Tangible VR: Diegetic Tangible Objects for Virtual Reality Narratives

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ABSTRACT

We present a system for diegetic tangible objects in virtual reality (VR) narratives. The system integrates a custom-designed sensor unit, built with low-cost off-the-shelf hardware, to track objects in VR and to support a variety of custom-made and found tangibles. In its current form, the sensor unit tracks the objects' orientation and supports the authoring of specifically designed interactions for each tangible object. We contribute our design rationale, sensor unit, and four proof of concept prototypes, including a cube, a stuffed animal, a treasure chest, and a wooden boat, demonstrating how we leverage passive and active haptics to create a closer link between real and virtual worlds. For developers and users of VR, we expand interaction possibilities to include the physical characteristics of tangible objects. For the field of tangible narratives, we expand the current use of diegetic objects.

Author Keywords

Tangible interaction; virtual reality; interactive narratives; tangible diegetic objects; narrative design; tangible design.

ACM Classification Keywords

H.5.1. [Information Interfaces and Presentation]: Multimedia Information Systems---*Artificial, augmented, and virtual realities*; H.5.2. [Information Interfaces and Presentation]: User Interfaces---*Input devices and strategies, Interaction styles*; K.8.0. [Personal Computing]: General: Games.

INTRODUCTION

The first generation of consumer virtual reality (VR) technology features headsets, controllers, and peripheral sensors that primarily track and represent the user's head and hand movement in virtual environments. For the most part, commercial VR does not track the rest of the body, and tangible interaction within virtual worlds consists of the haptic feedback of tracked controllers. The lack of a body and more complex tangible interaction in VR is currently a question of accuracy and consistency. The hardware and the emerging design trends of VR games and applications strive to minimize known issues of sensory conflict between the visual, vestibular, and proprioceptive systems, as mismatches can lead to discomfort. For example, the cockpit-style VR games (e.g., in spaceships and cars) are an attempt to create a closer connection to reality, with visual representations of seated experiences for users who are also seated.

We suggest that there may be lessons learned in research that deals with tangible and embodied interactions that can contribute to the current design challenges in VR and lead to a greater variety of connections between the real and the virtual. We argue that rich tangible interactions with everyday objects can be a helpful step towards engaging the body in VR. Furthermore, the visual and technological capabilities of VR may also be an opportunity to address gaps in tangible interaction research, particularly in its tangible narrative subset.

We propose to bridge these fields with a focus on tangible diegetic objects, i.e., interactive physical objects that have meaning within a virtual narrative environment. While controller-based interactions are the current standard consumer VR, their tangible and tactile qualities communicate limited information about the objects they represent or the storyworld in which they exist. In this regard, we emphasize the use of passive and active haptics for tangible objects: active haptics for programmed digital feedback (e.g., timed vibrations during an interaction) and passive haptics for their non-digital feedback (e.g., the weight and texture of an object). Bringing these considerations together expands the design space of tangible narratives, first in the choice of the objects themselves, and second in the visual affordances of VR, as any object can gain or lose its visual attributes.

In this paper, we contribute our design rationale, four tangible prototypes, and a self-contained, encased sensor unit that is designed to support a variety of custom-made and found tangibles. In its current form, the sensor tracks the objects' orientation as well as more specifically designed interactions. Using this sensor unit, our four proof of concept prototypes include: a cube to explore 360-degree

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object manipulation; a stuffed animal toy to explore soft tangibles and a combination of passive and active haptics; and two objects created by two high school students to explore the ability to bring one's own objects into VR.

Following the creation of our first cube prototype, we conducted an informal user test to assess user experience. With the results, we continued to iterate on our design and conducted a second user test with the stuffed animal prototype, leading to simple design guidelines that were then adopted by two high school students in the creation of their own tangible objects. Reflecting on the limitations of the current system, we discuss directions for future work as the technological capabilities of tracking tangible objects in VR continues to expand.

For developers as well as end-users, the system expands interaction possibilities in VR to include the physical and narrative characteristics of objects. For the field of tangible narratives, the system expands the current use of diegetic objects by conceptualizing user-created tangible objects, enabled in VR with our proof of concept sensor unit. Beyond narratives, our system could support industrial designers, who can incorporate physical products in VR; makers and hobbyists, who can build on our work to add more varied interactions in VR; as well as families and friends, who can enrich storytelling in casual settings by incorporating low-cost 3D printed objects or everyday items into VR.

RELATED WORK

VR and the Body

The first generation of commercial VR features tracked controllers and tracked headsets that enable a 1:1 representation of a user's head and hand movement in virtual environments. The room-scale experiences of the HTC Vive[1] or of larger dedicated spaces like The Void[2] also track and represent the user's position.

These representations of the body in VR raise new challenges for designers and raise new user expectations. The tracking technologies are not complete and not entirely reliable, and designers often mitigate these challenges by either omitting or abstracting the body. The "uncanny valley" of representation is said to result in the jarring feeling of seeing an imperfect but realistic virtual self, e.g., virtual fingers with a delayed response to actual movement. It is also difficult to accurately match the position of arms and legs, and their imperfect representation is said to be worse than their absence [10].

