Flexible Spaces: Dynamic Layout Generation for Infinite Walking in Virtual Environments

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ABSTRACT

Redirected walking techniques enable natural locomotion through immersive virtual environments (VEs) that are larger than the real world workspace. Most existing techniques rely upon manipulating the mapping between physical and virtual motions while the layout of the environment remains constant. However, if the primary focus of the experience is on the virtual world's content, rather than on its spatial layout, then the goal of redirected walking can be achieved through an entirely different strategy. In this paper, we introduce flexible spaces – a novel redirection technique that enables infinite real walking in virtual environments that do not require replication of real world layouts. Flexible spaces overcome the limitations and generalize the use of overlapping (impossible) spaces and change blindness by employing procedural layout generation. Our approach allows VE designers to focus on the content of the virtual world independent of the implementation details imposed by real walking, thereby making spatial manipulation techniques more practical for use in a variety of application domains.

Keywords: Virtual reality, walking, locomotion, reorientation techniques.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1 INTRODUCTION

Navigation is one of the most universal tasks performed in real and virtual environments [1]. In the real world, it is most commonly performed through walking - a simple and intuitive method of interaction with an environment. However, the support of natural walking in a virtual world remains a significant challenge. The tracking technology and the size of available workspace normally cannot accommodate large-scale virtual environments in a straightforward manner. To address the limitations of natural locomotion in large-scale virtual environments, researchers have developed a class of techniques known as redirected walking [2].

Traditionally, redirected walking involves manipulating the mapping between users' physical and virtual motions, resulting in a scaled rotation or translation in the virtual world. While effective, this approach is limited by the ability of our human perceptual system to tolerate the mismatch between visual and vestibular cues caused by it. Otherwise, manipulations become noticeable to users [3] and negatively impact the experience [4].

However, recent research has introduced several radically different techniques that do not employ self-motion gains, but instead manipulate the architectural layout of the virtual environment through change blindness illusions [5] and self-overlapping architecture [4]. While these perceptual illusions were shown to be extremely effective, there is still a need in generalized approaches for their applications.

In this paper, we introduce an approach for procedural generation of architectural layouts that support infinite walking through large highly-occluded virtual environments, which we refer to as *flexible spaces*. Our algorithm relies on self-overlapping architecture together with inability of humans to notice the changes in the environment if its consistency is maintained.

2 PREVIOUS WORK

Walking as a dynamic ability to navigate in VEs is of great interest for many 3D applications, such as rehabilitation, tourism, or entertainment. An obvious approach to bring real walking to VEs is a one-to-one mapping of the tracked user's head movements to the virtual camera in the VE is restricted by tracking technology and size of workspace.

The domination of visual cues over other senses allows to enlarge the virtual scene available for exploration with redirected walking [2]. The most basic approach is to stop the user at the boundary of the tracked space and instruct him to perform head turns in order to unnoticeably rotate the scene [6]. Other methods include introducing scene rotation with or without warning [7], or while the user is distracted by an unexpected event [8], [9]. Circular algorithms keep a user on a circular trajectory by returning him from outside or keeping him inside a circle during rotation in order to bring the user back to the center of the tracked space [8]. On the other side, rotation can be applied constantly on an unperceivable level as in [9] or by using system gains proportionally to the change in users' position and orientation [3]. In [3] the human sensitivity was evaluated towards changes of the gains from initial one-to-one mapping. It was found that humans are unable to feel a difference between virtual and real-world movement to a certain degree.

A completely different approach was proposed in [5], which used a perceptual phenomenon known as change blindness to redirect the user. According to [10], change blindness is a striking failure to see large changes that should be noticed easily. The technique was applied while the user was distracted by a task. By changing the positions of doors in a series of virtual rooms it was

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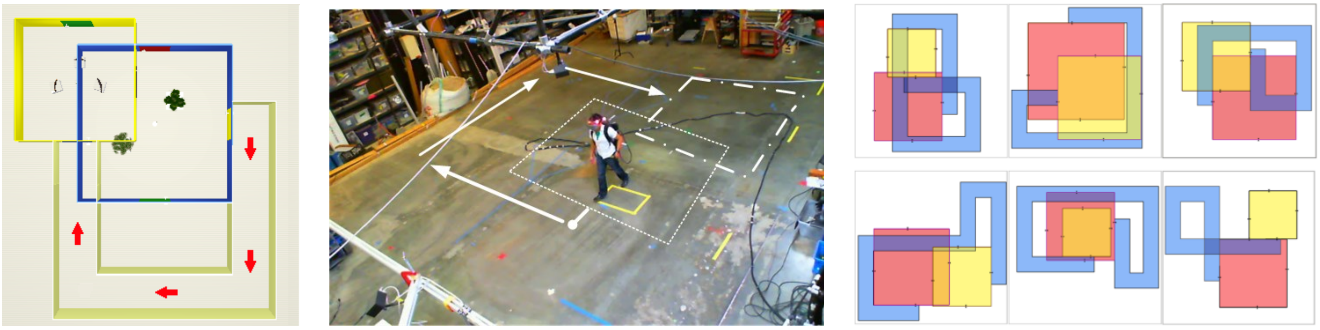

