Mutual Human Actuation

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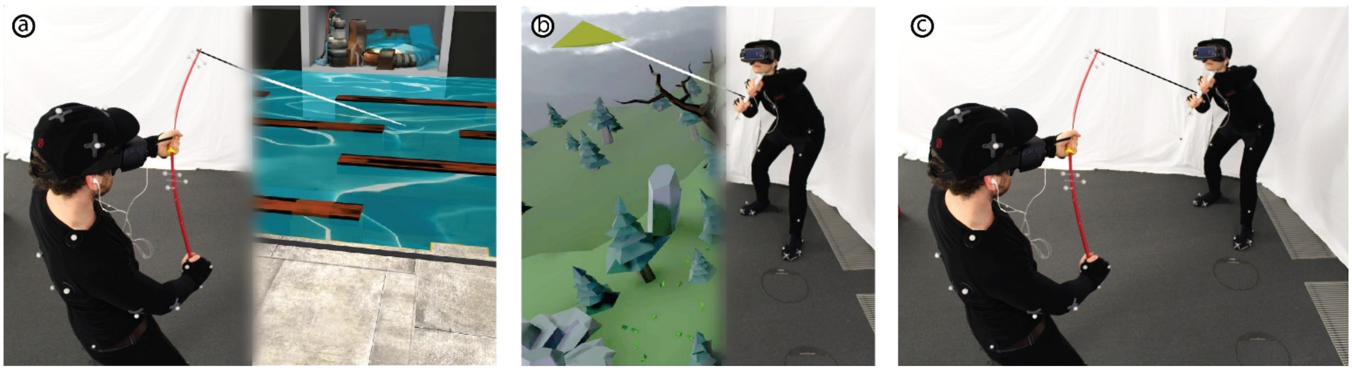

Figure 1: (a) This user, alone in his virtual world, is trying to pull a huge creature out of the water. He feels how the creature is struggling and pulling on his fishing rod. (b) At the same time, this other user, also alone in her virtual world, is struggling to control her kite during a heavy storm, which is whipping her kite through the air. (c) While users' experiences of force might suggest the presence of a force feedback machine, Mutual Turk achieves force feedback instead using *shared props* that transmit forces *between* users. The system orchestrates users so as to actuate their prop at just the right moment and with just the right force to produce the correct experience for the other user.

ABSTRACT
Human actuation is the idea of using people to provide large-scale force feedback to users. The Haptic Turk system, for example, used four human actuators to lift and push a virtual reality user; TurkDeck used ten human actuators to place and animate props for a single user. While the experience of human actuators was decent, it was still inferior to the experience these people could have had, had they participated as a user. In this paper, we address this issue by making *everyone* a user. We introduce *mutual* human actuation, a version of human actuation that works without dedicated human actuators. The key idea is to run pairs of users at the same time and have them provide human actuation to *each other*. Our system, Mutual Turk, achieves this by (1) offering shared props through which users can exchange forces while obscuring the fact that there is a human on the other side, and (2) synchronizing the two users' timelines such that their way of manipulating the shared props is consistent across both virtual worlds. We demonstrate mutual human actuation with an example experience in which users pilot kites though storms, tug fish out of ponds, are pummeled by hail, battle monsters, hop across chasms, push loaded carts, and ride in moving vehicles.

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INTRODUCTION
Many researchers argue that the next step in virtual reality is to allow users to not only see and hear, but also *feel* virtual worlds [8]. Researchers initially explored the use of mechanical machinery for that purpose, such as exoskeletons [1] or passive [13,19], robotically actuated [11] props.

Unfortunately, the size and weight of such mechanical equipment tends to be proportional to what they actuate, often constraining such equipment to arcades and lab environments.

Researchers therefore proposed creating similar effects by replacing the mechanical actuators with *human* actuators. Haptic Turk, for example, uses four such human actuators to lift, bump, and shake a single human user [2]. TurkDeck brings human actuation to real walking [3]. It allows a single user to explore a virtual reality experience that is brought to life by ten human actuators that continuously rearrange physical props and apply forces to the user.

While both systems produced highly-rated experiences for their users during user testing, unfortunately (1) the need to recruit four to ten human actuators means that these systems require a non-trivial amount of preparation, and (2) unsurprisingly, human actuators rated their experience significantly lower than the user's experience [2, 3].

In this paper, we address this issue by making *everyone* a user. We introduce *mutual* human actuation, a version of human actuation that works without dedicated human actuators.

