COMPUTER SCIENCE
DEPARTMENT

ANDRÉ TOMÁS RIBEIRO
Bachelor in Computer Science

PROCEDURAL GENERATION OF INTERIORS IN VIRTUAL REALITY(VR)

EXPLORING NEW NAVIGATION PARADIGMS

MASTER IN COMPUTER SCIENCE
SPECIALIZATION IN SPECIALIZATION NAME

NOVA University Lisbon
***Draft:** January 19, 2025*

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Abstract

Regardless of the language in which the dissertation is written, usually there are at least two abstracts: one abstract in the same language as the main text, and another abstract in some other language.

The abstracts' order varies with the school. If your school has specific regulations concerning the abstracts' order, the NOVAthesis LaTeX (novathesis) (LaTeX) template will respect them. Otherwise, the default rule in the novathesis template is to have in first place the abstract in *the same language as main text*, and then the abstract in *the other language*. For example, if the dissertation is written in Portuguese, the abstracts' order will be first Portuguese and then English, followed by the main text in Portuguese. If the dissertation is written in English, the abstracts' order will be first English and then Portuguese, followed by the main text in English. However, this order can be customized by adding one of the following to the file `5_packages.tex`.

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For example, for a main document written in German with abstracts written in German, English and Italian (by this order) use:

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Concerning its contents, the abstracts should not exceed one page and may answer the following questions (it is essential to adapt to the usual practices of your scientific area):

1. What is the problem?
2. Why is this problem interesting/challenging?
3. What is the proposed approach/solution/contribution?
4. What results (implications/consequences) from the solution?

Keywords: One keyword, Another keyword, Yet another keyword, One keyword more, The last keyword

Resumo

Independentemente da língua em que a dissertação está escrita, geralmente esta contém pelo menos dois resumos: um resumo na mesma língua do texto principal e outro resumo numa outra língua.

A ordem dos resumos varia de acordo com a escola. Se a sua escola tiver regulamentos específicos sobre a ordem dos resumos, o template (LaTeX) novathesis irá respeitá-los. Caso contrário, a regra padrão no template novathesis é ter em primeiro lugar o resumo *no mesmo idioma do texto principal* e depois o resumo *no outro idioma*. Por exemplo, se a dissertação for escrita em português, a ordem dos resumos será primeiro o português e depois o inglês, seguido do texto principal em português. Se a dissertação for escrita em inglês, a ordem dos resumos será primeiro em inglês e depois em português, seguida do texto principal em inglês. No entanto, esse pedido pode ser personalizado adicionando um dos seguintes ao arquivo `5_packages.tex`.

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Relativamente ao seu conteúdo, os resumos não devem ultrapassar uma página e frequentemente tentam responder às seguintes questões (é imprescindível a adaptação às práticas habituais da sua área científica):

1. Qual é o problema?
2. Porque é que é um problema interessante/desafiante?
3. Qual é a proposta de abordagem/solução?
4. Quais são as consequências/resultados da solução proposta?

Palavras-chave: Primeira palavra-chave, Outra palavra-chave, Mais uma palavra-chave, A última palavra-chave

Contents

List of Figures

Acronyms

HMD	Head-Mounted Display *(pp. 2, 6, 7)*
novathesis	NOVAthesis LaTeX *(pp. i, ii)*
UX	User Experience *(p. 1)*
VE	Virtual Environment *(pp. 1–7)*
VR	Virtual Reality *(pp. iv, 1–5, 8)*

1

Introduction

[TODO: Completely outdated]

The implementation and exploration of safe, expansive and immersive Virtual Environments (VEs) has evolved with the development of VR and its wide range of navigation techniques. These techniques influence several dimensions of User Experience (UX), such as efficiency, usability, immersion, comfort, and accessibility, and are, therefore, used in different contexts and situations.

In small physical spaces, the most commonly used navigation techniques rely on joystick-based movement and teleportation, due to the physical contraints of the environment. By cutting the use of Natural Walking, these techniques prove to be less immersive and unrealistic, as they trade the realism of walking elements for ease-of-use.

To address these limitations, new navigation paradigms have been developed. Some of these resource to the use of Impossible Spaces and Non-Euclidean Geometry to provide users the ability to naturally walk through extensive VEs, even whithin restricted physical spaces. By manipulating spatial perception and geometry, these techniques create the illusion of larger virtual spaces, enabling more intuitive and immersive navigation experiences.

