IADE Faculdade de Design,
Tecnologia e Comunicação
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LOCOMOTION IN VIRTUAL REALITY IN FULL SPACE ENVIRONMENTS

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Projeto apresentado ao IADE - Faculdade de Design, Tecnologia e Comunicação da Universidade Europeia, para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Creative Computing and Artificial Intelligence realizada sob a orientação científica do Doutor João Alfredo Fazendeiro Fernandes Dias, Professor Associado do IADE - Faculdade de Design, Tecnologia e Comunicação da Universidade Europeia

To my partner, AZ.

agradecimentos

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palavras-chave Realidade Virtual; Locomoção; Ambientes Virtuais

resumo

A Realidade Virual é uma tecnologia que permite ao utilizador explorar e interagir com um ambiente virtual em tempo real como se lá estivesse presente. É utilizada em diversas áreas como o entretenimento, educação e medicina devido à sua imersão e capacidade de representar a realidade. Ainda assim, existem problemas como o enjoo por simulação virtual e a falta de realismo que tornam esta tecnologia menos apelativa. A locomoção em ambientes virtuais é um dos principais fatores responsáveis por uma experiência em realidade virtual imersiva e agradável. Vários métodos de locomoção foram propostos, no entanto, estes têm falhas que acabam por influenciar negativamente a experiência. Este estudo compara a locomoção natural em espaços completos com a locomoção por joystick e a locomoção natural em espaços impossíveis através de três testes de forma a identificar qual o melhor método de locomoção a nível de imersão, realismo, usabilidade, aquisição de conhecimento espacial e nível de enjoo por simulação virtual. Os resultados mostram que a locomoção natural é o método que mais influencia positivamente a experiência quando comparado com os outros métodos de locomoção.

keywords virtual reality; locomotion; virtual environments

abstract

Virtual Reality is a technology that allows the user to explore and interact with a virtual environment in real time as if they were there. It is used in various fields such as entertainment, education, and medicine due to its immersion and ability to represent reality. Still, there are problems such as virtual simulation sickness and lack of realism that make this technology less appealing. Locomotion in virtual environments is one of the main factors responsible for an immersive and enjoyable virtual reality experience. Several methods of locomotion have been proposed, however, these have flaws that end up negatively influencing the experience. This study compares natural locomotion in complete spaces with joystick locomotion and natural locomotion in impossible spaces through three tests in order to identify the best locomotion method in terms of immersion, realism, usability, spatial knowledge acquisition and level of virtual simulation sickness. The results show that natural locomotion is the method that most positively influences the experience when compared to the other locomotion methods.

Contents

Acronyms

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CAVE Cave Automatic Virtual Environment. viii, 7, 19, 34

HMD Head-Mounted Display. 1, 17, 31, 33, 43, 45, 49

SSQ Sickness Simulation Questionnaire. 45, 52

VE Virtual Environment. viii, ix, 1, 2, 4, 5, 12, 21, 39–41, 48, 49, 51

VR Virtual Reality. vi, ix, 1–6, 8–10, 15, 17, 19, 20, 31, 32, 40, 43, 45, 57

List of Figures

List of Tables

1 Introduction

Virtual Reality (VR) is a term used to describe a Virtual Environment (VE) that users can explore and interact with in real time. The user sees this VE through a Head-Mounted Display (HMD) - an headset with screens that the user wears to track their movement, and interacts through the use of hand controllers. Virtual Reality has been available since the 1960s (Sutherland, 1965), and in recent years it has seen an increase in its development as a consumer product (Alsop, 2023), becoming more easily obtainable and used. Different applications in the area of entertainment such as games and interactive experiences have been developed, but also in other fields like healthcare, automotive, education, space and military (Alcanja, 2021). These applications have many aspects such as hardware, interaction and locomotion. Locomotion is an important component of VR applications since it can have a strong influence on user experience. Over the last years devices have been getting major improvements that allowed consumer level users to enjoy this type of entertainment. The hardware got cheaper and more complex and now allows for natural interaction as well as locomotion in the virtual environments, but the system still has some usability problems.

In the past, base stations were required to record the user's position, but technological advancements have made it possible to operate HMDs independently. They now have a number of sensors and may be utilized practically anywhere.

This chapter presents general information about virtual reality applications, their advantages and challenges, problem definition and motivation, and the organization of this dissertation.

1.1 Advantages of VR

Due to the level of immersion achieved with this technology, it is being used in different real-world scenarios and showing promising results. The main areas where virtual reality are being used are entertainment and training (Alcanja, 2021)(Wexelblat, 1993). These systems allow users to explore different places and experiences without leaving their physical environment.

This has many advantages, such as being able to experience situations that could endanger the life of the user like war zones, tornadoes, fires and floods or under water scenarios, but are required as part of training, in a safe environment.

It also allows remote maintenance and support services from experts located elsewhere, as well as in locations that could not get accessed otherwise. This also saves time as the user does not need to travel to the location.

Training can be repeated several times without costs, since there is no waste of materials or any dangers associated with training in VR.

Virtual reality can also reduce commute times and expenses by allowing the user to visit real world locations like houses, museums or facilities and provide accurate measurements of the spaces. This is useful for architecture, where the architect can plan before hand, housing sales, where buyers can visit multiple spaces without leaving the store, or teaching, where students can visit historical places from their classroom.

Tests in museums (Marto et al., 2022) have shown that VR can be used effectively by non-IT expert users of different ages as a central tool in their work processes in Real-World Urban Planning Context. A study allowed users to experience the reconstruction of a archaeological site and validate the varied reconstruction hypotheses (Roussou & Drettakis, 2005).

Another study was conducted to measure the effectiveness of VR applications for stress management training and stress reduction in the military, which proved to be effective not only in these areas but also in assessing individuals' resilience to stress and to identify the impact that stress can have on physiological reactivity and performance (Pallavicini et al., 2016). The ability to immerse the user in the VE makes VR a promising technology for entertainment, especially video games, since these aim to immerse the user in their world in order to become more entertaining. The similarity with reality in the interaction methods also allows for more imaginative experiences to be created. The immersion and realism it provides makes it a very suited system for not only video games, but also other interactive and cinematic experiences like virtual reality explorable movies.

Virtual reality also allows for corporate events and conferences to be conducted easily. Instead of physical gatherings, virtual events can be created where participants can attend and interact with speakers, exhibitors, and other attendees from anywhere in the world.

1.2 VR Challenges

Despite the advantages listed in the section above, there are still challenges to overcome and space for improvements. Immersion is an important feature in VR, and it refers to the degree to which a user feels "inside" the virtual environment and can interact with it as if it were real. One of the main challenges with consumer-level VR technology is that it can be difficult to create this sense of immersion, particularly when it comes to walking and movement within the virtual environment. The fact that the majority of VR experiences are designed to be experienced while sitting or standing in one spot rather than allowing users to move around freely is one explanation for this. As a result, users may find it challenging to fully interact with and explore the virtual environment, which may cause them to feel disconnected from it.

When taking part in VR experiences, users are typically forced to sit or stand in front of a desk or table. However, the latest head-mounted displays made by Samsung, HTC, and Oculus allow users to set up room-scale virtual environments. Users with a 6 degrees of freedom tracking system can sit, stand, or even walk in the pre-set regions. According to research, natural walking is preferred by users above other locomotion methods because it is what most people do on a daily basis (Cirio et al., 2009). It was also proven that this type of locomotion makes the experiences more immersive and realistic (Lochner & Gain, 2021).

To address this problem, some VR systems have implemented features such as "room-scale" tracking, which allows users to walk around a physical space and have their movements reflected in the virtual environment. However, this approach is still limited by the size of the physical space and can be cumbersome to set up and use. To overcome this lack of physical space, some developers have used self-overlapping architecture/impossible spaces to fit larger Virtual Environments in typical home or office environments (Serubugo et al., 2018) , for instance in the game Unseen Diplomacy (TriangularPixels, 2016). Some studies have been conducted on Impossible Spaces (Lochner & Gain, 2021)(Suma et al., 2012), which have proven to be effective with new to the experience users, but experienced ones were able to recognize the technique in action.

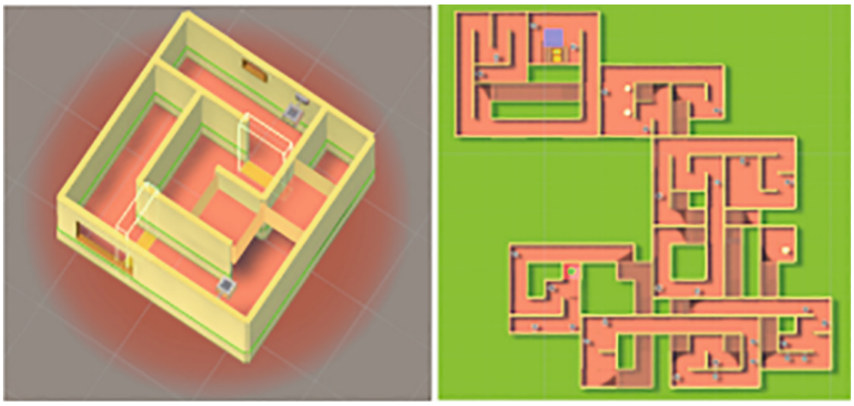


Figure 1: Self-Overlapping Maze representation. Source: Serubugo et al. (2018).

Overall, while VR technology has made significant strides in recent years, creating a sense of immersion and allowing users to walk and move freely within the virtual environment is still a major challenge that needs to be addressed in order to make VR more widely appealing and practical for a variety of applications.

1.3 Problem definition

Users rely on joystick movement to navigate through the VE, which can cause higher levels of motion sickness, since they normally lack the space to use Natural Walking as a mean movement(Buttussi & Chittaro, 2021)(Pixels, 2018). As the sizes of VE are normally bigger than the real physical spaces, users could not navigate fully just by walking without ending up bumping into real walls and objects.

In order to improve locomotion in VR, furthering related research is required. This thesis aims to answer the following question:

- Can natural walking in fully walkable non-overlapping spaces increase immersion over joystick locomotion and impossible environments (overlapping spaces)?

To answer this question we developed a test with three different VR experiences. The participants have to complete a set of predefined tasks while traversing the VE in three different methods of locomotion:

A) Natural Walking in fully walkable non-overlapping spaces

B) Natural Walking in overlapping spaces

C) Joystick locomotion

The effectiveness of the techniques will be measured through variables observed in the experience (e.g., number of bumps in objects, trespassing of walls) and a questionnaire to evaluate the experience and recreate the VE room arrangement.

This thesis aims to achieve the following objectives:

- Assess the impact of natural walking in fully walkable non-overlapping spaces on user immersion in VR experiences.
- Investigate the effects of natural walking in overlapping spaces on user immersion in comparison to other locomotion methods in VR.
- Evaluate the user experience and performance measures associated with natural walking in fully walkable non-overlapping spaces, overlapping spaces, and joystick locomotion. This assessment will include variables such as the occurrence of collisions with objects and the violation of virtual boundaries.
- Determine the potential advantages and disadvantages of natural walking in fully walkable non-overlapping spaces compared to other locomotion methods, taking into account aspects such as realism, presence, and the sense of embodiment.

1.4 Motivation

The advancement of locomotion techniques in VR is crucial to enhancing the overall quality of these experiences, with a particular focus on usability and immersion. Identifying the most effective locomotion method will not only contribute to the advancement of VR technology but also provide guidance for future research and development efforts in this field. Through understanding the advantages and disadvantages of each technique, we can direct further improvements and innovations towards creating more realistic, immersive, and user-friendly VR experiences.

The motivation behind this research relates to the need to address the limitations and challenges associated with current locomotion methods in VR. Joystick locomotion, although widely used, often fails to provide a natural and intuitive experience, leading to reduced immersion and presence. Additionally, environments with overlapping spaces can introduce unrealistic scenarios that may further impact the user's sense of presence and hinder the overall VR experience.

Through this research, we aim to determine whether natural walking in fully walkable non-overlapping spaces can offer a superior locomotion method compared to joystick locomotion and environments with overlapping spaces. The effectiveness and potential advantages of natural walking may be better understood by conducting a comprehensive evaluation of these locomotion techniques and comparing their impact on immersion, comfort, and overall experience.

Ultimately, the outcome of this research could help revolutionize the way users interact and navigate within virtual environments. Not only does it help understand how locomotion affects the usability and immersion of VR experiences, but also opens up new possibilities for various applications, such as gaming, training simulations, architectural walkthroughs, and therapeutic interventions. This work aims to improve the locomotion experience in order to increase user immersion, offer insightful information for further study, and eventually redefine the potential of locomotion in VR applications across a range of fields.

1.5 Thesis Structure

The rest of this thesis is structured as follows:

Chapter 2: State of the Art on Locomotion Techniques Projects critically examines the current studies made on different methods of locomotion and systems. The aim of this chapter is to introduce the advances and work done on this topic, and provide a foundation for the proposed methodology.

Chapter 3: Methodology details the research design, objectives, and specific methods employed in the study. This chapter provides information how the tests were done and evaluated.

Chapter 4: Virtual Environment System presents the different virtual environments, how they work and their components.

Chapter 5: Results presents the outcomes of the experiments conducted. Both quantitative and qualitative results are discussed, with data visualizations used to facilitate a comprehensive understanding.

Chapter 6: Conclusion and Future Work draws conclusions from the results of the user studies in this dissertation and specifies directions for future work.

2 State of the Art on Locomotion Techniques Projects

Virtual reality has been presented as one of the most promising technology in various fields, including gaming, entertainment, education, training, healthcare, architecture, and more (Alcanja, 2021). It provides unique possibilities for immersive experiences, allowing users to explore new worlds, acquire new skills, and engage with content in novel ways.

Although we are accustomed to experiencing Virtual Reality through the use of Head-mounted displays, other systems also allow the immersion of the users in virtual environments. An example of this are Cave Automatic Virtual Environment (CAVE), where the users are placed into a room with back-projectors which alter the appearance of the walls to create the virtual environment (Cruz-Neira et al., 1993), but the estimated costs of these systems are very expensive (Cruz-Neira et al., 1993) (Febretti et al., 2013). More recent systems combine different techniques to try lower the price of this system, but fail to either make it into the customer range (Juarez et al., 2010), the code is not open-source (Stuerzlinger et al., 2015) or has limitations in terms of hardware (Gonçalves & Bermúdez, 2018). These systems also need a vast amount of physical space and setup, which make them less attractive to users.