MUTUAL TURK

Mutual Turk is a real walking virtual reality system that implements mutual human actuation. The key idea behind Mutual Turk is that it runs *two* users at the same time, synchronizing their experience so that every time one user is manipulating an object in her virtual world, the other user is subjected to forces presumably caused by something in his virtual world.

Figure 1 shows an example. (a) One of the two users, alone in his virtual world, is trying to pull a huge creature out of the water. Through the fishing rob he feels how the creature is struggling. (b) At the same time, the other user, also alone in her virtual world, is struggling to control her kite during a heavy storm, which she feels pulling at her kite. (c) In reality, both users are connected by means of a shared prop, so that all forces they output become input to the other user. This is the main concept behind Mutual Turk. Mutual Turk's main functionality is that it orchestrates users so as to actuate props just at the right moment and just with the right force to produce the correct experience for the other user.

To maximize immersion, we generally design Mutual Turk experiences so as to set users' expectations of upcoming haptic effects. The kite/fishing rod prop, for example, achieves this as illustrated by Figure 2a. The particular arrangement of logs in this pool gives the fishing rod user a steering task to perform, i.e., in order to reel in and save the struggling creature at the end of the fishing line, the user has to pull the fishing rod left and right in just the right order so as to make the creature pass in between the logs.

Meanwhile, the up-front knowledge about the fishing rod's motion sequence allows Mutual Turk to manage the kite user's expectations of what she is about to feel. As shown in Figure 2b, Mutual Turk makes the white flags in the background fly in the direction of where the other user is *about to* steer, suggesting to the kite user that she wind is about to change. Once the fishing rod user starts pulling and the kite user experiences the directional pull, this pull matches the kite user's expectations.

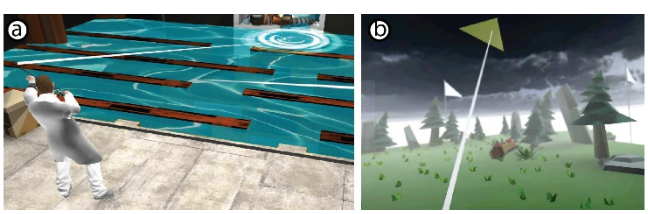

Figure 2: Visual puzzles allow us to pre-define the sequence of forces the respective user will produce.

SHARED PROPS

The key to enabling mutual human actuation is the use of shared props. Props allow users to exchange forces without revealing that these forces are generated by another human. If users' hands or any other part of the users' bodies were ever brought into immediate physical contact, this would instantaneously give away that the other side is human (through, e.g., skin softness, temperature, moisture, shape of hands). This is what the shared prop prevents. Thus, one way to think of Mutual Turk's shared props is as a means of masking the information exchanged between the users.

Different prop designs enable different levels of expressivity. We explored five: continuous force (most expressive), moving, impact, contactless sensations, and rearranging props (least expressive).

1. Continuous exchange of force between users' hands

The kite/fishing-rod prop from Figure 1 uses string to connect the two handles. This specific design allows the prop to eliminate much of the information about what is located at the other end of the prop—the only information that is transmitted is the direction and magnitude of the tension (Figure 3). This allows the system to re-envision the many dimensions that were filtered out, such as to render the kite at the end of a 100x longer tether.

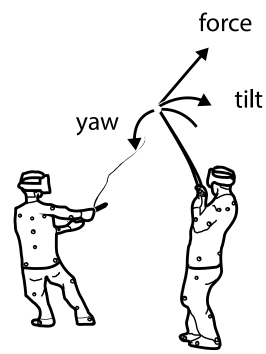

Figure 3 The fishing rod prop masks out all the information of what is on the other side, except the direction and magnitude of tension.

The reason why the fishing rod prop uses the additional tether for "obfuscation" is that the interaction is particularly expressive: the two users exchange forces over an extended period of time during which they modify their force output hundreds of times. And users feel each other's force "signal" well, as they hold the prop in their hands.

In contrast, less expressive interactions require less obfuscation, thus allowing the use of shared props that couple users more rigidly. This thereby allows transmitting additional degrees of freedom, such as translation etc. In the remainder of this section, we show four different classes of such less expressive interactions.

2. Continuous motion

In Figure 4a, the user pushes an empty cart under a faucet. (b) He watches as the faucet drops water into the tank.

(c) Meanwhile, in the other user's world, the world is collapsing and our user is making a dash for the escape pod. She hops onto the escape pod (thereby giving weight to the water tank in the first user's world). (d) She then rides the automated pod down an evacuation tunnel—(propelled by the first user pushing his cart), (e) just as the first user starts to push his (now much heavier) cart on to next destination.

