Expanding Reality with Virtual Impossible Spaces

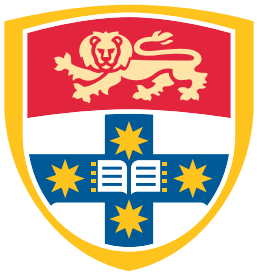
EDWARD MICHAEL KRANZ

Supervisor: Prof Eduardo Velloso

This thesis is submitted in partial fulfillment of
the requirements for the degree of
Bachelor of Advanced Computing

School of Computer Science
The University of Sydney
Australia

14 May 2025



THE UNIVERSITY OF
SYDNEY

Abstract

One of the greatest immersion breakers while using virtual reality is contact with the physical world. In the utopic model of virtual reality, the user is able to physically traverse the virtual world as if it were the same as physical reality. However, in the real world, we are limited by our environment and its obstacles.

This thesis explores natural-walking locomotion in VR impossible spaces with portal redirection. By utilising portals and non-Euclidean geometry, we can create virtual environments where multiple rooms overlay in the same physical space, allowing users to naturally walk through virtual worlds much larger than their physical boundaries. This technique enables full immersion without special hardware requirements beyond a standard VR headset, making it highly accessible.

This research builds upon existing work in impossible spaces, examining their effectiveness in enabling natural walking, potential applications in augmented reality, and exploring novel ways to validate and evaluate this technique beyond traditional metrics like the Simulator Sickness Questionnaire.

Throughout evaluation of impossible spaces in virtual reality, it was found that there was no determined taxonomy of impossible space techniques. This thesis attempts to explore all known techniques and define them.

Additionally, the design of impossible spaces was found to be awkward, as current world designers rely on Euclidean geometry, while impossible spaces can often be non-euclidean, which led to creating a new tool for designing impossible spaces.

We further explore the pain points of designing impossible spaces, including preserving the continuity of portal placement in respect to physical and virtual room boundaries.

Throughout this analysis of current techniques used to design impossible spaces, it became evident that there are no specialty tools for designing these spaces.

We proposed, designed, and built a web app, which allows users to design floor plans of impossible spaces, and export them to a 3D model format, which can be imported into Unity for building an impossible space. We used this tool to recreate impossible spaces previously by other papers, in order to demonstrate the efficacy of this new tool.

The tool was found to have been able to replicate these spaces entirely, while minimising the design time, and guaranteeing that the portals line up in respect to physical and virtual boundaries.

Acknowledgements

My sincerest gratitude to my supervisor, Professor Eduardo Velloso, who provided a great deal of guidance and advice on this thesis.

Thank you to the University of Sydney, and the School of Computer Science for providing the resources for me to undertake this research.

Finally, thank you to my family and friends for their support and sage advice during the writing of this thesis.

CONTENTS

Student Plagiarism: Compliance Statement ii

Abstract iii

Acknowledgements v

List of Figures viii

List of Tables ix

Chapter 1 Introduction 1

1.1 Problem at Hand 1

1.2 Locomotion in Virtual Reality 1

1.3 Redirection Techniques 2

1.4 Problem Definition 3

1.5 Aims and Objectives 3

1.6 Thesis Structure 3

Chapter 2 Literature Review 5

2.1 Theoretical Foundations 5

2.1.1 Space Perception in Virtual Environments 5

2.2 Natural Walking in Virtual Reality 6

2.2.1 Perspective Manipulation 7

2.3 VR Portal Implementations for Environmental Manipulation 8

2.3.1 Automatic Virtual Portals Placement for Efficient VR Navigation 8

2.3.2 Foldable Spaces 9

2.3.3 Reorientation in VR Environments Using Interactive Portals 10

2.3.4 Impossible Spaces and Storytelling 11

2.4 Impossible Spaces to Enable Natural Walking 11

Chapter 3 Methodology **13**

3.1 Implementing Portals in VR 13

3.2 Technical Implementation 16

3.3 Initial Demonstration of Impossible Spaces 16

3.4 Potential Implementation Approaches 17

3.5 Limitations 18

3.6 Preliminary Results 18

Chapter 4 Tool Development **20**

Chapter 5 Evaluation **22**

Chapter 6 Conclusion **23**

6.1 Summary 23

6.2 Contributions 23

6.3 Implications 24

6.4 Future Work 24

6.5 Final Remarks 25

Bibliography **26**

List of Figures

2.1 Annotated diagram from [1], showing the location of 'impossible spaces' in the taxonomy of natural walking techniques. 6

2.2 (b) Birds eye view of the routes made by portals, (c) The appearance of the portal in the simulation
Sourced from paper by Wang et al. [2]
©2022 IEEE 9

2.3 "An overview of overt redirection techniques derived from Foldable Spaces"
Sourced from paper by Han et al. [3]
©2022 IEEE 10

3.1 2-dimensional birdseye ray diagram detailing portals from a monoscopic perspective (non-VR) 14

3.2 2-dimensional birdseye ray diagram detailing portals from a stereoscopic perspective (VR) 15

3.3 Different views through the portal system showing the tunnel effect 17

4.1 A reproduction of the 50% overlap 'expanding room' from Suma et al [4]. 21

List of Tables

CHAPTER 1

Introduction

1.1 Problem at Hand

One of the greatest 'immersion breakers' while using virtual reality is contact with the physical world. In the utopic model of virtual reality, the user is able to physically traverse the virtual world as if it were the same as physical reality. However, in the real world, we are limited by our environment and its obstacles. Even if you are able to clear an eight square metre space, you are still bounded by the obstacles outside of that space, and thus would be limited to the same amount of virtual space as in real life due to the constraint of spatial alignment.

1.2 Locomotion in Virtual Reality

Locomotion in Virtual Reality (VR) is the act of moving around one's virtual environment. As the goal of VR is to achieve immersion, a good locomotion technique is one of the biggest problems to solve.