a b c

Figure 1 – The flexible spaces algorithm generates the layout dynamically, but maintains connections. a) A simple layout in flexible spaces. The corridor between blue and yellow rooms is rerouted every time the user leaves a room. b) User navigates in VE by walking through the corridors from one room to another while staying within tracked space. c) Possible layouts generated with the algorithm of flexible spaces.

possible to modify the direction of the user's movement within multiple scenes in a systematic way without it becoming noticeable.

Another approach to expand the size of the environment is using impossible spaces that are overlapping with each other [4]. While this paper is the most similar to our work in terms of the spatial manipulation employed, this study tested a specific scenario where two rooms that share a wall were partially overlapping in space and the research focused primarily on evaluating the perceptual effectiveness of this illusion. In contrast to our work, the overall topological structure of the VE was not fundamentally altered, and the tested environments were purpose-built by hand for the experiments. Therefore, our more general and automated approach might be considered to be an extension of the concept of the impossible spaces complemented by change blindness.

3 Flexible Spaces

Virtual training is one of the application areas for immersive VEs where real walking is potentially advantageous. For many scenarios it is important to create a representation of the environment called cognitive map for successful orientation in it (e.g. soldiers in a tactical training system) [11]. With this in mind, the VEs were trying to recreate the real world in detail while limiting the possible applications of redirection techniques.

We do not aim to copy the spatial layout of real, existing environments; instead, we focus on virtual, non-physical environments that resemble the real ones visually, but do not obey the same laws. Considering that cognitive maps are imprecise and often contain not graphical, but categorical and hierarchical representations of the world that sometimes cannot be represented as images [11], [12], there is an opportunity to extend the application of existing methods of spatial manipulation. If the purpose of the VE does not depend specifically on the spatial layout of the environment, we can relax the requirement for architectural conformity and allow more daring manipulations.

Therefore, we introduce the concept of *flexible spaces* - an impossible environment that violates the real world constancy in favor of providing the experience of seamless, unrestricted natural walking over a large-scale virtual space. We define a *flexible space* as a dynamic self-overlapping layout that executes automatic relocation and restructuring of parts of the environment to fit into the tracked space. Figure 1 shows examples of flexible spaces for two rooms. The user navigates from one room to another following one route and eventually comes back with a different route. Despite a self-overlapping layout his view is kept consistent.

One of the possible use cases of our approach is a virtual museum - a large-sized environment, where visitors are more interested in exhibits than specific paths. Corridors connect to rooms with related topics. Another application domain of flexible spaces is military training, in particular for training in search for key landmarks or other cues and for orientation in unfamiliar environment.

Consequently, this approach opens new possibilities for exploring the environment with less physical restrictions. To the best of our knowledge, our algorithm is the first attempt to generalize architectural manipulation illusions for practical use in immersive virtual environments.

3.1 Design

The test environment is designed as a complicated building that users are able to explore via real walking without invoking mapping manipulation, distractions or explicit user instructions. To this end, we distinguish between two subtypes of environment architecture: (1) informational – room: its features and content, and (2) transitional – corridors. The informational part of the VE undergoes minimal changes necessary to maintain consistent orientation cues. All changes are applied before the user enters the room. This eliminates the requirement for a specific route inside the room and allows the changes to be unnoticed. The transitional part (corridor) and targeted room position in the tracked space are procedurally generated and vary according to the algorithm described below.

We perform dynamic restructuring of the layout with random factors to avoid a buildup of knowledge of fixed layout patterns. It would be possible to pre-generated the whole VE using our algorithm. However, depending on the size of the environment, the user might learn the layout over time. This might expose the impossibility of the VE. From our perspective, flexible spaces alleviate the need for a detailed cognitive map shifting the responsibility for orientation cues to the VE, while a user decides where to go. The induced inconsistency encourages the user to succumb to such an approach. Moreover, flexible spaces do not limit the user's route supporting infinite walking.

According to our algorithm, rooms' positions are changed randomly and the positions of doors are changed to insure that it is possible to access rooms from all directions. We reserve a corridor wide space (1m from each side) along the perimeter of the tracked area, placing rooms in the *inner space*. Procedural generation automatically adjusts the VE to the tracked space.