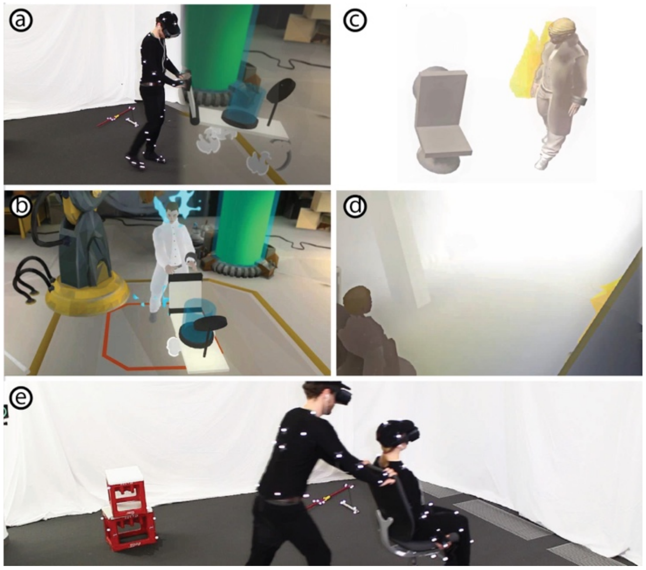

Figure 4: One user pushes cart around while the other enters and rides an escape pod.

The office chair prop transmits movement and rotation in one direction. In return, the user sitting on the chair affects the chair's inertia. Unlike the interactions in the previous category, only one user's hands are involved in driving the office chair. This allowed us to drop the tether and use a rigid prop instead.

3. Impact

The user in Figure 5a sees himself walking in stormy weather; he sees huge hailstones shooting down from the sky at an angle, hitting his body at various locations. (b) In the meanwhile, the other user is fighting back a monster using an improvised weapon made from a plastic tube she found at the lab.

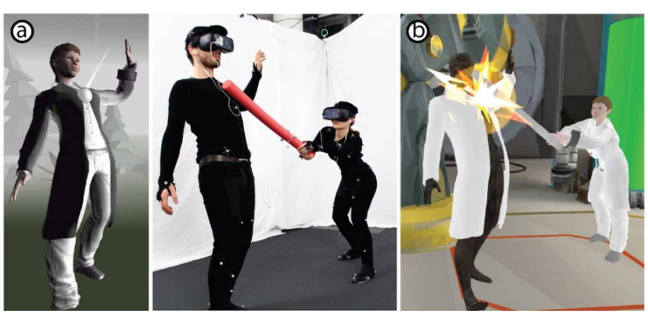

Figure 5: One user is getting bombarded by hail, as the other user is fighting a monster.

The foam stick used in this scene touches the other user for only very brief periods of time, which properly obfuscates the origin of the force.

4. Contactless sensations

In Figure 6a, our user is trying to fight her way back to lab against very heavy wind. (b) Meanwhile, our user in the other world is trying to get a fire going to distill the emulsion created earlier.

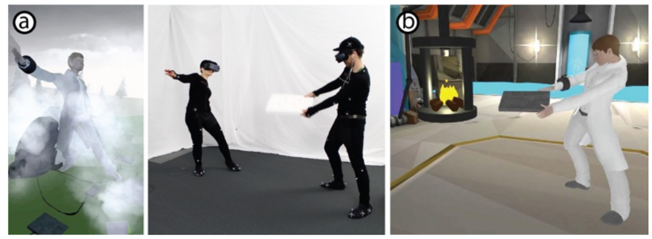

Figure 6: One user is trying to fight her way through heavy winds, while the other is trying to get a fire going.

The forces exchanged in this scene are obviously minimal. However, the interaction produces a strong tactile sensation (and certainly properly obfuscated).

5. Rearranging props

Finally, Figure 7a shows a user waiting for a series of pillars to rise in order to allow her to cross the pit ahead of her. As she lowers her right foot to probe the space below, she can feel the void. Once she sees that the pillar has fully risen, she can step on it. (b) In the meanwhile, the other user is solving a puzzle that requires him to place numbered boxes on matching tiles.

This is the least expressive type of exchange between two users as no physical contact between the two users is ever established. It thus is also the most obfuscated type of interaction.