Different categories of locomotion include [5]:

- Physical Locomotion
  - Natural walking
  - Treadmills
- Virtual Locomotion
  - Teleportation
  - Point and click
  - Joystick/controller based

- Gesture based
  - Arm swinging
  - Hand directed movement
- Vehicle based/stationary
  - User operates a vehicle, which is relatively stationary to the user, but moves around a virtual environment.

As it is 'natural', natural walking yields the greatest immersion, due to alignments with the user's vestibular senses. Perceived momentum is the same as that of the virtual environment. The limitation of natural walking is that typically, the virtual environment is larger than the real environment, making physical boundaries the key limitation of this technique.

1.3 Redirection Techniques

Redirection refers to the manipulation of the virtual environment around the user, such that a naturally walking user does not make contact with any physical boundaries. Redirection techniques include:

- Impossible/foldable spaces
  - Can utilise portals to overlay new environments on 'previously walked' physical space.
  - Moving the virtual environment around the user [3]
- Eye blink/saccadic redirection (typically rotating the environment when user blinks or moves eyes)
  - Difficult to achieve with production headsets, as low-latency eye tracking is required.

Other research has approached this problem, for example with Lochner and Gain [6]. However, this paper uses the simulator sickness questionnaire (SSQ), and game experience questionnaire (GEQ). Additionally, it is hardly controlled as the virtual environment was created differently for each locomotion technique, and the user is given different tasks for each technique, making it impossible to compare the techniques. Another paper, by Suma et al. [4] experiment with the same technique, which will be analyzed in the literature review.

1.4 Problem Definition

The defined problem space can be summarised to:

Natural-walking locomotion in VR impossible spaces with portal redirection has been established as a valid and promising overt redirection technique, with the ability to unlock unlimited virtual space while reconciling a limited physical space. However, there is no established taxonomy or design guideline for creating these spaces, as there is no practical structure or ruleset that would facilitate its adoption.

1.5 Aims and Objectives

While Impossible Spaces have appeared in past academic research, their implementations have been fairly limited and resource intensive. Additionally, there is excessive complexity to designing impossible spaces, which could be simplified. This research aims to explore:

- How to simplify the design of impossible spaces, potentially through a floor plan maker tool
- Exploration of alternative metrics beyond the iGroup Presence Questionnaire (IPQ) and Simulator Sickness Questionnaire (SSQ) [7, 8] for evaluating the effectiveness of this technique
- How physical obstacles can be utilised with this technique, including potential applications in augmented reality
- Efficient implementation of portals in VR, which are computationally expensive, especially for onboard graphics

1.6 Thesis Structure

The remainder of this thesis is structured as follows:

- Chapter 2 reviews related work in the field of locomotion in VR, redirection techniques, and impossible spaces.
- Chapter 3 presents the methodology for implementing and evaluating impossible spaces.
- Chapter 4 details the creation of our floor planning tool.

- Chapter 5 presents the evaluation of our floorplan design tool, by replicating existing impossible spaces with this tool, and evaluating the benefits and drawbacks of using this tool.
- Chapter 6 concludes the thesis and discusses future work.

CHAPTER 2

Literature Review

2.1 Theoretical Foundations

2.1.1 Space Perception in Virtual Environments

Space perception in virtual environments can be analysed by how congruent the user's perception of the virtual space is to the real world. The way that the player interacts with the virtual world can be observed to measure how a sense of space is perceived. Spatial perception can be broken down into spatial cognition, i.e., how they utilise logic to reason with a space, and spatial navigation, how they intuitively interact with the space.

Jansen et al. [9] explore spatial memory within virtual reality. Their experiment involved displaying a "data mountain" (like the desktop on a computer screen) interface on a wall display. The purpose of the experiment was to determine whether two factors affected players' ability to memorise and recall the layout of items – visual overview (if participants could see the entire information space, or if it was through a peephole), and locomotion (whether participants could move around in front of the display, or if they were stationary). The latter factor is quite relevant to our paper, as it emphasises the importance of locomotion for spatial cognition. The paper found that participants who had the combination of both overview and locomotion when memorising the data mountain found it easier to recall than the inverse factors. This suggests that natural walking locomotion improves spatial perception ability.

2.2 Natural Walking in Virtual Reality

The significance of impossible spaces in virtual reality is that it is a method of enabling 'unhindered natural walking' without the requirement for special hardware, such as treadmills, or a large real space.

Nilsson et al. [1] provide a comprehensive overview of how natural walking has been addressed in research so far. It highlights two challenges to achieving natural walking in VR:

- Enabling users to navigate virtual worlds that exceed the tracking space.
- Providing appropriate visual, tactile, and auditory feedback to establish realism and immersion.

The first challenge is considered to be the most difficult, and the paper categorises natural walking implementations into three main types:

- Repositioning systems (using hardware such as treadmills, see [10])
- Proxy gestures (e.g., walking with your arms, see [11])
- Redirection techniques, through the use of things like saccadic redirection or impossible spaces.

It is arguable whether proxy gestures should be considered natural walking, and methods involving omnidirectional treadmills can easily break immersion as there is no vestibular congruency, i.e., the user has no feeling of momentum when they are walking on the treadmill.

The paper further subdivides the category of 'redirection techniques' into 'perspective redirection', and 'environment redirection'.

