TilePoP: Tile-type Pop-up Prop for Virtual Reality

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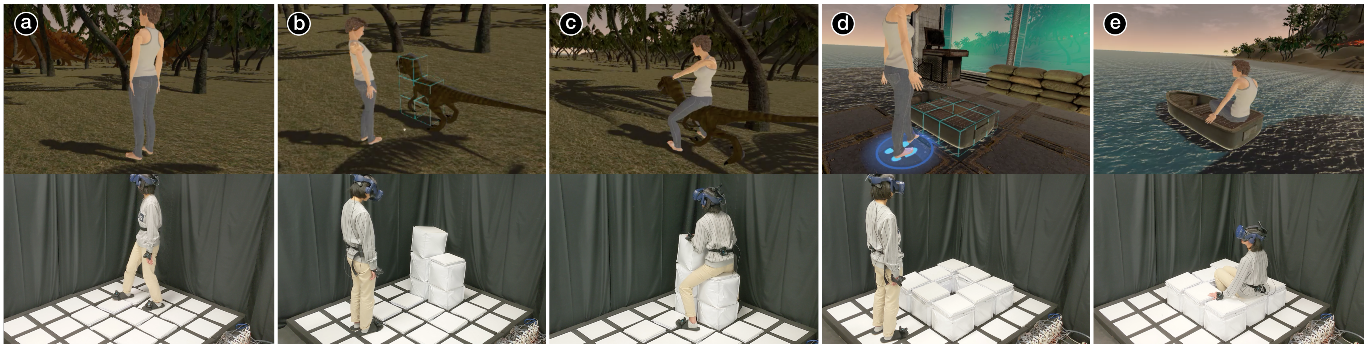

Figure 1. TilePoP is a pneumatic interface deployed as floor tiles that can pop up by inflating into physical shapes for whole-body interactions in VR. a) The user walks on the collapsed tiles. b) The tiles pop up into a shape approximating a dinosaur. c) The user mounts the prop. d) The tiles pop up into a boat shape. e) A user steps into the boat and sits down.

ABSTRACT

We present *TilePoP*, a new type of pneumatically-actuated interface deployed as floor tiles which dynamically pop up by inflating into large shapes constructing proxy objects for whole-body interactions in Virtual Reality. *TilePoP* consists of a 2D array of stacked cube-shaped airbags designed with specific folding structures, enabling each airbag to be inflated into a physical proxy and then deflated down back to its original tile shape when not in use. *TilePoP* is capable of providing haptic feedback for the whole body and can even support human body weight. Thus, it allows new interaction possibilities in VR. Herein, the design and implementation of *TilePoP* are described in detail along with demonstrations of its applications and the results of a preliminary user evaluation conducted to understand the users' experience with *TilePoP*.

Author Keywords

Shape-changing Interface; Virtual Reality; Haptics; Airbag

INTRODUCTION

The physical shape in the environment provides affordances for various whole-body interactions involving postures and behaviors [15]. For Virtual Reality (VR), most haptic feedback devices simulating physical shapes have been explored only at the scale of the hand (hand-scale, hereafter) [12, 11, 40, 44]. Large props placed spatially in VR have been proposed to imitate the physicality within a virtual environment as this can enhance realism [7]. However, prior props for whole-body interactions are often static [31] or human actuated [10].

We propose the concept of dynamically providing supporting shapes that are scaled to the entire human body (hereafter, body-scale) through shape-changing floor tiles. Inspired by the deployability of pneumatic interfaces [45, 36, 38, 44], we present this prototype entitled TilePoP (Tile-type Pop-up Prop). TilePoP is a new type of pneumatically-actuated interface deployed as floor tiles which dynamically pop up by inflating into 2.5D physical shapes in order to approximate virtual objects for whole-body interactions (Figure 1).

TilePoP consists of stacks of cube-shaped airbags arranged in a 2D array for constructing different shapes attached to the ground. Each airbag is fabricated with a specific folding structure and reinforced materials. When a virtual object appears, specific airbags are inflated to approximate the shape of that virtual object, providing physical haptic feedback to the users' entire body. Each of the pop-up tiles can withstand a body's weight, allowing for different body postures and actions such as sitting or stepping, according to the shape. When not in use, the airbags deflate and fold themselves back down to flat tiles thereby facilitating users to again walk on them.

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We detailed our design and implementation herein then explored various interactions enabled by TilePoP. We finally demonstrated the two applications and conveyed the results of a preliminary user evaluation conducted to understand users' experiences when interacting with TilePoP.

RELATED WORK

VR Haptic Feedback

Various types of haptic feedback have been utilized in VR scenarios. Here we briefly review prior works utilizing haptic feedback on manipulating virtual objects or when interacting with virtual environments.

Hand and Fingertip

Many studies in VR have been focused on generating haptic feedback on the hands and fingertips. For example, hand-held controllers render shapes and textures for the fingertips to "touch" [5, 28], and wearable haptic devices allow for natural manipulation using hands such as grasping [11, 12, 44, 19, 41]. For grounded solutions, robotics arms [33, 4] can be used to provide various haptic feedback for the hands. Tabletop shape displays [14, 40] can also afford the feeling of shapes for hands. These solutions provide fine-grained haptic feedback.

