Self-overlapping Maze and Map Design for Asymmetric Collaboration in Room-Scale Virtual Reality for Public Spaces

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Abstract. This paper addresses two problems of public room-scale Virtual Reality (VR) setups. These are the lack of walkable space due to the restricted room-scale tracking area, and the isolating experience provided by a single Head-Mounted Display (HMD). We propose and demonstrate a design for constructing a naturally walkable self-overlapping maze and a corresponding unfolded map to facilitate asymmetric collaboration between the participant wearing an HMD and the co-located participants without HMDs. Two experiments were conducted to evaluate the usability of the design and participants' experience. Our work can be useful when designing self-overlapping architectures for limited physical spaces and when supporting asymmetric experiences in public VR setups.

Keywords: Self-overlapping space · Virtual reality
Asymmetric collaboration · Room-scale virtual reality
Impossible spaces · Visualization · Public spaces · Computer graphics

1 Introduction

Virtual Reality (VR) is a rapidly developing technology that is increasingly often used by public cultural centers such as libraries and museums to entertain and immerse their visitors [1,2]. Recent advances such as room-scale virtual reality that is capable of tracking users' motions within physical room-sized areas allow for natural interaction as well as locomotion in virtual environments. However, this technology has two limitations when set up in public spaces. Walking in virtual environments requires a significant play area [3], which is often hard to find in a public space. Additionally, head-mounted displays (HMDs) tend to isolate users in single-person experiences [2].

We propose a design that addresses these limitations, where we develop a system that is capable of allowing people to walk in a large virtual environment, but also facilitates more engagement through asymmetric collaboration with the bystanders (non-HMD participants). The proposed design consists of a walkable self-overlapping VR maze as it represents a simple navigation-based task,

A. L. Brooks et al. (Eds.): ArtsIT 2017/DLI 2017, LNICST 229, pp. 194–203, 2018.
https://doi.org/10.1007/978-3-319-76908-0_19

and a map visualizing it on a side display near the VR setup for the non-HMD participants. The design is evaluated through two usability experiments to find out whether HMD users can walk in the expansive maze without interruptions. Furthermore, the design of the map is evaluated for whether it can be understood and used by the non-HMD participants. In summary, this paper makes the following novel contributions:

- A formal design and demonstration of how a self-overlapping maze-like architecture can be constructed for public VR setups
- Demonstration of how to visualize self-overlapping architectures on a map
- Evaluation of the system with the self-overlapping architecture with a large audience in a public cultural center

2 Related Work

Navigation in the real world is a universal task based on sensory information from several cognitive processes such as vision, proprioception, and vestibular information [4]. In VR, navigation is often achieved by using traditional navigation tools (controllers, keyboard, mouse, etc.), however these usually only facilitate visual information, and have a tendency to induce motion sickness [3,4]. Ruddle and Lessels [4] found that this can be overcome by free walking in VR.

A limitation with free walking in large virtual environments is that it requires a large tracking space. Several researchers [3,5,6] have attempted to overcome this in two ways. The first manipulates users' motion such as in the technique "redirected walking" [5], where the users' perceived motion is slowly amplified or diminished as they walk in the virtual environment [3]. The second manipulates the virtual environment with techniques such as the perceptual phenomenon "change blindness", where instantaneous architectural shifts are made to the virtual environment without users noticing [7]. Another technique is "self-overlapping architectures", where a large virtual environment is compressed into a smaller physical area by overlapping parts of the environment [3,6]. The advantage of self-overlapping architectures over the other techniques is that it is less affected by the spatial requirement and does not require a directed experience. However, it has not been studied how this technique can be applied to the limited space in public VR setups and visualized unfolded on a map, which is what is investigated in this study.

To overcome the single-user experience limitation, bystanders can be involved in the experience through an asymmetric collaboration with the HMD user, an approach rarely used for VR in public. In studies [8–10], asymmetric collaboration is facilitated by unifying participants' experiences through a common story and theme, using multiple media, different roles, and communication.

An example of a role-based asymmetric collaboration in room-scale VR is the local multiplayer game VR The Diner Duo [11], where two participants are assigned roles of a cook and a waiter that have to collaborate to serve the guests. However, the game makes little use of natural navigation in the room.

In our study, we want to extend this using self-overlapping architectures to allow natural navigation and also support asymmetric collaboration via a side display in a public VR setup.