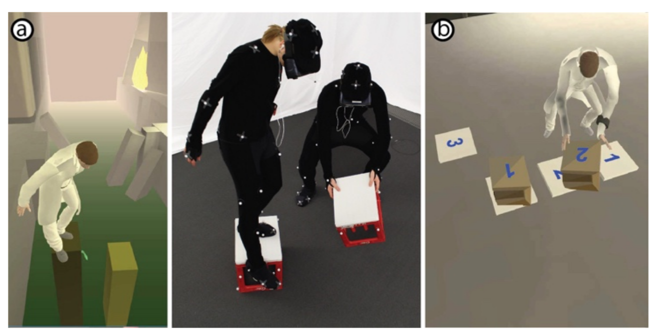

Figure 7: One user is waiting for the next pillar to rise, while the other user rearranges boxes to solve a puzzle.

Summary of props and their interactions

Figure 8 summarizes the categories for which the above were examples.

	expres-siveness	obfuscation required	example prop
continuous force exchange w/ hands	high	high	fishing rod
continuous motion			office chair
impact			water noodle
contactless interaction			boxes
rearranging props	low	low	foam plate

Figure 8: Classes of Mutual Turk props

SYNCHRONIZING USERS

As discussed earlier, the main function of the Mutual Turk system is to serve as scheduler, i.e., to orchestrate the two users in a way that their experiences are properly synchronized in time and space.

So far, we only looked at what we call *action sequences*, i.e., sequences during which the users already hold the shared prop and the subsequent interaction emerges largely from the use of this prop.

As illustrated by Figure 9, complete Mutual Turk experiences are more encompassing than this. Mutual Turk must not only synchronize the use of the shared props, but also their *acquisition* and *disposal*. A typical scene consists of a period of real walking within a designated area, the acquisition of a prop, the use of the prop forming an action sequence, the disposal of the prop, and return to unencumbered real walking. Experiences are then sequences of such scenes.

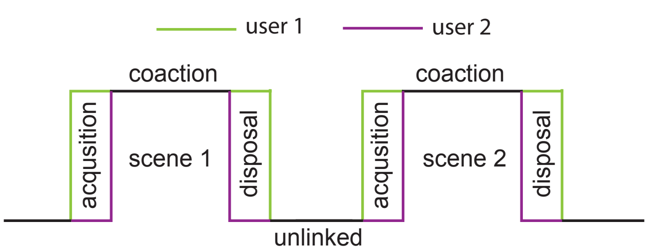

Figure 9: Mutual Turk experiences typically consist of multiple scenes, each of which consists of prop acquisition, use, and disposal.

Prop acquisition

To show an example, we returns one more time to the kite/fishing rod example. This time we are joining the two users early. They are still real walking unencumbered; all props are located on the ground and within the tracking volume.

Figure 10: (a) The scene starts by the creature across the pool crying for help as it falls into the water. (b) The fishing rod, lying on the ground next to our user, might just be the tool to rescue the creature. Our user picks it up and (c) holds his its end over the spot where the creature just fell in, waiting for the creature to reach for it. (d) As the position of the kite handle in the physical world stabilizes, (e) our user in the other world notices a kite stuck in a tree. The kite's handle is hanging down; she reaches out and grabs it.

Figure 10: Acquisition of props

Once both users have acquired their props, the action sequence begins and the fishing rod user can rescue the creature by steering it through the gaps between the logs, as already shown in Figure 2.

Prop disposal

Towards the end of the action sequence, the fishing rod user has reeled in the creature and pulled it out of the pool. Figure 11: (a) He now slowly lowers his fishing rod, ready to drop it.

(b) Meanwhile in the other world, the kite user has succeeded at collecting enough lightning energy using her kite. She returns to the tree, tugs the kite under one of its roots, and leaves it there.

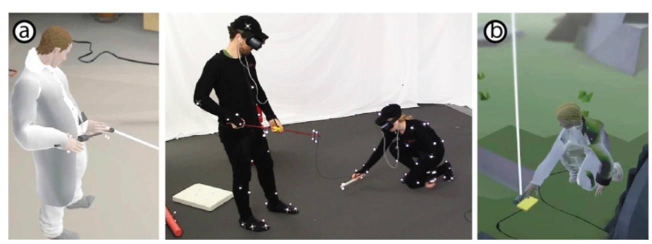

Figure 11: Disposal of props

Now that the kite user has let go of the prop, the fishing rod user has sole control and can put the fishing rod away. This completes the disposal sequence and both players engage in the next real walking sequence, walking towards the next prop acquisition.