Head, Limb, and Body

Researchers have implemented the use of haptic devices on various body parts, such as the Head-Mounted Display (HMD) to simulate force feedback for facial impact [8] and on the feet [39] to simulate terrains. On the body, suits with vibrators [27] or pneumatic airbags [13] can generate multiple tactile feedback on the skin. On the arms, exoskeleton [34] provides strong force for arms through external mechanical structures and pneumatic jamming can restrict arm movements [2]. Electrical Muscle Stimulation (EMS) provides force application with a relatively small device [29, 30].

As for providing body-scale haptic feedback, CirculaFloor [23] and Ground Surface Simulator [35] are grounded actuated floor devices that provide an infinite walking experience in VR. Haptic floor [6] explores interactive shape-changing floors used in performance. TilePoP is also a type of grounded actuated floor device. Differing from existing solutions, our system configuration focuses on rendering 2.5D and body-scale proxies, such as a chair, that allow users to interact with their VR environment using their entire body.

Haptic Shape Proxy

Real-world props that are similar to the virtual objects have been proposed as physical proxies and have been found effective at enhancing realism [7], as the props provide natural haptic feedback and affordances to users, bridging the gap between real-world physical experience and virtual world experience. For hand-scale manipulation, passive props can be prepared beforehand [20, 21] or mapped dynamically [18, 9]. Researchers also propose dynamic assembly [47, 43] to render proxy objects.

For body-scale haptic proxies, static blocks and boards coupled with projection are proposed to recreate a remote or virtual site [31, 37]. TurkDeck [10] proposed using human to arrange several primitive shape proxies for VR. Currently, there exists no research on providing dynamically changeable haptic proxies for body-scale interactions.

Pneumatic Shape-changing Interfaces

Pneumatic interfaces have been explored as shape-changing interfaces in HCI [3] for their deployability and their capability to produce complex shapes [46, 32]. Soft materials that deform and adapt to the virtual contents allow more realistic user interfaces [22]. The deployability of pneumatic interfaces have been used for displaying 3D models [24], a shape-changing mouse [26], and dynamic overlay buttons [17]. PneUI [45] demonstrates several pneumatic prototypes rendering curvatures, volumes, and textures. AeroMorph [36] introduces folding techniques to form 3D shapes from 2D fabrication of pneumatic airbags. Printflatables [38] extends the technique to human-scale fabrication. PuPoP [44] explores the application of pneumatic airbags serving as wearable props in VR. We push the usage of the pneumatic material further by exploring such an interface at body-scale interaction in VR.

WHOLE-BODY POP-UP PROPS CONSIDERATIONS

We aim to provide on-demand shapes for the environment that can facilitate whole-body interactions by allowing different human postures. As an initial exploration, we focused on interactions involving large supporting force, while focusing less on other considerations such as object manipulation (e.g. pick up and move, may be a trade-off for supporting stability) and response time (generally a trade-off for force). Here, we list the following considerations for designing whole-body pop-up props:

Body-scale supporting shapes. The props need to be able to dynamically construct large shapes and be strong enough to support a user's body weight to allow body-scale interactions. Users should be able to sit, lean, or embrace the prop.

Easily deployable. When not needed, the props should become as flat as possible to save the physical space. The props can be configured easily as modules according to needs.

Prop properties. Other material properties such as stiffness and pulsing are preferred for emulation of a wide range of virtual objects.

DESIGNING TILEPOP

We considered pneumatic materials as an initial exploration of this idea because of their shape-changing capabilities that meet our considerations. Inspired by previous work using static props [31] and a shape display [14], we focus on constructing shapes with block elements as they are common and can more easily allow designers to map VR contents to the shape, enabling a wide range of body-scale interactions. In the following subsections, we describe how we have designed from each individual block airbag to constructing the entire arrays of pop-up tiles.

Tile Material

We had developed different sizes (10 cm, 30 cm, 50 cm) of inflatable cube-shaped prototype during our iterative design. For a 50 cm cube, it was more stable when withstanding weight but took two minutes to deflate using our current system, while for 10 cm cubes, it was less stable when supporting the human body. Considering these tradeoffs, we then deliberated upon what the interactions could be and found that many interesting ones could be realized using 3-level 30 cm blocks, involving body-scale interactions such as stepping, sitting, leaning, etc. Thus, we choose to make a block element about the size of 30 cm in height.

