Compressing VR: Fitting Large Virtual Environments within Limited Physical Space

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Ideally, a virtual reality (VR) system should connect a real person to a computer simulated world, allowing the system to fully substitute the real world and its rules. Like the Holodeck featured on the TV series *Star Trek*, such a system should be able to provide an interactive, tangible virtual world that the user can explore without restrictions within a real room. One of the first ways someone might attempt to explore such a world would be to walk around. Nonetheless, as a result of restricted physical workspaces and technological limitations, the free and unlimited exploration of an arbitrary large-scale virtual environment (VE) is not possible in practice. We could rely on walk-like gestures or use additional devices to allow users to travel through VEs, while their physical locations do not change. However, real walking in VR provides important vestibular and proprioceptive cues that positively impact higher mental processes and improve the illusion of reality.[1]

In this article, we provide an overview of the existing approaches and techniques for enlarging the walkable virtual space. We specifically focus on the methods that use spatial manipulation for spatial compression, as it is one of the most promising, but underexplored methods for nonintrusive user redirection in a limited physical space. Researchers have developed several techniques to address the problem of free natural locomotion in VEs within an available real-world workspace. We distinguish the following types of spatial compression methods:

- basic reorientation,
- sense manipulation,
- rendering manipulation, and
- 3D scene manipulation.

All of them target the highest possible compression factors for any virtual space, and each has its own benefits and challenges.

Basic Reorientation

The most basic approach is to stop users at the boundary of the tracked space and ask them to return to its center and continue from the same point in the VE.[2] Rotation can also be instantaneously introduced based on the user's position in the real world.[3]

These basic approaches interrupt the VR experience and thus might adversely impact important characteristics of it, such as immersion and a sense of presence in the VE. More intricate methods of redirection exercise unperceivable manipulation, while the rendering and the user's immersive experience remain intact.

Sense Manipulation

One class of techniques known as *redirected walking* employs sense or orientation manipulation.[2] These methods build upon the principle that, during the multisensory integration process, visual cues are usually weighted as more accurate and therefore more important for orientation than other senses such as proprioception. Redirected walking uses the concept of camera manipulations based on gains. The user's dynamic motions are scaled according to the defined gains and then mapped to the translation and rotation of a virtual camera within a VE. The user reacts to the changes in the virtual camera's pose and adapts his/her motions accordingly, which in turn lets us keep the user within the real workspace.[2]

It is also possible to continuously apply the additional rotation. A generalized version of this

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approach is called the *circular algorithm*,[3] which mainly consists of two main types of manipulation and their combinations. The first keeps users on a small circular trajectory, allowing them to diverge in any direction. The other constantly redirects the user to the center of a big circle when the user performs a rotation. The goal is to make the additional rotation imperceptible to the user. For example, it may be applied when the user is performing fast head motions trying to follow a fast-moving object. This approach is referred to as the *distractor technique*.[4]

Human sensitivity limits the extent to which we can apply manipulations in virtual spaces[5] because such manipulations of primary senses should remain unnoticeable to users to minimize the possible adverse effects. Hence, sense manipulation still demands a considerably large real workspace. For instance, for users to continuously walk along a straight path in a VE with a curvature gain requires a squared workspace of almost 500 m^2.[5] Research has shown however that the radius might be decreased by a factor of two if the curvature gain is accompanied by translation gain.[6]

In practice, redirection by sense manipulation works well for moderately paced users who try to follow the planned path, but it can fail in other circumstances and scenarios. Therefore, sense manipulation is most suitable for outdoor open VEs where the virtual path might be easily adjusted to fit the real workspace. Nevertheless, the use of sense manipulation requires fine-tuning and extensive testing of each particular VE, and such testing should account for some unexpected user behavior.

Rendering Manipulation

Qi Sun and his colleagues proposed a novel rendering approach to spatial compression.[7] Their technique consists of a planar mapping of the constrained walking path with a custom reprojective rendering that is capable of wrapping an arbitrary VE into any real-world workspace. The obvious benefit of this approach is its flexibility. However, their method distorts the VE's visuals and makes it difficult for users to estimate the scale and exact shape of the environment.

Because this technique alters the user's perception of the environment, it needs to be explored further. Nevertheless, this approach could also be successfully applied to outdoor virtual scenes that involve content that is less sensitive to distortions.