CONTRIBUTION, BENEFIT, & LIMITATIONS

Our main contribution is the concept of mutual human actuation. The main benefit of this approach is that it eliminates the need for dedicated human actuators, instead allowing everyone to enjoy the experience of a user. At the same time, Mutual Turk still offers the benefits of human actuating system, i.e., it is allows creating human-scale force feedback without mechanical machines. We have created a proof-of-concept implementation.

The main limitation of Mutual Turk is that designing experiences for mutual human actuation requires additional care and design skill, as each scene is subject to at least twice the number of design requirements as regular virtual reality scenes, which tend to be designed around a single user. While designing for Mutual Turk requires extra care, it does indeed allow telling encompassing stories. The 10 interactions are in fact the snapshots from a single 30 min experience *Edison Jr.*: the user awakes, meets the ghost of Thomas Edison's, who instructs the player to harvest energy from a thunderstorm through a kite, save his new body from a pool using a rod, and finally collect items with a cart to revive him. We see mutual human actuation is a tool to add active haptics to any type of VR experience, e.g., theater plays, circus shows, theme park rides, etc.

Furthermore, Mutual Turk users can make mistakes while working on their tasks or they may choose to explore the world differently (e.g. leave the tracking volume) from how the system incentivizes them to. Mutual Turk handles this not that differently from regular real-walking VR systems. Mutual Turk uses visual guides to discourage users from touching one another/leaving the tracking space. That said, in our user study all participants followed the story arc.

RELATED WORK

The work that is presented in this paper is based on haptics and motion experience devices, passive haptics, and in particular human-actuation.

Haptics and motion experience devices

A wide range of devices has been created in order to provide users with a sense of touch and motion. Many of the standard stationary platforms are based on the 6-DOF Stewart platform based on six hydraulic cylinders [17]. HapSeat aims to emulate a motion platform by actuating both hands and the head to simulate the effect of self-motion [4].

Force feedback can be realized through a variety of approaches. FlexTorque creates force feedback using an arm exoskeleton using retractable belts [18]. Rope Revolution uses a rope as a tangible medium for force input and output [21]. Seminal work by McNeely introduced the idea of using a robotic arm to repositioning a single prop so as to simulate a surface wherever the user tries to touch [11].

Tactile sensations, such as the wind effect discussed in this paper, can also be generated using a range of devices, such as the AIREAL [16].

Passive Haptics

Previous work shows that props, also known as passive haptics can enhance the sense of presence. In a study by Hoffman [5], participants in virtual environment could guess an object's properties, such as the weight of a teapot more accurately if it had been given a physical representation. In a study by Insko et al. [7], participants immersed in a virtual environment had cross a virtual pit by balancing a ledge. Behavioral presence, heart rate, and skin conductivity were affected more, if the ledge was created using a physical wooden plank.

Several "passive haptic" systems use physical props in real walking environments. Low et al., for example, use Styrofoam walls onto which they project augmented reality experiences [10]. Similarly, mixed reality for military operations in urban terrain [6] uses passive haptics to add a haptic sense to otherwise virtual objects, terrain, and walls.

FlatWorld integrates large props into a physical world; *between* experiences these props can be rearranged to match the next virtual world [14]. Kohli et al. use redirected walking to allow users to encounter a stationary prop at different virtual locations [9]. In Substitutional Reality [15], researchers conducted a study on how much visual at what point a mismatch between physical and virtual props breaks believability.

Human actuation

Since the size and weight of mechanical machinery tends to be proportional to what they actuate, the use of mechanical motion equipment tends to be constrained to arcades and lab environments. In order to bring haptic and motion experiences to a wider audience, researchers proposed creating similar effects using *human actuators* [2].

Haptic Turk, for example, uses four such human actuators to lift, bump, and shake a single human user [2] in the form of a human motion platform. By making human actuators perform movements according to timed motion instructions, Haptic Turk assures that users' physical experience matches their virtual experience. TurkDeck extends the concepts of human actuation to real walking [3]. It allows a single user to explore a virtual reality experience that is brought to life by ten human actuators that continuously rearrange physical props and apply forces to the user.

Mutual Turk builds on Haptic Turk and TurkDeck, but eliminates the need for dedicated human actuators.

IMPLEMENTATION

As illustrated by Figure 12, Mutual Turk runs inside of *Unity 3D* and is written in *C#.* This includes (1) a native *OptiTrack NatNet* Unity plug-in that receives the tracking data directly from OptiTrack Motive (*MotiveDirect* [12], open sourced by the authors), (2) Petri net server and client (see below) and (3) our demo experience called "Edison, Jr." (in which users have to perform a series of experiments to help their ancestor regain physical form).