The final material is shown in Figure 2. To achieve airtight airbags that support a heavy weight, there are mainly two layers. For the inner airbag, we use an inflatable cube (35 cm in edge, Shen Zhen Ru Hong Toy Co.) made from thin PVC to ensure airtightness. This inflatable cube also comes with an outlet for inflation. However, the material is elastic and will extend when there is a large force placed on it. Thus, we add another layer of non-elastic PVC fabric (0.375 mm thick, Nan Ya Plastics Corp.). The PVC fabric is wrapped around the inner airbag and heat-sealed (using KF-520H heat sealer) to prevent the airbag from expanding when a user's weight is on it. For the top and bottom side, we attach laser-cutting acrylic plates (3 mm) to the airbag using adhesive tapes to make the airbag flat as a tile.

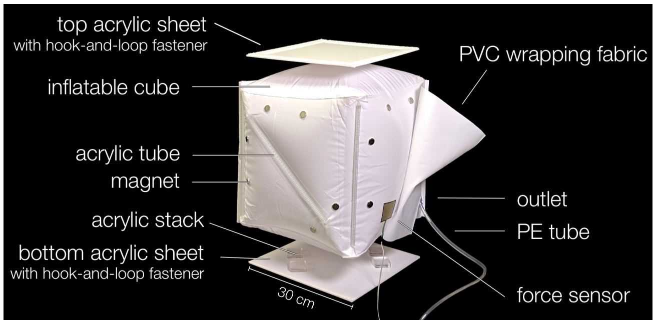

Figure 2. An expansion view of the material and structure of an airbag used in TilePoP.

A fully-inflated single airbag can withstand 120 kg of weight on its top surface. However, we avoid designing interactions that require users to stand on the inflated airbag, as the user may lose their balance on the airbag and fall down to the ground. Since the weight is supported by compressed air, the airbag cannot maintain the support of a user's body-weight *during* inflation or deflation.

Between the two layers, we place acrylic tubes sticks (8x6 mm) as constraints for the folding structure (discussed in the next subsection). Additional magnets are attached to help fold and align when the airbag is deflating. A force sensor is taped between the layers to sense the state of inflation. Hook-and-loop fasteners are affixed on the surface to allow stacking of the airbags.

Tile Folding Structure

In the early-stage design of the folding structure, we attached the acrylic tubes to constraint the folding process, as shown in Figure 3. However, we found that while the inflation works well, it does not always fold well when deflating as the sides of the surface would fall out of place occasionally. As a result, large extra space is required for this kind of folding, making it difficult to construct complex shapes by placing these airbags side by side.

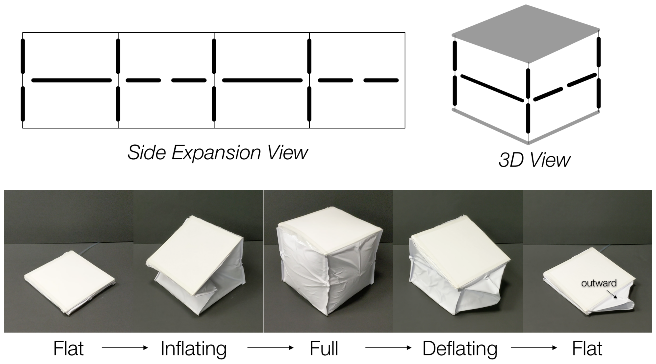

Figure 3. Box packaging folding. One possible folding outcome where the sides of the cube fold outward. (Thick lines in the illustration indicate acrylic tubes.)

Inspired by a spiral folding method [46, 25], we later on modified the structure and made it a cube version. This kind of folding structure rotates 90 degrees when folding. We attached the acrylic tubes to constraint the folding process as shown in Figure 4. As this folding mechanism allows only one outcome, the sides of the cube can be folded inward. While an ideal cube would fold into a flat square, the thickness of the material makes it unable to align when folded. Therefore, we make the cube a little longer in height, allowing the room for rotation.

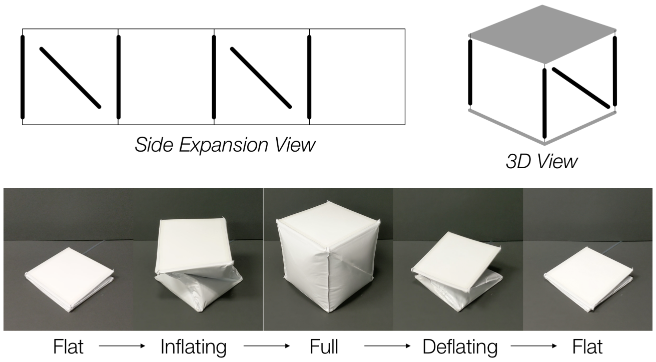

Figure 4. Spiral cube folding. This kind of folding provides consistent outcomes. (Thick lines in the illustration indicate acrylic tubes.)

We finally choose the spiral folding method as our final design as the outcome is consistent. Additional magnets are attached to help the airbag flatten and align during folding. Also, when flattened, to prevent the acrylic tubes from becoming fouled with each other, we only attached two diagonal tubes as they will fold flatly in parallel. To enhance users' balance when stepping on the flattened airbag, we added additional stacked acrylic plates as supporting columns (See Figure 2).