Scene Manipulation

Unlike the previous approaches, virtual scene manipulation has an enormous potential to increase the compression factor of VEs without the need to manipulate the users' senses in an unnatural way. The core approach in scene manipulation is to have different parts of a VE share the same real workspace. To do so, some parts or elements of a VE are relocated, overlapping in the real-world space based on the users' actions. Most importantly, these changes occur without the users noticing.

One basic spatial manipulation approach involves the use of *deterrents*. That is, during runtime, objects are inserted into the VE that users must avoid walking through, such as roadblocks, which forces them to take an alternate route within the environment.[8]

Other approaches go further, changing the VE's configuration more drastically while users explore the virtual space and perform tasks.

Change Blindness

Change blindness is an entirely different approach to spatial compression wherein the system or specific task distracts users so they fail to notice large changes in VEs.[9] In the first study,[10] users were asked to perform a task that required they turn their backs to a door. While the users were distracted, the door's location was moved to a different wall in the virtual room (see Figure 1a). An interesting outcome of the study was that, after exploring the virtual building, the study participants were able to draw a map of the environment despite substantial spatial manipulations.

A second study tested more significant scene modifications based on change blindnesss.[11] In this second study, the entire wall containing the door was moved several meters away from its original position; this change significantly enlarged the room in order to return users back to the real starting point. Such an approach is most suitable for environments that contain regular structures, although generalizing and expanding the approach to arbitrary spatial arrangements is still problematic.

Impossible Spaces

Another method to compress VEs is the use of *impossible spaces*.[12] This approach increases the amount of walkable space by making separate rooms overlap and partially share the real space with one another. There are two possible implementations of impossible spaces. One involves expanding the space available in adjacent rooms by moving their shared wall and increasing the overlap (see Figure 1b). At the same time, the outer walls, doors, and the connecting corridor do not change. The other implementation involves increasing the overlap