1.1 Motivation

1.2 Related Questions

Q1-Is it worthwhile to explore navigation through non-Stride techniques whilst in a constricted physical space?

Q2-Does using hyperbolic strides instead of linear ones lead to increased disorientation and cybersickness?

Q3-Do hyperbolic spaces effectively convey more control to the user compared to spaces with linear strides?

2

Related Work

With the objective of understanding the current state of the art in the field of Virtual Reality (VR) navigation and locomotion, this chapter presents several topics, techniques and studies that are relevant to this field.

[TODO: Add 'Background' section, introducing HMDs, VEs and give proper definitions on Navigation, Wayfinding and Motion] [10] [1] [16]

[TODO: Find a much more recent font for describing current technologies and devices]

2.1 Virtual Reality

VR has been given various definitions[16], but these tend to converge on the same few essential ideas: It is a real-time, interactive and immersive experience in a simulated 3D World (also referred as Virtual Environment (VE)), created through the use of different technologies as Head-Mounted Displays (HMDs) and several input/tracking devices that have been in active development and research as of late [4].

2.1.1 Head-Mounted Displays and Devices

2.1.2 Navigation of Virtual Enviornments

2.2 VR Locomotion Techniques

Locomotion (also denoted as "active travel" or just "travel"[13]), the act of moving from one place to another, is often considered one of the most fulcral aspects of VR interaction[19], as it permits navigation in VEs[3].

Throughout the advancements in VR research and technology, multiple locomotion techniques have been developed, all with different characteristics, addressing different needs and use cases[4]. It's due to the diversity of these techniques that various typonomies and classifcations have been proposed, throughout the years of VR development [4]. [TODO: ADD MORE REFS] The structure of this subsection is based on the typology of VR Locomotion Techniques proposed by Boletsis et al. [4] as it emcompesses most techniques according to the characteristics discussed in this section.

According with Boletsis et al.[4] locomotion techniques are distinguished by the type of interaction they require, the type of motion it produces and the type of VE it is designed for, as seen in Figure 2.1.

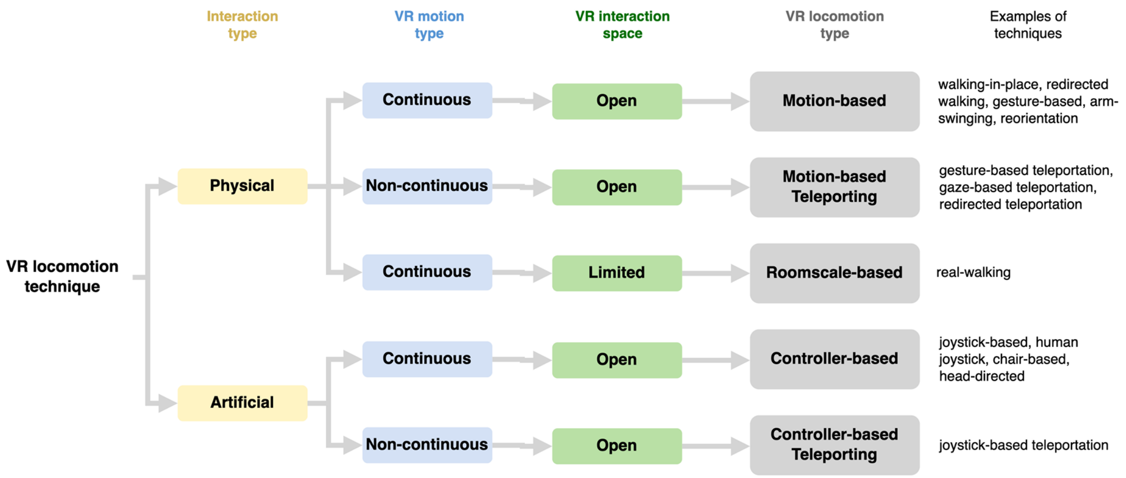

Figure 2.1: Typology of VR locomotion techniques by Boletsis et al.[4]

Regarding the interaction type, a locomotion technique can be "physical" - the input is based on the user's physical movement - or "artificial" - utilizes input devices for direct VR motion and navigation. VR motion types may be "continuous" - the transitions between positions is smooth and non-interrupting - or "non-continuous" - the transitions between positions are abrupt or instantaneous. Finally, the VR interaction space may be "open" - the VE is larger the the user's physical space - or "limited" - the physical environment constraints the VE's size.