Tile Arrangement

The spiral folding method requires additional rotational spacing around each cube (See Figure 5a), approximately 6 cm for our 30 cm cubes. To minimize these gaps, we choose to leave only 6 cm allowing one airbag to rotate and avoid neighboring airbags from colliding by inflating or deflating the airbags one by one. Additionally, we fill gaps with foam to prevent users from stepping into them. After airbags are inflated, they will slightly expand sideways to fill the gaps.

We connect hard PE tubes (8x6 mm) to the airbags because the PE tubes do not deform when deflating, so that the air can be discharged smoothly. We attached the tubing on the side fabric of the airbag using cable ties. As the folding is rotational, attaching on the edge of the airbag can prevent the tube from potentially bending, *i.e.*, going to 180 degrees. The tubes also go through the gap between the tiles.

The top surface of the airbag during inflation or deflation may be unstable, making any other inflated airbags on top of them unstable and easily toppled. Therefore, we choose to inflate airbags from the bottom up to ensure that already inflated airbags are always beneath the current inflating one. Similarly, we deflate the inflated airbag from the topmost one first so that it does not impact the stability of the stack.

Considering a flattened tile has a constant height (3 cm), we made our cubes longer in height to compensate for the height, *i.e.*, 33 cm. As a result, the height difference of each stacked tiles can be consistent, allowing our array of stacked airbags to render uniform voxels (Figure 5b).

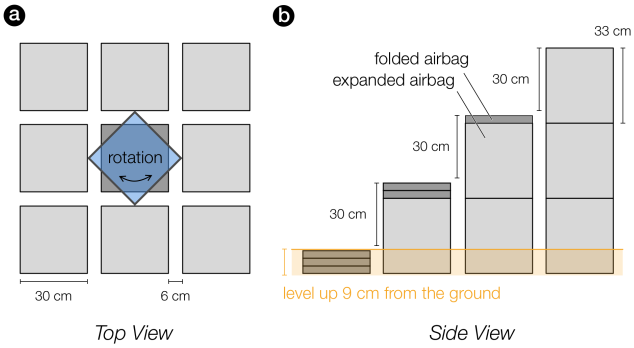

Figure 5. Tile arrangement considerations. a) Spacing between airbags is required to allow rotation of the spiral folding method. b) Compensation for the height when inflated.

SYSTEM IMPLEMENTATION

We finally constructed an array of airbags on the floor as 3x3 tiles stacked with 3 airbags each, resulting in 27 airbags in total. To enlarge the VR interaction space that is available when using TilePoP, we created dummy tiles made from acrylic sheets to level up the surrounding floor as high as the folded pop-up tiles (9 cm). The whole configuration is shown in Figure 6.

Pneumatic Control

All airbags are actuated with a single air compressor (DR-115, 1.5 HP, Swan, 22 L Tank) and a vacuum pump (THV140, 0.5 HP, Lintell) controlled using ball valves actuated with servos (MG-996R, TowerPro) with custom 3D-printed supports. Ball valves prevent leakage of air pressure from both sides. The air compressor keeps the air in the tank at 100 psi. To accelerate the deflating, an additional air tank (46 L) is connected to the vacuum pump as the vacuum can be stored beforehand. Deflation is generally several times slower than inflation because of the airflow largely depending on the delta of pressure. For inflation, the delta is about 6 atm and, for deflation, it is only less than 1 atm. The air compressor and vacuum pump were placed in the room next to the VR tracking space to reduce the machine noise.

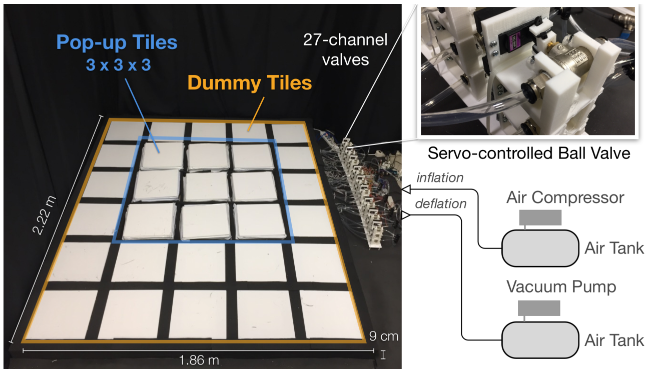

Figure 6. TilePoP and its pneumatically-actuated system.

To control the inflation and deflation, we initially tried using air pressure sensors. However, the airflow of our system is too fast making the sensors always report high pressure, which is not the final pressure in the airbag. Therefore, we use force sensors (FSR-406, Interlink Electronics) attached to the surface of the inner airbag. The sensor will contact the outer layer with force when inflated, therefore we can use the force value to determine if the airbags are fully inflated. We set the threshold at 1.8 N, where we measured the air pressure is 2.5 psi. For deflation, the force sensor senses collapse when the airbag rotates 90 degrees, allowing us to also control the deflation. The threshold of the air pressure sensor is calibrated once after installation of the tile. The sensors are connected to Arduino Mega with multiplexers (CD4051B).