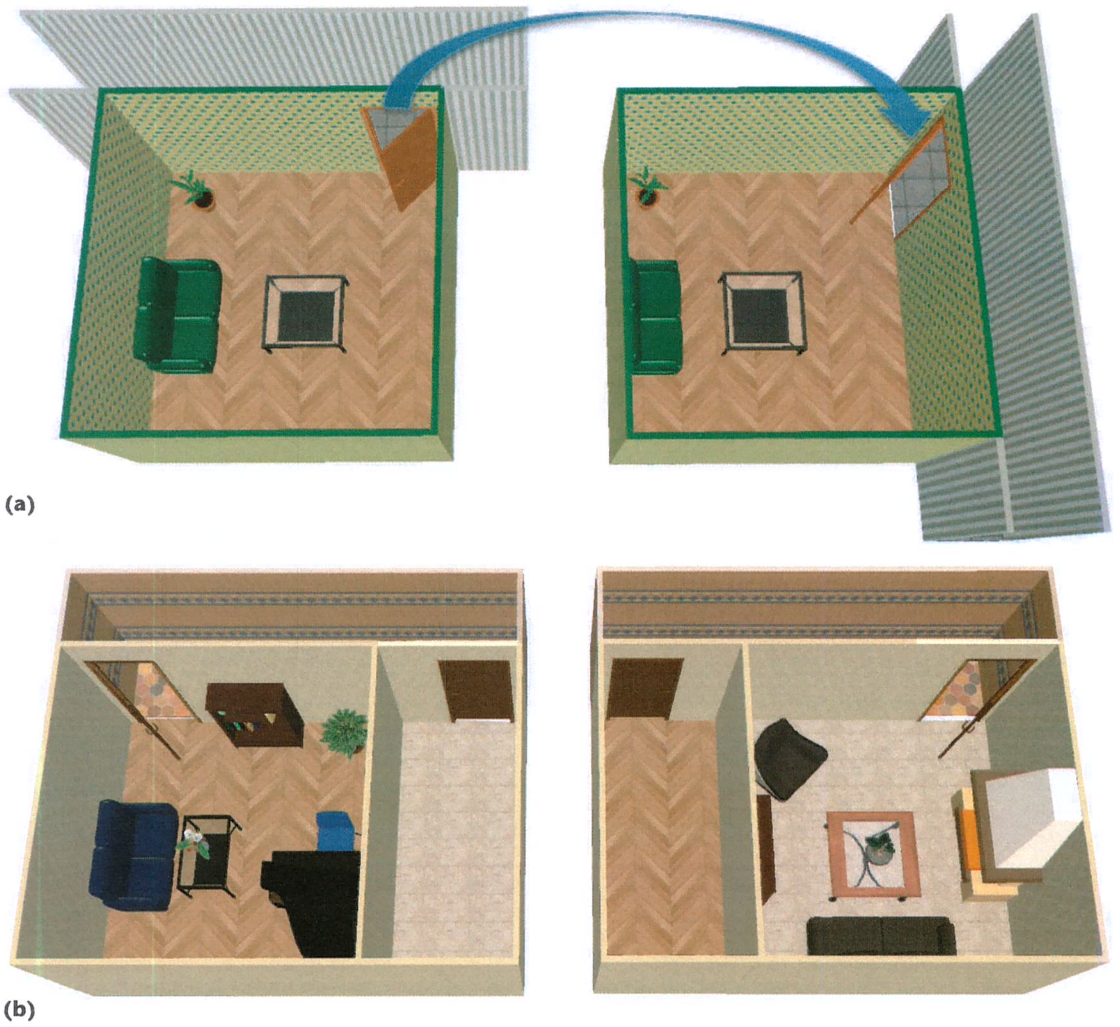

Figure 1. Spatial manipulations: (a) In the change blindness approach, the door is relocated in the virtual environment (VE) when the user is distracted by a task.[10] (b) The impossible spaces approach lets us extend a room setup with 50 percent overlap. The wall between the rooms is relocated based on the users' actions in order to enlarge the room they are about to visit using the overlap area.[12]

by bringing the two rooms closer to each other to minimize the space needed for them as well as the length of their connecting corridor. A study on impossible spaces showed that when blind walking between the identically placed objects in both rooms nonnaïve users failed to estimate the actual distances between the rooms correctly. That result suggests the use of impossible spaces efficiently increases the sizes of walkable virtual environments.

We preformed a follow-up study for impossible spaces showing that, by changing the complexity of the corridor, it is possible to increase the amount of unperceived overlap.[13] In this case, we define the complexity by the corridor's length and the number of corners in it. We used an expanding implementation of impossible spaces and explored whether the overlap perception depends on the corridor that connects the rooms. As in the earlier study, we used blind walking as a measure. Figure 2 illustrates the three types of corridors we designed: a simple corridor; a U-shaped corridor, with which we extended a simple corridor an additional 10 meters, detaching it from the rooms' perimeter; and a C-shaped corridor, which we extended with another 10 meters and four additional turns.

Although the simple length extension did somewhat decrease the users' overlap perception, our results showed that it was not particularly efficient in terms of the use of available space. However, the more complex C-shaped corridor substantially impacted the users' spatial perception when compared with the simple and U-shaped corridors. The estimated distances between the rooms in this case suggested that the rooms were far apart from each other. Moreover, some of the participants also stated that the rooms were not aligned.

In later work, we further delved into the corridor-dependent effects on spatial perception by addressing the corridor configuration parameters

