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David M. Krum, Evan A. Suma, and Mark Bolas

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Introduction

The Institute for Creative Technologies (ICT) at the University of Southern California is a University Affiliated Research Center focused on the development of engaging, memorable, and effective interactive media to revolutionize learning in training, education, and other fields. In support of these applications, the Mixed Reality Lab researches and develops immersive technologies and techniques to build mixed reality environments.

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Mixed reality is a term that describes environments and experiences that combine elements that are real with elements that are virtual. For example, mixed reality experiences might be provided by physical rooms where windows are simulated by display screens, or by head mounted displays (HMDs) that use cameras and graphics engines to overlay virtual objects over a view of the real world.

To create effective mixed reality training scenarios, it is important to immerse users in simulated experiences that convincingly replicate the mental, physical, and emotional aspects of a real world situation. The Mixed Reality Lab's early work in this area was known as the FlatWorld project, which created a system of "digital flats" as building blocks for mixed reality environments [6]. Our current research direction has been influenced by two high impact aspects of FlatWorld: the ability to create highly navigable environments and the ability to present virtual human characters. Our most recent research has thus recently centered on the use of full body tracking systems and immersive displays in order to support realistic physical locomotion and strong engagement with virtual human characters.

To provide full body tracking, we have been building and refining the Intelligent Reality Sizable Tracked Augmented Graphics Environment, or IR STAGE, which is a full motion capture stage. We constructed the IR STAGE with the following two goals in mind: (1) provide accurate full body motion capture to support sharing space with virtual human characters; and (2) accomplish head tracking over an area large enough to conduct experiments with stretching virtual space. To achieve these goals, we segmented the space into two separate units. IR STAGE 1 is a 36 × 40 ft space that is optimized for full body tracking in a manner similar to the motion capture setups used by the film industry. A total of 46 PhaseSpace Impulse motion capture cameras are arranged at multiple heights in a circular pattern with a typical radius of 15–20 ft and aimed in at the center region. This provides accurate and robust tracking of LED markers that can be placed anywhere on the body, making it suitable for our projects in sharing space with virtual humans, though the most precise tracking is limited primarily to the central region of the space. In contrast, IR STAGE 2 is optimized for head tracking over an entire 36 × 36 ft space all the way out to the borders. To achieve this goal, a total of 52 PhaseSpace cameras were hung from a ceiling mounted grid. To spread out the tracking over such a wide area, 44 cameras were placed at a height of 13 ft, pitched downwards at a 45° angle, and aimed in various directions to cover the space. In our tests, ceiling-mounted cameras were the least accurate in tracking marker height, so we also placed an additional eight cameras around the borders at a height of 6 ft. We found that arranging LED markers in a circular perimeter about the head-mounted display provides reliable rigid body head tracking throughout the entire space, which supports our work in stretching space. Though the two IR STAGE units are currently optimized for their respective goals and can currently operate independently, our long term vision is to unify the system into a single 80 × 36 ft space that can robustly provide both head tracking and full body motion capture throughout the entire workspace.

Previous Work

Our current research direction has evolved from several bodies of prior work, including efforts related to large tracked spaces, redirected walking, and our group's own work with mixed reality environments and virtual human characters.

In film and theater, a key element of stagecraft has been the flat, a modular, movable panel used to present background scenery. The FlatWorld project updated the flat concept to create "digital flats" for mixed reality, with new features like 3D imagery, 3D audio, and 4D sensory actuators like fans for wind and rumble floors for vibration. Digital flats can be easily positioned and projected upon to simulate walls or viewports, such as windows and doors. They can also be combined with physical props, like chairs and tables, and standard flats, representing solid walls, to create rooms, alleyways, and other structures. Many users can freely navigate these environments at the same time. Furthermore, flats and props can be quickly re-staged in a number of different arrangements, satisfying training requirements for reconfigurable environments. Other particularly notable FlatWorld innovations include the use of semi-transparent screens for portraying virtual humans, and adaptive projection, allowing transient effects, like bullet holes, to appear on a wall or floor.