Headsets To allow for unencumbered real walking, we used Samsung S6s mounted into GearVR headsets with earphones attached. Both headsets run their own Unity app where a Mutual Turk client and the adventure experience are embedded. Via our wireless network, the Mutual Turk client receives the tracking data and communicates with the Mutual Turk server to synchronize its Petri net with the other Mutual Turk clients.

Tracking We use nine *OptiTrack Prime 17w* cameras to track a 5m x 5m tracking space, running the *OptiTrack Motive 2.10* tracking software. Users wear motion capture suits. To make props trackable, we attached rigid body markers, 6.7mm to 9.5mm. Figure 13 shows where the markers are attached to our shared prop.

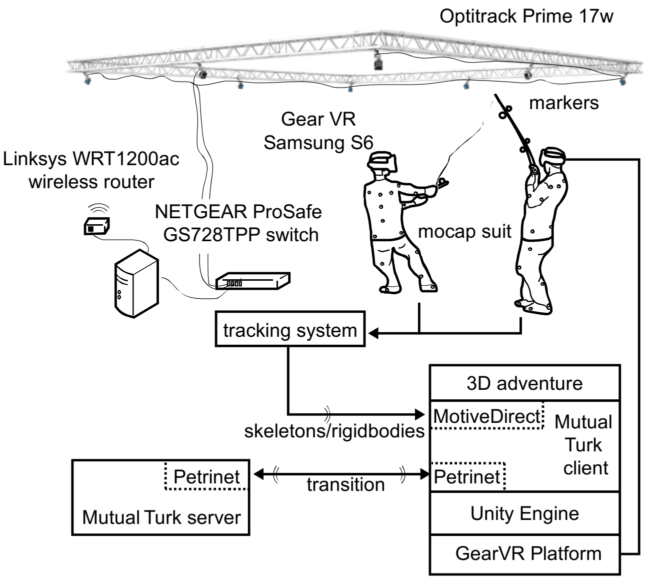

Figure 12: The Mutual Turk system

Mutual Turk runs in real time with two users. We achieved 40+ fps by making VR scenes low-poly, simple lights, etc. In addition, we enabled time warping to guarantee interactive rates. The maximum delay between visual & haptics was around 25ms. The devices receive tracking updates wirelessly at 120 Hz with ping interval 5ms in average.

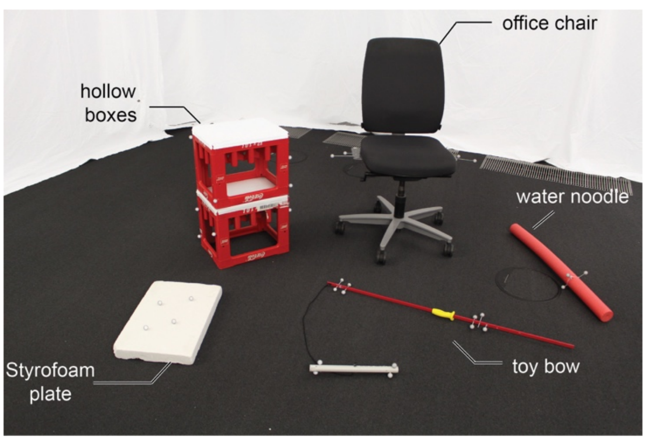

Figure 13: All props used in the *Edison, Jr.* experience

Tracking acquisition and disposal

Mutual Turk determines when to advance the global timeline using simple rules, such as "fishing rod user is touching the fishing rod and the fishing rod prop has started to move".

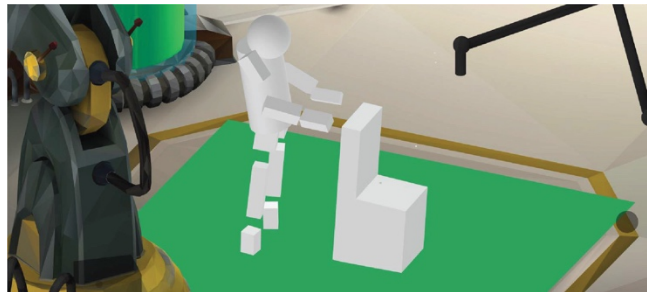

Figure 14: Behind the scene, Mutual Turk tracks users and objects using simple primitives

In order to detect acquisition and disposal with additional accuracy, we overwrite Unity's collider with the following custom code. (1) Our system approximates the volume of the user's body by padding the mo-cap suit marker locations with volumetric primitives as shown in Figure 14. (2) Our system determines collisions by ray casting from the body primitives to the props (down-sampled to 10 rays per cubic meter in order to run on the mobile phones in the GearVR headsets). (3) Our system determines that an object has been picked up, if the standard deviation of the position offset history in the past 0.5 seconds is > 1cm.