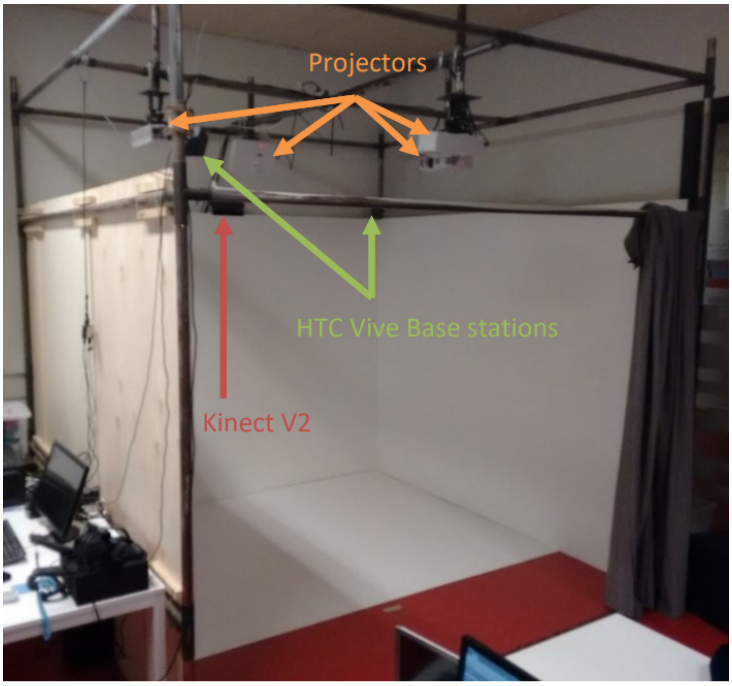


Figure 2: KAVE system - a low cost CAVE system that uses a Kinect for tracking. Source: Gonçalves and Bermúdez (2018)

Locomotion in virtual environments is an important aspect that can affect user experience significantly in terms of immersion, comfort, enjoyment, frustration and tiredness, regardless of the method of display.

Several studies have been made to test effectiveness and immersion of different locomotion techniques in VR (Usoh et al., 1999)(Boletsis & Cedergren, 2019)(Cardoso & Perrotta, 2019)(Christou & Aristidou, 2017). The major problem observed during locomotion in virtual environments is the occurrence of motion sickness, which can manifest as feelings of nausea, disorientation, or tired eyes. Motion sickness often leads to a loss of immersion and negatively affects the overall user experience (Kolasinski, 1995). In the following sections we will provide a taxonomy for virtual reality locomotion techniques (Figure 3) and present relevant studies done throughout time.

Locomotion techniques in VR can be organized into three levels. This work divides the previous studies into the categories of algorithm based locomotion techniques and tool based locomotion techniques. The first category is divided in two groups, natural walking and gesture based locomotion, and the second into stationary and mobile tools. Finally, these categories are divided in two each, the first into redirected walking and environment change, the second into walking in place and flying/leaning. On the second group of categories, the the first is divided into walkers and standard controllers, and the last into wearables and robots. When dividing in the first level, it were only consider algorithms that can be implemented across different types of hardware (e.g., tracking systems or computer vision) and not algorithms used in the creation of specific devices, like omnidirectional treadmills or motion footpads.

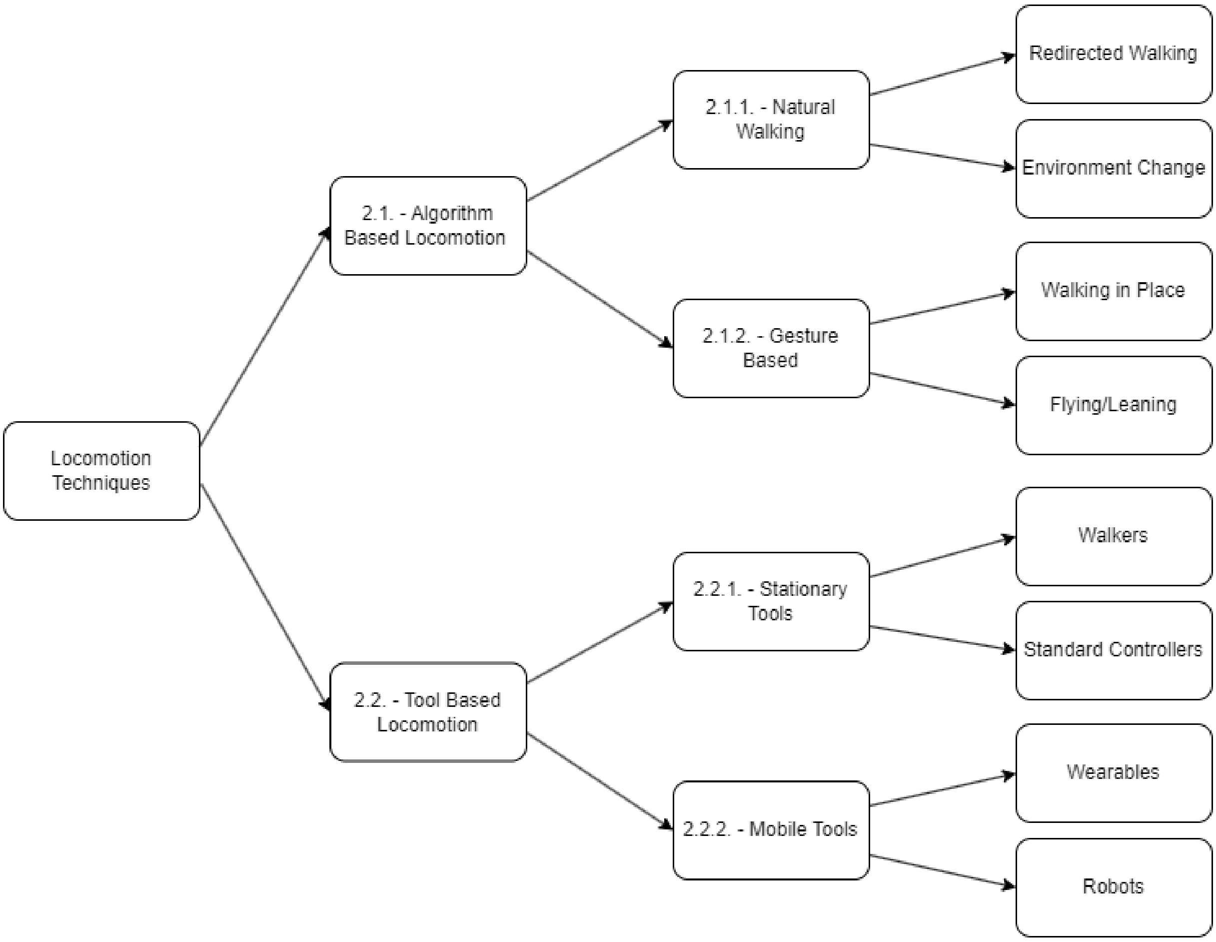


Figure 3: Taxonomy for locomotion technique studies.

2.1 Algorithm Based Locomotion Techniques

Algorithms are a major component of some locomotion systems used in immersive virtual environments. Although some tool based techniques use algorithms, these are not directly connected to the VR system but to the specific hardware created. In this section we will discuss techniques that do not require specific hardware. The second level of this category is divided into: natural walking and gesture based techniques. We will present some advantages and disadvantages of both and studies made on them.

2.1.1 Natural Walking

Natural walking is considered to be the most natural method of locomotion in VR, since it is the method more used by humans in the real world. Studies also show that it is more immersive when compared to other types of locomotion (Usoh et al., 1999)(Langbehn et al., 2018). Furthermore, it also proved to be superior in navigation tasks (Ruddle &

Lessels, 2009), better spacial knowledge (Langbehn et al., 2018)(Ruddle et al., 2011), and cognitive demands (Marsh et al., 2013). The main limitation with this technique is the size of the usable walking area. The VR systems with base stations limit the user to the tracking area that these create (M. Whitton et al., 2005), while baseless systems do not require base stations, but do not give enough safety to the user so that we can walk freely without bumping into the surrounding real world environment.

To solve these issues, different techniques have been implemented to allow users to traverse large virtual environments through natural walking. These techniques are explored further in the following sub-sections.

Redirected Walking

Redirected Walking is a method that manipulates the user's visual cues to keep him inside the tracking area (Razzaque et al., 2001). Distances in VR are usually underestimated when compared with the actual distances (Interrante et al., 2006), as well as traveled distances (Frenz et al., 2007).

Different variations of redirected walking techniques have been presented. Steinicke et al. (2010) proposed that different types of gains could be applied to the user movement. They reported that users could have up to about 49% increased or 20% less in their physical rotation than their perceived virtual rotation without starting to see the difference. Their walking distance could be scaled down by 14% or scaled up by 26%, allowing users to travel different distances in the virtual environment than the ones being traveled in the real world, and minimum circular arc of 22 meters for curvature gains (Figure 4).

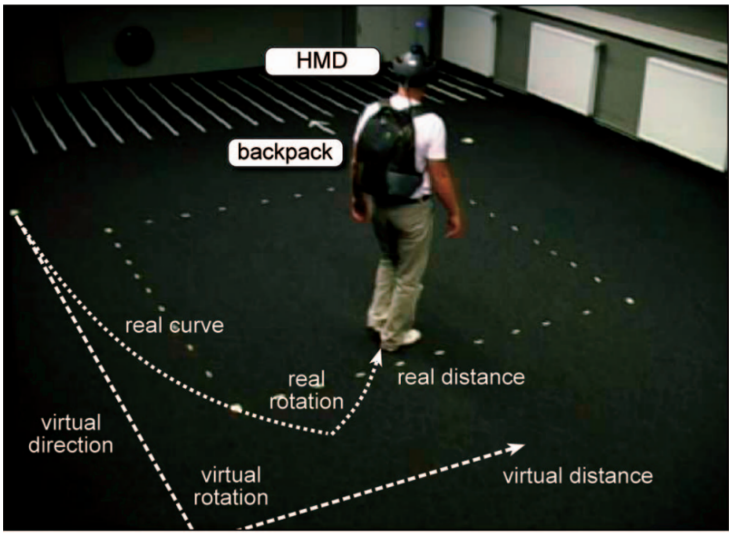
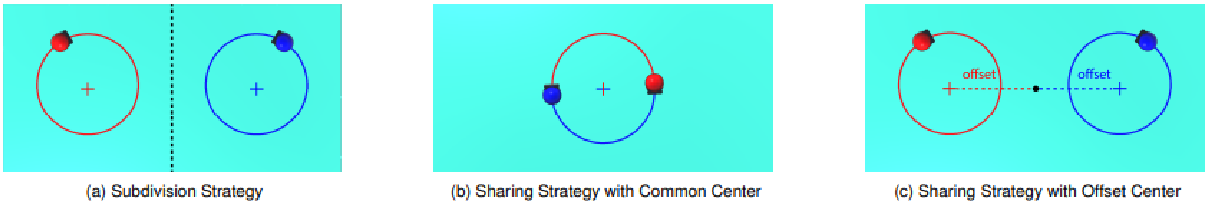


Figure 4: Redirected walking scenario: Through redirection, the path taken in the virtual environment and in the real world changes in order to keep the user inside the tracking area. Source: Steinicke et al. (2010).

This technique as been presented in more sophisticated ways (Figure 5), to solve multiple users locomotion in a shared space (Nilsson et al., 2018), where the authors were able to reduce the number of total interruptions by 17.6% and user collision prevention events by 58.3%.



(a) Subdivision Strategy

(b) Sharing Strategy with Common Center

(c) Sharing Strategy with Offset Center

Figure 5: Sharing Strategies. Illustration of three methods for implementing two-user redirected walking based on the sharing strategy. Source: Nilsson et al. (2018).

Users might still reach the limits of the areas, even when using redirection techniques, and in those cases a different method of redirection can be implemented to redirect the user back to the tracked area. Williams et al. proposed three resetting methods as solutions to this problem (Williams et al., 2007). These methods are "Freeze-Backup", "Freeze-Turn" and "2-1 Turn" (Figure 6). When the system recognizes that the user has reached the boundaries of the tracked area, it acts in order to reset the position of the user.

The Freeze-Backup method resets the position of the user by freezing the movement in the virtual world once the user reaches the boundary. The user is then asked to reset it's position in the real world by taking some steps back. Orientation tracking is active while this is happening so that the user can see physical obstacles and look around. Once he reaches the desired position, the display is unfrozen.

On the Freeze-Turn method the system freezes the display once the user reaches the boundary. He is then asked to turn around 180 degrees, inverting his walking direction. The screen is then unfrozen, and the user is able to continue moving forward on his path in the virtual environment, while in the physical world moving in the opposite direction to the previous one.

Lastly, on the 2:1-Turn, upon reaching the border the user is asked to do a 360 degree rotation on the virtual world before progressing. The rotational gain of this movement is scaled by two, meaning that the user only rotates 180 degrees in the physical world, but does a full rotation in the virtual one. This results in the user being turn backwards towards the middle of the tracking area, but being able to continue moving forwards in the virtual one.

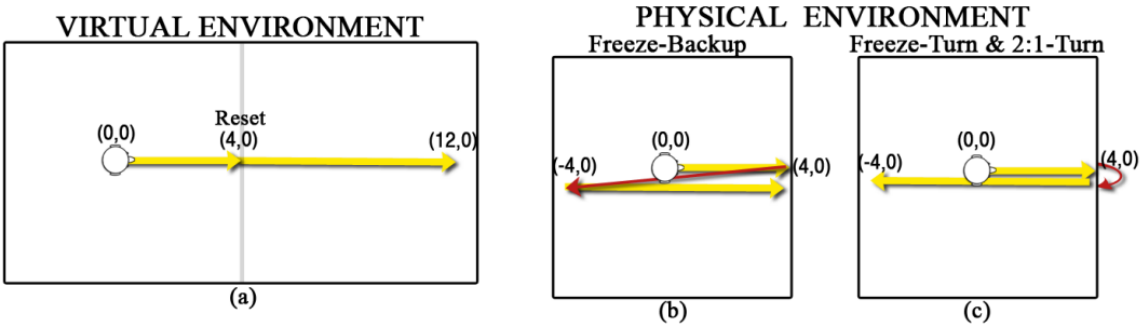


Figure 6: (a) Locomotion perceived by the user in the virtual environment; (b) Freeze-Backup movement of the user; (c) Freeze-Turn and 2:1-Turn movement of the user; Yellow arrows are the user's movement inside the VE; Red arrows are the physical movement not represented in the VE. Source: Williams et al. (2007).

The problem with these methods is that they create interruptions in the user experience that lead to a break in immersion and have a negative impact on the quality of the experience.

To solve this issue, Peck et al. (2010) and Sra et al. (2018) implemented distractors

(Figure 7) that appear when there is a need to rotate the users away from the border and towards the center of the tracked area. Sra et al. (2018) went further and tried to integrate these distractors into the narrative of the experience. This proved to have positive effects, but requires specific development for different experiences.

Figure 7: Interaction with Object and with Character. The background blurries and orientation is changed to rotate the user towards the center of the tracking area. Source: Sra et al. (2018).

Another solution involves using haptic feedback cues to modify the spatial perception of the user (Matsumoto et al., 2016). The user walks around a curved wall while touching it (Figure 8), walking in circle in the real world, but their perception and the representation in the virtual world is that he is walking forward in the experience. The use of these haptic feedbacks was reported to improve the virtual experience significantly (Insko, 2001).