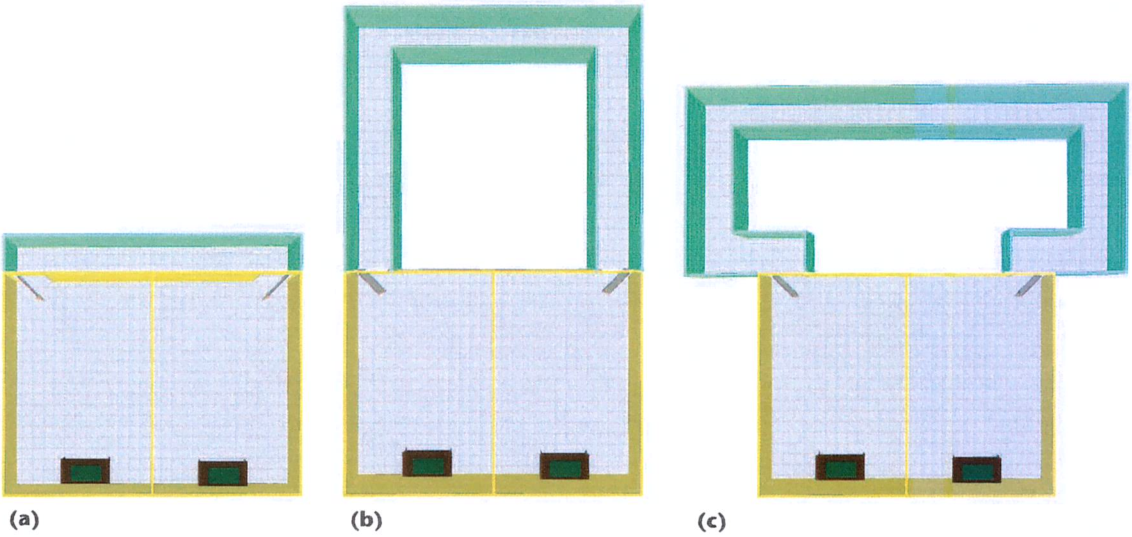

Figure 2. Virtual layouts with different corridors: (a) a simple short corridor, (b) a U-shaped corridor, and (c) a C-shaped corridor. The overlap was implemented by moving the wall between the rooms.

and geometry.[14] Furthermore, we diverged from the simple right-angled geometry. Instead, we used smooth curves and scrutinized their effect on spatial perception. We used two rectangular rooms of identical sizes that were aligned and overlapped by 50 percent throughout the experiment and focused only on corridor configuration. We hypothesized that the spatial perception in self-overlapping VEs might be influenced by the following properties of the connecting corridor:

- the number of corners,
- the sequence of corners,
- the positions of the corridor endpoints (doors) relative to the overlap zone, and
- the path's symmetry or asymmetry.

Based on these criteria, we created nine right-angled layouts, five of which were symmetrical and four asymmetrical. Figure 3a shows the right-angled asymmetrical layout. We also created a second set of layouts where the right-angled corridors were substituted with curved versions and tested this set separately. In this second set, we eliminated the corners and straight parts of the corridors that could be used as landmarks or for directional hints. Our objective was to see whether users would still perceive the room alignment and overlap in the same way and to evaluate the potential use of curved paths for spatial manipulations.

In addition, we assumed that asymmetrical layouts might feel different when participants walked in alternating directions. Therefore, we had the participants explore such layouts twice, in clockwise and counterclockwise directions. To measure the participants' spatial perception, we introduced a new approach: interactive visual reconstruction using semitransparent representations of the rooms (see Figure 3c). We also explained to our participants the possibility of the overlapping, adjacent, and completely detached rooms, challenging them to estimate the original room arrangement in each case separately.

The study results confirmed the importance of all the corridor parameters we have discussed here,

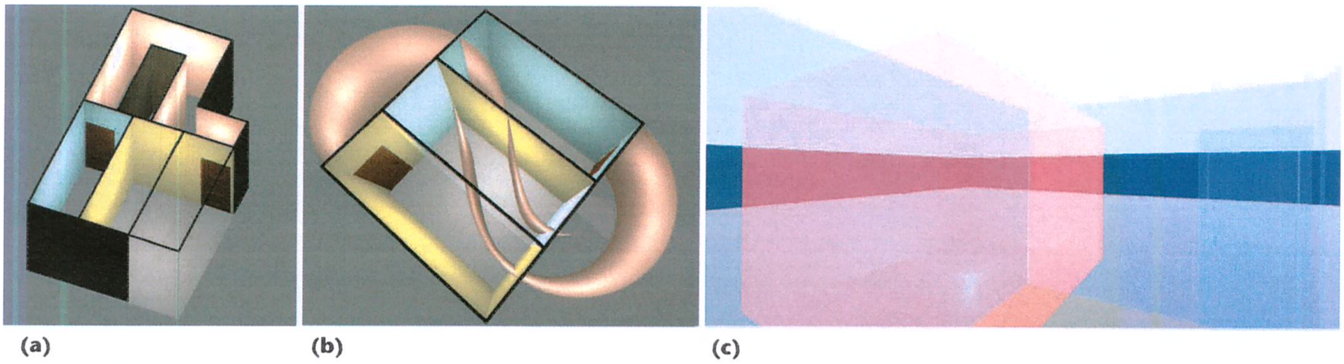

Figure 3. Experimental environment on the use of corridors in impossible spaces: (a) 3D models of symmetric and asymmetric right-angled layouts and (b) 3D models with curved corridors. (c) During task performance, participants were shown semitransparent representations of the rooms.