The inflation time for a single airbag is 5 s and the deflation time for that is 20 s, measured when the air tanks are fully compressed or vacuumed. The time increases as the air in the tank is consumed faster than the speed the air pump provided.

All servos and sensors are controlled using Arduino Mega and communicate to a PC through Serial Port.

Tracking & Display

We use HTC VIVE Pro for VR tracking and display. HTC VIVE Wireless module is used to prevent the cable from tangling with our props. The users wear HTC VIVE Trackers to approximately track the entire body using Inverse Kinesthetic (IK) models (two trackers on each wrist, one tracker on the back of the waist, and two trackers on each foot). For additional props, we also use HTC VIVE Trackers.

The whole interaction space is tracked with four external lighthouses (HTC VIVE Base Station 2.0). The position and orientation of TilePoP are calibrated and aligned with the virtual scene using the Trackers during setup stages. All touch interactions using hands and props are tracked using the HTC VIVE Trackers whose virtual counterparts collide with the virtual TilePoP in the Unity 3D program.

Unity 3D communicates through OSC protocol with a Processing program that controls the Arduino Mega.

INTERACTIONS USING TILEPOP

We describe the interactions provided by TilePoP and demonstrate examples built with our prototype. The interactions include on-demand shapes for the whole body, interacting with additional props, and emulation of material properties.

On-demand Shapes for the Whole Body

TilePoP can construct large shapes on demand to provide touch sensations and physical support to various body parts. VR interactions involving dynamic posture change can be enabled, when a small tracking space is available. Some examples are shown in Figure 7. A box displayed with one single block can provide stepping and sitting (Figure 7a). A chair can be provided for a user to sit with their back reclining on the backrest (Figure 7b). A table that is three blocks high can provide support for users to lean on (Figure 7c). Several blocks can construct a plane, such as a raft that can support the entire body when lying down (Figure 7d). Since TilePoP serves as props, the same shape can afford different behaviors and interactions depending on the virtual content and the users.

Regarding the response time, TilePoP is suitable for rendering static VR objects (e.g. walls in a shooting game) or slow transformation of objects with visual compensation (discussed in the next section).

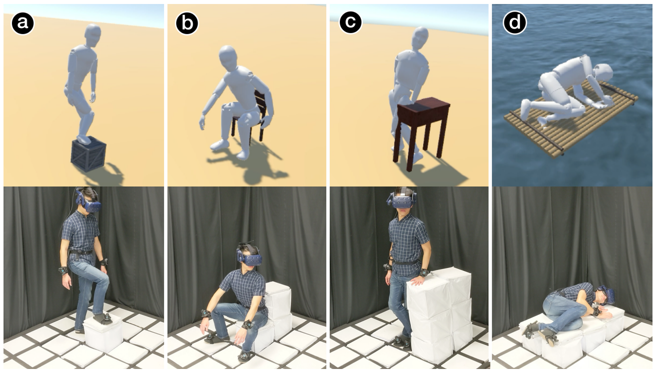

Figure 7. On-demand shapes provided by TilePoP for haptic interaction with the whole body. a) A box for stepping. b) A chair for sitting. c) A table for leaning. d) A raft to lie on.

Interacting with Additional Props

In addition to interactions involving direct contact with the body, TilePoP can interact with additional props. For example, TilePoP can construct a dynamic drum set with different heights to allow drumming with props serving as drum sticks, attached to HTC VIVE Trackers (Figure 8a). TilePoP can also provide dynamic obstacles or point-gaining blocks for a soccer game (Figure 8b), where the players kick a tracked ball (transparent inflatable ball with a Tracker inside). The blocks can provide a physical surface that interacts with the ball allowing it to rebound.

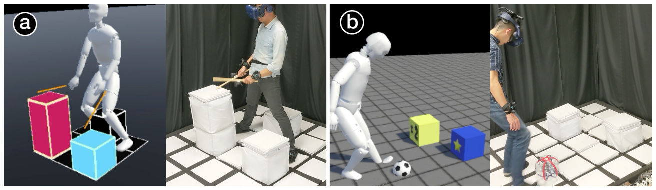

Figure 8. TilePoP can interact with additional props. a) Drumming with stick props on drums provided by TilePoP. b) Playing soccer with a ball prop where TilePoP serves as obstacles and points

Emulation of Material Properties

Since TilePoP is pneumatically-actuated, a range of stiffness (Figure 9a) can be emulated by inflating airbags with different levels of pressure threshold. We use the force sensors on the blocks to approximate the air pressure. By controlling sudden deflation and inflation, low-frequency pulsing haptic feedback such as a heartbeat or breathing can be emulated (Figure 9b).

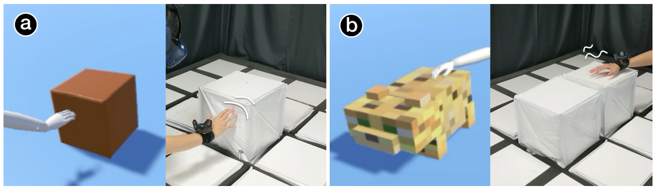

Figure 9. Material properties such as a) softness and b) breathing of a cat can be emulated.

