systems. I also believe that in the long run, this proposed work will allow for investigations of variations of virtual-human user interactions, resulting in more publications and discussion in this particular domain.

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