Different sets of these characteristics define the different types of locomotion techniques that are to be discussed in the following sections. It is also important to note that these techniques may be used in combination with each other, i.e., a technique integrating two or more other techniques [4].

2.2.1 Joystick

Controller-Based locomotion techniques are used in an open VR interaction space, with continuous motion and require an artificial means of input, such as a controller or other similar input devices[2]. Joystick-based locomotion is not only the most prevalent of this type of techniques, it is also one of the most used techniques in research [4].

Joystick-Based locomotion can be described in the following manner: given a user in a VE from a VR application, the way that they navigate in said VE is dependent on a joystick controller. The joystick rests in a neutral position until the user applies force, changing its value in a certain axis, normally from -1 to 1 (see Figure 2.2). The values registered on the joystick's horizontal and vertical axis will make the user continuously translate from one

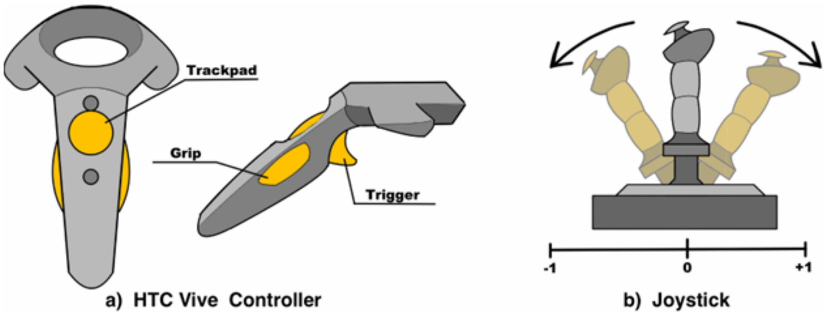

Figure 2.2: Diagram of Vive Controller and Joystick [9]

position to the next in the direction related to the user's gaze direction, i.e., if the user is looking in a certain direction and applies vertical of 1 they will move in the yaw direction of their gaze at full speed [9].

The artificial means of creating input for movement makes joystick locomotion consiedered not physically demanding and a high ease-of-use technique, especially noticed in users who have prior experience with similar controllers [18]. This locomotion type also registers moderate-to-high levels of immersion when used, mostly due with the motion's uninterruptive nature [3].

Though intuitive and not physically demanding, joystick locomotion has a caveat that pretains to the user's comfort. This locomotion type can create motion sickness, due to the conflicting movement cues from user's proprioception, their vestibular sense and from their vision, as the user is physically stationary whilst they move in the VE[13]. This is especially felt by unexpericienced VR users. [18]

It's due to this discomfort and the lack of sufficient levels of immersion that this locomotion technique isn't the most approppriate for the pruposes of this research, and thus it will not be implemented. [TODO: Rework this]

2.2.2 Teleportation

Teleporting differs from Controller-Based locomotion techniques in that it is non-continuous, as, instead of moving continuously, users are interrumptly teleported from one location to the next during their navigation [2], and much like Joystick-Based locomotion it is one of the most used locomotion techniques[4].

When teleporting, a user dictates where they want to teleport to, usually by holding down some input button on a controller and pointing to the pretained destination with said controller, releasing said input when the destination has been chosen. On release the user moves to the selected destination instantaneously (see Figure 2.3) [9, 18].

The uncontinuouty of this locomotion methods' creates strengths and weaknesses. On the positive side, the discrete jumps prevent feelings of cybersickness by not having a conflicting continuous motion occuring while the user is stationary [3, 18], and is generally more efficient at percurring long distances[9]. On the other hand the jumps can create