VISUAL INTEGRATION OF TILEPOP

In order to integrate TilePoP into VR seamlessly, we highlight some interaction techniques to communicate the states of the props and compensate for the transformation time.

Visual States of the Props

To enable natural visual-haptic experience, TilePoP should be interacted with only when the tiles are totally inflated or deflated. Therefore, a mechanism for preventing users from interacting with the non-completed props is important; otherwise, the users might fail to receive correct haptics.

Furthermore, due to safety concerns, when some props are inflating, the users should avoid stepping on the tiles. While no visual indication is needed if the user is far from the props, we implemented a warning indication (see an example in Figure 10a) to be shown when the user nears the inflating or deflating props by a certain distance to prevent the user from walking through.

Showing the visual indication that some props are fully inflated and ready for interaction can smooth the experience as well. Especially for shapes that do not perfectly match the blocks, visual blocks (see an example in Figure 10b) help the user interact with the props more accurately and more safely.

Compensating for the Transformation Time

There are many approaches to mitigate the time needed for inflating and deflating time needed for TilePoP as it renders

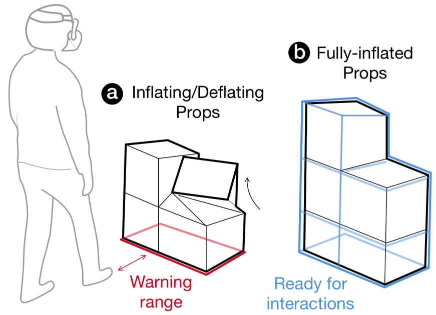

Figure 10. Communicate the states of the pop-up tiles in VR. a) A warning indication when the user is close to inflating or deflating props. b) An invitation indicator to show the props are fully-inflated and ready for interaction.

shapes. One solution is to use appropriate animation during the transformation, such as visual effects of rising or smoke. It is more suitable for object appearing than disappearing as inflation is much faster than deflation in general. However, for larger shapes, it might still take too long for some applications. Another solution is to inflate in advance or deflate afterward. For VR experiences involving sequential events, these underlying actions can be implemented along the sequence where the users are less likely to interact there. Warning indication should be shown if the users come close to the transforming props.

To further influence fluid scene transformation, we can reuse part of the shapes of two virtual objects if they have common shapes. For example, the dinosaur prop (Figure 1b) and the boat prop (Figure 1d) have parts in common; thus some transformation time can be saved by reusing them (Figure 11a). If the time required for transformation is still long, one can design experiences that guide the users to leave the TilePoP area and do some pure virtual interactions. After transformation of TilePoP is ready, the users can be guided back to interact with the pop-up prop (Figure 11b).

Another way to reuse the props is to leverage illusion in VR, such as Impossible Spaces [42], which is explored with passive props in iTurk [9]. Two overlapping rooms connected with a corridor allow users to interact with the same props while believing they are in two different locations.

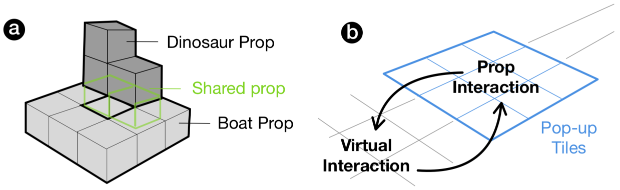

Figure 11. Techniques to mitigate long transformation time. a) Reuse shared parts acmong different props. b) Design switching of prop and virtual interaction in different places to allow enough time for prop transformation.

DEMO APPLICATIONS

We created two demo applications to show how TilePoP can be integrated into full VR experiences. In the following paragraphs, we emphasize the state of TilePoP in *italics* and the interactions of the user in **bold text**.

Jurassic Island Escape

Inspired by the movie Jurassic World, we created an experience where users try to escape from a dinosaur island about to be destroyed by an erupting volcano.

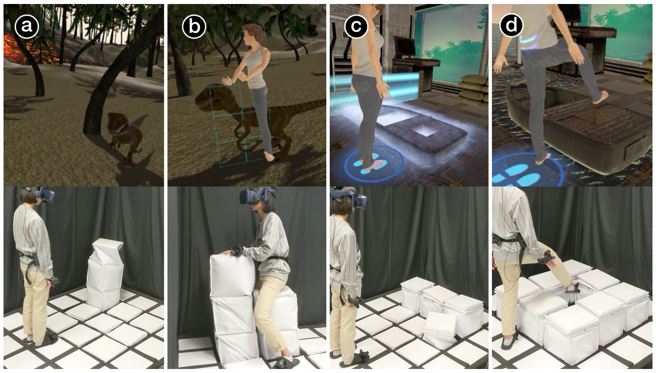

Figure 12. Jurassic Island Escape. a) The dinosaur comes while the prop is inflating. b) The player mounts the dinosaur prop. c) The boat rises while the prop is inflating. d) The player steps into the boat prop.