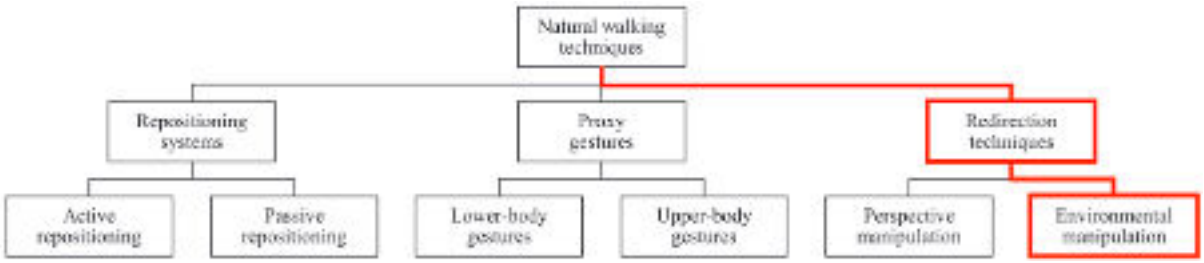


FIGURE 2.1: Annotated diagram from [1], showing the location of 'impossible spaces' in the taxonomy of natural walking techniques.

The paper by Nilsson et al. [1] provides a comprehensive overview of all current approaches to achieving natural walking in virtual reality, and highlights the strengths and weaknesses of each. As the focus of this paper is that of "environmental manipulation" through impossible spaces, we will focus on analysing this in particular.

2.2.1 Perspective Manipulation

While not within scope of this thesis, it is important to provide some background and analysis on the field of "perspective manipulation". This will provide some context on the challenges faced in this field, which can be used for comparison to any challenges which might arise for "environmental manipulation".

The paper by Sun et al. [12], titled "Towards Virtual Reality Infinite Walking: Dynamic Saccadic Redirection", explores the technique of saccadic redirection. Saccadic redirection hinges on a natural human perception phenomenon, wherein people experience an extremely brief period of blindness upon changing gaze. A 'saccade' is the rapid eye movement when changing focus between two fixed points, and during this period, we are unable to perceive changes in our environment.

The paper exploits this phenomenon by automatically manipulating the orientation of the player in the virtual environment during a saccade. It uses eye tracking to detect saccades, and an algorithm to determine how the environment is manipulated.

This technique has the benefit of worlds not requiring special design, as portals do not need to be considered, and the redirection occurs naturally.

This technique is fundamentally limited. Saccades are extremely brief, so this method requires highly precise hardware and software. Additionally, if the user does not switch gaze and trigger redirection, there is a risk of physical collision with a real world boundary. Finally, the paper finds that small amounts of environmental manipulation are imperceptible, however, immersion could be broken if the player is rotated too much, and may even cause simulator sickness.

2.3 VR Portal Implementations for Environmental Manipulation

2.3.1 Automatic Virtual Portals Placement for Efficient VR Navigation

The paper by Wang et al. [2] explores the usage of portals in VR for two purposes:

- Improving navigation efficiency.
- Enabling natural walking.

While utilising portals for navigation is not a novel technique, the automation of their placement is indeed. The paper proposes two main methods for automating the placement of portals:

- **Visibility Importance-Based Portal Placement (VIPP)**
  In essence, this technique automates portal placement by prioritising importance or relevance to the user.
- **Simulated Annealing Optimized Portal Placement (SAPP)**
  This method automates portal placement by prioritising walkability, and focuses on placing portals with the greatest potential to minimise walking distance.

The paper does not conclude the usefulness of this technique, or measure their intuitiveness. However, it is successful in providing two novel techniques for automatic portal placement, which do address the prevention of players encountering physical boundaries.

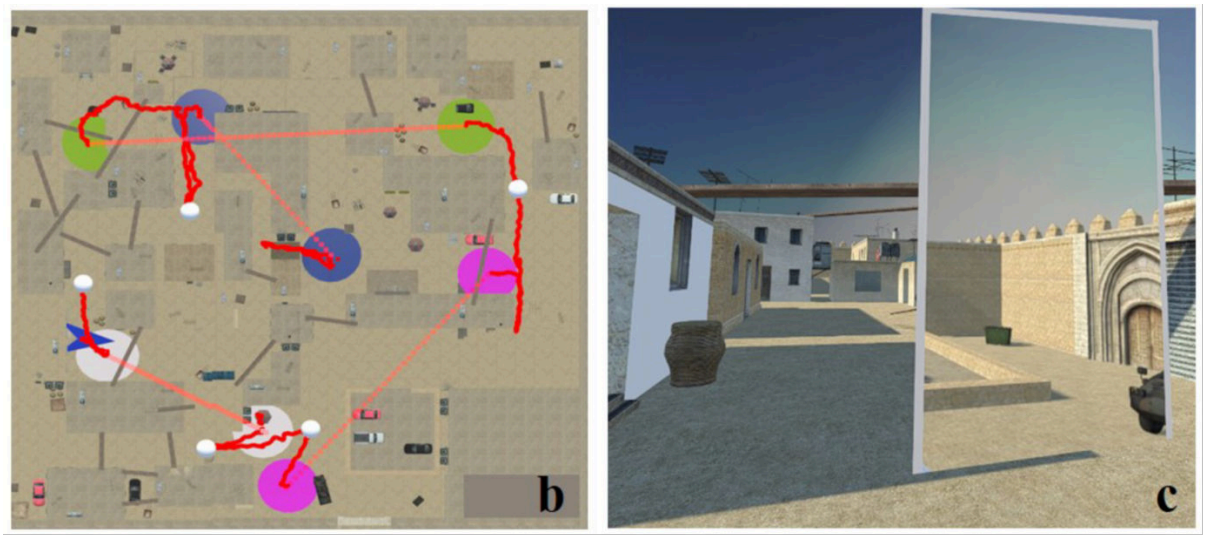


FIGURE 2.2: (b) Birds eye view of the routes made by portals, (c) The appearance of the portal in the simulation
Sourced from paper by Wang et al. [2]
©2022 IEEE

2.3.2 Foldable Spaces

Han et al. [3] explore the concept of 'Foldable Spaces' as a technique for environmental manipulation as means of enabling natural walking in VR. This is a novel approach towards overt redirection, wherein the environment folds around the user. It can be seen as an alternative to teleportation-based reorientation/recentering. Teleportation based recentering ("stop and reset" [3]) is potentially disorienting, due to its abruptness. Foldable spaces animate the manipulation of the world 'folding' around the user, to reveal new paths in the world which will allow the player to continue natural walking without physical collision.