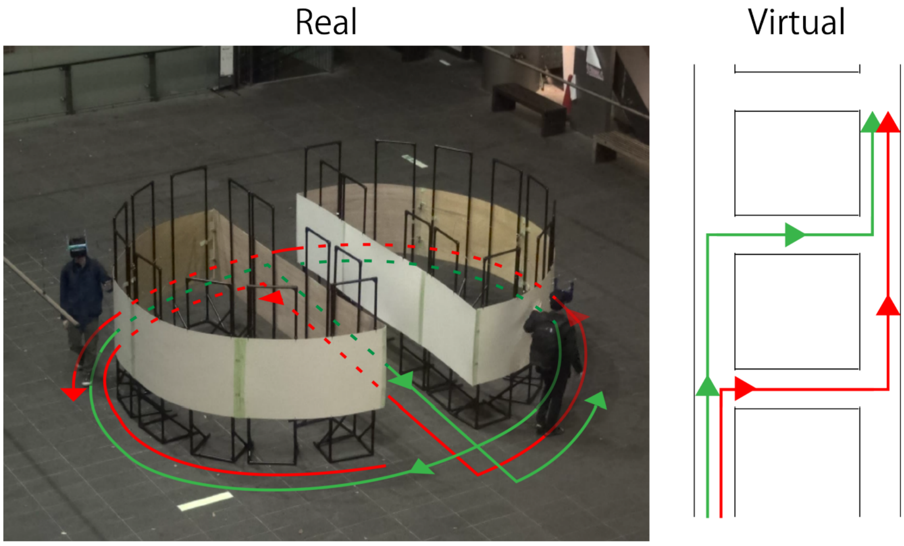


Figure 8: Multiple users using the Unlimited Corridor. Source:Matsumoto et al. (2016).

The main issue with these solutions is that, even though it reduces the required space to implement the experiences, still required larger than consumer-level room-scale setups (Pixels, 2018) or installation of physical elements to create haptic feedback.

Environment Change

Another alternative to increase the distance covered with natural walking in virtual environments is altering the user's surrounding environment. Different solutions have been proposed and tested. Some suggested changing the architecture of the virtual environment, others suggested teleporting the user to a different location on the environment through portals that direct to other locations.

Suma et al. (2012) proposed a technique called "Impossible Spaces", in which the layouts of the rooms in an indoor architecture self-overlap, creating and environment that would be impossible in the real world (Figure 9). This allows for a larger virtual environment to be fitted into a smaller physical area. They concluded that users could not detect the use of this technique up to 56% overlap. Users could not perceive distances in overlapping rooms, even when they identified that the technique was in use. The problem with this technique is that it can only be employed in indoor environments, due to the need of walls enclosing the spaces. The architecture of these spaces is also limited by the technique, since there is a need for rooms to be adjacent to enable the overlapping.

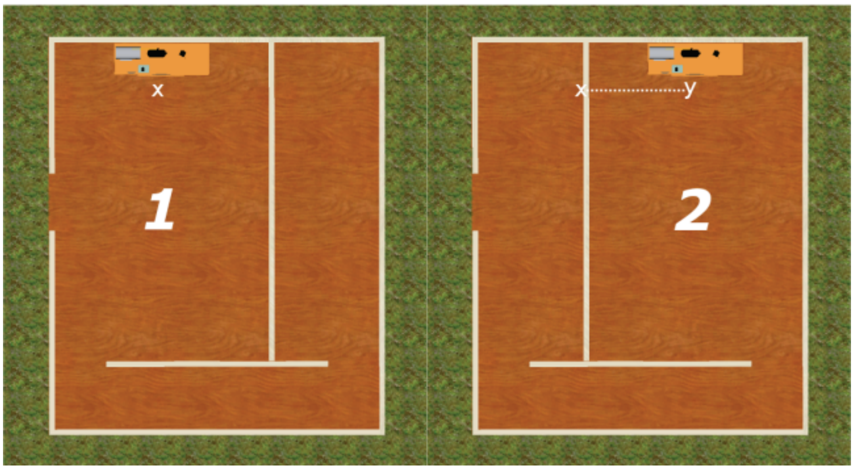


Figure 9: Representation of an Impossible Space. Source: Suma et al. (2012).

A similar method called "Flexible Spaces" was proposed, where impossible spaces are used to create infinite procedural layouts of indoor environments (Vasylevska et al., 2013). Using corridors to connect the rooms, the user is redirected by exiting one space in a border of the area, walking through a corridor to reorient himself, and enters another space with enough room to explore (Figure 10). These layouts end up with long corridors and complex layouts, which could be hard to use in VR experiences and also created orientation issues with the participants.

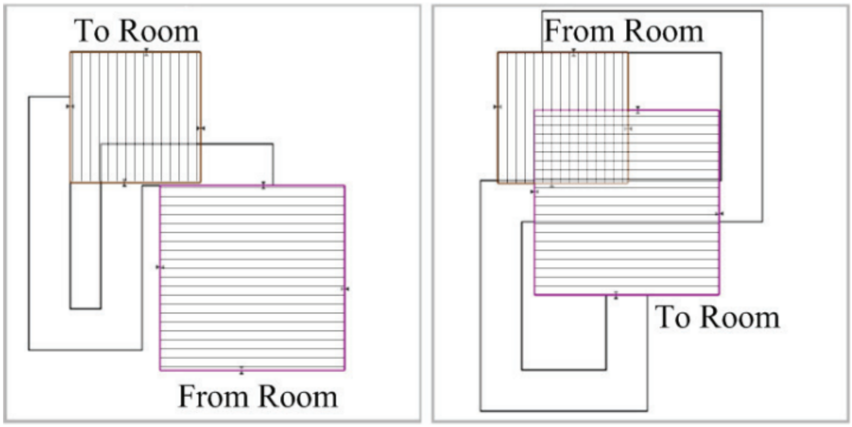


Figure 10: Representation of a Flexible Space. Source: Vasylevska et al. (2013).

Another technique used to increase natural walking through environment changes is the use of portals in which the user can enter to be transported to a new location. Bruder et al. (2009) suggested a system which allows users to summon portals to a selected division of an indoor virtual environment. The user selects a division from a miniature and can then go through a portal to move to that location (Figure 11). Once the user is through, the portal closes and the user can explore the new environment. When finished, he can open a new portal back to the selection environment. With this method, exploration of different locations is enabled in a small physical space, at the cost of realism and stops in the exploration.

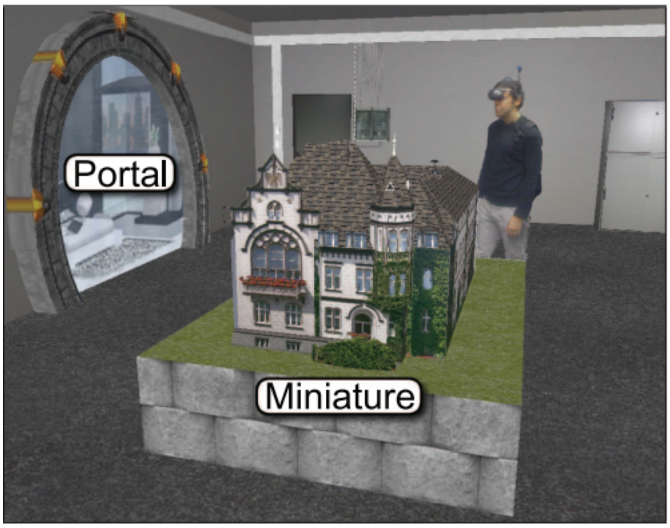


Figure 11: Use of portals to increase locomotion distances. Source: Bruder et al. (2009).

Another study used a combination of redirection techniques with portals (Liu et al., 2018) to maintain the user inside the tracking area. The user can explore a virtual environment inside the tracked area freely through natural walking, and when he wants to change to a different one, he creates a portal that opens a passage to the new location. The position where this portal can be to the left or right of the user, and it is calculated in a way that makes the user face the center of the tracked area once he transposes the portal (Figure 12). This method allows for redirection of the user without inducing motion sickness since it discontinuously translates the user's viewpoint and no optical flow is generated. Realism is still an issue with this technique.

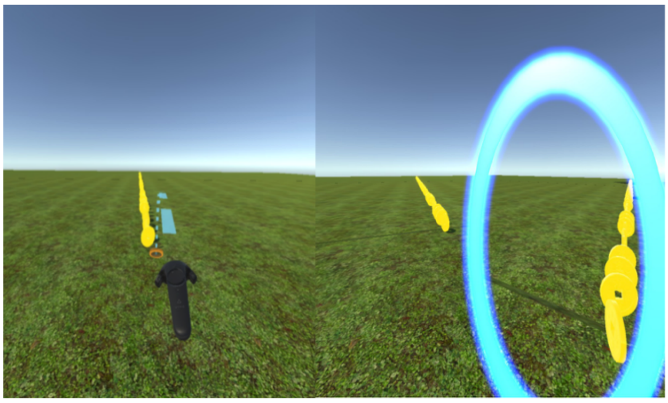


Figure 12: Use of portals to reorient the user to the center of the tracking zone. Portals appear at the left or right of the user to turn him in the desired orientation. Source: Liu et al. (2018).

2.1.2 Gesture Based Techniques

When there is not enough space that allows the user to move around with natural walking, one solution is to use body gestures that simulate the movement we do when walking. One of the gestures closest to reality is walking in place, making it the most natural gesture to use in VR (Steinicke et al., 2013), as it resembles natural walking. Other gestures can also be found in virtual experiences, such as leaning or bending. Lastly, flying is also known to be easy to implement and simple to use, although it is not the most effective in immersion and realism (Usoh et al., 1999).

Walking in Place

Walking in place, as the name suggests, is a technique where the user simulates natural walking, without moving out of place. Since the user stays in the same place, he can explore the virtual environment freely without reaching the boarders of the tracking area. A study proposed four implementations (Figure 13) of measuring gestures that represent walking in place (Tan et al., 2022). The Head-bob Implementation tracks the movement of the users head through the HMD. The direction in which the user moves is connected to which direction he is looking, and their forward speed is based on the assumption that users bob their bodies when walking, and by consequence, their head.

Another way of detecting user walking in place is through Arm-swing. In this implementation trackers or the hand controllers are used to verify arm swing, translating it into direction and speed. This is based on the assumption that users swing their arms when moving.

Leg-lift follows the same idea as before, but strapping the trackers onto the legs of the user. The direction of the movement is determined by an additional tracker at the waist of the user, as leg trackers tend to move out of place. The user gestures a marching action to move forward, alternately raising each knee. This implementation is based on the assumption that users lift their legs as they walk.

Finally, a full-body implementation combines all the previous methods to create a more precise tracking and allow the users to freely rotate their head, as it no longer determines the direction of the movement.

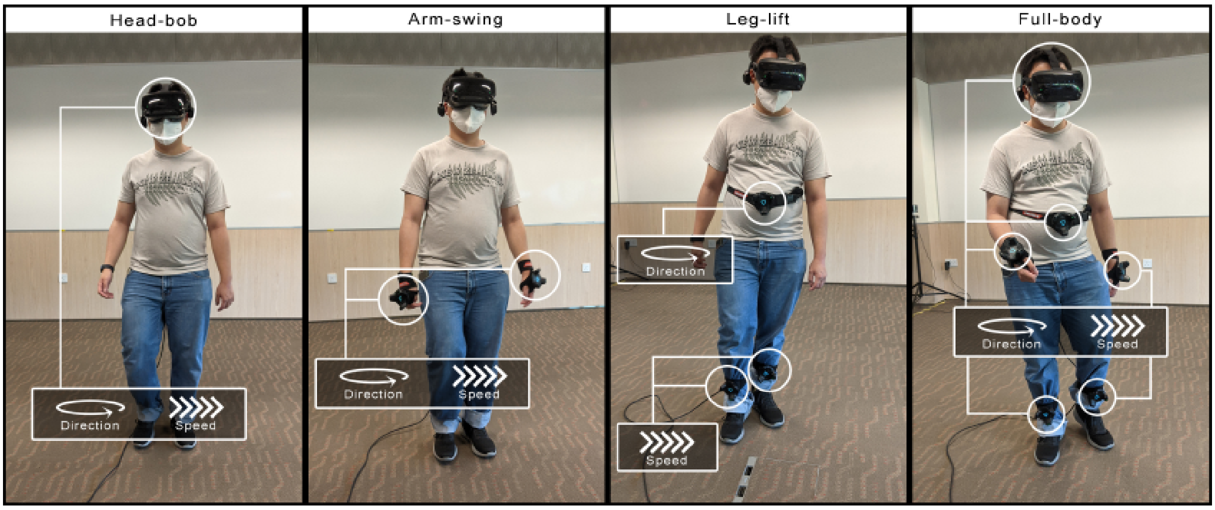


Figure 13: Four walk-in-place techniques with different gestures combinations. Source: Tan et al. (2022).

Another study by Nilsson et al. (2013) proposed two different gestures (Figure 14). In the first one - "Wiping Gesture" - the users bring their heel backward while maintaining the upper leg relatively steady in a vertical position, opposite to the leg-lift raise of the knee. The second gesture was called the "Tapping Gesture", in which the users lifted their heels of the ground alternately, keeping the toes in contact with the floor, not raising their feet.

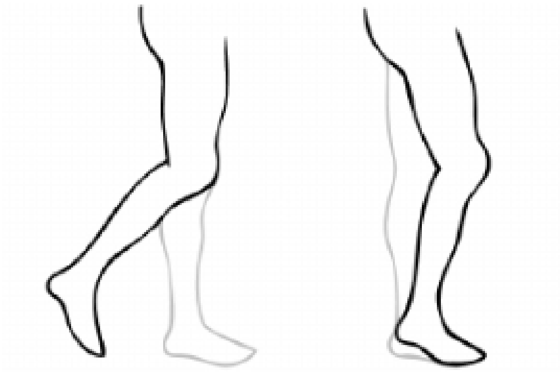


Figure 14: Representation of the Wiping and Tapping gestures. Source: Nilsson et al. (2013).

The study perceived the Tapping Gesture the most natural gestured compared with the Wiping and Leg-lift, as well as the one with the perceived required physical effort closer to real walking.

Systems that do not require trackers attached to the users have also been proposed. Zielinski et al. (2011) proposed a technique called ”Shadow Walking”, in which a camera is positioned under a floor screen where the user is standing (Figure 15). This camera captures the shadows created by the feet of the user, who, by walking in place, changes them in size as the feet are raised. A fifty per cent difference in size between the larger and smaller shadows is considered a mid-step, moving the user inside the virtual environment. The problem with this technique is that it requires a six-sided CAVE system, which is a very rare VR system in general.