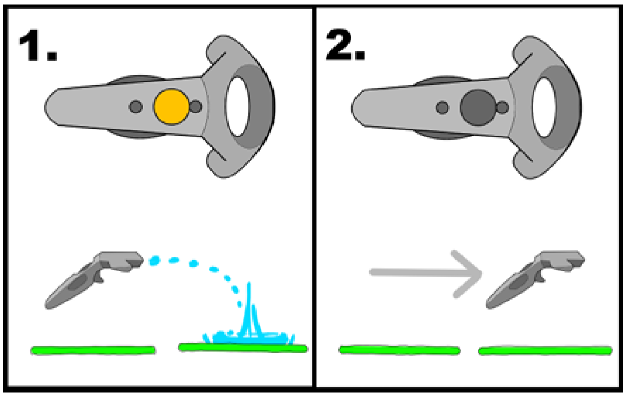

Figure 2.3: Graphical Representation of Teleporting [9]

some disorientation and loss of immersion, as after teleporting the user takes more time to fully comprehend their surroundings [13], exerting more cognitive effort and in turn breaking the ilusion of the VE.

To mitigate this lack of immersion, studies tried to provide less artificial manners of perfoming teleportation. However, even with similar or slightly better results in regards to immersion, users still perfered using controllers rather then the purposed controller-free [5], and even hands-free teleportation techniques [23].

Even so, in various comparison studies, teleportation has been identified as a prefered locomotion method over other frequently used alternatives, mostly due to the lack of motion sickness and high ease-of-use [3, 13].

Although comprehending this technique's strengths and weaknesses is important for the full understanding of the problem at hand, teleporting proves to be a non suitable technique for this research, due to the lack of immersion it provides, and therefore its implementation was not considered.

2.2.3 Omni-Directional Treadmills

As a type of locomotion techniques that require physical interaction for continuous motion in open VR interaction spaces, Motion-Based techniques are rooted on the user's physical movement for their navigation in a VE [2], which poses the question: How can a user physically navigate a VE larger than their physical environment without reaching the limits of their available space?

According to Nilsson et al. [20], it's possible to identify yet another three sub-types of Motion-Based locomotion techniques, all of which try to solve this problem, with these being Repositioning Systems, Proxy Gestures and Redirected Walking.

Repositioning Systems refer to input devices that try to counter-act users' foward motion when walking, essentially keeping them in place, ranging from more devices with a more "active" approach to the repositioning like threadmills to more "passive" options like friction-free platforms Figure 2.4.

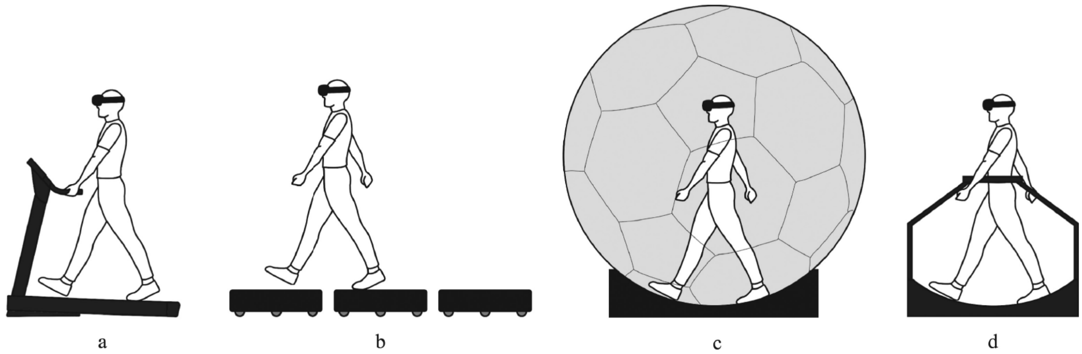

Figure 2.4: Four examples of repositional systems: (a) Traditional Linear Treadmill, (b) motorized floor tiles, (c) a human-sized hamster ball, and (d) a friction-free platform. [20]

One of the most common Repositioning Systems are Omni-Directional Treadmills - devices that sense the direction of users' steps whilst walking in a 360 degree space, maitaining the user at the center of their available space, translating the users steps as movement in the VE. User studies seem to indicate that the motion caused, although not reaching quite exactly the feeling of real walking (with some users indicating a feeling more similar to running or skating rather than walking), this locomotion method evokes high levels of presence, similar to real walking [27].

However, despite taking an almost accurate walking motion as input, offering high levels of immersion and providing a promissing solution for the physical limitations of walking in a constricted space, these devices are often expensive and tend to be difficult to operate [7]. In addition, performing quick turns or side-steps may cause users to lose balance [20] and more natural walking techniques like the later discussed Redirected Walking are prefered by users [27]. It's for these reasons that this research pretends to provide a more suitable, immersive and affordable alternative to a technique like Omni-Directional Treadmills, thus this technique was not chosen for further study and/or improvement in this research.