As of the beginning of 2017, a common solution within the game industry is to use floating and gloved cartoon hands without a body [10, 15, 18]. The goal in these cases is to avoid any mismatch between what the player sees and feels, emphasizing meaningful and accurate interaction over visual representation. While we know very little about their methods, these industry perspectives are an important consideration for current VR design. VR has begun to engage a relatively large consumer audience, and it is likely that there has been more VR hardware and software produced in the last year than any point in its history.

Tangible Narratives

As a subset of the field of tangible, embodied, and embedded interfaces, tangible narratives have attempted to create meaningful interactions that engage the body. These narratives employ storytelling characteristics such as plot, character, or setting, although not necessarily all three [9]. In this context, we define meaningful interaction as any interaction that is significant to the narrative or to the body, or both. Examples include grouping characters mapped to physical pawns to better understand their complex relationships [19], or connecting physical triangles that represent story components like character, action and setting to create and discover stories [8].

Such systems are generally said to offer users embodied kinesthetic actions that support emergent and exploratory interactions. Other forms of embodied narrative interaction include, for example, holding a vibrating controller when it represents a slipping on-screen rope, or pointing it in a dark corridor when it represents a flashlight [5].

Externalizing a virtual object allows designers to emphasize its passive haptic qualities (e.g., its texture, size, and weight) while also making use of the animations and environment of its virtual counterpart. The "sympathetic interface" of *Swamped!* externalizes an on-screen chicken as an interactive plush toy, allowing users to control a series of virtual actions [13]. Larger scale embodied narratives have precedence in projects like KidsRoom, a playspace that includes interactions with physical and virtual objects to advance a narrative [3].

Threshold Objects and Diegetic Content

To determine how these embodied interactions or tangible objects contribute to their narratives, we can begin by asking whether they are diegetic. Diegetic interactions and objects exist within the space and time of a narrative's world and can be an effective strategy for interaction design and for narrative design [9]. For narrative design, diegetic objects and interactions can communicate additional characteristics of the storyworld. For interaction design, diegetic objects and interactions can communicate to the user how to perform an interaction, based in part on the affordances defined by the object as well as its storyworld. For example, the glowing visual qualities of an orb could communicate that it has magical properties and exists in a world of magic, while its suppleness and subsequent visual or haptic feedback could help to communicate that squeezing the orb is necessary when casting a spell.

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[1] https://www.htcvive.com/

[2] https://thevoid.com/

Janet Murray's proposed "threshold objects" function in much the same way, aiding the user to cross the threshold into a designed experience; these could be physical objects, but also could pertain to dimensions of "space, character, time, social conventions" [22]. Ideally, the threshold object anchors the user in the storyworld while also limiting their interaction possibilities to maintain a believable narrative consistency. In a recent review of 21 tangible narrative systems, only a quarter of the systems used diegetic tangibles, a clear opportunity for future work [9].

Current VR game design uses diegetic content as a solution to some of the design differences between "flat" video games and VR video games. VR game designers argue that conventional menus and UI are ineffective in VR, and instead offer that functionality using narratively-contextual in-game objects, e.g., a companion character instead of a menu (game designer Kimberly Voll [30], describing *Fantastic Contraption*), or a virtual backpack instead of a non-diegetic inventory (game designer Colin Northway [23], describing *The Gallery*). Diegetic UIs communicate information about the world and circumvent the challenge of where and how to place conventional menus or other non-diegetic UI in VR.

There is a similar necessity in sound design for VR, as the position and direction of sound is more apparent to a user who can turn their head or move within a virtual environment [29]. Non-diegetic music, i.e., the score that helps communicate the emotional nuances of a game, can seem out of place when coming from specific points in a VR environment. One solution is to create a diegetic source of the music within the world (e.g., a radio); the VR game *Land's End* offers another solution, "tuning" the world to a specific key so that interactions with in-game objects cue sounds that harmonize [21]. Like other diegetic content, sound can communicate important contextual information about the storyworld or the objects within it [1].

Bridging the Real and Virtual

Bringing these perspectives together suggests the possibility of a diegetic tangible object in VR that helps to bridge the real and virtual worlds. There are several systems that address at least one of the challenges of such an object. Metaspace II uses fiducial markers to track an object in a system that also attempts full body tracking for two users [27]. The passive haptics of the object, i.e., its inherent tangible characteristics, are said to enhance immersion, but the object (a large cube) allows very little tactile examination, especially as the user must keep the fiducial marker visible to a camera's view. The same is true of the objects in Real Virtuality [4], with optical markers placed "in areas that users are unlikely to touch," to avoid occlusion. These are best when integrated into the design, as with their example of a torch with optical markers close to a virtual flame.