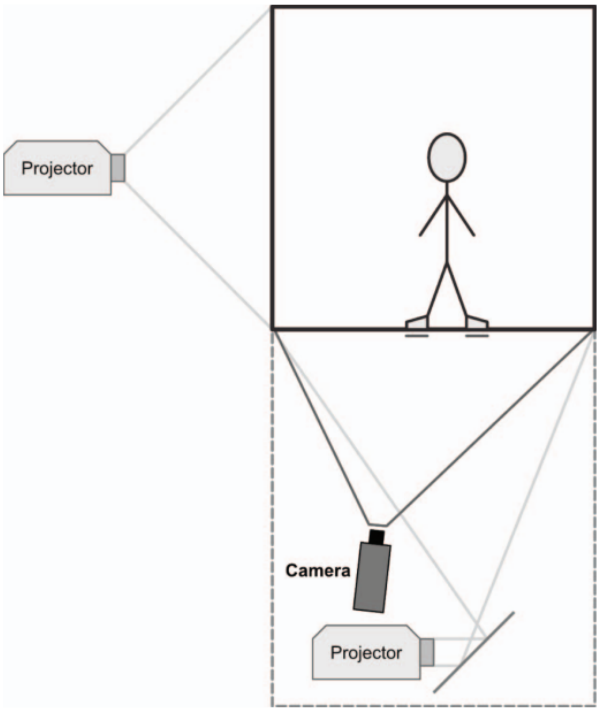


Figure 15: Representation of the setup of the Shadow Walking technique. Source: Zielinski et al. (2011).

Another study proposed locomotion by tracking the steps of a user walking in place on top of Wii balance board (Williams et al., 2011). This system can be used while wearing a head mounted display, The velocity at which the user moves is related to how fast the user step on the board and the direction of the movement is updated according to the direction in which they are looking. This method proved to be more effective over joystick locomotion, making the users explore more the environments, and close to natural in terms of spatial awareness. The issue with this method is related to the hardware. Some users commented that the board was small and sometimes steeped on the corners of the board.

Flying/Leaning

A simpler way for users to move inside VR is through flying. This technique allows the user to make some input, either through joystick input or a leaning body gesture input, and update his viewport automatically in the virtual environment. This input can be continuous, such as having to keep pushing the joystick forward to maintain the movement, or a singular action, like pushing a button, to start and stop the movement. The main difference between flying by leaning compared with using a joystick is that in flying the direction that the users moves towards is defined by the orientation of a user's tracked body part - head, hand or torso. The travel direction is usually chosen by the direction in which the user is looking towards as it as been stated as the most natural and easier method to learn (Bowman et al., 1997). This does not allow the user to look around, as he would change the direction of his movement. A solution to this is to use a pointing gesture instead, which allows the users to point to their travel destination and move constantly in that direction while looking around.

This method of locomotion is very straightforward and easy to implement, but studies have shown that it is less effective in terms of immersion and sense of presence when compared with other methods like redirected walking and walking in place (Usoh et al., 1999). One other issue is the lack of speed control on this technique, which reduces the naturalness of the technique.

Leaning tries to solve this issue by giving more control of the rotation and speed of the movement. By leaning forward and backwards the user controls the direction and speed of the movement and leaning sideways rotates the orientation of the viewpoint.

Valkov et al. (2010) proposed a method in which a Nintendo Wii Balance Board is used to detect the users shift in body weight, representing the movement through a human transporter metaphor. This method has proved easy to learn, but had problems in turning in place and over long distances. Another similar study (Harris et al., 2014) compared locomotion by leaning like a human joystick and walk in place navigation on top of a balance board (Figure 16). Leaning proved to be less tiresome than walking in place, but users started moving later with leaning. Authors hypothesised that this could be due to users not being used to the balance board and afraid of slipping off. Leaning provided a better control of the movement and users preferred it over walking in place and joystick locomotion.

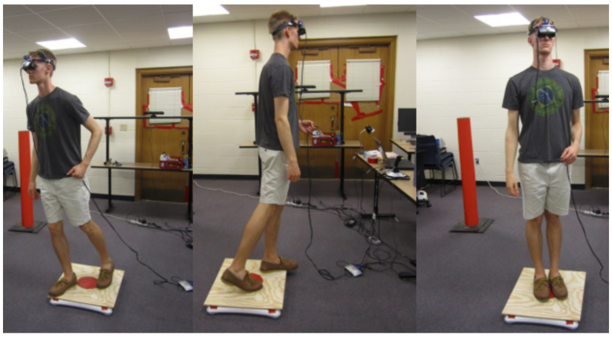


Figure 16: Human Joystick device. Source: Harris et al. (2014).

Different techniques can also be mixed to create more ease on the exploration of virtual environments. Cirio et al. (2009) proposed a system which allows the user to move by natural walking while inside the tracked area, and upon reaching the border, a tape which he can push appears (Figure 17). When the user pushes the tape, the viewpoint moves inside the virtual experience. The further the user pushes the tape, the faster he moves in that direction. He can go back to natural walking by moving towards the center of the area. This method can provide information to the user about the boundaries of the walking area, and allows for a combination of precise movement with natural walking but also endless exploration of the virtual environments with the flying technique. This method was more natural and less tiring when compared with the 2:1 Turn and the Freeze-backup techniques.

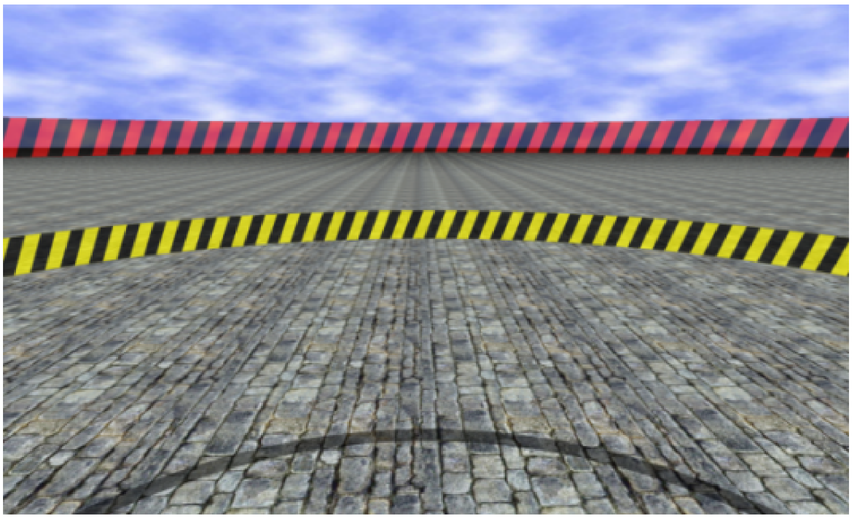


Figure 17: Magic Tape technique. Users push the tape to move inside the VE when at the limit of the tracking area. Source: Cirio et al. (2009).

Another study mixed natural walking with teleportation through gestures to allow users to explore virtual environments (Bolte, 2011). The users could walk freely while inside the tracking area and to more further than allowed, could use a jumping gesture to teleport forward in their head direction.

With the advancement in technology and knowledge, new methods of skeleton tracking allowed for different ways of gesture tracking (Figure 18). A study proposed the tracking of non-critical to detect gestures through a camera, leaving important body parts like the arms, hands and head free to be used for interactions (Guy et al., 2015). The study tested different body movements to measure accuracy, required effort, ease of use and social acceptance. Results showed preference in shoulder rotation and the bust rotation as favorites to control rotation and speed respectively.

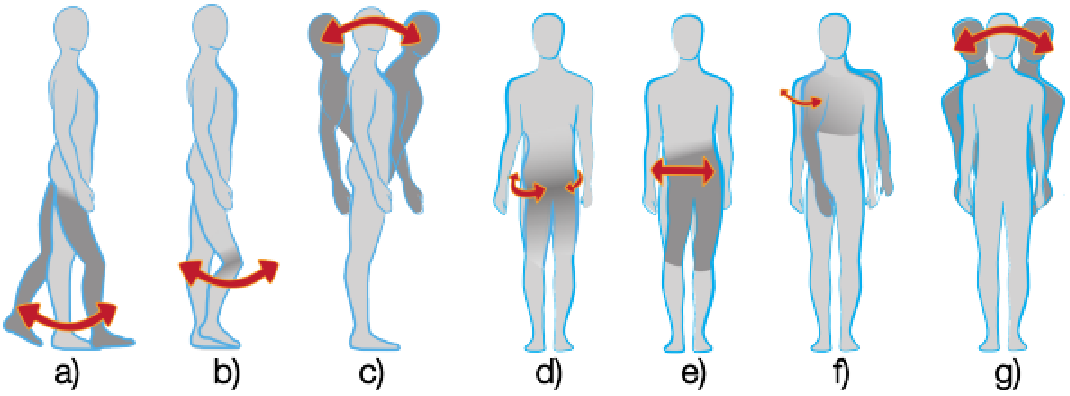


Figure 18: Different gestures for the LazyNav technique. a) do a step (the user just puts one foot forward or backward) b) bend knees c) bend bust d) rotate hips e) translate hips f) rotate shoulders g) lean bust. Source: Guy et al. (2015).

2.2 Tool Based Locomotion Techniques

Many of the previous techniques are based on algorithms that use optical or magnetic devices. These can give the position and rotation of the user rather precisely and reasonably fast. However, there are situations where these techniques are not totally usable, such as poor lighting environments, objects obstructing the tracking or the impossibility of the use of wearable trackers. To solve these issues, techniques that rely on independent mechanical hardware were designed and developed. In this section we will present studies and examples made on them.

2.2.1 Stationary Tools

Stationary systems, as the name suggests, are tools that are used while standing in the same place. These systems allow the users to walk in virtual environments by doing some kind of physical effort that resemble a method of locomotion of the real world, by using a tool attach to the ground, or by a triggering mechanism like a mouse or joystick. Since the user stays in the same place while moving in the virtual world, there is no need for tracking of the user position. This is also safer, since there is no chance of the user leaving the tracking area or colliding with physical objects. The main groups of stationary tools are walker machines and joystick-like controllers.

Walkers

These systems use treadmills, bicycle machines and similar exercise equipment to increase realism and enable virtual reality locomotion.

The U.S. Army's Dismounted Infantry Training Program develop and tested three different stationary locomotion tools (Darken et al., 1997). The first system made use of a unicycle to control the movement of the user (Figure 19). Pedaling forward or backwards controlled the speed of the movement and twisting the seat with the waist and thighs rotates the orientation. It did not feel natural and did not allow for sidesteps.

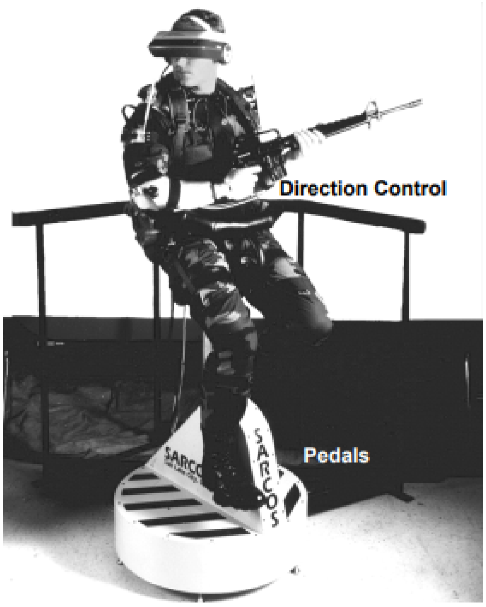


Figure 19: Unicycle locomotion system. Source: Darken et al. (1997).

The second system used a unidirectional treadmill and the user was constrained by the waist with a mechanical arm (Figure 20). This arm is used to provide feedback to the system and provoke force-feedback on the user. This system is similar to the previous one, but the user walks or jogs instead of cycling. The user can move in one direction only, and rotations are specified by turning the waist, which updates the direction in the visual display.

Figure 20: Unicycle locomotion system. Source: Darken et al. (1997).

The third system, called "Omni-Directional Treadmill" makes use of two rotary motors that moved the treadmill belts when the user walks and a mechanical tracking arm that attaches to the user's waist and lower back, keeping them in place allowing them to walk freely in any direction (Figure 21). The study showed that these systems need accurate user tracking and precise speed control not to unbalance users.

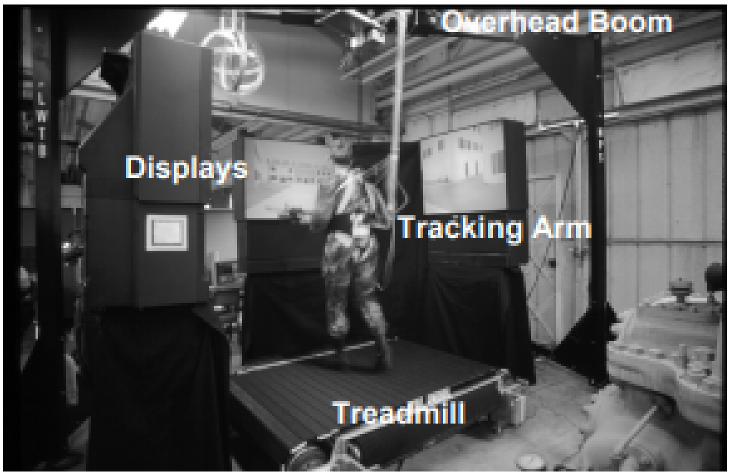


Figure 21: Soldier on Omni-Directional Treadmill. Source: Darken et al. (1997).

A similar system was developed following the same principals as the Omni-Directional Treadmill (Iwata, 1999a)(Iwata, 1999b), but used sensors on the knees of the user did not require them to be restricted in place (Figure 22). The treadmill nullifies the movement of the user when he steps outside the tracking dead zone. This method was compared with a controller based system and had a mean error distance significantly lower.

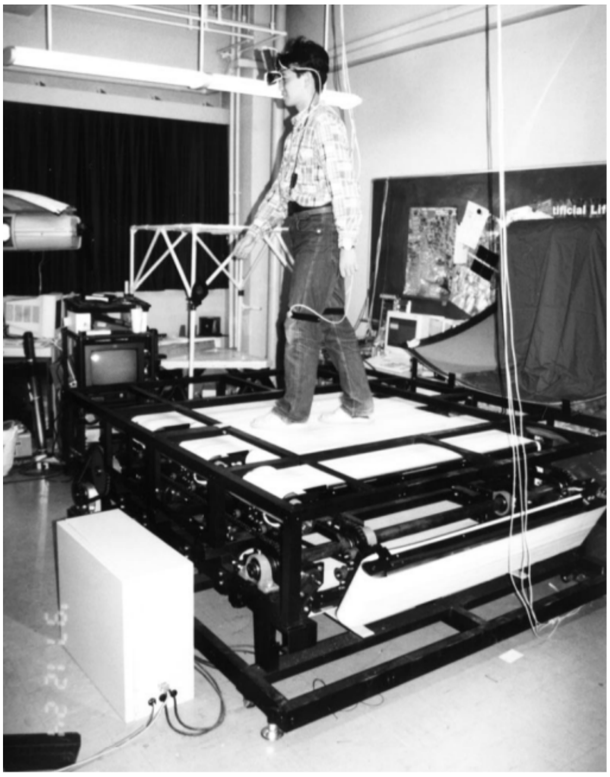


Figure 22: Overall view of the Torus Treadmill. User has sensors attached to his knees Source: Iwata (1999b).