Riding a Dinosaur

The game begins with the player randomly **walking** around the island (Figure 1a). After some moments, a dinosaur runs toward the player, as the prop *inflates* (Figure 12a). When the dinosaur arrives, the prop is *fully inflated*, indicated with additional blue lines that illustrate the actual airbags. Then the player can **mount** the dinosaur prop (Figure 12b). During the ride to the pier, the player can **rest** their hands on the head of the dinosaur.

Taking a Boat

After the dinosaur arrives at the pier, the user **dismounts** from the dinosaur and then walks over to a spot to step on a glowing footprint for identity scanning that will open the floor gate. During the scanning, the dinosaur runs away while the prop *deflates*. After the scanning, the floor gate opens and the boat inside rises with smoke visual effect (Figure 12c). In the meantime, the boat prop is *inflated*. After the boat rises, the player **steps into** the boat (Figure 12d) and **sits** on its wooden bench (Figure 1e). Finally, the boat moves forward out to sea.

Block World Builder

This application is inspired by the video game Minecraft [1]. We let the user create physical blocks using direct touch and a hand-held prop.

Create Blocks Using Direct Touch

The user can create a block by **touching** the top surface of the existing blocks (Figure 13a), which is the ground when the game starts. An animation is shown to the user as the block is being *inflated* (Figure 13b). Then the user can continue

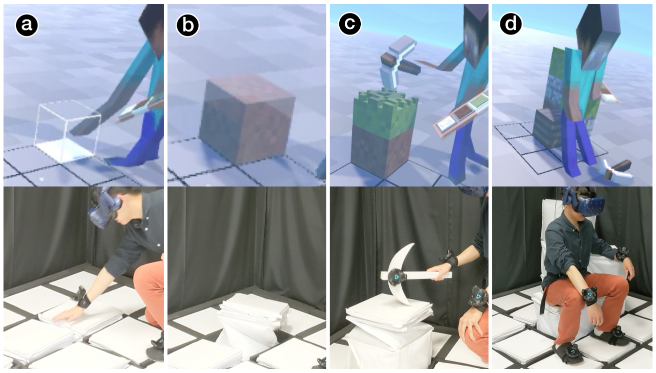

Figure 13. Block World Builder. a) The user touches the ground to create a block. b) The prop for the block is inflating. c) The user destroys a block by striking it with a pickaxe prop. d) The user sits on the blocks physically.

building another block by touching the top surface of existing blocks.

By selecting different textures using the menu on their non-dominant hand, the user can build blocks with different appearances. If the users finish their building, they can switch to the Hand mode which allows the users to touch the shape of the blocks without triggering creation. The users can then **sit** on the blocks that they just built (Figure 13d).

Destroy Blocks Using a Prop

The user destroys the blocks by holding a pickaxe prop (attached with a Tracker) to **strike** on the block (Figure 13c). The user can keep striking the pickaxe prop and continuously feel the descending, *i.e.*, *deflating*, of the pop-up tiles while an animation is being shown.

PRELIMINARY USER EVALUATION

We conducted a preliminary user evaluation to understand users' experience of using TilePoP in VR. Each participant experienced the two aforementioned demo applications, Jurassic Island Escape and Block World Builder.

Participants

Nine paid participants (6 females and 3 males) between the ages of 21 and 26 took part. All of the participants had had experience with VR technologies.

Procedure

At the beginning of the study, participants were informed about how TilePoP works. For the application Jurassic Island Escape, the participants were instructed that virtual objects will be shown with blue outlines implying that it is ready to be interacted while red ones indicate the props are transforming. For Block World Builder, the participants were informed about how to interact with the blocks with direct touch and the pickaxe prop. For the two applications, the border of the tracking space is shown as blue outlines to prevent the participants from falling. After these instructions, participants entered the tracking space and put on the VR headset with headphones playing gaming sounds. Experimenters assisted the participants to affix the trackers on their waist and their wrists. All participants wore slippers with Trackers attached for whole-body tracking and also the contact area with the floor was enlarged making walking on the tiles more safely. One experimenter was present throughout the study to ensure participants' safety, and also monitored the state of the system and shut off the inlet valve manually in the case of inflation controls not working properly. After the VR experience, participants were asked about their overall impression of the two applications and a semi-structured interview was then conducted.

Results & Discussion

All participants found the two applications fun and enjoyable, and were surprised that they can physically interact with some objects in VR with their body.