Deeper tactile examination is available in non-VR tangibles like those of The Reading Glove, which consists of several diegetic objects that cue recordings of sections of a narrative when touched [28]. These objects can be handled and examined, and were chosen by the designers for their unique physical properties. A potentially limiting aspect of this kind of narrative is that it requires an installation which could affect its scope and length; furthermore, if diegetic, the tangible objects could be unusable for a narrative with a different storyworld. However, passive haptics have been shown to increase a sense of presence in virtual environments, as in the example of a 1.5-inch wooden board simulating a ledge in front of a pit [20]. The focus on enhancing the passive haptics of the objects can be contrasted with design that focuses on "enhancing the user" in projects like Impacto and Affordance++, both using electrical muscle stimulation to simulate haptic feedback [16, 17].

With tangibles objects in VR, designers can potentially use a single object to visually represent multiple objects. Snake Charmer is a robot arm that dynamically presents the textured faces of an object (e.g., a cube) so that a VR user can touch what seems like multiple unique objects [2]. The system tracks the user's hand to predict what object the user intends to touch. One of the system's limitations is that as the object is attached to a robot, it cannot be freely held and manipulated.

The Tangible Proxies system offers a possible solution, using object tracking and AR to overlay pre-set virtual objects onto physical objects in the immediate environment, e.g., any household cylindrical object could act as the handle for a virtual flashlight [12]. Similarly, Substitutional Reality [25] proposes several alternate levels of VR overlays drawing on the physical characteristics of the user's real environment. These range from 1:1 matching of actual objects to complete changes in the object's type and function. The authors report that participants found exact matches to be best for "believability" in VR, with the next best solution being objects having similar affordances. The three preceding systems have not yet been used for storytelling.

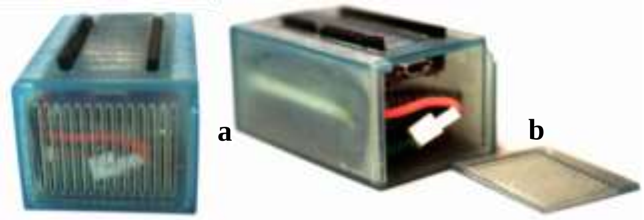

Figure 1 (a, b). The sensor unit, consisting of an IMU, a Blend Micro, and a battery.

DESIGN RATIONALE

We use lessons learned from tangible interaction research, VR design, and tangible narrative systems to address the lack of diegetic objects in tangible narratives and to contribute to the increasing development of physical interactions in VR. From tangible interaction research, we borrow an emphasis on the physical and tactile properties of tangible objects, allowing for emergent and embodied interactions with these objects. From VR, we employ the visual flexibility of the environment as well as of the objects themselves. From tangible narratives, we employ narrative and diegetic objects as a means to create a context for tangible interaction that appropriately bridges the real and the virtual.

We propose a device-agnostic sensor unit to create this link (Figure 1a, b), offering the ability to import an object of one's choosing into VR, detect and align the object's actual and virtual orientation, add sensors and interactions, and subsequently allow the object to become visually more than the sum of its parts in VR. As with Tangible Proxies or current tracked VR controllers, any tracked object can visually become any other object from scene to scene. What many of these current systems lack is the tangible specificity of objects like those in non-VR applications like the Reading Glove. We suggest that by combining the capabilities of a sensor unit with a greater focus on the tangible and diegetic qualities of the objects, we can create a richer link between the real and the virtual, helping to adapt and appropriate any handheld object into VR and support multiple tangibles and multiple narratives.

As proofs of concept, we created four diegetic objects for narrative environments in VR, each using passive and/or active haptics and supported by our sensor unit. The objects are interactive and situated within a sketch of a narrative that helps to explain to the user what interactions are required. Each object also explores a particular aspect of tangible design to show the potential variety of physical characteristics; incidentally, these characteristics also serve to differentiate these objects and interactions from conventional controller-based interactions in VR.

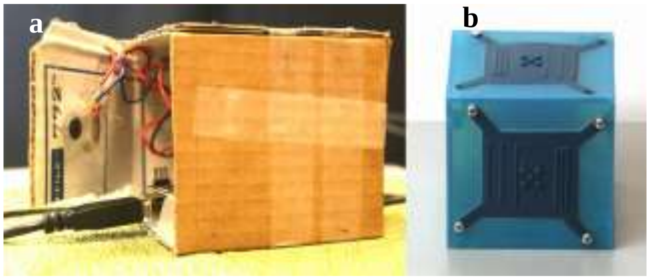

Figure 2 (a, b). First and second iteration of a tangible cube prototype featuring 360-degree object manipulation.

Our first tangible object is an interactive cube (Figure 2a, b). Like Metaspace II [27], the cube can be picked up and held; like Snake Charmer [2], each of its six sides has unique tactile characteristics, e.g. various patterns of raised bumps and lines. In addition to these passive haptics, we add visual, auditory, and active haptic feedback throughout the interaction, using VR and sensors inside the cube. Our cube demonstrates an interaction that requires full 360-degree manipulation of an object. The affordances of the cube (i.e., the fact that it has six sides and can be freely rotated in two hands) contributes to how it is used and examined.