Virtual humans can play important roles in learning and training systems as opponents, collaborators, spectators, instructors, and guides. The goal is to create virtual human characters that are treated just like real humans, or create reactions similar to those that real humans create. A key metric for such virtual humans is "co-presence", which is the perception that character has a physical, social, and emotional existence. The ICT has produced a variety of virtual human characters. One notable example, co-developed by our lab, is SGT Star, an information guide employed by the US Army Accessions Command to speak about Army careers at public events. In our lab, SGT Star is presented on a semi-transparent screen, providing a simulated 3D appearance. This presentation seemingly pulls the character off of a flat projected screen, enabling motion parallax cues between the character and background scene. However, since users cannot walk past the character (into the screen) and the character and cannot emerge from the screen, the character still inhabits a different space which is unreachable and virtual.

Physical locomotion (walking, running, etc.) has been recognized as essential for simulations in which the soldier interacts directly with the surrounding environment. Virtual locomotion techniques that simulate walking (e.g. joystick or button presses) have been shown to be inferior to real walking in many experiments, including studies of spatial orientation [2], attention [13], search task performance [10], and sense of presence [15]. Additionally, since virtual locomotion does not realistically portray the energy and effort of real world movement, it might provide negative training in scenarios where tactical movement and coordination are important, such as urban combat. Despite the advantages of real walking, however, physical workspace constraints and motion tracking hardware limitations have historically made it impractical for deployment in large-scale virtual environments.

The Department of Defense (DoD) has long been interested in methods for allowing soldiers to physically walk around in unlimitedly large virtual training worlds. A number of hardware-based solutions have been developed, such as omnidirectional treadmills [3, 11] and large hamster-ball contraptions [16]. Walking-in-place techniques have also been explored as a middle ground between real walking and virtual locomotion [5, 14]. However, advances in wide-area tracking technology have made it possible to construct tracking spaces that are large enough to support real walking for many applications [17, 18]. Unfortunately, these large tracking spaces still have finite boundaries which ultimately limit the size of the virtual environment to fit within the available physical space.

To relax the physical size restrictions imposed by the tracking space, Razzaque proposed a technique known as redirected walking, which subtly rotates the virtual environment to steer the user's walking path away from the boundaries of the tracking area [8]. This technique can be augmented using a visual distractor to provoke head turns, making it easier to apply the rotation imperceptibly [7]. Alternatively, it is also possible to apply a scale factor to walking movements in the forward travel direction, allowing the user to cover greater distances in the virtual world [4]. Since all of these techniques introduce a visual–vestibular conflict by manipulating the mapping between real and virtual motions, it is important that rotational and scale gains be applied slowly and gradually, so that the user does not notice and, perhaps more importantly, does not experience motion sickness.

Sharing Space with Virtual Humans

Characters in virtual reality environments often appear to be two dimensional or distant (either perceived or real). These shortfalls may weaken engagement, and thus the efficacy of training. By incorporating a wide field of view HMD and full body tracking, we aim to convince users they are sharing the same volumetric space with virtual humans. This will help enhance the illusion that the virtual human is a sentient entity with whom the user can socially relate.

Humans have a strong drive to relate socially with objects that display even only a glimmer of personality. In fact, while many humans may not consciously perceive that they are interacting with unintelligent objects in a social fashion, they often still fall into the human tendency to ascribe personalities and emotions to things, like animals, computers, and cars [9]. Removing barriers to this tendency can elicit more realistic responses to virtual human characters.

By employing full body tracking, and wide field of view displays, like Fakespace Labs Wide5 HMD (providing up to 150° of horizontal field of view), we are attempting to create uniquely compelling experiences with virtual humans. In the following sections, we will describe a number of anecdotes and experiments we have performed using a wide field of view HMD and full body tracking for shared space experiences with virtual humans.

Avatars and Self-Representation

In many virtual environments, user avatars are either invisible, incomplete, or do not correctly follow the movements of the user. Full body tracking allows a correct self-representation of the user's own body in the virtual environment, increasing the level of self-immersion and placing the user on the same level as the virtual human.

The importance of self-representation became apparent to us in one virtual scene which utilized an environment from a Unity game engine demo. This scene presents a wooden bridge over water. The roughhewn construction of the bridge, with some broken wooden planks and large gaps in between, invites careful placement of the user's feet. Without a good representation of the user's feet, the scene feels artificial. There is no way for the user's feet to visually interact with the treacherous bridge. By adding trackers to the user's feet, the user is able to place each foot on the appropriate plank, avoid holes, and thus respond to the precariousness of the bridge.