An issue with this system is that the user has to be careful not to step outside the treadmill area. In more recent studies (Schwaiger et al., 2007)(Souman et al., 2011), an improved Omni-directional treadmill based on the torus design was developed and compared with real walking (Figure 23). The system proved to be effective in keeping the user at the center of the area with imperceptible accelerations and low vibrations and noise. The issue with this system is its size and cost, making it not suitable for consumer level users.

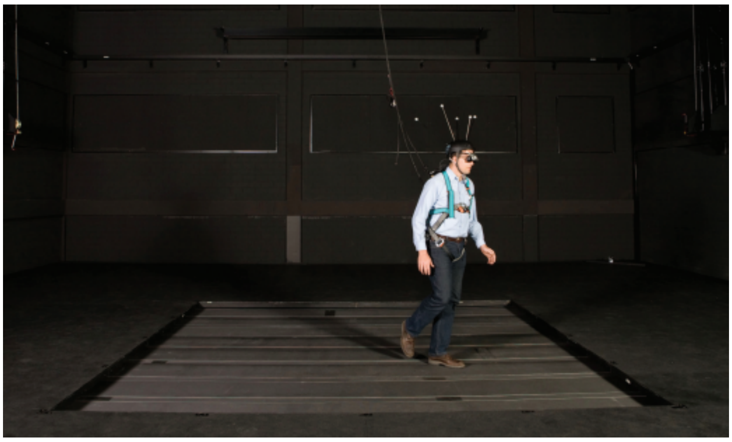


Figure 23: CyberWalk, an improved Omni-directional treadmill. Source: Souman et al. (2011).

Walker systems where the user natural walks in the same place due to the lack of traction were also proposed. This can be archived by using a low friction surface with suitable shoes or by using ball bearings. In order to keep the user at the center of the system and not sliding out the tool, complementary techniques also need to be used.

One solution is to have a concave platform that uses gravity, using a stationary restriction to physically keep the user in place, or using motor systems. A study proposed tracking of locomotion using a concave platform (Figure 24) with ball-bearing pressure sensors to track the walking of the user (Huang, 2003). When the user walks, their feet roll and activate the sensors on the bearings, calculating the movement as they walk. The user is kept in place by a loop around the waist, and the gravity and concave shaped base.

Figure 24: Omnidirectional ball-bearing disc locomotion device. Source: Huang (2003).

A similar system also used a ball-bearing base, but instead of sensors in the bearings, a camera was used to track the movement of the user (Suryajaya et al., 2009).

Since these systems use a concave base and restrict the users to keep them in place, walking is not as natural as in real life. A study (Luca et al., 2012) tried to solve these issues by combining a ball-bearing system on top of a belt system (Figure 25). The belt system would rotate according to the user's direction, and move in the same direction of the user, rotating the ball-bearings, which, when in contact with the sole of the shoes of the user, would push him in the opposite direction, moving him towards the center of the platform. The system uses a top view camera to detect the direction and movement of the user to control the platform. This allowed for a plane platform and no need of a restriction method on the user. The small area requires the user to take small steps when moving.

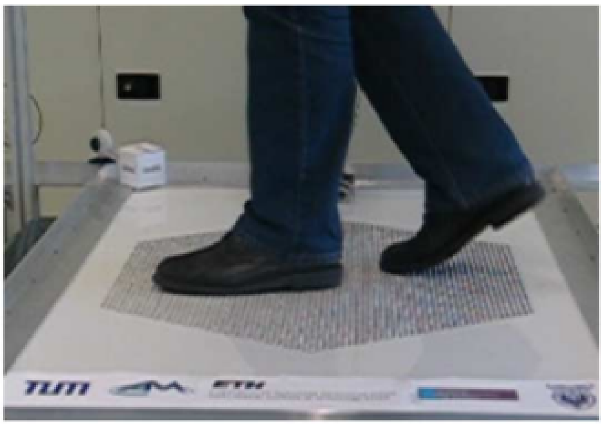


Figure 25: CyberCarpet platform: a planar ball-bearing locomotion device. Source: Luca et al. (2012)

Hollerbach et al. (2000) proposed a system that can simulate slopes of up to 20 degree angles, in order to simulate going up and down hills (Figure 26). A treadmill can be tilted via it's base, and an arm measures the movement and orientation of the user and moves the belt according to this movement, to keep the user in place.

Figure 26: Tiltable treadmill at max capacity. Source: Hollerbach et al. (2000).

A more recent study evaluated the "KatWalk" (Figure 27) system (Cherni et al., 2021). It is a consumer available locomotion device composed of a heavy base with a slippery curved platform and a restraining crane. The user is maintained in the center of the device by an harness and can walk and run in any direction thanks to a special type of shoes. This system proved to have a positive influence on immersion, but also cause symptoms of motion sickness.

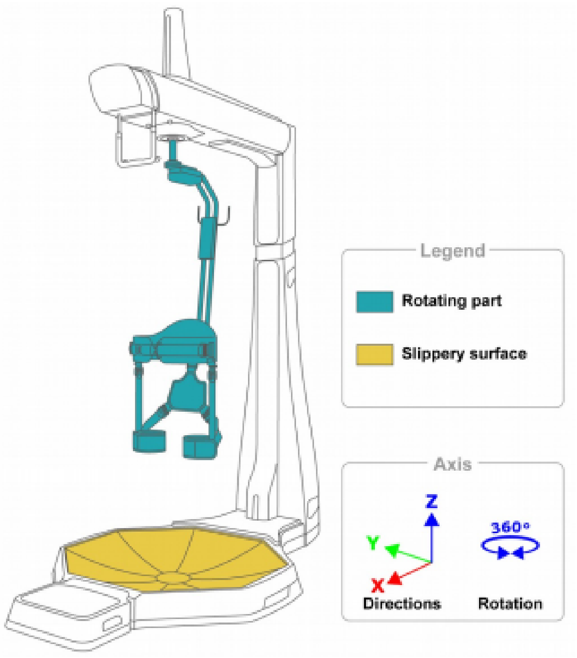


Figure 27: KatWalk omnidirectional treadmill geometry. Source: Cherni et al. (2021).

These systems were designed to allow for natural walking with tool based techniques in order to increase realism and immersion. Other studies have been conducted where devices use gestures to control movement. A study used leaning as a method to control the locomotion (Pettré et al., 2011). This worked like a human joystick, where the user leans on a board back and forth to control movement and sideways to control the rotation of the viewport in the virtual environment (Figure 28). The position of the board was maintained with springs and the user holds a safeguard to help leaning.

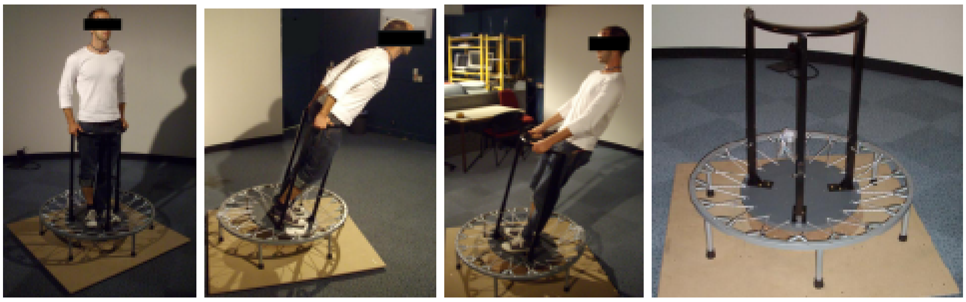


Figure 28: Demonstration of Joyman in use. Source: Pettré et al. (2011).

Another study proposed a device called "Walking-Pad", which is used to track walking in place gestures (Bouguila et al., 2004). This device is a platform with a grid of switch sensors that can track walking gestures and jumping (Figure 29). When walking in place with a forward direction, the viewpoint moves forward, and by walking in a sideways direction the viewpoint rotates. Jumping in place allows to climb objects in the virtual world. Re

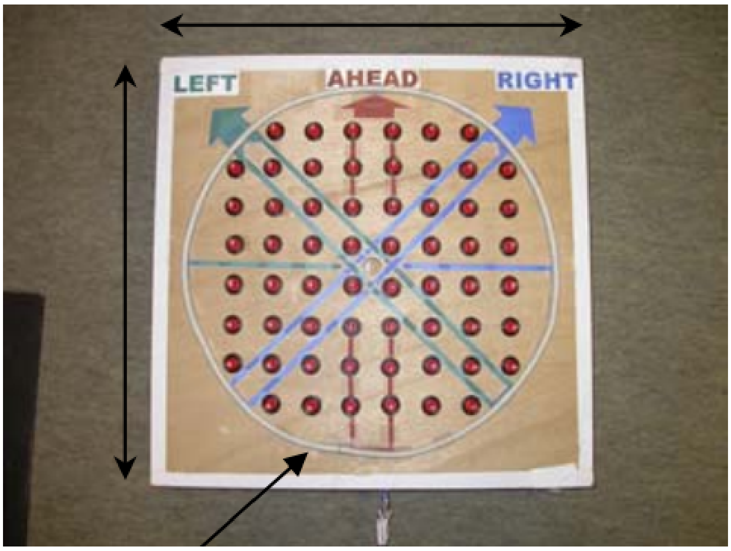


Figure 29: Walking-Pad. Source: Bouguila et al. (2004).

Other studies evaluated the use of everyday objects as locomotion devices. Feng et al. (2015) designed a system where the user sits in a stool and could lean forward and rotate around to control the navigation in the VR. The HMD sensors tracked this inputs and vibration and wind feedback would be given to the user by fans on the walls and vibration actuators on the floor. Another study used a stepper machine to receive input for the locomotion (Matthies et al., 2014). They proposed a system that allowed costumer level users to create their own device with low cost components. They used an Arduino and a potentiometer to measure the movement of the stepper, and a more advanced system could also measure if the user was crouching (Figure 30). This method proved to be better in terms of immersion and joy when compared to joystick and wand locomotion, but not statistically significant. It was also harder to use, as expected.

Figure 30: User crouching while using a VR-Stepper for locomotion. Source: Matthies et al. (2014).

Nilsson et al. (2015) did a study to compare a stepper machine, a Wii Balance Board, keyboard and mouse and a wobbly board for locomotion control in a virtual reality skiing game. The stepper machine proved to be the best in terms of enjoyment and the second best in ease of use, while the wobbly board the worse in both results.

More complex systems have also been proposed. Fernandes et al. (2003) proposed a system called "Cybersphere" (Figure 31), where the user is inside a two spheres, a projection sphere and a rotation sensing sphere. The virtual environment is projected onto the first sphere, and the user could move freely in any direction infinitely, thanks to the second one.

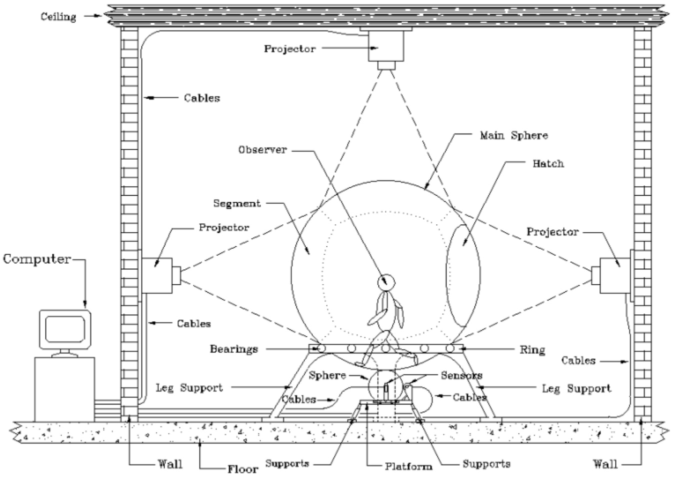


Figure 31: Schematic of the Cybersphere. Source: Fernandes et al. (2003).

A similar system (Figure 32) was proposed, which allowed the user to use an HMD (Medina et al., 2008). They reported that users felt difficulty running or turning fast while inside the sphere, and first person view subjects had balance disturbance after the experiment. Another study compared this system with natural walking and joystick locomotion (Nabiyouni et al., 2015). This system proved to be the the slowest, hardest to use and less precise, as well as being a lot different from natural walking all together.

Figure 32: User inside the Virtusphere. Source: Nabiyouni et al. (2015).

Another system (Figure 33) proposed had the users feet attached to eight motors with strings (Iwata et al., 2007). The system recognizes that the user walks and pulls him back to the center. This pull is only applied when the foot is on the ground. A sensor is used in each foot to detect this information. When the user changes directions, a turntable rotates the ring of motors in order to maintaining the forward direction of walking. This system seemed to be neither easy nor natural for inexperienced users.

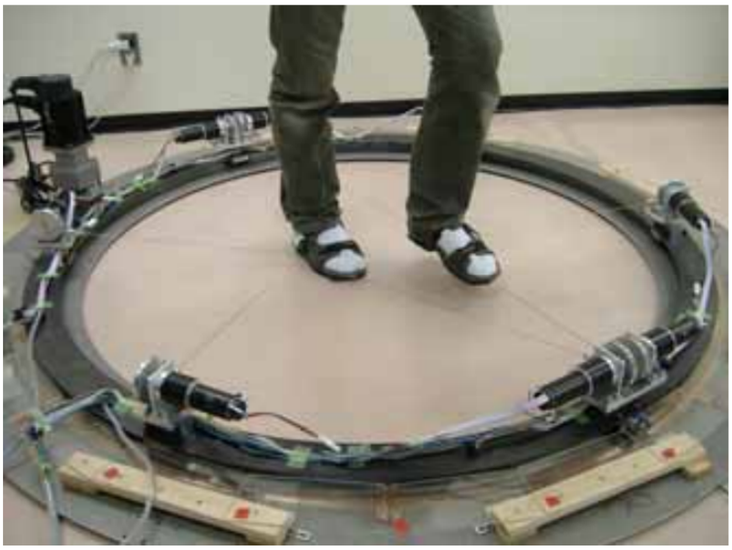


Figure 33: Overview of the String Walker device. Source: Iwata et al. (2007).

Standard Controllers

Standard Controllers such as joysticks, hand controllers and keyboard and mouse are the most commonly used locomotion devices (M. C. Whitton & Razzaque, 2008)(Yan & Lindeman, 2015). These controllers are usually cheap, easy to install, and most users either have them already or they come with the Virtual Reality kit. There have been several studies comparing different locomotion techniques that use standard controllers. Keyboards only allow for binary user input and controllers may give less control to the user compared with joysticks. A study compared the use of these three controllers to complete a predefined path (Cirio et al., 2013). Locomotion with joystick proved to be closer to real world trajectories and had less stops and reorientations to proceed to the target.