3 Design

Room-scale VR is a design paradigm that uses 360° tracking equipment to monitor the user's physical movement in all directions inside a tracked play area. There are essentially two high-end room-scale solutions – the HTC Vive setup with a play area of approximately 3.5 m × 3.5 m, and Oculus Rift for a play area of 2.5 m × 2.5 m. Our design and the experiments conducted use the HTC Vive setup, however findings can also be used for the Oculus Rift. Based on the equipment and related work, the design aims to fulfil the following criteria:

– The maze has to be walkable in VR in a limited physical space that is approximately 2.5 m × 2.5 m
– Using the technique of self-overlapping architectures, changes for updating the maze should not be noticeable to the HMD participant
– The overall area of the walkable maze should be perceived larger than the actual physical space
– To support asymmetric collaboration, the maze should be visualized on a map allowing non-HMD participants to engage in the experience

3.1 Constructing a Self-overlapping Maze

We define one part of the virtual environment that fills the 2.5 m × 2.5 m physical space as a "cell". Each cell of the self-overlapping maze can consist of informational rooms and transitional corridors. Rooms provide natural open area for placing objects, which is more constrained in corridors. Decorative and thematic content can be added that can be game-related, such as treasure and puzzles, or culture-related, such as architecture and historical structures like cathedral interiors. Transitional corridors are passageways whose primary purpose is to connect different rooms. When positioned right, corridors can help change the direction the user is walking in, thus breaking the pattern of for instance walking in a circle. Despite being transitional, they can also include game or cultural content such as scenery that can be seen through windows.

A cell can be split into a grid layout to define the placement of corridors and rooms in the virtual environment. With the average width of a person being approximately 0.456 m [12], different grid layouts were considered as shown in Fig. 1.

Without use of doors, the smallest grid that would allow for having corridors split in branching paths in the maze, is a 3 × 3 grid. This grid would consist of nine tiles, each with a size of 0.75 m × 0.75 m. On the other hand, taking into account the minimum corridor, which the users would need to walk in, the largest grid is a 5 × 5 grid. It would consist of 25 tiles, each with a size of 0.5 m × 0.5 m.

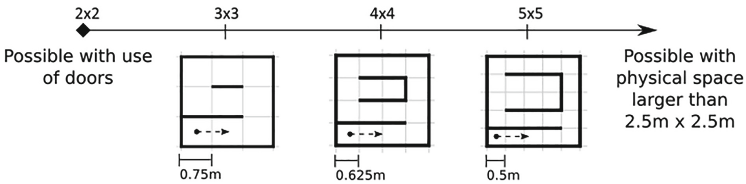

Fig. 1. Possible grid layouts for the 2.5 m × 2.5 m self-overlapping maze

Choosing the right grid layout would be based on the size of the physical tracking area and the amount of variation needed for a single cell, while still considering the minimum width for a person. For this study with a 2.5 m × 2.5 m tracking space, a 4 × 4 grid layout is used, which consists of 16 tiles, each with a size of 0.625 m × 0.625 m. Findings from our design can however also be applied for the other grid layouts. Grid layouts can also be combined to add variation to the width of corridors and rooms.

In order to create a self-overlapping maze, several cells are made and placed on top of each other. These are then swapped one after the other, allowing the user to move forward. The result is an architecture whose perceived area is larger than the physical space of 2.5 m × 2.5 m. When swapping one cell out with another, the tile where the user is positioned and the content seen on its neighbouring tiles have to be maintained and duplicated on following cells until they are out of the user's field of view. Figure 2 demonstrates a walkable VR maze designed with 26 cells. Windows are also added at places marked by double lines. The transitional tiles, where one cell is swapped for the other, are marked by numbers.

3.2 Visualizing a Self-overlapping Maze on a Map

In order to encourage asymmetric collaboration with the non-HMD participants and engage them in the experience of the HMD participant, a map is designed to represent the self-overlapping maze in a top-down orthographic view. To accurately visualize the maze on the map, the overlapping cells in Fig. 2 are reused. They are unfolded in such a way that they do not overlap. This is achieved by laying each cell next to the side of its previous cell depending on the direction that the user would be heading to when swapping to the new cell. Unfolding cells leaves gaps between the transitional tiles (marked by numbers in Fig. 3) that have to be connected. This is achieved by adding tiles in the gaps to prolong some of the corridors so that they connect with the following cells, as is demonstrated in Fig. 3 for instance between transitional tiles 2 and 3.