Puppeteering

Full body tracking can also enable virtual puppeteering, allowing a virtual character to be voiced and animated in real time. While an autonomous virtual character is certainly a goal, virtual puppeteering could have a role in custom character control, multitasking (or supervisory) control of multiple characters, and studying user reactions to virtual characters.

In an early experiment with puppeteered characters, we placed a number of tracking markers on an operator's arms. These markers controlled the arm movements of a virtual character. The user, wearing a Wide5 HMD, would approach and reach out towards the virtual character. The virtual character (following the operator's movements) would begin to wave his hands more and more wildly, and then progress to knocking the user's hands away and pushing the user away. These actions were startling to us as users since we, as experienced VR users, do not expect virtual characters to strike out or push us away. Such events can cause users to become a little more wary of the virtual characters and afford them a little more personal space.

Another example of virtual human puppeteering is at FITE/CHAOS, a military training installation at Camp Pendleton, California (see Fig. 5.1). An actor, fluent in Pashto, a language of Afghanistan, is wearing a motion capture suit, studded with LED markers, and wearing additional markers around his mouth. This enables him to control the character in real-time and speak with proper lip syncing. The actor's cultural and linguistic knowledge, as reflected in his speech and movements, is carried through the motion capture system and embodied by the virtual character.

Fig. 5.1 Virtual character being puppeteered at Camp Pendleton, California

Virtual Human Presentation

While projection screens are often used to present virtual characters, they fall flat in several respects. Without stereoscopic displays, the characters are only presented in 2D. Without head tracking of the user, the characters and scenes cannot be portrayed with the proper perspective. Furthermore, a projector and a screen can only display a correct perspective for a single user, since only one image can be displayed at a time. An additional issue for projection screens is that they seemingly create a barrier between the space of the user and the space of the character. The user cannot walk past the screen into the character's space, and the character cannot emerge from the screen to enter the user's space.

We are using wide area tracking and a wide field of view display to create scenes where the user and the virtual human can freely move around and past each other. This allows the user to have a stronger sense of personal space, which can overlap with the virtual character's personal space, and allow non-verbal social interactions.

We presented a user with a virtual character, an American Old West outlaw, on both a projected screen (Fig. 5.2) and then later in an HMD on the IR STAGE (Fig. 5.3a, b). While the character was engaging on the projected screen, there was a more interesting response on the IR STAGE. When the character approached, the user took a step back, as noted by the initial position (marked by the green line) and the final position (marked by the red line) as seen in Fig. 5.3a, b. We theorize that this may have been in response to several factors: (1) avoiding the character due to the 3D stereo imagery of the HMD, (2) maintaining a visual framing around the character so as to keep the character in full view, or (3) maintaining an appropriate social distance (proxemics) from the character.

Fig. 5.2 A virtual character on a projected screen

With a typical projector and screen configuration, only one image is displayed, so every observer views that same imagery. This leads to problems with the eye gaze and gestures. If the virtual human tries to gaze or point at a particular person in a crowd, it may look like the virtual human is looking and pointing at everyone. By equipping each user with a head mounted projector, using retroreflective screens, and employing a tracking system, we can provide each user with personalized perspective correct imagery. This system, called REFLCT (Retroreflective Environments For Learner-Centered Training) is designed to unobtrusively deliver mixed reality training experiences (see Fig. 5.4a, b) [1]. The REFLCT system:

- Places no glass or optics in front of a user's face.
- Needs only a single projector per user.
- Provides each user with a unique and perspective correct image.
- Situates imagery within a physical themed and prop based environment.
- Can be low power, lightweight, and wireless.
- Works in normal room brightness.

Each user only sees the imagery from their own projector, since the retroreflective screens bounce light straight back towards the light source. This system allows each user to experience a perspective correct viewpoint, enabling each user to unambiguously perceive whether a virtual character is establishing eye contact, gesturing, or pointing a weapon at them. Furthermore, since no bulky optics cover the users' eyes, trainees can also establish eye contact with each other.