As a contrast to the convention of hard physical interfaces, especially those for video games and the first generation of controllers for VR, our second object is a furry, hollow raccoon toy, i.e., a soft tangible. In addition to the passive haptics of its synthetic fur, we designed a skeletal cage to give its body structural integrity and provide the user with a more complex tactile sensation when stroking the fur. We supplement the passive haptics with active haptics for specific feedback in the interaction scenario: the animal has a heartbeat that is either calm or accelerated, and can also move its head. VR adds two unique features to the interaction. The first is that it reduces the animal to its core tangible properties, with a particular size, shape, and length, meaning that the animal in VR can be any animal with corresponding features. For example, we used a stuffed raccoon (Figure 3) to represent a squirrel in VR. The second is that because the user's view of the tangible is obscured by their headset, the avatar of the animal can regain all its virtual properties when it is set down, moving and interacting within the virtual environment.

Figure 3. A soft tangible prototype featuring active and passive haptics.

With our third and fourth tangible objects (Figure 4a, b), a wooden boat and a treasure chest, we hope to emphasize the ease with which storytellers and users can create or appropriate their own tangibles within virtual environments.

With the opportunity to collaborate with two high school students for a month, we used traits common to our first two objects to establish a set of simple design guidelines for the creation of new diegetic tangibles:

- the object can physically house the sensor unit;
- the object is diegetic, with emphasis on its physical affordances; and
- the interaction scenario benefits from the visual affordances of VR.

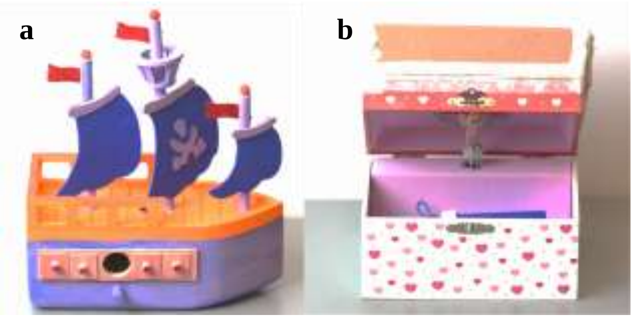

Figure 4 (a) A painted wooden boat and (b) a constructed treasure chest created to help develop basic guidelines for the system.

IMPLEMENTATION

The diegetic tangible objects described in our design rationale require tracked interactions in VR environments. Overall, the system consists of a VR headset, four tangible objects, the core sensor unit common to each object, peripheral sensors and actuators providing active haptics specific to the interaction, and modified passive haptics to augment the tangible qualities of the objects. We created the VR environments in Unity and used an Oculus DK2 headset as our display. The DK2 lacks the faster refresh rates, the upgraded screen and upgraded lenses of newer headsets, but visually it served our purposes with low polygon cartoon environments. We designed ambient sound for each environment for atmospheric and narrative effect.

To track the user's hands in VR, we used a Leap Motion sensor mounted to the headset. The Leap Motion uses IR cameras and infrared LEDs to detect and track hand position data; we used a default hand asset to visually represent the hands in VR.

Figure 5. A Blend Micro board, IMU, and battery.

Sensor Unit

To support the simple integration of custom diegetic tangible objects and found objects in VR narratives, we designed a core sensor unit that can be inserted into any tangible object with adequate size specifications. As a proof of concept, our aim was to enable basic object tracking while also supporting additional interactions. We set three key goals when designing our sensor unit: scalability, modularity, and reusability.

We built our sensor unit using low-cost, off-the-shelf hardware to support easy scalability of these units. The key components of the sensor unit are: a 6-DOF inertial measurement unit (IMU), with built in accelerometer, gyroscope, and magnetometer; a 650mAh rechargeable battery; and an Arduino-based microcontroller to interface the data from the IMU and other sensors with the VR application (Figure 5).

For the first iteration, we used a wired Arduino to power the IMU. For the second iteration, we designed and 3D printed a sensor case to hold a battery-powered Arduino-based Blend Micro board[3] and an IMU. The top of the case exposes the pins of the Blend Micro, providing support for attaching different sensors for each diegetic tangible. This feature implies that any designer (or hobbyist user) could add any additional sensors that are specifically necessary for a particular interaction, as with the piezo elements in our cube interaction, or the conductive fabric in our squirrel interaction. The sensor data and IMU data are transmitted to a computer over Bluetooth to track the object's orientation and other interactions.

We developed custom software scripts for both Arduino and Unity to simplify the integration of our sensor units into any VR environment built in Unity. The scripts can be attached to any virtual object in Unity to connect it with its physical counterpart. In addition, users can specify what sensors are attached to the Arduino-based board in order to author custom interactions. For example, piezo buzzers, or force-sensitive resistors attached to a board can quickly be defined in Unity and linked to trigger or react to events within a narrative.