In some cases, it is not possible to place the connected cells right next to each other, and therefore in order to continue the unfolding, the next cell is placed further away, resulting in some prolongations crossing over each other. These crossings form prolonged bridges and tunnels, which is also demonstrated in Fig. 3 in the orange transition for example between transitional tiles 3 and 4.

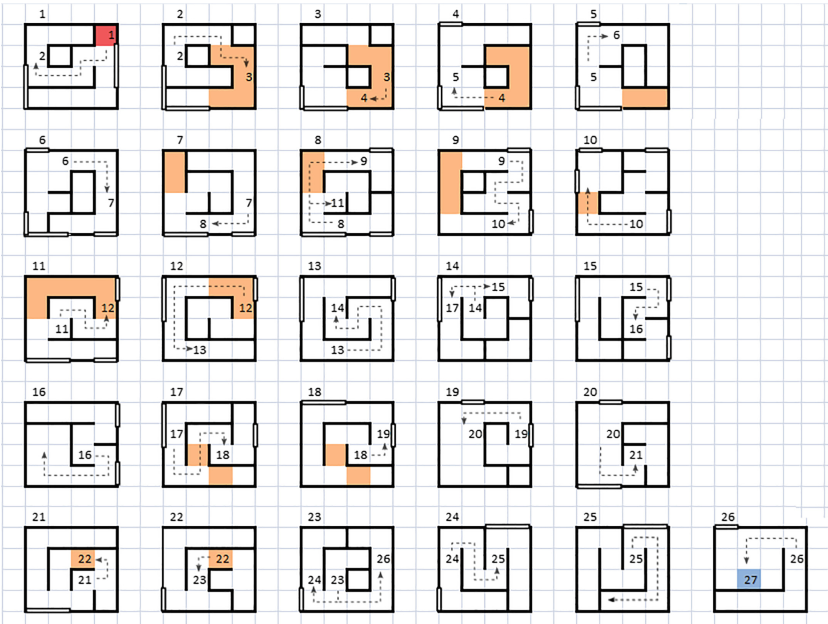

Fig. 2. A self-overlapping maze with 26 cells. Double lines mark the windows and orange tiles mark the tunnels corresponding to the map (see Sect. 3.2) (Color figure online)

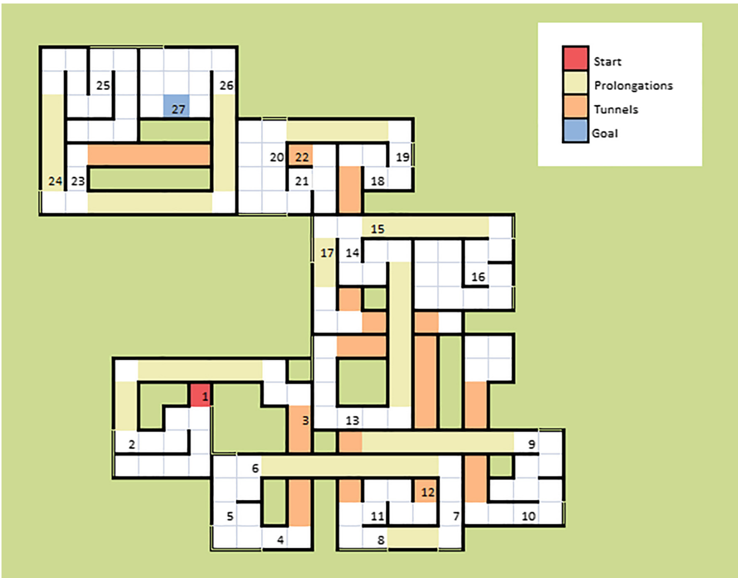

Fig. 3. A map visualization with an unfolded version of the self-overlapping maze

The bridges and tunnels that emerge on the map have to also be replicated in the overlapping cells in Fig. 2. In this case, they can be represented in form of small tunnels – areas with lower ceiling in the maze (marked as orange tiles in Fig. 2). Besides the self-overlapping architecture, the map has to also represent the movement of the HMD users and the direction they are facing for the non-HMD participants to be able to guide them. This can be achieved using a mimicking object, an avatar, with clear indication of the front side, such as a circle with a pointy edge. This avatar can mimic the HMD user's movement, and when it reaches the prolonged areas, the movements can be scaled to cover the prolonged distance in the map.