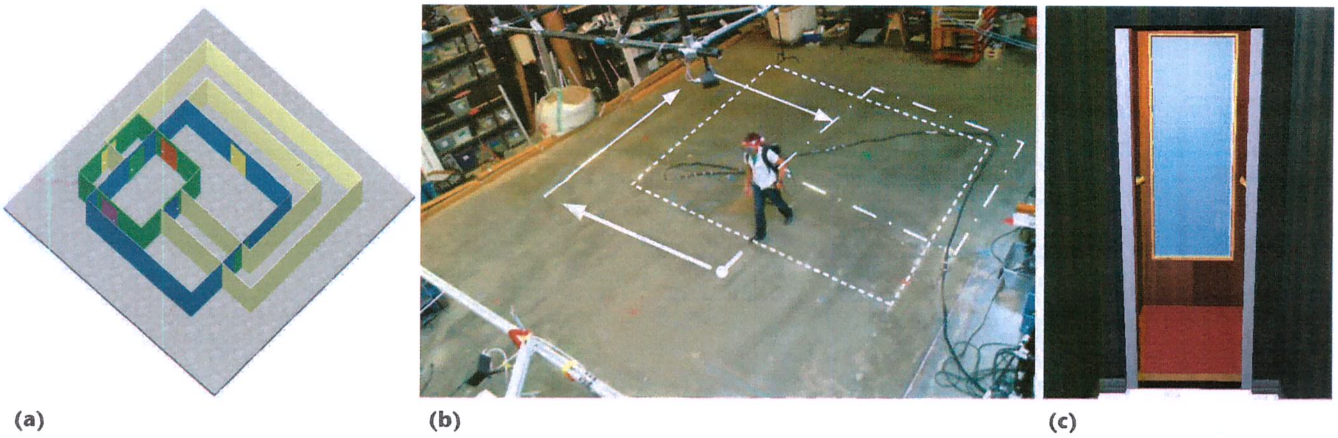

Figure 4. Flexible spaces: (a) a basic procedurally generated VE, (b) a user exploring the flexible spaces in the VE, and (c) an elevator extension.

the presence of distortions in the spatial perception, and differences in the perception of an asymmetric layout depending on the walking direction. Our results also suggest that participants were still able to perceive the overlap area and room alignment when they walked right-angled corridors.

The layout set with curved corridors provided an increased variation in estimated spatial arrangements and caused the participants to estimate larger distances between rooms compared with the right-angled set. The results indicated that in many configurations the participants believed there was space between the rooms. Unlike the right-angled layouts, some participants also asked whether the rooms had been rotated, which suggests a perceived change of room orientation.

Overall, the best results in both studies were achieved with the S-shaped corridor (see Figure 3b), which reliably created a long distance between the rooms. The S-shaped corridor was also the most space efficient because of the triple overlap as it passed directly through the area where the rooms overlap.

Earlier studies have confirmed distortions in spatial perception for larger real scenes, but to the best of our knowledge, our study is the first to directly observe a similar effect for small-scale self-overlapping VEs. Based on the obtained results, we suggest considering the parameters of the path that connects different spaces when designing impossible VEs. If possible, loop-like paths should be avoided as they might increase the perceived overlap. Meanwhile, the corridors that change the turning directions seem to be more realistic and decrease the overlap. The positions of doors relative to the overlap also matters, and it is best to position them as far from the overlap and each other as possible. The use of asymmetric corridors also proved to be efficient. However, the walking direction and placement of the elements that change the corridor's direction should be taken into account.

Flexible Spaces

The *flexible spaces approach* is one of the first attempts to merge several techniques. Our approach is based on the assumption that detailed spatial knowledge might be useful for navigation but is not necessary for all environments, particularly those that focus on information and content or impression and experience. A perfect example of such real-world settings is a large museum with signs that substitute the map of the building or the insides of a pyramid where loss of orientation is part of the experience.