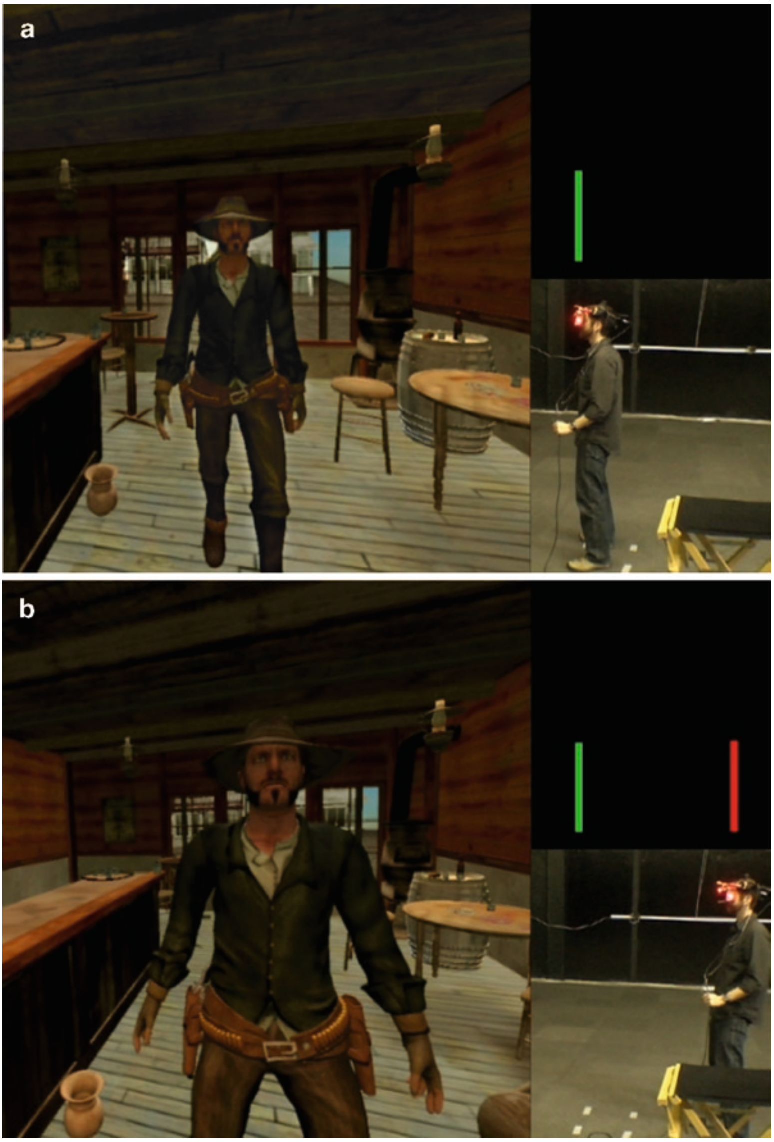

Fig. 5.3 (**a**, **b**) Stepping back in reaction to a virtual character on the IR STAGE

Stretching Space in Virtual Environments

We are particularly interested in combining redirection techniques with mixed reality stimuli to provide a more compelling illusion of walking through a virtually unlimited space. We believe the use of passive haptic feedback, physical props, and different walking surfaces can be used to augment this sense of immersion.

Fig. 5.4 (**a**, **b**) The REFLCT head mounted projector and associated projected imagery

Our first experiments with mixed reality redirection involved combining a scaled translational gain technique with a force-sensitive push cart. We constructed a heavy wheeled cart that was tracked in the IR STAGE, allowing us to render a virtual representation for the user to interact with when wearing the HMD. The amount of force the user applied to push the cart was used to calculate a scale gain on their virtual motion, effectively stretching the physical space to allow travel over greater virtual distances. To test this apparatus, we designed a hospital scenario in which the user was instructed to push a gurney through a building. Our preliminary tests have suggested that the spatial manipulations are less noticeable to the user when pushing the cart. We believe there are two possible explanations for this phenomenon. First, pushing on the cart provides distraction which may prevent the user from noticing the scaling. Secondly, since pushing the cart requires physical exertion, it may be that the increased physical effort psychologically prepares the user to move over a greater distance.