Petri net

Internally, Mutual Turk considers the two users and their acquisition and disposal of props as a concurrent state machine. It manages this state machine as a Petri net [20]. This allows Mutual Turk to ensure that the overall story arc does not progress until both users are ready for it. The Petri net is also useful for level designers to detect and avoid potential dead locks, i.e., situations where both users would be waiting for each other.

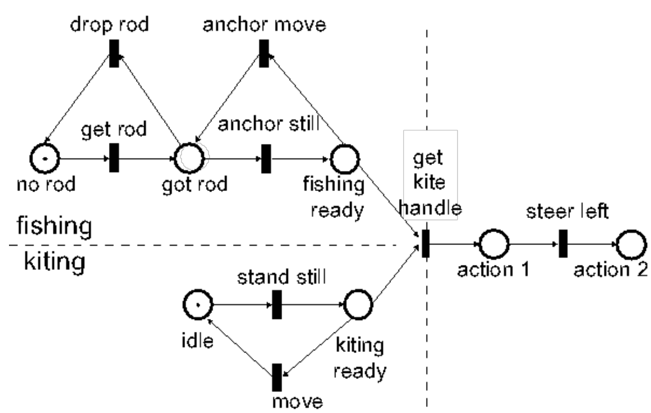

Figure 15: The Petri net diagram that governs the acquisition sequence of the fishing rod-vs.-kite scene

Figure 15 shows the Petri net of the fishing rod vs. kite acquisition sequence described earlier. As we see, in the first half of the Petri net, the fishing user and the kite user have no influence on each other. The fishing user has the freedom to pick up or drop the fishing rod anytime and the kite user has the freedom to walk around as well. Only when they both are in their correct respective locations and the kite user has grabbed the handle, both users get to move on. One can extend the Petri net to continue the experience of the remaining user as a single-user without mutual haptics experience if one of the users refuse to progress.

Tracking and extrapolation during action sequences

Mutual Turk tracks users' props at all times. During action sequences, it extrapolates the props' movement, which allows Mutual Turk to anticipate interactions between the prop and the other user. In the hail vs. zombie scene (Figure 5), for example, Mutual Turk extrapolates the movement of the foam stick to determine when and where it will hit the other user. Based on this, the system either generates a new hailstone with and send it off towards the anticipated collision point or it alters the movement path of an existing hailstone, so as to hit the predicted location. Until the impact actually occurs, Mutual Turk continues to track prop and user and readjust the movement path of the hailstone accordingly.

In the fishing rod vs. kite scene, Mutual Turk needs to know the amount of tension on the tether, e.g., in order to determine whether the user is pulling hard enough to reel in the creature, but also to render the kite and fishing line visuals properly. Figure 16 illustrates how the fishing rod/kite prop allows Mutual Turk to sense this tension. The key idea is that the prop bears *two* markers on the fishing rod side. The angle between the two markers indicates how much the rod is currently bent, which indicates the applied force.

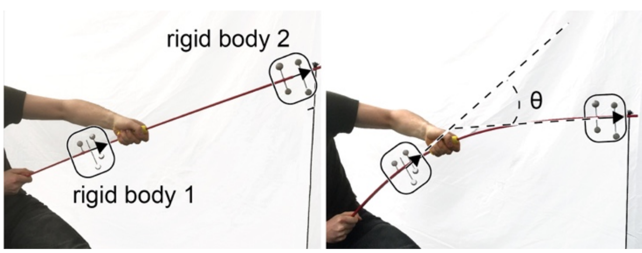

Figure 16: Mutual Turk computes the tension applied to the fishing line based on how much the prop is bent.

Placing props in a limited tracking volume

We generally design our experiences so that props are located along the edge of the tracking space and make users return props to their original place after use. This keeps the center area free of obstacles, allowing us to use that space for real walking. To prevent users from accidentally stepping on any props, Mutual Turk camouflages the props that are not currently available with virtual objects, such as by placing a big virtual robotic arm in the same location where the boxes are.

DESIGNING A MUTUAL TURK EXPERIENCE

Designing Mutual Turk requires additional effort, because any interaction has to satisfy *two* user experiences at the same time. When we designed the Edison Jr. experience described throughout this paper, we proceeded as follows.