At present, the sensor unit tracks the object's orientation but not its absolute position. We experimented with vision-based object tracking solutions with a Kinect camera using fiducial markers and color detection, but we found these to be insufficient for our design requirements (see discussion for details). For this reason, we ensured that the tangibles were graspable and in the correct physical location relative to the user for this iteration. We also created a "summon mode" for the Leap Motion so that when an object is held, the VR version of the object attaches the virtual object to the user's hands in order to maintain visual continuity in the event that tracking is lost.

In our prototypes we explored both active and passive haptic feedback, demonstrating the sensor unit's potential for modularity and reusability. We used piezo elements to detect taps in the first iteration of the cube, and force sensitive resistors in the second for more accuracy. We used soft, indented plastic on each face of the cube for additional passive haptics and to provide a tactile cue for the

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[3] http://redbearlab.com/blendmicro/

interactive points. Both iterations use 10mm vibration motors to provide feedback. We used conductive yarn for the squirrel interaction to detect touch along its fur, a vibration motor with two preset vibration patterns for its heartbeat, and a servo motor to turn its head. We added additional passive haptics to support the existing physical qualities of the objects, including a wireframe skeleton supported by clay for the inside of the squirrel; unique tactile patterns on the softer touch points of the cube; and the relatively heavy weight of the treasure chest.

INTERACTION SCENARIOS

In each interaction scenario, the user is seated and not required to physically stand or walk. There is also no VR locomotion; this is to prevent the potential discomfort of a cue mismatch and to focus the user's attention on the tangible interactions. After putting on the HMD and headphones, the user can look at the environment in 360 degrees and listen to the ambient sounds of the environment (e.g., wind and rustling leaves). The user has no avatar, but can see a tracked virtual representation of their hands. Each scene fades in as it begins and out when it ends. The current version of the narrative is simplistic as our goal here is the conceptual application of diegetic objects with expanded tangible interactions. We employed the interactive narrative trope of a companion character who introduces problems for the user to solve while also helping to explain how to solve the problems. In our case this character is a talking squirrel, ostensibly travelling with the player from location to location, solving problems along the way.

Figure 6. A user interacting with the cube prototype.

Cube: The user is positioned in front of a glowing cube and a talking squirrel in a cartoon forest. In dialogue boxes, the squirrel tells the user that the forest is in danger and can only be saved by solving the cube puzzle: tapping the faces of the cube in the correct sequence (Figure 6). The puzzle is an adaptation of a popular memory game called "Simon." Each face of the cube is a different color and the faces light up in sync with tones. The user must memorize the sequence and tap the faces in the correct order. The successful completion of the task plays the forest song, and the animals thank the user for saving the forest. The interaction includes several forms of feedback: visual, as each of the faces shows flashes of color; aural, as each face represents a tone; active haptics, as the faces vibrate when tones are played; and passive haptics, as the cube can be handled and rotated in 360 degrees.

Squirrel: The user is positioned in a cave and the squirrel from the previous interaction is scared and tells the user that it cannot go any further. A mouse tells the user that petting the squirrel might help calm the squirrel down. The user picks up the squirrel and can feel its fur, its delicate ribcage, and a fast heartbeat in its chest. Stroking the squirrel's back slows its heartbeat (Figure 7); it turns its head from left to right and tells the user that it is ready to continue. Once the user sets the squirrel down, it runs off and returns with another magic cube like the one from the first interaction. Again, the interaction includes visual and aural feedback in the squirrel's recovery and the sounds of the environment, but the tangible qualities of the squirrel are the focus of this interaction. The active haptics (its heartbeat and head movement) support the several tangible qualities of its passive haptics (its size, fur, and ribcage). In this interaction, the active haptics help to communicate the urgency of the task, while the passive haptics help to communicate how to perform that task, i.e., as one might hold and care for a real animal.

Figure 7. A user interacting with the squirrel prototype.

Found objects: As part of a month-long research exchange program, we recruited two high school students to design a pair of custom tangible objects using our sensor unit. The students were given the three guidelines mentioned in our design rationale: 1. the object can physically house the sensor unit; 2. the object is diegetic, with emphasis on its physical affordances; and 3. the interaction scenario benefits from the visual affordances of VR. The first student painted a wooden boat and designed an interaction in which users in an overhead view could dock the boat at virtual ports and transition to a first person view of that location. The second student modified a music box to resemble a treasure chest and designed an interaction in which the user could open the chest to explore its magical contents. The students then made a Unity environment that was narratively consistent with their object, and 3D-scanned their object to place it into the environment. Using the sensor unit, they were able to link the virtual object to the real object. To tie all our tangible objects together within a single narrative, we included the squirrel in the students' scenario to help guide the user's actions; the boat became the way that the user travels from the forest location to the cave location; and the treasure chest became the object that the squirrel retrieves in the cave.