We have also begun experimenting with a redirection technique that leverages change blindness to stretch the physical space without manipulating the mapping between physical and virtual motions [12]. This technique alters the structure of the environment in subtle ways behind the user's back. Since the human visual system relies upon transient optical motion to detect changes to a scene, these structural alterations are very difficult to detect when they are applied outside the user's field of view. It is important to note that the user's motions are never scaled or rotated; instead, we simply structure the environment in such a way that the user naturally follows the path we lay out in the virtual world. For example, by moving a door in the corner of a virtual room, we can get the user to exit the room and proceed in a different direction without noticing. To demonstrate this approach, we have constructed a military training scenario where the user walks through a 3,000 ft^2 virtual village with multiple buildings while staying within a 900 ft^2 physical area (see Fig. 5.5a, b). We have also tested the change blindness technique in an interior office building environment. Our formal studies of this technique have shown it to stunningly effective. Out of 77 participants, each experiencing the redirection technique 12 times, only one person noticed the scene changes. Perhaps more importantly, we found that despite the changing environment, participants were able draw coherent sketch maps of the environment. A pointing task also revealed that they were able to maintain their spatial orientation within the virtual world.

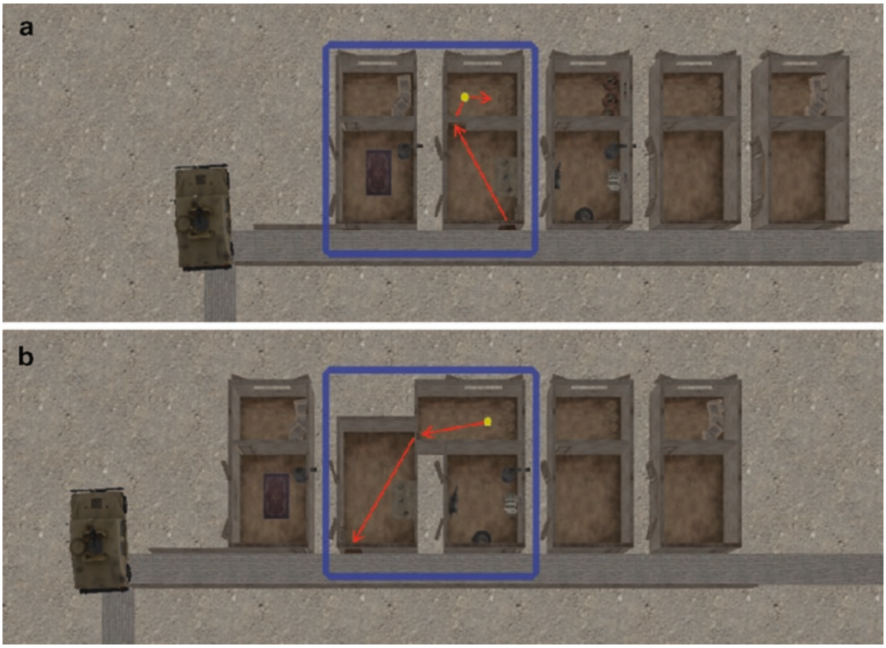

Fig. 5.5 (**a**, **b**) Users search multiple houses for a stash of hidden weapons. When the user enters the back room of each building (**a**), the doorway and the surrounding environment is altered, without affecting the user's view of the room (**b**). The user can explore the entire village without walking outside of the physical space

In addition to being nearly imperceptible, change blindness redirection is also well-suited for combining with mixed reality stimuli. For example, in our military training scenario, we repeatedly redirect the user over a 30 ft long gravel walkway. When exiting a virtual building, the tactile sensation of walking on a different surface contributes to the sense of being outside and walking on an expansive, continuous roadway between buildings. We are continuing to look for novel ways to leverage the advanced motion sensing capabilities of the IR STAGE to augment the illusion of stretching space, particularly those that engage the user's whole body.

Conclusion

The construction of the IR STAGE will continue to enable a variety of experiments that examine how humans perceive virtual environments and virtual human characters. We can explore how humans respond to virtual humans when several barriers between their worlds are dissolved. This will lead to opportunities for more believable characters, better rapport, improved assessment of intent, and better non-verbal communication. Furthermore, real-time tracking data allows systems to multiply the physical space available for locomotion. Redirection and other techniques can be applied to full effect when users are distracted and unable to see manipulations of the environment that steer them away from walls. As we expand the lexicon of redirection, it will become feasible to create training scenarios that are longer and more elaborate, with users roaming freely while completely immersed in their virtual world.

We feel that the IR STAGE and related infrastructure will be a valuable scientific apparatus that can provide the means to answer a variety of questions in immersion, interaction, and human perception.

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