Jurassic Island Escape

Most participants felt that the TilePoP simulates the shape of the boat better than that of the dinosaur. However, some participants stated being able to mount the dinosaur and rest their hands on it felt real and enhanced enjoyment (P1). P3 stated that while getting on the dinosaur, the blue lines which indicate the actual inflated airbag somewhat disrupted their sense of immersion in VR, but after riding for a while (the blue lines vanished), he started to believe the shape perfectly matched that of the dinosaur. This indicates that the feeling of shapes might be modified with visual content. Some participants feel the lack of dynamics for the running of the dinosaur and suggested that "*I wish the dinosaur would move up and down.*" (P5, P7)

Before stepping into the boat, the participants often touched the edge of the boat to ensure there were inflated props. P4 said the action made her feel that the prop is *trustworthy*. Most participants think that the boat feels realistic because the shape of the seat on the boat is flat. P3 expressed surprise that he could actually put his legs into the boat. In contrast to riding the dinosaur, P1 thinks that the moving visual images with the slightly wobbling of the props made the boat moving feel real, though the prop did not move at all.

In terms of noise, most participants found themselves immersed in the virtual scene and did not regard the noises of the pump and inflation as annoying. Some participants felt that during the rising of the boat, the noise of the pump fit in the scene by coincidence, suggesting certain content design can minimize the loss of immersion.

Block World Builder

All participants enjoyed Block World Builder a lot, stating that it is fun and satisfying as it allows building real physical blocks dynamically. P5 states that the direct touch gesture of creating blocks reminds her of magic. Some participants touched the prop as it inflated. "*Being able to build whatever I want and feel it grows is great*" (P3, P4) Some participants enjoyed striking the blocks using the pickaxe prop and stated that they can feel the descending of the block props through it (P4, P8, P9).

Compared to the previous application, participants mostly felt that the block building experience was *super real* (P2). P3 even thought that the blocks were connected, although there were actually gaps on the surface between the airbags. Despite the fact that individual airbags are not perfectly aligned with the virtual block, the participants still believe the virtual blocks and the physical ones *align perfectly* (P2).

P2 built a stone block and were amazed by the fact that he can actually sit on it, stating that "*it is remarkable*". P4 tried to build stairs; however, the current prototype is not yet stable enough for stepping up. P4 and P8 say that they wish the interaction space could be larger and stacked with more pop-up tiles.

In terms of safety, the participants can feel the slight softness of the folded pop-up tiles, though it does not interfere with walking and their interactions in VR.

In general, the participants provide positive feedback on using TilePoP.

LIMITATIONS & FUTURE WORK

Speed

The inflation and deflation time of the current prototype are limited to the volume of the air in the tanks and the power of air pumps. A faster speed would allow simulation of dynamic objects. By using large air tanks, more compressed air and vacuum can be stored beforehand to make intermittent interaction faster. To allow continuous fast airflow, air pumps with greater power should be used. Connecting more tubes into each airbag can also accelerate the airflow, though it might interfere with the folding structure. The noise of the air pumps can be mitigated by putting them in another room or a noise-reducing box.

By using structural airbags, such as tube-like pneumatic actuation [16], large shapes may be formed without the need for inflation of the whole volume. In addition to pneumatic actuation, other deployable mechanisms might be suitable for future exploration. For example, using linkages and motors may be alternative solutions.

Shapes

TilePoP currently only supports 2.5D shapes attached to the ground. No overhanging shapes or detachable structures can be rendered. More complex shapes, such as bending and extruding from sides, can be explored further by integrating them into the tile folding structures. To increase the output fidelity, a possible approach is to attach small airbags onto the surface of the current ones as to render textures, similar to [45]. The block-shaped nature may not be suitable for rendering some contents, such as life form, but with an appropriate visual design, it could still provide immersive experiences as demonstrated with the dinosaur prop in the application Jurassic Island Escape.

An height of three blocks is supported with the current prototype. The airbags can be stacked high because they are lightweight. For higher stacks, more collapsed airbags are on top, thus more unstable when the airbag at the bottom is being inflated or deflated. Formal technical evaluation will be needed for future work. Some participants in our preliminary user evaluation wish the props could be movable. Making detachable pop-up tiles or actuating passive props can be potential directions for expanding the interactions offered by this floor-mounted interface.

Other shapes of tiles, such as hexagons [46], can offer shorter width of their gaps between tiles and is worth exploring; however, the shapes they construct may be less general than using block-shaped elements. Combining different sizes or shapes of tiles can also be useful for specific applications.

Regarding the complexity of fabrication, we believe that the process could be improved by using a large heat-sealing machine, which can heat seal strong and airtight bags, reducing the need for two layers in our current design.

Support

The current prototype does not support standing on the airbag because the top surface is supported by air which is compressible and not stable. The airbags become more unstable when stacked in a high manner. One possible solution might be to use structured air tubes or embedding strong rigid material serving as a skeleton inside, such as [46], to provide support while preserving the surface feeling of the pneumatic airbags. In this way, rendering a set of stairs allow being stepped on can be possible.

CONCLUSION

In this paper, we present TilePoP, a new type of pneumatically-actuated interface deployed as floor tiles that can be inflated into large props for whole-body interactions in VR. We have described the design and implementation details of TilePoP herein as well as demonstrating its two applications. In addition, we conducted a preliminary user evaluation to understand the experience of using TilePoP and the results of which are also reported herein. With TilePoP, we hope to inspire future research on dynamic proxy interfaces for Virtual Reality.

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