The paper compares various different folding techniques, and compares them to "stop and reset", finding them to be more immersive.

This redirection method is considered to be "overt" rather than "subtle" (see [12]), as the user is made immediately aware of the redirection taking place.

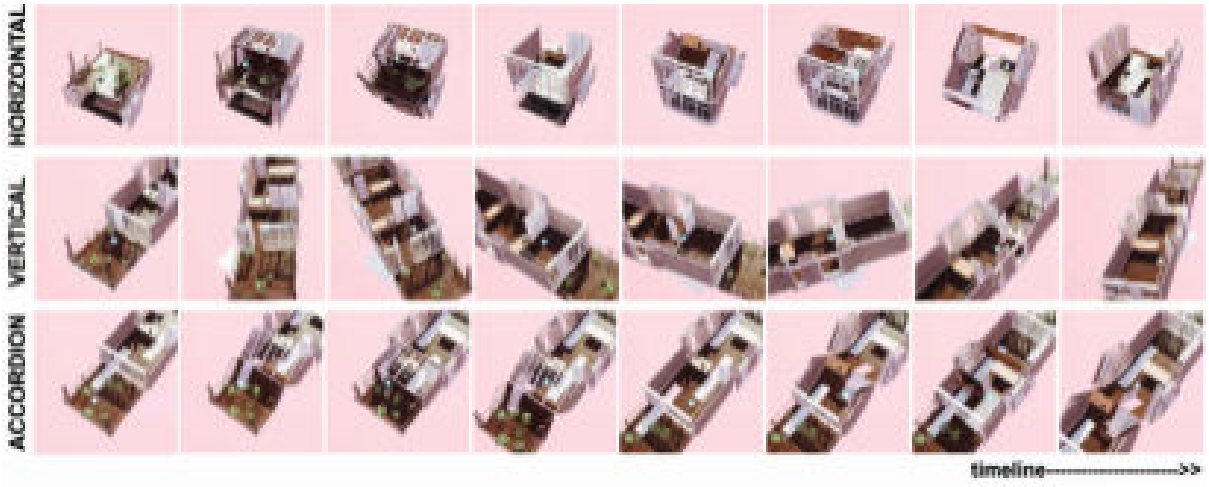


FIGURE 2.3: "An overview of overt redirection techniques derived from Foldable Spaces"
Sourced from paper by Han et al. [3]
©2022 IEEE

2.3.3 Reorientation in VR Environments Using Interactive Portals

Freitag et al. [13] explore the usage of portals in virtual reality as means of reorientation. This technique involves an automatic portal placement when the player is near a physical boundary, which encourages the player to re-center themselves in their physical space, while maintaining immersion in the virtual space. Under the taxonomy defined by Nilsson et al. [1], this implementation of natural walking falls under both perspective manipulation and environmental manipulation, particularly through their use of portals.

The paper found that this technique improved immersion, as physical walking distance markedly increased compared to the other techniques. Additionally, it found that tasks utilising natural walking took longer to complete, as walking was required to reach targets. However, the increased physical walking distance does not necessarily imply greater immersion, and certainly does not prove the efficacy of the technique.

While natural walking is important to enabling immersion in a virtual environment, it is important that this extra time taken does not introduce tedium in the game, as the goal of immersion is to make an experience intuitive, and therefore, fun. While this implementation does successfully highlight and

measure the use of redirection in VR, there are ways in which impossible spaces can be embraced in the design of an environment, to encourage fun [14].

Ziegler et al. [15] highlight the importance in measuring fun during Virtual Reality experimentation, which is often overlooked. They use a three-question survey of fun: (1) "I had a good time playing the game," (2) "The game was enjoyable," and (3) "I had fun playing the game."

2.3.4 Impossible Spaces and Storytelling

Impossible spaces can also be manipulated to support a narrative. Overdijk [14] explores the concept of 'circulation', employed by a game called *Lavrynthos*, utilising architecture to provide an intuitive path. With 'virtual trickery', through the use of portals, visual continuity through render textures, and other non-Euclidean world design, the game is able to enable natural walking in a small, confined real space, while being perceptibly larger in-game.

The case study suggests that the impact of natural walking has great benefits in enhancing embodiment (immersion), and the player's emotional engagement within the narrative. Additionally, the game imperceptibly and dynamically adapts the world to the player movements, which "offers an interactive narrative where space is integral to storytelling" [14].

This case study of the game, which is a first of its kind – utilising impossible spaces in VR, suggests that impossible spaces offer the ability to enable natural walking in an interactive virtual environment, without breaking immersion, wherein the player might typically need to 're-center'.

2.4 Impossible Spaces to Enable Natural Walking

The usage of impossible spaces to enable natural walking is explored by Lochner and Gain [6], and Suma et al. [4], wherein these papers employ a similar type of non-Euclidean world design to fit an infinite amount of virtual walkable space into a finite physical space, without the use of perspective manipulation, but rather, environmental [1].

Suma et al. [4] creates a simple demonstration of this technique, by having two rooms which overlap, and each need to be accessed by a hallway. While the player walks through the hallway, they travel

through a portal which enables them to enter the new room. The paper explores different levels of overlap, and different floorplans, using the Simulator Sickness Questionnaire (SSQ) [5] to gather data. They observed that 12 out of 14 players did not notice the impossible spaces. This study introduces a very powerful method to enable natural walking, and proves that this method of redirection is generally imperceptible, in addition to negligible effects on simulator sickness.