The flexible spaces algorithm also relies on the fact that cognitive maps are often distorted, sometimes to the degree that they cannot be represented by images.[15] These distortions originate in the hierarchical structure of the cognitive maps and mental heuristics that help us to remember information about the environment. Thus, human perception gives us a way to create a new class of information- and content-oriented environments that provide consistent connections between their parts (predefined bidirectional links between the rooms) but that modify the details in between with a changeable architecture.

Our algorithm creates a procedurally generated self-overlapping and self-reorganizing dynamic VE that automatically regenerates the environment within the available workspace. In this approach, we united change blindness and impossible spaces, taking them to the extreme by allowing constant restructuring of the VE. Unlike previous work, our version of change blindness is task independent. The flexible spaces approach maintains the connections between the parts of the VE but does not repeat the layouts. The changes in the layout occur as soon as the user leaves a room or a corridor, and they are occluded by the other elements of the VE. Figures 4a and 4b show a procedurally generated layout for a VE with two rooms and a user exploring it. (See earlier work for a detailed explanation of the flexible spaces algorithm.[16])

The constantly changing nature of the algorithm prevents users from building up spatial knowledge and forces them to rely on other means for orientation. Following the museum metaphor, we introduced room-to-door color coding. For example, a red door always leads to a red room, making it content independent.

In our pilot study, we demonstrated that spatial overlap could be efficiently used in cases where it is not necessary for users to learn the spatial arrangement. Our test participants perceived the VE as something possible in the real world, which demonstrates the benefits of spatial manipulations for efficient workspace usage.

Another advantage of the flexible spaces algorithm is its versatility. It can be used in the originally proposed version or to generate unique, single-use layouts for each session. The algorithm supports an unlimited number and different sizes and shapes of rooms or other confined spaces, and it can easily be adapted to different room designs. Unlike other techniques, the flexible spaces algorithm guarantees unlimited walking with successful redirection and undetectable spatial overlap of up to 100 percent. In a case with a particularly dense spatial arrangement, it is possible to extend the environment to different levels with portals, flying, or a haptic elevator simulation (see Figure 4c).[17]

Challenges

Spatial manipulation still requires a rather large real space to create a believable VE. At the same time, our experience with flexible spaces and self-overlapping architectures suggests that users might consciously accept spatial manipulations. However, some users might also find the concept of an unrealistic architecture to be disturbing. Moreover, there might be an unexplored spectrum of new rules and techniques that users might consciously accept. As a next step, we plan to evolve the flexible spaces algorithm to accommodate curved geometry. That, in turn, might improve the compatibility with rotation and curvature gains. As for the existing methods, we consider combining multiple existing nonintrusive approaches for real walking support into a single ultimate technique to be one of the hardest tasks in achieving more efficient virtual space compression. Although some attempts have already been made, no perfect technique has been found yet. There are still open problems with large open spaces and support for a completely free exploration within a limited real workspace. To complicate matters further, the various types of VEs with real walking support are not universal and often require adaptation to specific real-world workspaces.

Another challenge for VR systems with large workspaces is estimating how many people a workspace could fit. Moreover, how do we support the simultaneous free exploration of multiple users within the same VR system? For that, we need fast, reliable, and smart path-prediction algorithms that take the user's behavioral specifics into consideration and novel methods to effectively counter any unexpected user behavior.

At this stage, VR researchers and developers should continue to explore and learn to exploit the limits of human vision, perception, and cognition in close contact with psychologists. Unfortunately, a large gap still exists between experimental psychology that uses very simple setups and stimulus and the demands of the striving field of VR. This gap needs to be bridged in order to keep pace with VR technology.

Lastly, the spread of consumer hardware is finally opening up possibilities for studying human adaptation to VR over a large population of users, but it raises concerns regarding the consequences of a long-term VR exposure. Simultaneously, we need to address the individual differences and sensitivity of various users. For example, some users still suffer from cybersickness, which sense manipulation might contribute to or help to counter. It is crucial for both research and industry to determine what is causing these unpleasant symptoms and learn how to control them. Whether users will develop an increased tolerance to the factors causing cybersickness after long-term exposure to VR is still an unanswered question.

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