EVALUATION

We conducted two preliminary user studies. The first assessed the first iteration of our cube interaction, and the second assessed the first iteration of our squirrel interaction. As the responses to the first were largely about known technical issues, we focused the second test on user experience, specifically directing participants to look beyond, for example, representational inaccuracies. We asked participants to elaborate on what they felt and to speculate on other physical interactions with this system. We did not expect our interactions to be difficult for the participants, but in both tests we used a NASA TLX [11] to assess such aspects as frustration and task difficulty. As these quantitative tests did not show any significant challenges for the participants, we do not include the results here. Due to the brevity of the tests, we also did not expect our participants to suffer the discomfort and side effects of VR, and indeed none of our participants reported any physical discomfort. Nevertheless, in future tests we hope to add further quantitative assessment tools like the Simulator Sickness Questionnaire [14].

First Iteration User Test

While designing and implementing the squirrel interaction, we conducted an informal user test of the cube interaction. We recruited eight lab colleagues (4 male, 4 female) between the ages of 18 and 24, each of whom had limited knowledge of the project. Participants were asked to play two versions of the interaction, one with a keyboard, mouse, and monitor, the other in VR with the tangible object. We made observations during each interaction and asked our participants to complete two questionnaires, the NASA TLX and a custom questionnaire to assess general user experience and collect open-ended feedback.

In their responses to our custom questionnaire, participants reported that they preferred the VR version of the game, noting that it was more “natural” and “intuitive” than the desktop version. We suspect, however, that the novelty of the VR version may have been enough to influence participant responses. We compared responses between the desktop version and VR version in an attempt to separate and to specify what is frustrating about the tangible interaction, the game, and/or the environment. The following aspects were noted by one or more users: 1.) the wires connecting the cube to the Arduino made it difficult to manipulate the cube; 2.) the hand tracking lagged and felt inaccurate; 3.) the cube tracking lagged and felt inaccurate; 4.) the vibrating haptic feedback felt imprecise (the buzzing sometimes vibrated adjacent faces of the cube); and 5.) the text in the dialogue boxes was too small and difficult to read.

Second Iteration User Test

We ran a second user test in our lab with eight participants recruited from the local community (five male and three female) between the ages of 18 and 34. Two of the participants (both male) had also participated in the first study. We conducted qualitative semi-structured interviews during and immediately after the interactions to assess user experience. The semi-structured format was chosen to direct participants away from discussion about known technical issues and representational inaccuracies. We were interested in participant experience, first impressions, and general responses. The interactions and interviews were video recorded for further review and to take into account how participants physically responded to the interactions. After the interactions and interview, participants completed two questionnaires. We used the NASA TLX questionnaire as in the first user test, and extended our custom qualitative questionnaire to include specific questions about user experience as well as general questions about tangible interaction. We used discourse analysis to code and analyze responses [7]. Given the scope of this study, we do not make any claim to the generalizability of our participants' responses. We use these findings to gauge the feasibility of our conceptual design and inform directions for future work.

We prepared three stages of interactions, during which participants were asked questions and prompted to talk through their experience. In each stage, participants wore an Oculus DK2 headset and were seated in front of a desk. The order of the stages was the same for each participant in an attempt to introduce features gradually and to establish a level of consistency. The three stages were as follows: 1. Hands: After familiarizing themselves with a cartoon environment by looking around and identifying animals in the scene, we asked participants to raise their hands to see how their hands were represented in VR. 2. Cube: participants were handed a 3D printed cube with differing visuals but matching rotation in VR. For this test, the cube was a passive haptic tangible: it could be handled but was not otherwise interactive (we decided to forgo the full cube interaction as the squirrel was our focus for this test). 3. Squirrel: Participants played through the squirrel interaction, in which they read through text boxes and held and petted the squirrel prototype. Although we had prepared audio feedback and an ambient soundscape, we did not include these for this test so that the participant did not have to listen and respond to the interviewer over the sounds of the interaction.

During and after the three stages, we asked participants to comment on whether or not the interactions helped to bring them into VR, and which of the three stages was the most effective in this regard. The majority of the participants (6/8) rated the interactions in the same order as they were presented, with the squirrel interaction (presented last) being the most "immersive." Although the increasing intricacy of the stages is likely to have influenced this response, participants were visibly more engaged during the squirrel interaction, and 5 out of 8 participants commented that the squirrel felt "alive," (P3, Male; P4, Male; P7, Female), "lifelike" (P1, Male; P4, Male), and variants of "real," (P2, Female; P7, Female). The squirrel's fur and heartbeat were cited as the most common reason for this response (three participants each), with other participants also noting its squirming, breathing, and dialogue. These aspects are interesting because they suggest that participants extrapolated beyond what the haptic feedback provided: the squirrel's head moved but it did not completely squirm, and the squirrel had a heartbeat but did not otherwise show breathing.