Lochner and Gain [6] base their paper on the same environment design as Suma et al. [4], however create the more familiar environment of a 'home', with props. In their experiment design, they create tasks which require the user to manipulate objects in the scene, while traversing overlapping rooms. In embracing a more detailed room design than Suma et al. [4], they are able to make the experience more fun for participants.

Both papers highlight the fundamental limitation of this technique, which is that rooms in the simulation cannot be larger than the physical space, and also that there were occasional issues of physical boundary collision due to errors in space tracking by the VR headset.

CHAPTER 3

Methodology

3.1 Implementing Portals in VR

Implementing portals in VR has had many challenges. A good way to understand how portals work in VR is first by understanding how portals work on a normal screen. The video "Coding Adventure: Portals", by Sebastian Lague [16] contains a comprehensive explanation on how portals work in video games.

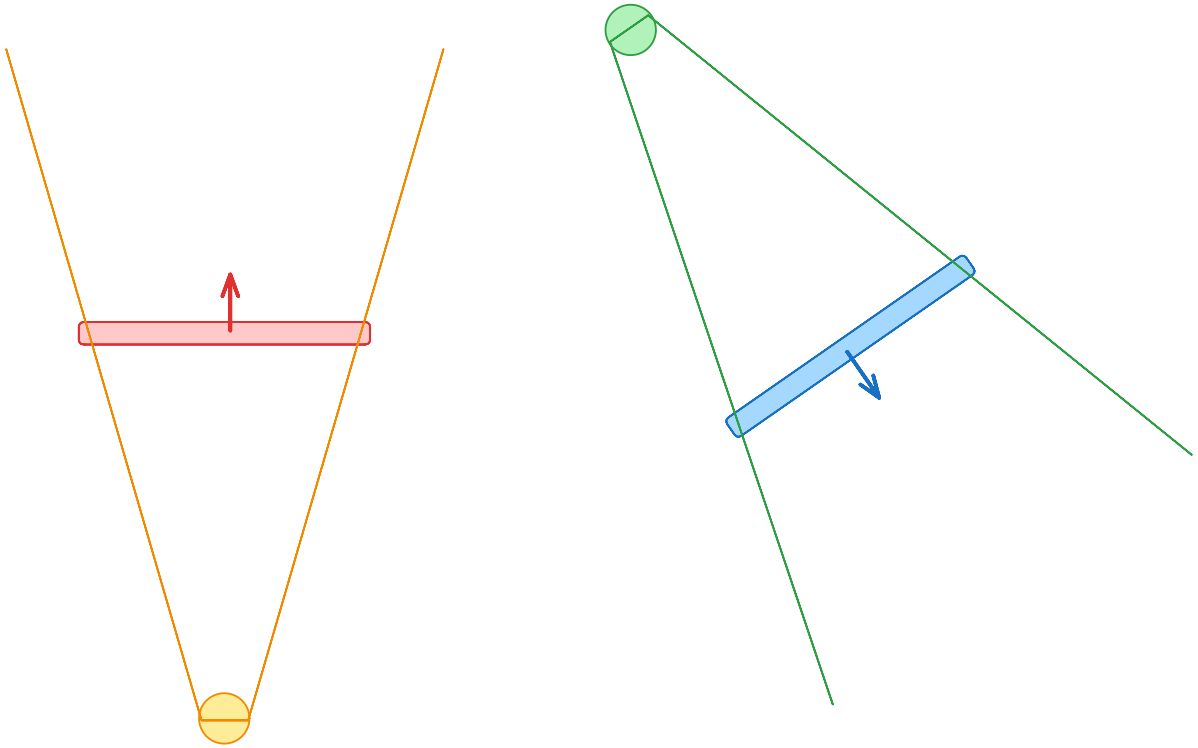


FIGURE 3.1: 2-dimensional birdseye ray diagram detailing portals from a monoscopic perspective (non-VR)

The ray diagram shown above provides an abstracted way of understanding how portals can be rendered by a graphics engine. The yellow circle and lines represent the player's camera, looking through portal A (red). In order to determine what to render within that portal, we must place a virtual camera (green) in the same position, however relative to the corresponding portal (blue). Then, the image bounded by the rays passing through the secondary portal can be projected onto the primary portal. This fundamentally describes the rules for rendering portals. (A) - The virtual camera must be in the same position as the primary camera, relative to the primary portal's corresponding 'secondary' portal. (B) - The virtual camera's perspective bounded by the secondary portal can then be projected onto the primary camera's perspective of the primary portal.

In terms of the perspective when travelling through the portal, a brief position switch is required to maintain the above rules. We can make this seamless by having the switch take place in-between frames, so that there is no disturbance to the user's perspective.

Implementing these portals in VR requires us to account for the perspectives of each eye.