Another study compared locomotion through a joystick controller with real walking in a CAVE-like environment and with an head mounted display (Grechkin et al., 2014). The subjects had to board a train in a virtual environment using the different combinations. Locomotion through joystick proved to be the fastest method of locomotion, and also the fastest when boarding the train, since it was not directly connected to moving in the physical space. The different methods also influenced how subjects choose to board the train.

Langbehn et al. (2018) compared locomotion through joystick with teleportation and redirected walking. They evaluated the user's spatial knowledge acquisition, motion sickness, presence and user preference. The joystick method proved to be the worse in both spatial knowledge acquisition and user preference. No significant results were found in the other scores.

Another study compared natural walking with two methods that involved joystick locomotion (Riecke et al., 2010). In the first, the joystick controlled the full locomotion, while in the second, real world rotation controlled orientation and the joystick only movement. The task was to move around on the virtual environment and find specific objects. Natural walking and joystick locomotion with natural rotations both outperformed joystick locomotion. The results showed that, when natural walking is not possible, the use of rotations to control the direction of joystick locomotion is a great improvement to static joystick navigation.

In a more recent study Klamka et al. (2015) proposed different combinations of pedal controllers to control locomotion in top view virtual environments. They introduced three different pedals (Figure 32) - a one-directional pedal in which the users just press down when they want to activate it, a two-directional pedal or foot-rocker in which the user tilts back and forth with his heel or toes and a multi-directional pedal or foot-joystick which allows the users to push the pedal in any direction thanks to it being mounted in a ball joint. They compared combinations of these pedals with gaze navigation control. Users had to traverse a top-view map in order to reach a destination. Results showed positive results in the use of these combinations, specially symmetrical pedal combined with gaze-directed zoom. Even though the view-point of this test - top-view - is not the standard for virtual reality locomotion, the same devices could be implemented to control first person viewpoints.

Figure 34: a) One-directional Pedals, b) Two-directional FootRocker and c) Multi-directional Foot-Joystick. Source: Klamka et al. (2015).

Looking at these studies, we can conclude that standard controllers are a locomotion device that most users are used to and have at their disposal usually. Some techniques could be employed to use them as locomotion systems, but lead to low immersion and sense of presence when compared with more natural methods of locomotion.

2.2.2 Mobile Tools

Mobile tools are locomotion devices design to be used independently of surrounding tracking devices and can be used practically anywhere. They are usually worn and sense and transmit gestures to the system. In this sub-section mobile tools will be presented the two main groups: wearables and robots.

Wearables

These are tools normally worn on the body of the users. Recently, advancements in consumer level virtual reality systems allow these to start tracking their environments and allow users to freely use these systems without the need of outside tracking devices. The "Guardian" system has been presented by Meta, where the user draws the playable area of the environment surrounding the user and the head mounted display keeps track of that area and warns the user when he is close to the limit (Meta, 2022).

For head mounted display systems that cannot track the surrounding environment, other wearable devices were proposed. One of the first devices proposed was a pair of tracking boots that allowed the user to walk freely while his steps were tracked (Choi & Ricci, 1997). Four sensors in each boot in a cross shaped positioning allowed for the tracking of forwards and backwards walking, as well as detecting leaning. These boots could be worn over the user's shoes to provide more ergonomic convenience.

A more recent study (Matthies et al., 2013) proposed a device (Figure 35) that is placed as the insole of the user's shoes to detect walking and provide feedback. The device has six sensors placed in different positions of the foot to track pressure when walking, a Peltier that allows changes of temperature on the feet of the user to simulate different ground environments and increase immersion and four vibration motors provide tactile feedback that can signal additional information.

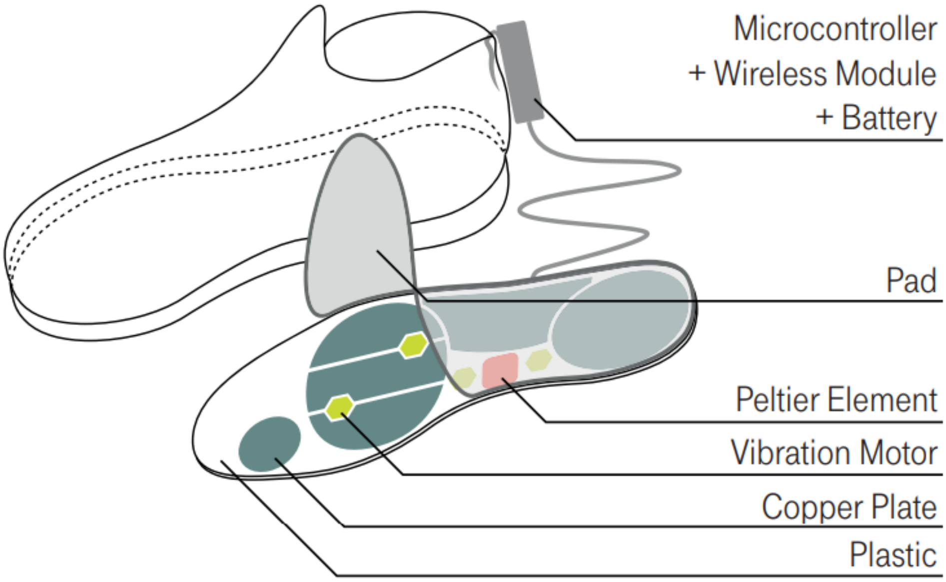


Figure 35: Conceptual design of the device. Source: Matthies et al. (2013).

While the previous systems used pressure sensors to track the walking of the user, de la Rubia and Diaz-Estrella (2015) proposed a system that makes use of four inertial sensors to allow natural walking. Two sensors (Figure 36) are placed on each foot, which allows tracking of every kind of step and it's direction, a sensor is placed on the head of the user tracks it's orientation and a forth sensor is placed on the shoulder of the user to allow for corrections of errors in yaw angles and better readings of the user's position and direction. This system is easy and fast to get equipped and also portable. Results showed some problems in position tracking when users got close to real world objects.

Figure 36: Sensor attached to the shoe using tailor-made straps. Source: de la Rubia and Diaz-Estrella (2015).

Iwata et al. (2006) proposed a wearable device (Figure 37) that allows the user to natural walk while being maintained in place. The user wears a pair of motorized roller skates and a backpack and is tracked by optical sensors. The motors roll the wheels of the roller skates when the user walks, allowing for exploration of large virtual environments without the need of a large trackable area. The system needed accurate low-latency tracking otherwise sudden movements would occur.

Figure 37: Overall view of the Powered Shoes. Source: Iwata et al. (2006).

Robots

Iwata et al. (2005) proposed a system (Figure 38) that allows users to infinitely natural walk in virtual environments with the aid of robot movable tiles that are able to rearrange themselves as the user moves. Four tiles track the position of the user by averaging his knees position. Once this point moves out of the dead zone two of the platforms reposition themselves so that the user could continue walking, while the other two keep the user in the center of the tracking zone. Each tile had 568mm width and depth and they supported a maximum walking velocity of 330mm/s. A second version of this system allowed simulation of walking on staircases by controlling the height of the tiles. This prototype required the users to walk slowly and with small steps at a time. It also relied on the balance and motor abilities of the user.

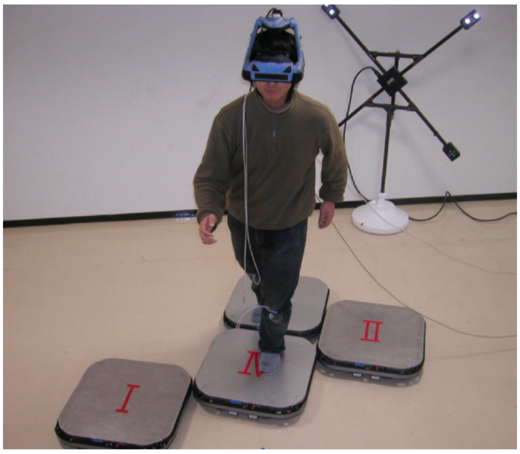


Figure 38: Overall view of CirculaFloor. Source: Iwata et al. (2005).

3 Summary

A researched of both Algorithm Based locomotion techniques and Tool Based locomotion techniques have been presented. The following two tables present the major studies in Algorithm Based locomotion (Table 1) and Tool Based locomotion (Table 2).

Algorithm Based locomotion uses algorithms to allow the user to move inside the VE, not being necessary the use of external hardware to do the direct tracking of the movement. The issue with these is either that they require a large space to be implemented or are not realistic.

Table 1: Overview of Algorithm Based Locomotion Techniques.

	Advantages	Problems
Steinicke et al. (2010)	Allows for continuous natural walking locomotion	Requires a large area
Nilsson et al. (2018)	Allows for multiple users at once	Requires a large area
Williams et al. (2007)	Reorients/reposition the user to the center of tracking area	Stops the action to reset
Sra et al. (2018)	Reorients the user to the center of the area	Requires implementation dependent on the narrative
Matsumoto et al. (2016)	Uses haptic feedback to allow infinite locomotion	Requires space and installation of the structure
Suma et al. (2012)	Allows larger VE to be fitted into smaller physical areas	Is limited to interior VE and environments are not realistic
Vasylevska et al. (2013)	Creates infinite procedural layouts of indoor environments	Is limited to interior VE and users have orientation issues
Bruder et al. (2009)	Allows exploration of different locations in a small physical space	Not realistic and has stops in the exploration
Liu et al. (2018)	Reorients the user to the center of the tracking area	Not realistic
Tan et al. (2022)	Allows for locomotion in VR without moving in the real world	Not natural
Nilsson et al. (2013)	Allows for locomotion in VR without moving in the real world with perceived required physical effort closer to real walking	Not natural
Zielinski et al. (2011)	Allows for Walk in place locomotion	Requires a large device and its setup
Williams et al. (2011)	Allows for Walk in place locomotion	Device is small and users have problems walking in place in such small space

Usoh et al. (1999)	Easy to implement	Lacks control
Valkov et al. (2010)	Easy to learn	Has problems in turning in place and over long distances
Harris et al. (2014)	Less tiresome	Users take longer to start moving
Cirio et al. (2009)	Allows for natural walking and flying when walking is not possible	Uses a virtual object that might break immersion to control flying
Guy et al. (2015)	Allows locomotion through non-critical body parts	Not natural

Tool Based locomotion techniques use external hardware to allow for detection of the user's movement and locomotion inside the VE. The issue with these is that they either require special devices that can be expensive and occupy a large space or require the user to move in specific ways and have good motor skills .

Table 2: Overview of Algorithm Based Locomotion Techniques.

Darken et al. (1997)	Uses a treadmill to allow natural walking locomotion in place	Uses a constraining mechanical tracking arm and requires accurate user tracking and precise speed control. The device occupies a large space
Iwata (1999b)	Uses sensors to control the treadmill, allowing user to not be constrained	Large device and requires low movement speed so that the user does not step outside the treadmill area
Souman et al. (2011)	Effective in keeping the user at the center of the area with imperceptible accelerations and low vibrations and noise	Large size and cost

Huang (2003)	Uses a concave ball-bearing platform with ball-bearing pressure sensors to track the walking of the user	The base is concave and the user is constrained in place by the waist
Suryajaya et al. (2009)	Uses a concave ball-bearing platform and camera to track the user's movement	The base is concave and the user is constrained in place by the waist
Luca et al. (2012)	Uses a planar ball-bearing platform that keeps the user in it's center by rolling a underneath treadmill	Requires small steps so that the user does not leave
Hollerbach et al. (2000)	Allows simulation of slopes up to 20 degree angles	Constrains the user with a mechanical arm
Pettré et al. (2011)	Uses a device in which the user leans in the direction in which he wants to move	Not natural and needs a special device
Bouguila et al. (2004)	Uses a device with switch sensors to track walk in place and jump gestures	Requires specific device and users need to be careful not to step outside the small device
Feng et al. (2015)	Uses everyday objects as locomotion devices	User is seated and locomotion is not natural
Matthies et al. (2014)	System can be created by the user. Uses an Arduino and a stepper device to control locomotion	Hard to use
Fernandes et al. (2003)	User can walk infinitely inside two spheres, with the projection on the outside one	Hard to control and requires the device which is expensive and takes a lot of space

Medina et al. (2008)	User can walk infinitely inside a sphere while wearing a HMD	Hard to control and requires the device which is expensive and takes a lot of space. Users also reported balance disturbance after the experience
Iwata et al. (2007)	User can walk infinitely while their feet are tracked via motors with strings	System seemed neither easy nor natural for inexperience users
Cirio et al. (2013)	Compared keyboard, controller and joystick locomotion	These methods are not as natural as natural walking
Grechkin et al. (2014)	Tested single time-based action in which joystick locomotion was faster completing the action over natural walking	This was a single time based action and not a full VR experience
Langbehn et al. (2018)	Compared joystick locomotion, teleportation and redirected walking	Joystick locomotion was the worse in spatial knowledge acquisition and user preference
Klamka et al. (2015)	Proposed a combination of different pedal controllers	Tested in top-view locomotion only and is a in-place technique that requires a special device
Choi and Ricci (1997)	Uses a pair of special tracking boots for locomotion	Special device is needed
Matthies et al. (2013)	Uses an insole with trackers for locomotion	Special device is needed
de la Rubia and Diaz-Estrella (2015)	Uses for inertial sensors to track natural walking	Special trackers are needed and results showed tracking problems when user was close to objects
Iwata et al. (2006)	Proposed a device that allows the user walk in place through a pair of motorized roller skates	Heavy device and depends on the balance of the user.

Iwata et al. (2005)	User can walk infinitely while their feet are tracked via motors with strings	System seemed neither easy nor natural for inexperience users
Iwata et al. (2005)	Allows users to infinitely natural walk in virtual environments with the aid of robot movable tiles	Users need to walk slow and with small steps

Despite the positive points pointed out by the research done previously, the locomotion methods presented have drawbacks that negatively influence the user experience when traversing the virtual environments. The most prominent problems identified are that the use of special devices make the techniques not available for every user and that direct changes in the locomotion reduces immersion and reality of the experiences. With these issues identified is now possible to study a solution that tries to solve them.

4 Methodology

In this chapter we propose the implementation of a VR test to compare the effects of natural walking in VEs over joystick locomotion and overlapping spaces. In order to compare natural walking in full spaces, joystick locomotion and overlapping spaces in VR, three VE were created where the participant has to complete tasks while traversing the environment with the different techniques. The environment was created in Unity3D and a Meta Quest 2 system was used to immerse the user in the VE.

The tasks are simple, as the main focus is to test locomotion and not interaction. The participant has to pick up an object from a table by grabbing it with the hand-held controller. This type of interaction was chosen based on previous research that indicates that it is the most immersive interaction method (Streppel et al., 2018), and the most close to reality one. He should then traverse to another location and put the cube down in a box and then go back to the corridor that connects both rooms and press a button on a wall to open the exit door at the right of the corridor. The experiment is over once the participant finishes all tasks and exits though the door. The participant will complete the tasks three times, each with a different type of locomotion. For the first two experiments the participant does not use the VR hand controllers for locomotion. The tracking of the movement is done via the sensors on the HMD, that tracks the movement of the participant and transposes it into the virtual experience.