Although we were not specifically testing for an emotional response to the squirrel and its fur (as suggested by Flagg & MacLean [6]), several participants laughed or smiled during the squirrel interaction; three participants talked to the squirrel; and P2, who cried out (and then laughed) when first holding the squirrel, reported that her heart rate sped up during the interaction. P4's description of the three stages was perhaps the most evocative of the differences between the experiences. With hands only: "I can't interact with the environment... it feels like I'm at a zoo"; with hands and the cube: "Now I've stepped over the rail and I'm... part of the exhibit"; with hands and the squirrel: "You're not just interacting with the environment; the environment is also interacting with you."

We observed that participants' expectations of what should be possible in VR quickly increased. With only hands in VR, one participant noted that he would like to have arms (P1, Male); another said, "I love it. But I would like to hold things now" (P7, Female). After holding the cube, P5 (Female) said, "It kind of feels as if I'm part of the world," but later wrote that she would also have liked to "throw it or bounce it." Seeing his hands in VR, P8 commented, "I can see my hands but I cannot touch anything." These expectations may have also made it difficult for participants to avoid talking about technical issues, as several participants remarked on and returned to the inaccuracies of the hand tracking and cube tracking. We speculate that the more familiar the interaction, the higher one's expectations for accurate control. The less familiar interaction with the squirrel did not receive the same amount of immediate suggestions for improvement, although its tracking and visual representation were arguably less accurate: the tangible squirrel's head moved when nervous, but the virtual squirrel was largely static when held.

As the text size was much larger compared to the first test, only one participant (P5) commented on the text, saying that she would have preferred voiceover as the text drew her attention away from the squirrel. Out of our eight participants, one (P8) was ambivalent about the overall experience, suggesting that haptic gloves would be better than tangibles due in part to scalability (he did not want tangible game objects occupying space in his home).

DISCUSSION AND FUTURE WORK

As the VR industry continues to improve the hardware of its headsets, controllers and tracking systems, designers are testing and developing best practices for VR. Users, particularly those playing the first generation VR games and applications, are the unofficial test subjects, experiencing the discomfort of VR and the current design principles that strive to minimize that discomfort. Many of the challenges of VR and the potential sensory conflict between the visual, vestibular, and proprioceptive systems are still unsolved, but the improvement of such aspects as framerate, visual output, and tracking help to widen the potential for tangible and embodied interaction research in VR. Due to the emergence of these best practices, we were able to confirm some of our own concurrent findings, e.g., preferred options for where and how to place text. Although preliminary, our efforts to bridge research in tangible narratives and VR suggest several opportunities for future work.

Controllers and Diegetic Tangibles

For tangible interactions in VR, the current trend appears to be a reliance on controllers that are held for the entire length of the interaction experience. Controllers can visually represent whatever objects designers choose, but lack the tangible properties of those objects. Diegetic tangible interactions are an opportunity for storytellers and users to reintroduce the complex tangibility of objects into visually dynamic environments. The precision of conventional controller-based input is a standard by which diegetic tangible interaction can be measured, and from a narrative design standpoint diegetic objects are best considered in addition to conventional controllers. Each has its own benefits, and the spectrum from controllers to diegetic tangibles suggests several options for the use of tangibles in VR. For example, we might classify objects like plastic steering wheels and guns[4] as closer to the controller side of the spectrum, offering a degree of realism but not necessarily any expectation of complex tangible interaction. We propose that the ability to design unique interactions for a specific object lends itself to the objects' diegetic believability in a narrative.

In order to build on principles of scalability, modularity, and reusability, we designed a proof of concept sensor unit to enable object tracking while also allowing for the addition of interaction-specific sensors. Exposing Arduino-based functionality may allow designers and users to leverage knowledge from physical computing [24] with low-cost hardware sensors to create or enhance custom-

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[4] http://iliumvr.com/

made VR experiences with diegetic objects. Using our sensor unit, any handheld object could potentially be brought into VR in order to emphasize or enhance its physical characteristics.

In our cube interaction, we show that an object can be rotated and examined so that each surface is a potential for interaction or discovery. In our squirrel interaction, we show that an object can regain all its virtual characteristics the moment it is set down, as our squirrel runs away into the environment and comes back to be held again. A variety of tracked objects could potentially appear and disappear for the user when necessary for the narrative. Our third and fourth objects, a painted wooden boat and a built treasure chest, show the relative simplicity of bringing objects into a VR environment using our three broad guidelines.

Although it is increasingly easy to bring these objects into VR, these interactions do not yet have the precision of commercial VR controllers. By design, controllers are both ignored and precise. They are tools that are meant to be used rather than seen or tangibly explored. Tangible objects in VR are both a visual and tangible focus but are currently imprecise, and are not necessarily used as tools. With the increase in focus there is also an increase in the importance of how the objects are tracked and represented in virtual space.