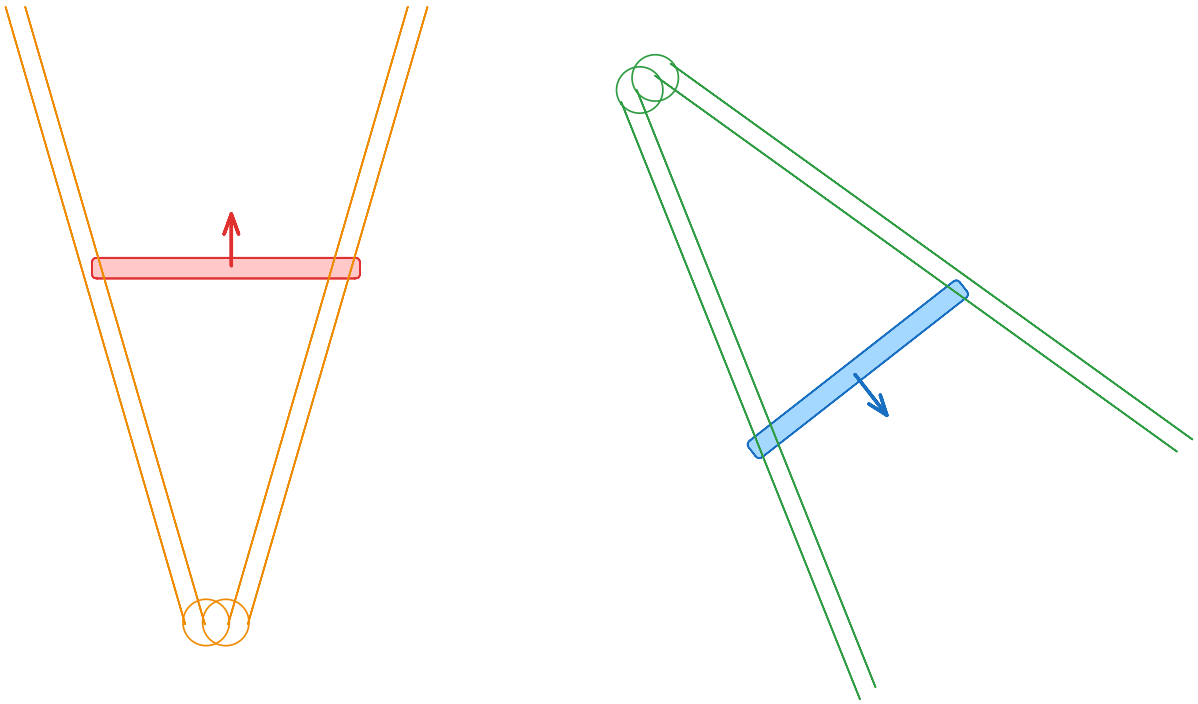


FIGURE 3.2: 2-dimensional birdseye ray diagram detailing portals from a stereoscopic perspective (VR)

The implementation of portals in virtual reality can be shown by the above diagram, it simply requires this process to take place for each eye, having four cameras instead of two.

Rendering a single camera onboard a virtual reality in isolation is considered to be computationally heavy, so implementing this four times requires a great deal of optimisation to run smoothly.

- Rendering virtual cameras with decreased graphical fidelity.
- Only rendering virtual cameras when within view of a portal.
- Only rendering the viewable portion of the virtual camera (Frustrum Culling)
- Only rendering virtual cameras when within a certain distance of a portal.
- Limiting the amount of recursion if multiple portals are placed.

3.2 Technical Implementation

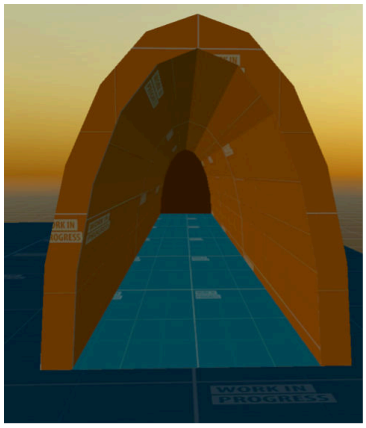
Due to the complexity of implementing portals in VR, particularly due to the difficulties surrounding optimisation and recursion, we are using an asset 'Portals for VR', created by Tom Goethals [17]. We deemed this acceptable, as the graphical implementation of portals in VR is not the primary focus of this paper, and this asset utilises a number of advanced techniques to handle the complexities we faced, surrounding that of portal recursion, and framerate optimisation.

3.3 Initial Demonstration of Impossible Spaces

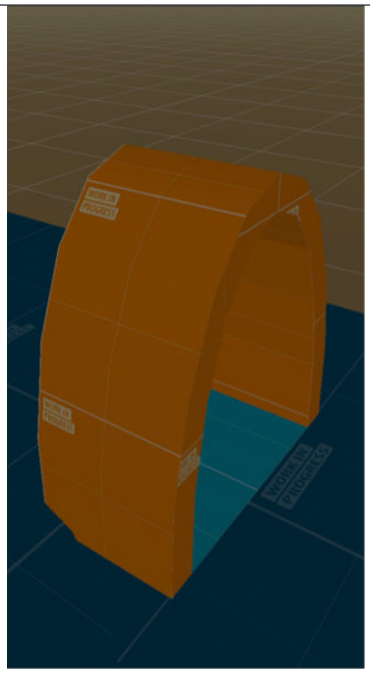
We used a short/long tunnel example as it is a very fast and effective way of communicating the idea of impossible spaces. Using portals allows us to achieve this, and also overlap multiple rooms over the same physical space.

In this demonstration [18], a tunnel appears to be much longer when looking into it from one side, but much shorter when viewed from the outside. This is achieved by placing portals at the entrance to the short tunnel, and the exit of the long tunnel.

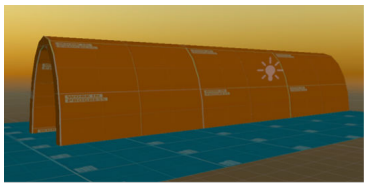
The long tunnel does exist somewhere else in the game; however it is accessed by walking through the short portal. Portal recursion allows us to see through two portals at once, and allows us to see out the end of the tunnel. To enable this, we have two portals:



View through portal showing long tunnel



View of short tunnel from outside



View of long tunnel from outside

FIGURE 3.3: Different views through the portal system showing the tunnel effect

- Portal #1: From the front of the short tunnel, to the front of the long tunnel.
- Portal #2: From the end of the long tunnel, to the end of the short tunnel.

In the same spirit, we can use this technique to make rooms feel much bigger.

3.4 Potential Implementation Approaches

Different ways that portals can be included in rooms, to place spaces upon each other include:

- The "corner fold" places a portal in the corner, maximising the room space.
- The "tunnel fold" places a portal somewhere in a 'hallway' of the room, which could be more immersive due to the physical analogy of a hallway.
- The "room split" fold, enables multiple doorways into the same room.