3.3 Implementing the Design

The proposed design was implemented in the Unity 3D game engine with the SteamVR plugin for VR development, and 3D models were created in Blender. As shown in Fig. 4, a 3D cell consisted mainly of wall and floor tiles and was set up in a Unity scene to fit in the 2.5 m × 2.5 m tracking area. In each cell, Unity's colliders were added on the transitional tiles to detect the user and when to swap to the next cell. Finally, the 3D cells were unfolded to form the map.

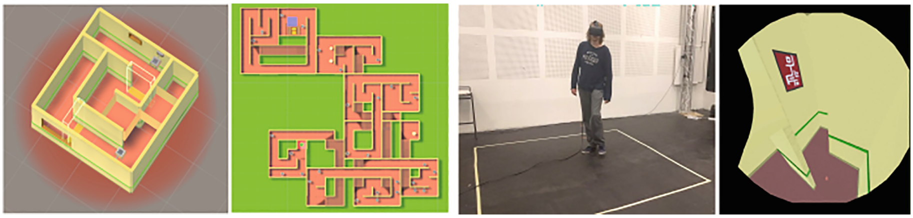

Fig. 4. From left: a 3D cell with colliders marked by yellow rectangles; the map; the 2.5 m × 2.5 m physical space; and the view in the HMD (Color figure online)

The map from Fig. 4 is presented on the side display for the purpose of facilitating asymmetric collaboration between the HMD and non-HMD participants. Here, two roles emerge based on the medium, which can be combined with a theme. We set the theme of exploration in a castle, with the role of a navigator for the non-HMD participants and the role of an explorer for the HMD participant. After implementing, the design was evaluated in two experiments described in the following sections.

4 Experiment 1: Testing the Design in a Lab

To evaluate the experience and usability of the proposed design, a usability test was conducted in a VR lab. In total, 18 participants between the age of 20 and 34 were tested in pairs. One participant was equipped with an HMD and acted as an explorer, while the other with the role of the navigator was instructed to guide the HMD participant to the end of the maze. After completing the maze, each participant was given a separate questionnaire based on their role to rate the five-point Likert items shown in Table 1. Furthermore, open questions were added to the HMD questionnaire to get responses on whether the HMD users noticed updates to the maze and their estimation of the size of the whole maze. Lastly, a short semi-structured interview was conducted with every participant.

Table 1. Likert items for the HMD and non-HMD role on a five-point scale (1: Not at all, 5: Very much)

Role	Items
HMD	**HQ1:** To what extent did the maze allow you to freely walk in the VR environment?
	HQ2: I got motion sick during the experience
	HQ3: To what extent did the help from the person without the HMD help you progress in the maze?
	HQ4: To what extent did you use the guidance of the other participant without the HMD?
Non-HMD	NQ1: How representative was the movement of the HMD participant on the map?
	NQ2: To what degree did the sudden speeding up of the HMD participant's movements on the map affect your guidance and communication?
	NQ3: To what extent did the map involve you in the VR experience?
	NQ4: To what extent did the map facilitate collaboration between you and the HMD participant?

4.1 Results and Discussion

Responses from the Likert items are summarized in Fig. 5. They show that HMD participants could freely walk in the self-overlapping maze (HQ1: $M = 3.44$) and generally did not notice the updates in the maze. When asked about the size of the whole maze, most HMD participants gave larger measurement than the actual physical size of $2.5\,\text{m} \times 2.5\,\text{m}$. Responses from the experiment also show that natural walking in the self-overlapping maze did not elicit motion sickness (HQ2: $M = 1.89$).

For the map, most responses show that the non-HMD participants rated the avatar's movement to correspond well with that of the HMD participant (NQ1: $M = 3.89$, NQ2: $M = 2.56$). The directions from the non-HMD participants were also rated as mostly helpful (HQ3: $M = 3.67$). Observations showed that some non-HMD participants struggled to find the exit of tunnels that were placed too close to each other, as was also mentioned by seven participants.