Tracking and Representation

The limitations of our proposed system suggest future work. As our contribution is conceptual design and a set of prototypes, a more complete integration of diegetic tangibles into interactive narratives could be explored. To achieve this, more accurate object tracking is necessary: the ability to pick an object up and set it down again requires the system to consistently and accurately track the object, even when it is not being used. The benefit to designers is that the object could be brought in and out of the narrative, with the system dynamically adjusting the object's VR position to match the real object's position.

Our user tests seem to suggest that there is an uncanny valley of object manipulation like the uncanny valley of bodily representation. Our ability to grasp and manipulate objects comes with high expectations, and perhaps the relative familiarity of an interaction increases these expectations: the tracking and visual representation with our squirrel interaction was arguably less accurate than our other interactions but received fewer immediate calls for improvement. Future work could look to assess this apparent discrepancy, examining what aspects of a tangible-virtual interaction affect player engagement.

Throughout the design process we explored solutions for object tracking, but these were found to be insufficient for our purposes. Marker-based tracking suffers from hand occlusion, and depending on their placement and size, markers can also interfere with the tangible qualities of the objects. The tracking limitations of optical systems could be alleviated by using high-precision electromagnetic (EM) trackers that track objects without a line-of-sight. However, current EM sensors are bulky (e.g., Polhemus wireless trackers[5]) or tethered (e.g., Ascension Tech's 6DOF sensors[6]) limiting their usefulness in unrestricted object tracking.

A further concern is the latency introduced with any additional hardware. The Leap Motion hand tracker adds latency of up to 50ms depending on the hardware configuration. In addition, the tangible sensor unit could only transfer up to 20kB of sensor data per second with our current setup. Combined with the latency of the VR headset, these added noticeable lag when interacting with the tangibles. It should be possible to reduce these latencies by modifying our software system and communication architecture.

The addition of colors for accurate color tracking can interfere with the visual qualities of the objects when those qualities are unique, as in our painted boat prototype. Ideally, the system should work even when the object is precious and unchangeable, like an heirloom for a story of one's family. Designers and users should have the option to leave the surface of the object unaffected.

Opportunities for Tangible VR

Recent games and apps for VR have begun to illustrate its uses beyond games and beyond single user experiences. These forms offer new possibilities for tangible VR. For example, physical objects could be brought into social environments as informal props and story objects. The same is true for larger multi-user VR environments, with diegetic objects being exchanged or traded from user to user: the inventory of role-playing games made real. VR-enabled tangible objects could also be used for asymmetrical gameplay, with one or more users wearing a headset and one or more users not wearing a headset (as demonstrated by Sajjadi, Gutierrez, Trullemans & de Troyer [26]).

When the user is primarily a viewer, as in 360-degree video and cinematic VR, tangible objects could be exploratory objects, not affecting the narrative but adding to it. Tangibles in VR could also be used as a way to test or demonstrate existing and imagined qualities of the objects, ranging from specific products created by industrial designers, to 3D printed objects by casual makers and hobbyists, to those chosen or created by families and friends hoping to share or recreate real experiences within virtual environments.

The ease with which the two high school students used our sensor system to create and import tangible objects into a virtual environment (also of their own creation) suggests that for each of these forms of VR, our system could encourage users and audiences to incorporate their own

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[5] http://polhemus.com/motion-tracking/all-trackers/patriot-wireless

[6] http://www.ascension-tech.com/products/sensors/

physical objects into dynamic virtual environments. Further work with the sensor unit could also broaden the scope of tangible objects and tangible interactions in VR. A soft and deformable casing for the sensor unit could allow greater flexibility when integrating the sensor unit into complex objects that use a variety of textures, materials, and form factors.

CONCLUSION

We presented four tangible objects designed to bridge the gap between the real and the virtual in narrative VR. This effort relies on lessons learned in tangible and embodied interaction research, VR design, and tangible narrative systems to address the lack of diegetic objects in tangible narratives and to contribute to the increasing development of physical interactions in VR.

The core of our system is a wireless, adaptable sensor unit that supports the design of tangible objects for VR, first in the increase of tangibles that are brought into VR, and second in the dynamic visuals of VR. Using our sensor unit to track the objects we emphasize the physical characteristics of diegetic tangibles.

Our first two objects, an interactive cube and an interactive squirrel, stand in contrast to conventional controller-based input in VR narratives. The ability to interact with all six faces of the cube and the ability to pet the squirrel showcase custom-designed interactions that adhere to (and benefit from) the unique tangible qualities of those objects. In initiating the design of a third and fourth object, we established a set of basic guidelines for tangible narratives that use our system: 1. the object can physically house the sensor unit; 2. the object is diegetic, with emphasis on its physical affordances; and 3. the interaction scenario benefits from the visual affordances of VR.

We expect that the technical challenges of implementing this system will quickly resolve with the emergence of new hardware and tracking technologies. These improvements can help to incorporate tangibles in VR, both for narratives and other uses. With this work, tangible objects can broaden the promise of VR and its many possible worlds with the ability to physically interact with those worlds.

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