The success and time taken to complete the tasks are measured in order to assure the usefulness of the test. Unfinished experiences were not considered, and all three experiences had to be completed.

The number of bumps against virtual or physical objects are counted, as well as the number of virtual walls trespassed to measure effectiveness of the technique. The ideal experience should not have bumps on objects nor trespassing of walls.

The test was developed in Unity and participants used the Oculus Quest 2 system in standalone mode. The video feed of the HMD was recorded and reviewed post test. Participants were asked to fill a consent form and a Sickness Simulation Questionnaire (SSQ) followed by one of the VR test. The recording of the experience was used to evaluate the bumping of virtual objects and the trespassing of walls. The bumping of physical objects was counted during the experiments through visual observation.

The objective of the tests is to identify which type of locomotion is more immersive, causes less negative effects on the participants and helps increase spatial knowledge acquisition on the environments explored. To evaluate the symptoms of nausea, oculomotor disturbance and disorientation of the different locomotion techniques, the Simulator Sickness Questionnaire (Robert S. Kennedy & Lilienthal, 1993) (Appendix B) was applied at the start of the experiment and at end of each test. This questionnaire measures computation of nausea [N], oculomotor disturbance [OD], disorientation [D] and total simulator sickness [TSS] (Eqn. 1). The total score was calculated with the equation:

$$TSS = ([N] + [OD] + [D])3.74 \tag{1}$$

In the same questionnaire, questions about ease of use and immersion were also asked to compare the methods in these areas.

The participants were also asked to answer a survey regarding the test in order to evaluate their perception of the immersion and ease of use of the locomotion technique (Appendix A). This survey evaluates the difficulty in understanding the use of the method and difficulty of use, the required effort, if the user felt in control of the movement, their enjoyment in using the locomotion method, if they felt frustrated, immersed, visiting the virtual world or viewing a scene and if the experience method felt real.

Lastly, participants were also asked to draw a representation of the environment as precise as they remembered (Appendix C). Each environment has eight unique objects in different positions that that differ from test to test and that the participant should identify and represent on the exercise. Remembering the objects and their locations was evaluated to understand how well did participants remembered the space.

The order in which participants take the tests change from participant to participant, to prevent influence of the previous tests on the results. After completing and answering the surveys regarding the tests, participants are also asked to complete a questionnaire (Appendix D) ranking the three tests in the immersion and ease of use questions.

5 Virtual Environment System

This chapter explains how the system created for the evaluation of this thesis was design and developed. All three VE require the same tasks to be completed in order for the test to be considered positively completed.

The object (Figure 39) which the user has to pick up and place in the left room has a grabbable component, making it possible to be picked up and carried. For that, the user can use his hand controller to control the position of his virtual hands, that when colliding with the object, enable the user to press the activate button on his controller, attaching the object to the colliding hand. Either hand can be used to do this action.

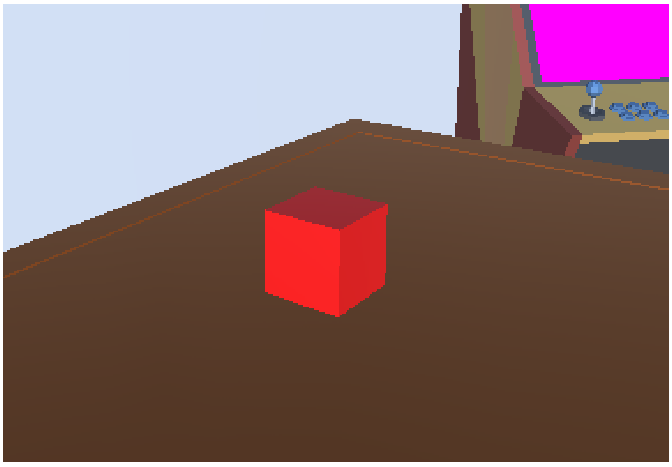


Figure 39: Grabbable object.

The user can walk to the adjacent room by natural walking, and when inside, place the object inside a box (Figure 40) on top of a table. The box has an invisible collider that detects if the object in inside or not. Once inside, a button appears on the corridor outside the room. This button opens the door that leads to the end of the experience, and can be activated when pressed. To press the button, the user moves one of his virtual hands towards it until it collides. Either hand can be used.

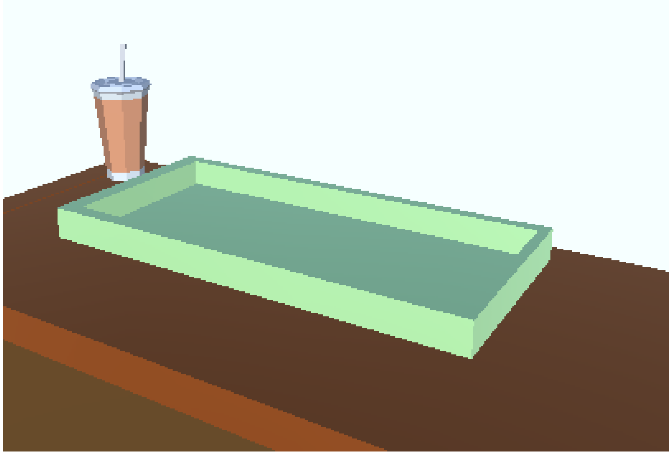


Figure 40: Box where the user has to place the grabbable object

5.1 Natural Walking in Full Space

In the natural walking in full space test the participant walks freely in order to traverse the environment, in full-size room with the normal furniture position, simulating a real world environment. The VE has obstacles positioned in the same position as the ones in the real world, so that the participant has to avoid colliding with them. The environment is composed of two rooms connected by a side corridor and have entrances in the furthest point possible (Figure 41). An exit door that allows the user to complete the test is positioned on the corridor, next to the room the user visits first.

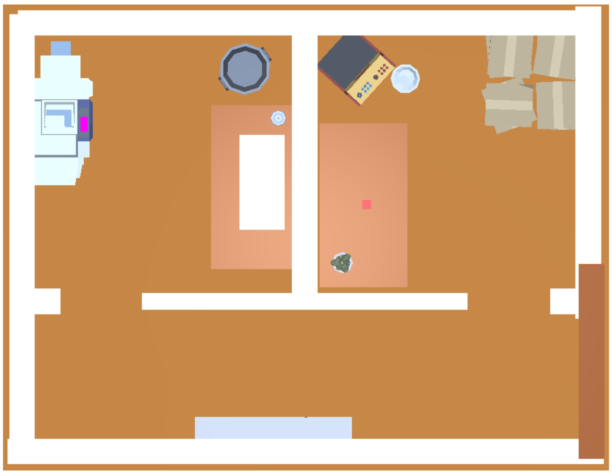


Figure 41: Layout of the Full Space test environment.

To move in the virtual world, the user walks around the physical room and his position is updated in the virtual environment taking into account the same distance travelled.

The virtual world was viewed from a camera that was attached to the position of the virtual head and this view was rendered to the HMD. The movement and the rotation of the user's head affected the virtual camera's position and rotation so that a realistic view of the virtual world could be displayed in the HMD.

5.2 Natural Walking in Impossible Spaces

In the natural walking in impossible spaces test the participant walks freely in order to traverse the environment, in a VE in which two rooms overlap, creating a impossible space. The size of these rooms is the same as the rooms from the full space, but the total area of the environment is smaller in length. The two rooms have a overlap of forty percent (Figure 42), based on the research by Suma et al. (2012), and are connected by a side corridor and have entrances in the furthest point possible. The corridor is shorter than in the predecessor test due to the overlapping technique (Figure 43)(Figure 44). The exit door and button are positioned in the same place as the previous test.

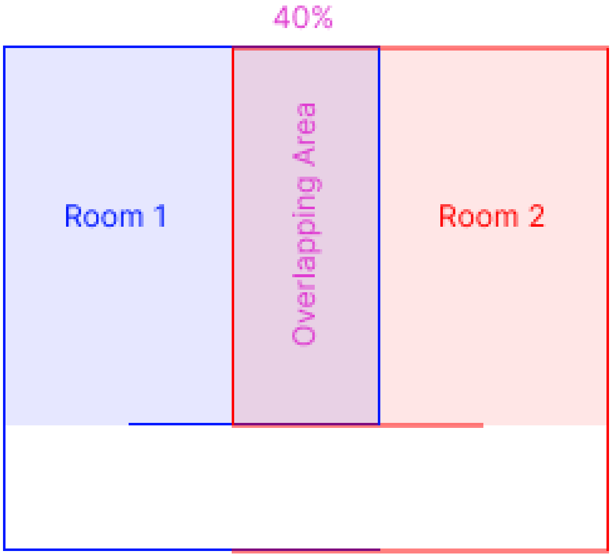


Figure 42: Representation of the overlap and layout of the impossible space.

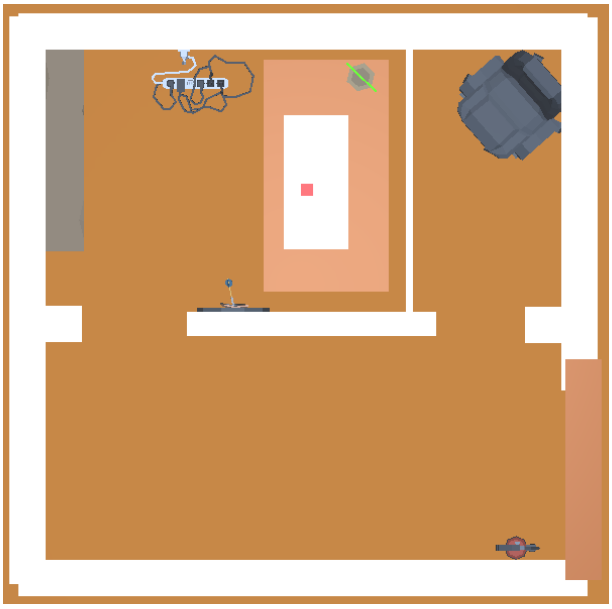


Figure 43: Layout of the Impossible Space test environment with left room active.

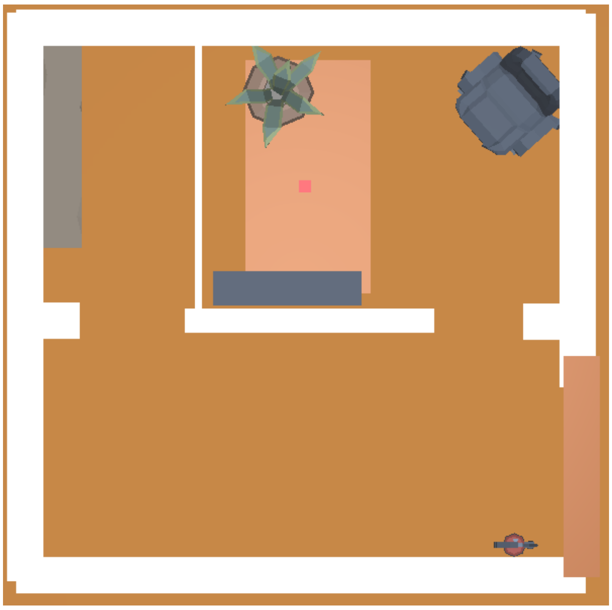


Figure 44: Layout of the Impossible Spaces test environment with right room active.

The swap of the rooms happens when the user transposes the halfway point of the corridor towards either side. A invisible trigger zone is positioned before the entrance to each room, that when entered by the user deactivates the opposite room and activates the associated room. This change happens before the user can look into the room so as not to break the realism and immersion.

5.3 Joystick locomotion

In the joystick locomotion test the participant traverses the VE using the controller joysticks. The left hand controller joystick controls the participant movement and the right hand controller joystick the rotation. The participant can look around by rotating their head, but rotation for locomotion should only be made through the controller.

The environment has the same layout as the full space, with changes in the objects that the user has to recall (Figure 45).

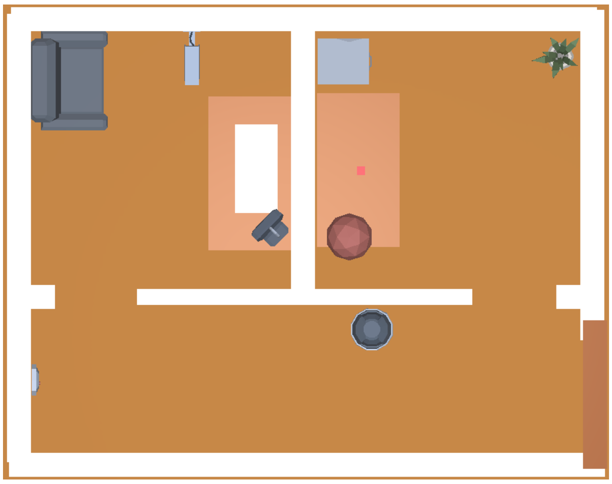


Figure 45: Layout of the Joystick test environment.

When using the joystick locomotion , the user can control the velocity of the movement and rotation with the push of the joysticks. Movement is made at a maximum velocity of 1 meter per second and a snap turn of 30 degree angle each time.

6 Evaluation

In this chapter we present the results obtained from the different experiments conducted to assess the differences between locomotion using joystick locomotion, natural walking in impossible spaces and natural walking in full spaces, and compare the results to understand which is the most effective method of locomotion.

The purpose of this chapter is to present the data collected and observations, in a structured manner, to serve as a foundation for a comprehensive exploration of the implications and significance of the findings. The subsequent discussion chapter will delve deeper into the interpretation of these results.

6.1 Data Collection and Analysis

A total of 43 people participated in the study (29 male, 14 female), with a mean age of 24.81 (SD = 6.8). When asked about their experience with VR experiences, 13 participants indicated that they had no experience, 11 were beginners, 12 were casuals, 4 were experienced and 3 was an expert. When it came to experience with 3D video games, 9 participants indicated that they had no experience, 7 were beginners, 10 were casuals and 13 were experienced and 4 were experts. They were recruited from different classes from the university, and were offered no compensation for participating. They were required to be over the age of 18, able to walk without assistance, able to communicate in spoken and written English, and have normal or corrected-to-normal vision.

All tests were executed in the same location, with the participants starting all in the same position. The joystick locomotion method required no walking, the participant standing in place, while the impossible and full spaces used a space of 3.5 meters by 3.5 meters and 3,95 meters by 5,25 meters respectfully, where users could walk freely.

To evaluate how these methods of locomotion caused symptoms of nausea, oculomotor disturbance and disorientation, all users answered to a SSQ before starting the experience and after each test. These were then compared to understand if the different methods of locomotion had any impact on the user.