To ensure that users can navigate successfully we decided that the connections assigned to each room should not change and should be bidirectional. So that users could return to the previous rooms at any moment. While in a custom built environment the information for orientation is purposely provided by a designer, for content oriented flexible VEs a simpler solution is to extend the room specific information to the doors that lead to these rooms. In our test environment we used rooms' wall colors for this purpose (partially shown in Figure 1 a).

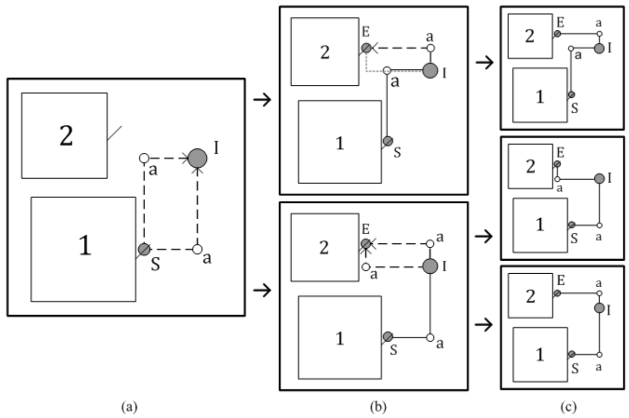

Figure 2: The path generation: The algorithm has 3 main stages: a – random selection of the intermediate point *I*, b – selection of the closes end-point *E* and random selection of additional points *a* between *S* and *I*, c – random selection of points *a* between *I* and *E*.

3.2 Algorithm

Our algorithm for procedural layout generation computes room positions and generates connecting corridors in the following way (see Figure 2):

1) The user inside initial room 1 selects and opens a door to a target room 2.
2) The target room 2 is relocated randomly in the *inner space* of the tracked area so that it fits in it. There are no restrictions on the room position. Initial and target rooms may fully overlap.
3) The position of the opened door is taken as a starting point *S* of the corridor.
4) Then an intermediary point *I* is selected randomly (see Figure 2 a). A first point *I* is selected with a condition that its position is not inside or behind the initial room. This insures that the room space is not broken immediately after user leaves the room. Similarly, the last *I* point should not be inside the target room. With multiple *I* points it is important to insure that the coordinates of the consecutive points are not too close to each other which is defined by a minimum segment size.
5) A door of the target room 2 is selected on the basis of minimal distance to the last intermediary point *I*. The position of the door is taken as the end-point of the corridor – point *E* as shown at Figure 2 b.
6) To connect the main points of the corridor additional points *a* are calculated. The decision which additional point is chosen for corridor construction is also made randomly, except the cases when a chosen *a* conflicts with a previous choice and creates a deadlock or if it is next to the *E* or *S* points and breaks into the room. Figure 2 c shows the possible corridors that could be built depending on the choice of additional points. One *a* is discarded because of a deadlock.
7) When the corridor route calculation is finished the doors in the target room are relocated so that the door at the point *E* corresponds to the initial room and the rest of the doors are relocated relative to it.
8) After that the corridor is built.

The length of the corridor depends on the number of intermediate points. Absence of *I* points is equivalent to a short straight corridor or a corridor with a maximum of three corners. During initial testing, the corridors of this type exposed the technique and, therefore, were declared inefficient and excluded from the test VE.

The shape of the corridor depends on the size and location of the rooms it connects. With each intermediate point the maximum amount of the corners is increased by two and the length of the corridor depends on the specific location of the point. We suggest using 1 or 2 *I* points per corridor. Examples of layouts for suggested settings are shown in Figure 1 (a, c). There is a tradeoff between available modifications of a corridor and the sizes of the rooms it connects. The variability of the corridor is automatically reduced to avoid overlap detection, so that the corridor does not intersect with the room in the proximity of the door.

Our approach does not limit the number of rooms in a VE. To provide users a consistent view of the environment despite dense overlaps we render only part of the VE at a time based on the user's position in the VE and his movement direction. We determine which objects can be seen by the user and do not render occluded objects. .

3.3 Limitations

The necessity of the *inner space* puts constraints on the size of the tracked area that should fit at least one room and provide a corridor reserved space (at least 1m wide) around them. The algorithm supports rectangular rooms and may be extended to other shapes where walls are parallel to x- or z- axes. In case of a room approaching the size of the *inner space* our solution will be equivalent to impossible spaces with a noticeable overlap. A potential way to solve the issue of interconnecting multiple large rooms will be the nonlinear application of translational gain and/or to increase the number of *I* points in the corridor.

The corridor length for rectangular tracked spaces has an upper limit described by $n \cdot (P-4c)$, where *n* is the number of *I* points, *P* is the perimeter of the tracked space and *c* is the corridor width. In practice the average lengths of the corridors tend to 44% and 38.5% of the said limit for one and two *I* points respectively. In our 9x9m test VE the corresponding lengths are 14.25 and 24.95 m.