2.2.4 Walking-In-Place and Arm-Swinging

Proxy Gestures techniques, contrarly to Repositioning Systems like the Omni-Directional Treadmills, offer inexpensive and easy-to-learn solutions to the problem caused by physical constraints during Motion-Based locomotion techniques [20]. Locomotion in these techniques is based on gestures that emulate walking motions, keeping users moving their limbs, but stationary at the same time.

Walking-In-Place is the most common of these techniques [3, 20]. To emulate walking, users perform a gesture comparable to "marching on the spot" in order to move in the direction they are facing, sometimes relying on sensors for detecting the legs' movements [7], yet the detection can recurr solely to HMDs [14].

Although it might sound counter-intuitive for simulating physical walking, Arm-Swinging is a technique that switches the motion performed by users from the lower body to the upper body. In this technique users swing their arms back and forth interchangeably, to move in the direction they are facing. The objective is to perform a gesture comparable to how humans naturally swing their arms when they walk, with the arm's movements being detected either by armband-like sensors [7], or just by controllers users hold in their hands [9].

The fact that both these techniques have the capability to only rely on HMDs and their associated Controllers makes them more accessible, easier to use and thus a more prevelant technique for common users [20]. Additionally, the motion-based input provides a more approppriate proprioceptive feedback similar to real walking than Joystick and Teleportation techniques and hence usually grade higher in immersion ratings [3].

Despite this, these techniques present some caveats. Walking-In-Place can be physically demanding and potentially induces motion sickness after prolonged use [3, 7], making it not the best solution for use-cases in which users have to navigate anextensive VE. Arm-Swinging, although not the same magnitude, is also limited by this weak point [9],but it is additionally limited by the fact that users can't use their arms for interaction while moving [20].

Although both techniques prove useful for addressing the problems caused by physical limitations while moving, their strong points and weak points indicate them as non suitable for the context of this research. [TODO: Rework this]

2.2.5 Redirected Walking

[TODO: Talk about the difference of Natural Walking against artificial input locomotion types][19]

[TODO: Talk about (the need for) Redirected Walking][19][6][25][21][20][27] [7]

[TODO: Address that due to the high levels of ease-of-use and immersion, this is the indicated type of locomotion for addressing the problem of maitaining high immersion levels in VR whilst there are contraints in physical space during Navigation]

2.2.6 Summary

[TODO: Present table with techniques, comparing strong and weak points]

[TODO: Go over why continuous motion-based locomotion provided by RDW is the most relevant for this research and connect it with the Motivation (address the gap for high immersion yet physically limited locomotion)]

2.3 Non-Euclidean Space in VR

[TODO: Add an introduction to the topic. Explain Euclidean vs Non-Euclidean.] [22] [29] [12] [11] [17] [24] [28] [26] [8] [15]

[TODO: Shorten this and add relations with other articles [10]. Much of the core concepts here (Cognitive Maps, Wayfinding etc.) might be addressed in the soon to be Background section]

In 2019, Warren conducted an experimental biology paper on Non-Euclidean Navigation[29], with the purpose of defying the assumptions of how humans and animals navigate. Traditionally, according to the Cognitive Map Hypothesis, humans rely on Euclidean cognivitive maps, essencially a mental map, for orientation and navigation. Warren, though, pruposes a new hypothesis instead: humans navigate according to Cognitive Graphs, stating that spatial knowledge is instead described as a labeled graph with nodes that link places and paths, each with their own local metric data for distances.

To test his theory he conducted a VR experiment in which two groups of users had to traverse a maze, yet one group travesed the maze normally whilst the other traversed a maze with the inclusion of invisible wormholes that seemlessly transported them from one position to another creating a Non-Euclidean Impossible space, as seen in Figure 2.5.