6.2 Presentation of Results

All participants were able to complete the three tests successfully. The time of each test was measured starting from the moment where the user started moving. The average time of completion of the tests were:

- Joystick locomotion - 1 minute and 34 seconds
- Natural Walking in Impossible Spaces - 54 seconds
- Natural Walking in Fully Walkable Spaces - 1 minute and 7 seconds

6.2.1 Usability Results

According to the results (Table 2)(Image 46) users responses to the Usability Questionaire (Appendix A), both natural walking in Impossible and Full Spaces had a positive impact on the experience over the Joystick locomotion method. Participants felt more in control and more enjoyment traversing the spaces these ways.

Joystick locomotion was the method with the worse performance. Users reported that it was the hardest to use as it's controls are not as natural as natural walking. It was the method which cause the highest number of collisions against virtual walls - 13 in 43. No body trespassing happened in either natural walking in impossible or full spaces.

Table 3: Results of the Usability Survey.

	Joystick Locomotion	Impossible Spaces	Full Spaces
Difficulty in Understanding	2,232558	1,302326	1,116279
Difficulty in Operate	3	1,209302	1,232558
Required Effort	2,837209	1,418605	1,325581
In Control	2,860465	4,604651	4,837209
Enjoyment	2,232558	4,534884	4,744186
Frustration	3,162791	1,27907	1,255814

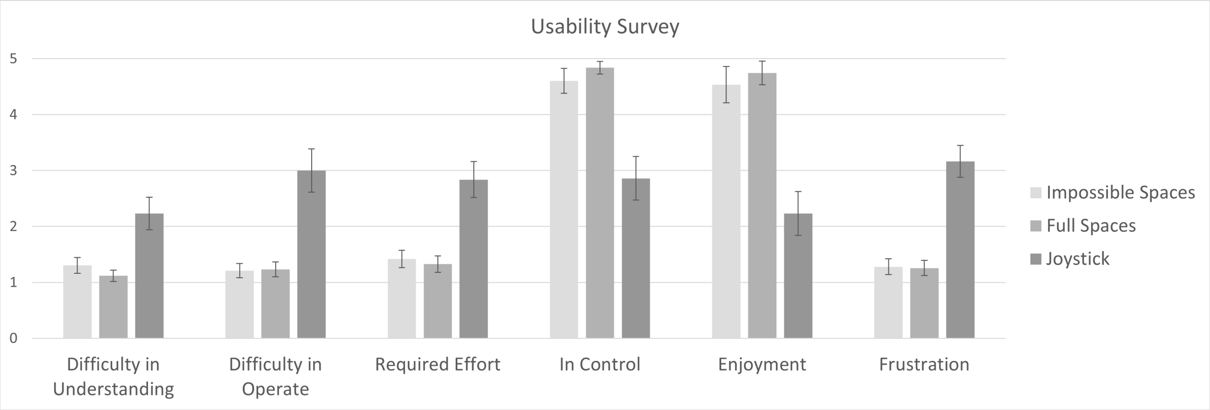


Figure 46: Results of the Usability Survey.

Answer values range from 1 to 5. In difficulty to understand and operate, 1 is easy and 5 is difficult, in required effort, frustration, in control and enjoyment 1 is low and 5 is high.

6.2.2 Immersion Results

The results (Table 3)(Image 47) from the immersion questionnaire showed that natural walking in both impossible and full spaces felt more immersive and an higher level of realism. Seven of the more experienced users in video games pointed out that the Impossible Space environment felt strange, but that it had no real impact on their immersion.

Joystick locomotion proved to be the worse technique rated in terms of realism and immersion.

Table 4: Results of the Immersion Survey.

	Joystick Locomotion	Impossible Spaces	Full Spaces
Immersion	2,744186047	3,697674419	3,651162791
Realism	2,209302326	2,88372093	2,88372093
Visiting vs Viewing the Space	2,465116279	3,279069767	3,255813953

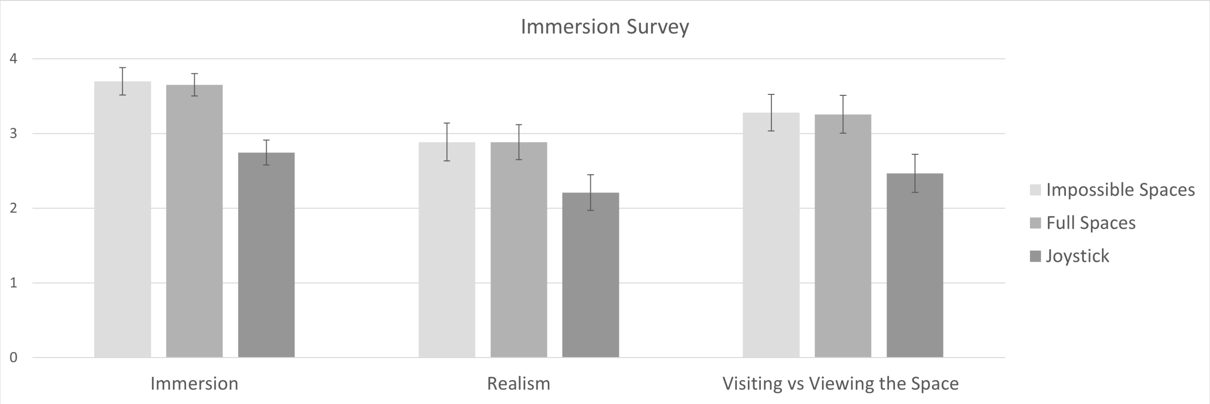


Figure 47: Results of the Immersion Survey.

Answers range from 1 to 4, 1 being low immersion, realism and viewing the space and 4 high immersion and realism and visiting the space.

6.2.3 Spacial Knowledge Acquisition Results

The drawing representation exercise results (Table 4)(Image 48) demonstrated that participants remembered better the full space environment traversed with natural walking. Some positioning of objects in the impossible spaces experiment had some out of place locations.

Table 5: Results of the Immersion Survey

	Joystick Locomotion	Impossible Spaces	Full Spaces
Objects Remembered	2,813953488	3,2,860465116	4,395348837
Correct place	2,651162791	1,88372093	4,11627907

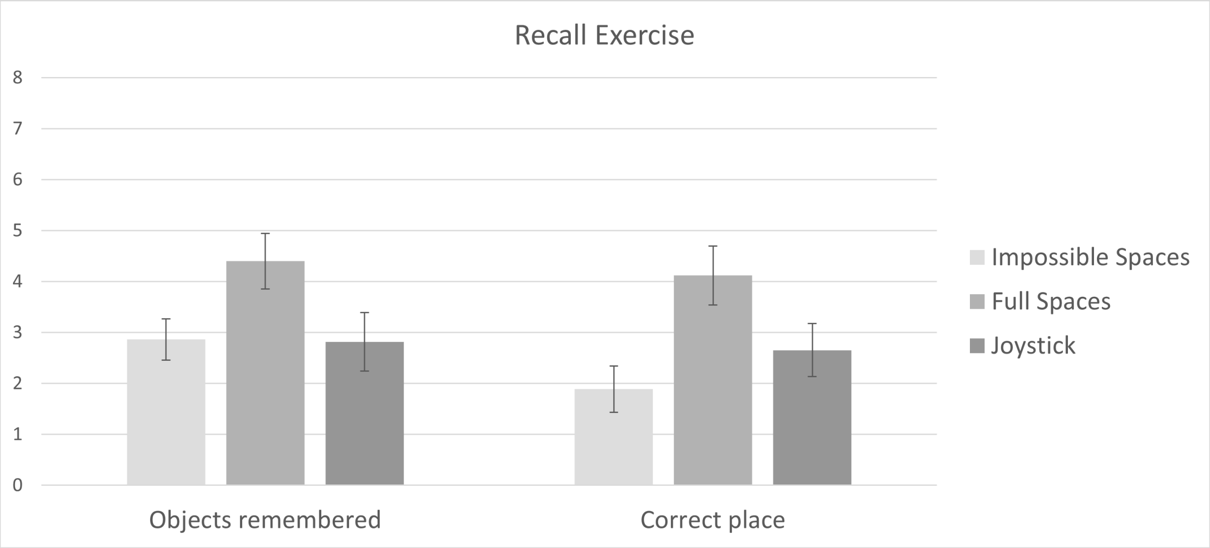


Figure 48: Results of the recall environment drawing exercise.

The results presented are the average values of objects remembered and well positioned.

6.2.4 Simulation Sickness Results

Participants experienced the highest increase in self-reported sickness from before the experiment (M = 5.13, SD = 9.12) compared with after the joystick locomotion test (M = 30.00, SD = 27.43), confirmed by a paired samples t-test, t(42) = 6.16, p $\leq$ .001. Both Impossible (M = 6.30, SD = 10.50) and Full Space (M = 5.13, SD = 7.90) were not statistically significant. Joystick locomotion also provoked the worst Disorientation Value from the three (M = 39.17, SD = 38.94).

When asked to rank the three locomotion methods, 20 participants ranked locomotion in full spaces with the most positive assessment, 20 ranked impossible and full space locomotion equally and 3 ranked impossible space locomotion with the most positive assessment. No participant preferred joystick locomotion over the other methods.

6.3 Interpretation and Discussion

Based on these results, we can claim that natural walking both in full and impossible spaces has a superior positive impact over joystick locomotion, as also pointed by Usoh et al. (1999).

When exact representation and spatial knowledge acquisition of space is important, natural walking in full spaces proved to be the superior method of locomotion. This is important when the goal is to create real life experiences and simulations.

Joystick locomotion, even though easy to implement, proved to be the less effective when immersion and realism are significant for a good experience. as well as more simulator sickness inductive.

6.4 Limitations

Given that the participants had varying degrees of VR experience and that this would have an effect on how the locomotion was perceived, it might be argued that the results provided here represent a broad generalization of the experience.

Another point to note would be that the tasks in the experiments do not fully cover every interaction that could be made in VR experiments, specially in video games. In the future more tests could be made in order to evaluate how these variables could affect the outcoming results.

7 Conclusion and Future Work

With this thesis, we wanted to understand how could immersion and realism be improved in virtual experiences through locomotion. We tested three locomotion methods: joystick, natural walking in impossible spaces and natural walking in full spaces, and compared the results of these tests to understand which locomotion method increases immersion the most and creates a more positive experience. This concluding chapter presents the findings of this study and their implications, and presents future studies to be considered.

7.1 Summary of Findings

Our results show that locomotion in virtual spaces using natural walking gives the user a more immersive and realistic experience, as well as giving more control of the movement over joystick locomotion. The number of collisions with virtual objects was significantly higher with the joystick locomotion, as well as the time it took to complete the tasks. When precision in locomotion is important for the experience, natural walking should be chosen over joystick locomotion, despite it's ease of implementation. This also proved to be an important factor in realism and immersion, making joystick locomotion seem less realistic.

In the Simulation Sickness questionnaire users reported little to no increase in simulation sickness symptoms when traversing the virtual environments using natural walking, both on impossible and full spaces. Joystick locomotion had the highest negative impact on the users, both on Total Sickness and Disorientation Value.

Subjects were able to correctly remember objects and it's positions when using natural walking in full spaces. Natural walking in impossible spaces resulted in some mistakes in positioning, but not statistically significant. This can be decisive when virtual experiences need to represent truthfully simulations of real world environments or training situations. Joystick locomotion proved to be the worst method for spatial knowledge acquisition.

7.2 Implications of the results

Natural walking in full spaces proved to be the best method of locomotion when realism and immersion are a requirement. This makes it the recommended technique when designing and developing virtual reality experiences that aim to simulate the real world.

It has also been proven that, when possible, natural walking should be used over joystick locomotion, since it induces less simulator sickness symptoms.

7.3 Future Work

Based on the findings and limitations of this research, several options for future investigation can be pursued to expand upon the knowledge gained in this study. The comparison of full space locomotion with other methods of locomotion could help shape the investigation and development path to take, whether it is the pursue of full space locomotion or another method. Another compelling investigation is to understand how different methods of interaction come together with this type of locomotion.

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A Appendix: Locomotion Assessment Questionnaire for VEs

Title: Locomotion Assessment Survey for Virtual Environments

Information: This survey assesses your experience with different types of locomotion in Virtual Environments

Demographic Information
Age:
Gender:
Occupation:
Left or right handed:

Level of experience with Virtual Reality experiences:

- ☐ No experience
- ☐ Beginner
- ☐ Casual
- ☐ Experienced
- ☐ Expert

Level of experience with 3D video games:

- ☐ No experience
- ☐ Beginner
- ☐ Casual
- ☐ Experienced
- ☐ Expert

How **easy** was it to <u>understand</u> this method?

- ☐ Completely easy
- ☐ Easy
- ☐ Neutral
- ☐ Not easy
- ☐ Not easy at all

How **easy** was it to <u>operate</u> this method?

- ☐ Completely easy
- ☐ Easy
- ☐ Neutral
- ☐ Not easy
- ☐ Not easy at all

How much **effort** did you have to move with this method?

- ☐ A lot of effort
- ☐ Some effort
- ☐ Neutral
- ☐ Minimal effort
- ☐ No effort

Did you feel like you were **in control** of the walking?

- ☐ Completely in control
- ☐ In control
- ☐ Neutral
- ☐ Not in control
- ☐ Not in control all

Did you **enjoy** using this walking method?

- ☐ Completely enjoyed
- ☐ Enjoyed
- ☐ Neutral
- ☐ Did not enjoy
- ☐ Did not enjoy at all

Did this locomotion method make you **frustrated**?

- ☐ Completely frustrated
- ☐ Frustrated
- ☐ Neutral
- ☐ Not frustrated
- ☐ Not frustrated all

Did you have a sense of being in the **virtual world**?

- ☐ Completely in the virtual world
- ☐ Mostly in the virtual world
- ☐ Somewhat in the virtual world
- ☐ Not in the virtual world at all

Did you feel like the **virtual world** was real?

- ☐ Completely real
- ☐ Mostly real
- ☐ Somewhat real
- ☐ Not real at all

Did you feel like you were **visiting the virtual world** or **viewing a scene**?

- ☐ Completely **visiting the virtual world**
- ☐ Mostly **visiting the virtual world**
- ☐ Mostly **viewing a scene**
- ☐ Completely **viewing a scene**

B Appendix: Simulator Sickness Questionnaire

Simulator Sickness Questionnaire (SSQ) - How are you feeling **now**? Select <u>one</u> for each.

	None	**Minimal**	**Moderate**	**Major**
Nausea				
General discomfort				
Stomach awareness				
Sweating				
Increased salivation				
Vertigo				
Burping				
Difficulty concentrating				
Difficulty focusing				
Eyestrain				
Fatigue				
Headache				
Blurred vision				
Dizzy (eyes open)				
Dizzy (eyes closed)				
Fullness of head				

C Appendix: Representation Exercise

Is there anything you liked/disliked/suggest about this locomotion method? If so, please describe.

Draw a representation of the Virtual Environment as you remember it. Try to be as precise as possible.

D Appendix: Comparison Questionnaire

Rank the methods from the best (1) to worse (3) in the following categories.

	Joystick	Impossible Space	Full Space
Understanding			
Ease of use			
Effort			
Control			
Fun			
Frustration			
Immersion			
Realism			