3.5 Limitations

Impossible spaces as a method of enabling natural walking is a very promising method of achieving full immersion in VR with no special hardware, and a limited play area. However, there are fundamental limitations which must be respected:

- The size of rooms cannot exceed that of the physical play area. However, the ability to stack an unlimited number of rooms over the same physical space does make up for this.
- Virtual environments must be designed to accommodate the subversive transition between rooms.

The goal for this thesis is to understand what has already been done in this narrow field, and attempt to expand upon it. For example, the level of detail used in the simulations for the paper by Suma et al. [4] was rather low, which may have led participants to notice the inconsistencies of physical space in the simulation.

By exploring this technique further, with more detailed scenes, which are not just houses – and with the possibility of incorporating real objects into the world, with (AR implementation), I hope to further the development of this technique, as it serves as a low-cost, highly accessible technique for enabling natural walking in virtual reality.

3.6 Preliminary Results

During the preliminary exploration of the problem space, we created a practical implementation of impossible spaces for the purposes of overt redirection in virtual reality.

The result of this methodology, and our literature review has led to a number of key observations about this subject.

- Perspective manipulation is too difficult, requiring special hardware, and can be inconsistent [12].
- Impossible spaces are effective in reusing physical space in the virtual world, without users noticing [4, 6].

- Natural walking enables a greater degree of immersion in VR [1].
- Natural walking has the potential to enhance user engagement, emotional connection, and narrative potency when used effectively in a virtual experience [14].
- **There is no framework, or tool for designing impossible spaces.**

Our findings highlight the efficacy of impossible spaces, however notice the lack of definition and tools around the problem area. This leads us to creating a purpose-built tool to support the creation of impossible spaces.

CHAPTER 4

Tool Development

The fundamental building block of impossible spaces, is a way to change the user's state.

While impossible spaces are possible without use of portals, such as by Suma et al [4] where a state change is used while the user walks in a hallway, portals enable seamless state changes, where hallways like this are no longer necessary to facilitate a 'common space' during change of state. The only thing that needs common is the position of the portal, relative to the room the player is in.

We found that using portals to facilitate state change allows us to be much more flexible in how we design impossible spaces, with there only being two rules.

- A virtual room cannot be larger than a player's physical playing space.
- Corresponding portals in each virtual room must be in the same position, relative to the room they are located in.

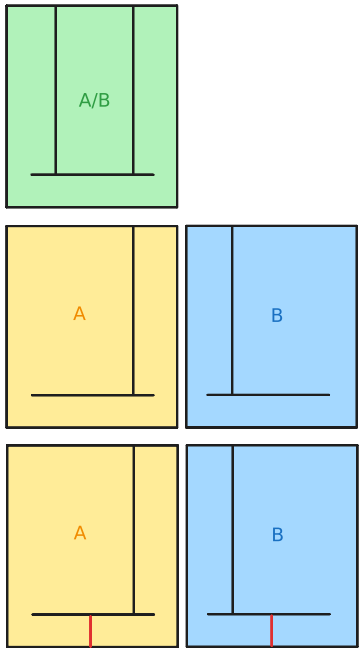


FIGURE 4.1: A reproduction of the 50% overlap 'expanding room' from Suma et al [4].

The first row depicts the physical depiction of the overlapping rooms. The second row depicts the individual rooms. The third row depicts the position required for a 'state change' where the red line is a portal.

CHAPTER 5

Evaluation

CHAPTER 6

Conclusion

6.1 Summary

This thesis explores the use of impossible spaces in virtual reality as a method to enable natural walking within limited physical spaces. By utilising portals and non-Euclidean geometry, we can create virtual environments where multiple rooms overlay in the same physical space, allowing users to naturally walk through virtual worlds much larger than their physical boundaries.

The current progress includes a successful implementation of portals in VR using Unity, which forms the technical foundation for creating impossible spaces. We have created a demonstration of the impossible spaces concept using a short/long tunnel example, which effectively illustrates the principle of spatial manipulation in VR.

6.2 Contributions

While this research is still in progress, it aims to make the following contributions:

- A comprehensive review of existing approaches to enabling natural walking in VR, with a focus on impossible spaces and portal redirection.
- An implementation of portals in VR that can be used to create impossible spaces, built on established tools and frameworks.
- An evaluation of different approaches to implementing impossible spaces, including corner fold, tunnel fold, and room split designs.

- Insights into how the level of detail in virtual environments affects users' perception of impossible spaces.
- Exploration of alternative metrics for evaluating the effectiveness of impossible spaces beyond traditional questionnaires.

6.3 Implications

The findings of this research have implications for the design of VR experiences that aim to enable natural walking within limited physical spaces. By understanding how to effectively implement impossible spaces, developers can create more immersive and engaging VR experiences without requiring large tracking areas or special hardware.

Additionally, the exploration of metrics beyond traditional questionnaires may provide new ways to evaluate the effectiveness of VR locomotion techniques, which could benefit the broader field of VR research.

6.4 Future Work

Future work on this topic could explore:

- The application of impossible spaces in augmented reality, where virtual content is overlaid on the real world.
- The development of tools to simplify the design of impossible spaces, such as a floor plan maker.
- The integration of impossible spaces with other locomotion techniques, such as teleportation, to create hybrid approaches.
- The use of impossible spaces in narrative-driven VR experiences, building on the work of Overdijk [14].
- The exploration of how different user groups (e.g., experienced VR users vs. novices) perceive and interact with impossible spaces.

6.5 Final Remarks

Impossible spaces offer a promising approach to enabling natural walking in VR without requiring special hardware or large physical spaces. By continuing to explore and refine this technique, we can contribute to the development of more immersive and accessible VR experiences.