In terms of asymmetric collaboration, observations showed that participants used their roles, and the HMD participants used the guidance from the non-HMD participants (HQ4: $M = 3.89$). In the interviews, two HMD participants

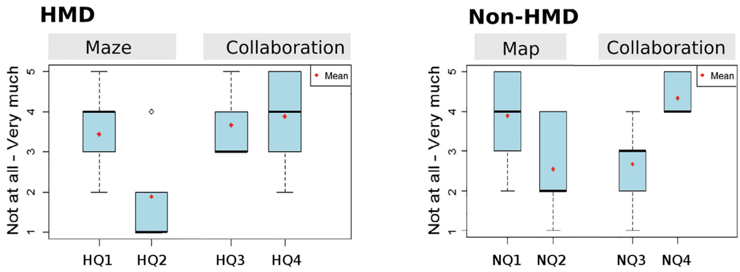

Fig. 5. Box plots of ratings on HMD and non-HMD experience from Table 1

mentioned that they "couldn't have continued without help from the non-HMD participant". Non-HMD participants also stated that the map facilitated their collaboration with the HMD participants (NQ4: $M = 4.33$), and a few mentioned in the interview that the fact that their directions were followed made them more part of the experience. Two participants said: "I felt part of the experience because she was reacting to what I was saying, we worked on it connected". Further improvements are however needed since the ratings showed that the map facilitated only average involvement of the non-HMD participants in the VR experience (NQ3: $M = 2.67$). Non-HMD participants could for instance be given more tasks for their role or be presented with more information and a mirrored view of the virtual world.

5 Experiment 2: Testing the Design in a Public Library

After testing in the lab, the second experiment was conducted as an observational study to evaluate the proposed design in a public library. Before testing, the system was improved to include more spacing around tunnels. The proposed system was tried by a total of 20 participants, of which two were female and 18 male with an estimated age of 9 to 40 years. Figure 6 shows pictures taken from the experiment, where the participants were instructed to collaborate and find a diamond in the maze.

Fig. 6. The setup of the experiment and participants interacting with the system

During the experiment, the number of participants and playthroughs was counted. One playthrough was considered the whole session where participants maintained their roles. Besides this, intuitiveness and usability were also observed by how far participants progressed without giving up. Furthermore, to evaluate collaboration, we observed whether participants fulfilled their roles and were communicating. Lastly, engagement was evaluated by whether they completed the maze, tried the system again, and by the number of spectators standing by and watching.

5.1 Results and Discussion

The system was played through 21 times. Based on the observations, as can be seen in Table 2, results on the intuitiveness and usability from the field study are similar to those from Experiment 1. 16 (78%) playthroughs completed the maze and found the diamond. The remaining five either accidentally pulled out the HMD wire or got confused at a more complex tunnel junction. All participants were observed to be engaged in the experience. 17 (81%) out of the 20 participants tried both the HMD and non-HMD role. There were only four participants observed to have retried their roles, which could be attributed to the fact that there only was one maze for them to solve. Lastly, a total of 30 spectators were observed in 13 (62%) out of 21 playthroughs, which shows that the system is able to asymmetrically involve the co-located people outside VR.

Table 2. Observations from the test. See Fig. 3 for transitional tiles 3 and 13

Observation	Count
Number of playthroughs	21
How many reach transitional tile 3 - understand the prolongations	21 (100%)
How many reach transitional tile 13 - understand the complex tunnels	17 (81%)
Do they collaborate - helping and using each other's contribution	21 (100%)
How many completed the maze	16 (78%)
Number of participants	20
How many participants tried both roles	17 (85%)
How many participants tried one role more than once	4 (20%)

6 Conclusion

This paper has proposed a self-overlapping maze that the HMD participant can naturally walk through, and a corresponding unfolded map to asymmetrically involve the non-HMD participants in a public VR setup. We have demonstrated a design for how to construct such a self-overlapping maze by creating cells that overlap to fit in a limited physical space of $2.5\,\text{m} \times 2.5\,\text{m}$. Furthermore, we presented how to create a map that can show the whole maze at once, where prolongations, tunnels, and bridges are added to create transitions from one cell to the next. Two experiments were conducted, one in a lab and one in a public library, to evaluate the proposed design. Results show that the self-overlapping maze is experienced as freely walkable while the map is mostly understandable with only visualization of tunnels requiring improvements.

Our work can be generalized and applied in other areas working with VR setups that can be walkable in small physical spaces or include non-HMD participants. Such areas could include architectural installations, where the designed buildings could be experienced through natural walking. Future work should investigate how to improve the visualization of the tunnels and bridges on the map, so that the non-HMD participants can clearly see where the tunnels start and where they lead. Lastly, the possibility of creating the self-overlapping maze and map procedurally, and the influence of sound could be further investigated.

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