The algorithm is limited to individual spaces interconnected by walkways bound by natural constraints. Nevertheless, it is theoretically applicable to outdoor environments that contain sight-occluding elements like hedges that limit the visibility and may serve as substitutes for the walls.

3.4 Implementation

The algorithm was implemented using the Unity Pro game engine. For tests we used a Fakespace Wide5 head-mounted display with 150° horizontal and 88° vertical field-of-view and PhaseSpace Impulse Motion Capture System with 52 high-resolution cameras mounted through-out a 9.14m x 9.14m area. To allow capture of the participant's head movements seven active LED markers were rigidly attached to the display. The test environment ran on a dual Intel Core i7 2.93 GHz PC running Windows 7, 6Gb of RAM, and a NVIDIA GTX 570 graphics card. Each eye is rendered 60 frames per second. Tracking data was received by the engine using a VRPN plugin [13].

3.5 Preliminary Testing

To test the flexible spaces approach we limited the environment to 5 rooms of different sizes, so that the users would take some routes several times during test sessions. We defined the connections between the rooms and content with numbered tokens. The environment was tested by five people; three males and two females, with average age 30,4. Two of them were naïve users. We explained to users the meaning of the door colors and instructed them to think aloud while in the VE. Each person spent approximately 30-35 minutes in the VE and performed two sessions: first - with the task to remember the correspondence between rooms and numbered tokens, second - with the task to obtain the tokens in ascending order.

We observed that search task was performed successfully and faster than exploration. This suggests that users are able to successfully navigate in flexible spaces. One participant commented “So many turns. It’s like a maze.” and we got similar comments from the rest of the users. During the interview naïve users indicated they felt that it might be possible to build the VE in the real world. The users seemed to be comfortable with following the corridors to reach the targeted room. When asked to compare the sizes of the VE and tracked area they testified that flexible spaces were perceived to be larger.

Once when the user entered the room and then immediately decided to return to the previous room the change of the corridor was suspected, as the corridors were changing every time the user opens the door. We suggest countering such situations with preserving the structure of the last visited corridor unless the user opens another door. We also got some comments for small inner parts of the corridor, approx. 0,5 m wide, which was equivalent to the defined minimal corridor segment, formed by two corners placed close to each other. They were described as “a bit weird”. That might be amended by increasing this parameter to 1 or 2 m.

Observational data and feedback given in interviews suggest that with modifications mentioned above, our technique tends to be unnoticed by users. Based on our informal observations, we suggest that the probability that the spatial manipulation will remain unnoticed depends on the length and number of corners in the corridors. Short corridors with no intermediate points were remembered and exposed the technique, while corridors with more than two points were too long to be practical. The effectiveness of our approach, therefore, seems to depend on both the number of corners and distances between them. Ultimately, we suggest that there may be a tradeoff between obscuring the user’s sense of direction and invoking a sense of feeling lost. We assume that this effect might also be related to inherent for VEs lack of cues for orientation. We plan to overcome this issue with wayfinding aids, such as displaying a connection graph of the environment with the user’s relative position.

In our future research, we will formally study and evaluate the difference between flexible spaces and impossible environments which are pre-generated with the same algorithm. We are particularly interested in differences in size, distance and overlap perception in these two environments. Additionally, we will assess their influence on ability to orient one-self. We would like to investigate the relation between room overlap detection and corridor’s length and twists. We would like to extend the study of impossible spaces and evaluate the perception of overlap between large sized rooms and corridors for relatively small tracked spaces.

4 Conclusion

In this paper we describe a new approach for dynamically generating environment layouts that support infinite real walking through large virtual worlds in a limited tracked space. This method is especially useful for VEs where the content and experience of the environment is more important than the specific spatial layout, such as virtual museums, cybertherapy, entertainment, virtual sightseeing, exploration of fictional environments, and many more. The developed algorithm also avoids any unnatural manipulation of the user’s motion parameters, and so does not introduce any of the visual-vestibular conflicts imposed by other common redirected walking techniques. In our proof-of-concept example, we demonstrate a large-scale environment that creates the illusion of a familiar world (an interior building with rooms and corridors), but does not follow the same physical laws as the real world. With the addition of environmental cues to assist in wayfinding, our preliminary qualitative observations with pilot participants have suggested that this approach yields intuitive navigation that might be augmented by a connection graph. Furthermore, the illusion does not appear obvious to users, and we speculate that the dynamically generated corridors and self-overlapping room layouts will have minimal or nonexistent adverse impact on users’ experiences in the virtual environment. We plan to formally investigate these questions in future work. Thus, the flexible spaces approach represents a new important step towards making spatial manipulation techniques for infinite real walking more practical and generalizable for a variety of application domains.

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