Bibliography

[1] N. C. Nilsson, S. Serafin, F. Steinicke, and R. Nordahl, "Natural Walking in Virtual Reality: A Review," *Comput. Entertain.*, vol. 16, no. 2, pp. 8:1–8:22, Apr. 2018. [Online]. Available: https://dl.acm.org/doi/10.1145/3180658

[2] L. Wang, Y. Liu, X. Liu, and J. Wu, "Automatic Virtual Portals Placement for Efficient VR Navigation," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, Mar. 2022, pp. 628–629. [Online]. Available: https://ieeexplore.ieee.org/document/9757419

[3] J. Han, A. V. Moere, and A. L. Simeone, "Foldable Spaces: An Overt Redirection Approach for Natural Walking in Virtual Reality," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Mar. 2022, pp. 167–175, iSSN: 2642-5254. [Online]. Available: https://ieeexplore.ieee.org/document/9756751

[4] E. A. Suma, Z. Lipps, S. Finkelstein, D. M. Krum, and M. Bolas, "Impossible Spaces: Maximizing Natural Walking in Virtual Environments with Self-Overlapping Architecture," *IEEE Transactions on Visualization and Computer Graphics*, vol. 18, no. 4, pp. 555–564, Apr. 2012, conference Name: IEEE Transactions on Visualization and Computer Graphics. [Online]. Available: https://ieeexplore.ieee.org/document/6165136

[5] E. Langbehn, P. Lubos, and F. Steinicke, "Evaluation of Locomotion Techniques for Room-Scale VR: Joystick, Teleportation, and Redirected Walking," in *Proceedings of the Virtual Reality International Conference - Laval Virtual*, ser. VRIC '18. New York, NY, USA: Association for Computing Machinery, Apr. 2018, pp. 1–9. [Online]. Available: https://dl.acm.org/doi/10.1145/3234253.3234291

[6] D. C. Lochner and J. E. Gain, "VR Natural Walking in Impossible Spaces," in *Proceedings of the 14th ACM SIGGRAPH Conference on Motion, Interaction and Games*, ser. MIG '21. New York, NY, USA: Association for Computing Machinery, Nov. 2021, pp. 1–9. [Online]. Available: https://dl.acm.org/doi/10.1145/3487983.3488305

[7] W. M. Felton and R. E. Jackson, "Presence: A Review," *International Journal of Human–Computer Interaction*, vol. 38, no. 1, pp. 1–18, Jan. 2022, publisher: Taylor & Francis _eprint: https://doi.org/10.1080/10447318.2021.1921368. [Online]. Available: https://doi.org/10.1080/10447318.2021.1921368

[8] R. Skarbez, F. P. Brooks, Jr., and M. C. Whitton, "A Survey of Presence and Related Concepts," *ACM Comput. Surv.*, vol. 50, no. 6, pp. 96:1–96:39, Nov. 2017. [Online]. Available: https://dl.acm.org/doi/10.1145/3134301

[9] Y. Jansen, J. Schjerlund, and K. Hornbæk, "Effects of Locomotion and Visual Overview on Spatial Memory when Interacting with Wall Displays," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, ser. CHI '19. New York, NY, USA: Association for Computing Machinery, May 2019, pp. 1–12. [Online]. Available: https://dl.acm.org/doi/10.1145/3290605.3300521

[10] Z. Wang, H. Wei, K. Zhang, and L. Xie, "Real Walking in Place: HEX-CORE-PROTOTYPE Omnidirectional Treadmill," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Mar. 2020, pp. 382–387, iSSN: 2642-5254. [Online]. Available: https://ieeexplore.ieee.org/document/9089561

[11] S. Cmentowski and J. Krüger, "Tug & Swing: Traveling in Virtual Environments with Point-Tugging and Arm-Swinging," in *2023 IEEE Conference on Games (CoG)*, Aug. 2023, pp. 1–8, iSSN: 2325-4289. [Online]. Available: https://ieeexplore.ieee.org/document/10333137

[12] Q. Sun, A. Patney, L.-Y. Wei, O. Shapira, J. Lu, P. Asente, S. Zhu, M. Mcguire, D. Luebke, and A. Kaufman, "Towards virtual reality infinite walking: dynamic saccadic redirection," *ACM Trans. Graph.*, vol. 37, no. 4, pp. 67:1–67:13, Jul. 2018. [Online]. Available: https://dl.acm.org/doi/10.1145/3197517.3201294

[13] S. Freitag, D. Rausch, and T. Kuhlen, "Reorientation in virtual environments using interactive portals," in *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, Mar. 2014, pp. 119–122. [Online]. Available: https://ieeexplore.ieee.org/document/6798852

[14] M. Overdijk, "Circulation and Narrative in a Virtual Environment," in *Interactive Storytelling*, L. Holloway-Attaway and J. T. Murray, Eds. Cham: Springer Nature Switzerland, 2023, pp. 504–516.

[15] P. Ziegler, D. Roth, A. Knots, M. Kreuzer, and S. von Mammen, "Simulator Sick but Still Immersed: A Comparison of Head-Object Collision Handling and Their Impact on Fun, Immersion, and Simulator Sickness," in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Mar. 2018, pp. 743–744. [Online]. Available: https://ieeexplore.ieee.org/document/8446221

[16] Sebastian Lague, "Coding Adventure: Portals," Feb. 2020. [Online]. Available: https://www.youtube.com/watch?v=cWpFZbjtSQg

[17] T. Goethals, "Portals for VR | VFX | Unity Asset Store," Nov. 2024. [Online]. Available: https://assetstore.unity.com/packages/vfx/portals-for-vr-228871

[18] E. Kranz, "Impossible Spaces in VR – Engine Running," Nov. 2024. [Online]. Available: https://www.youtube.com/shorts/JELkOCyqP0Q