#1 Designing a single user experience

We started by designing a user experience for a single user. In order to balance both users' experiences, we composed half of the experience from scenes where the first user actively actuates the environment (and thus the other user) and the other half from scenes where the first user primarily experiences actuation by the environment (and thus the other user). Based on this experience, we create matching passive props. We then tested the experience using dedicated human actuators.

#2 Ideating the other experience based on the first one

We then ideated multiple scenes for the second user that might take place during the first single user's experience, while considering the first user's experience as design constraint. We combined the respective props into shared props and tested them.

In many cases, we succeeded at finding second user experiences without modifying the first user's experience; in some cases, we revisited the first user's experience in order to improve the second user's experience.

#3 Restructuring the two timelines

We then tested the experience and swapped some scenes and tweaked scenes until both experiences flowed well.

In the particular case of the Edison Jr. experience presented throughout this paper, we then doubled the length of the overall experience by combining the first user's experience and the second user's experience into a "canon", i.e. while one user is on the 1st half of his or her experience, the other is in the 2nd half.

USER STUDY

We conducted a user study to validate our Mutual Turk system. We recruited 12 participants (age 19-23) in 6 pairs from our institute. 3 participants had never worn a head mounted display and none had experienced full body motion capture in VR before. Each participant experienced a 10-min subset of the *Edison Jr.* experience (flying kite, pushing cart, using fishing rod, riding escape pod) using Mutual Turk and a control condition that only had passive haptics. The order was counter-balanced. After each condition, they filled in a custom questionnaire (measuring overall enjoyment and perceived realism) and the Presence Questionnaire [22].

Results

Figure 17 shows the main result of our study: participants enjoyed their experience significantly more in the Mutual Turk condition than in the passive haptics baseline condition (6.2/7) vs. (3.9/7) (Student's $t(22)= 6.0$, $p<0.01$). In terms of perceived realism, Mutual Turk received significantly higher rating as well (5.1/7) vs. (3.4/7) ($t(22)= 3.4$, $p<0.01$).

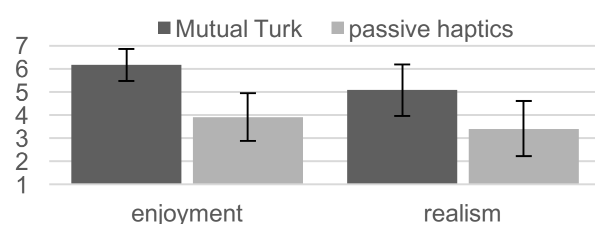

Figure 17: Participants enjoyed their experience more in the Mutual Turk condition

To better understand what caused the higher enjoyment, Figure 18 shows all the presence scores. Mutual Turk received higher overall presence score (5.1/7) vs. (4.7/7) ($t(22)= 2.1$, $p<0.05$).

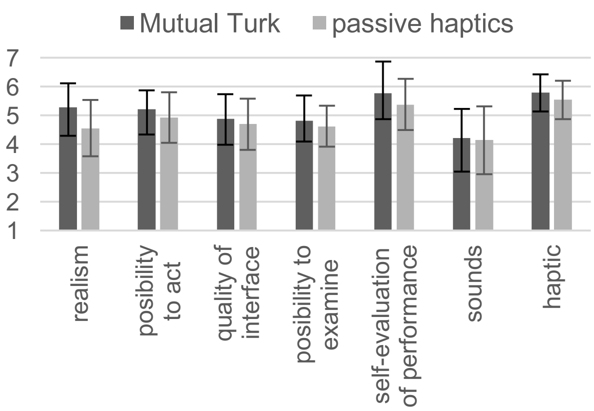

Figure 18: Presence scores

All participants said that they enjoyed the experience more with Mutual Turk because they could feel the force feedback. “It was very crucial for me to have the force feedback when flying a kite and fishing”, said p1. Participants did feel the force feedback was matching to their expectation. “It felt exactly as what would happen in the virtual world”, said p7. No participant experienced any performance issues during the test. “The system is responsive and real-time both on tracking and haptics”, said p2. Although all the participants had never experienced full-body motion captured VR, p10 explicitly said “the real-walking VR only amazed me in the beginning for a couple of minutes, but later it was all about the haptic feedback”.

CONCLUSION AND FUTURE WORK

In this paper, we introduced the concept of *mutual* human actuation, presented a simple implementation based on Unity 3D, and demonstrated this system at the example of a simple demo experience. The main benefit of our approach is that it eliminates the need for dedicated human actuators and instead allows everyone to enjoy their experience in the role of a user. As future work, we are planning to extend mutual human actuation to more than two users.

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