After being firstly tasked to explore the mazes and find four of the objects present in the maze and not the route they took between them (Bookcase to Cactus and Well to Sink), the groups were then prompted to go from object 'A' to an object 'B' without the mazes structures and relying on their spatial knowledge alone. The results shown in Figure 2.6 and the paths from the first task on Figure 2.5 reveal that the participants in the Non-Euclidean maze were biased by the use of wormholes, revealing that despite the irregularities created by the presence of wormholes, participants were able to reach their targets even with the geometric discrepancies created by the wormholes, and that local metric cues and graph-like navigation strategies were enough to guide users to the pertained destination.

Further proving his hypothesis, Warren demonstrates how Non-Euclidean spaces are primed for use in VR Navigation that provide advantages for Natural Walking VR applications, as seen in the following sections.

2.3.1 Impossible Spaces

[TODO: Present various papers on Impossible Spaces]

2.3.2 Hyperbolic Spaces

[TODO: Present various papers on hyperbolic Spaces]

2.4 Space Modification Techniques

[TODO: Add proper introduction. This section is for common techniques used to create the spaces referred before]

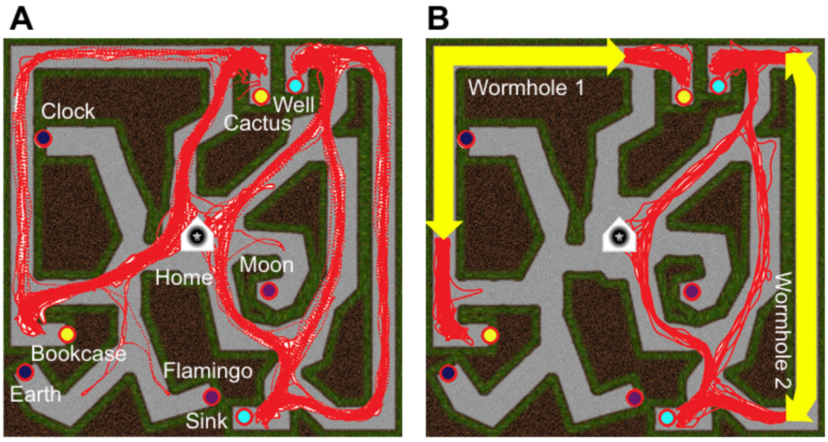

Figure 2.5: Traversed mazes in Warrens' study. Red lines indicate the paths users took. A is the Euclidean maze, B is the Non-Euclidean maze [29]

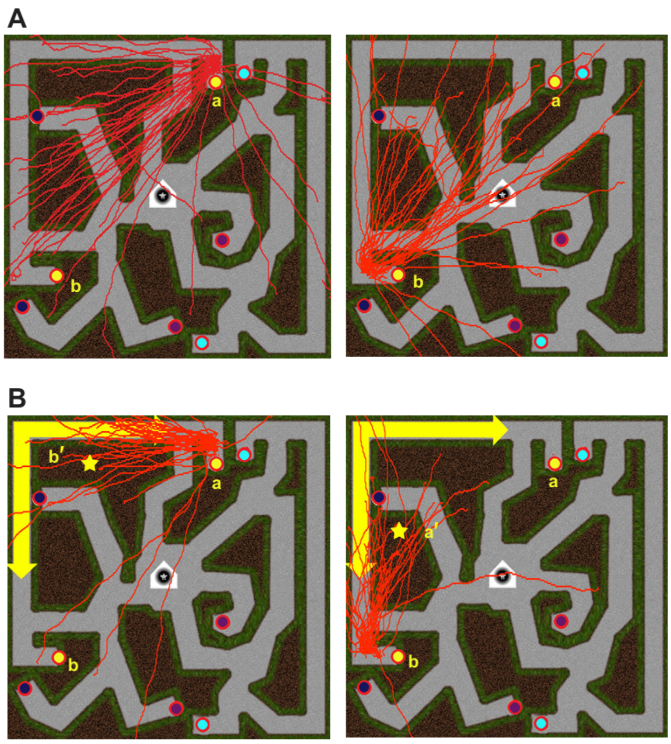

Figure 2.6: Paths taken between objects Bookcase and Cactus in Euclidean maze A and Non-Euclidean maze B. Stars in maze B indicate the location of the object in Euclidean coordinates [29]

2.4.1 Procedural Content Generation

[TODO: Introduce the basics of PCG and how to use it for VEs]

2.4.2 Spatial Compression

[TODO: Present papers on Spatial Compression]

3

Plan and Analysis

4

Conclusion

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