7 Ways to Improve Your Virtual Experience - Exploring the Obstacles of Mainstream VR

Andrey Krekhov

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Abstract

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Abstract (different language)

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Acknowledgement

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Contents

1 Introduction

Virtual Reality (VR) has taken foot in everyday life. Or didn't it? We are caught between two camps: On one hand, industry took critical leaps forward and established affordable living room VR setups. Software complanies are extending their products to VR and promise unique benefits, be it for entertainment or business purposes. On the other hand, however, researchers are getting more and more vocal (cf. Figure 1.1) regarding the omnipresent obstacles of VR that haven't changed that much in the last decades: limited locomotion, inferior interaction, or the risk of cybersickness, to name a few.

As prospective or even established researchers, we often question ourselves which impact our work in a certain area might have and whether it is "worth it". So, is VR doomed as some people claim, or are there good chances that our research efforts will be rewarded? Exactly that is the central question that unites the publications gathered in this thesis. As the title already reveals, we will dive into seven different VR entities to win an impression whether and how research might change the status quo of mainstream VR. The particular contributions range from foundamental techniques, such as novel locomotion approaches, to application domains, such as scientific visualization. To make the manuscript more readable, the introduction section is dedicated to answering three major questions of the reader:

- *Why was the thesis written (and why should I read it)?*
- *What is the thesis (not) about?*
- *How is the manuscript organized?*

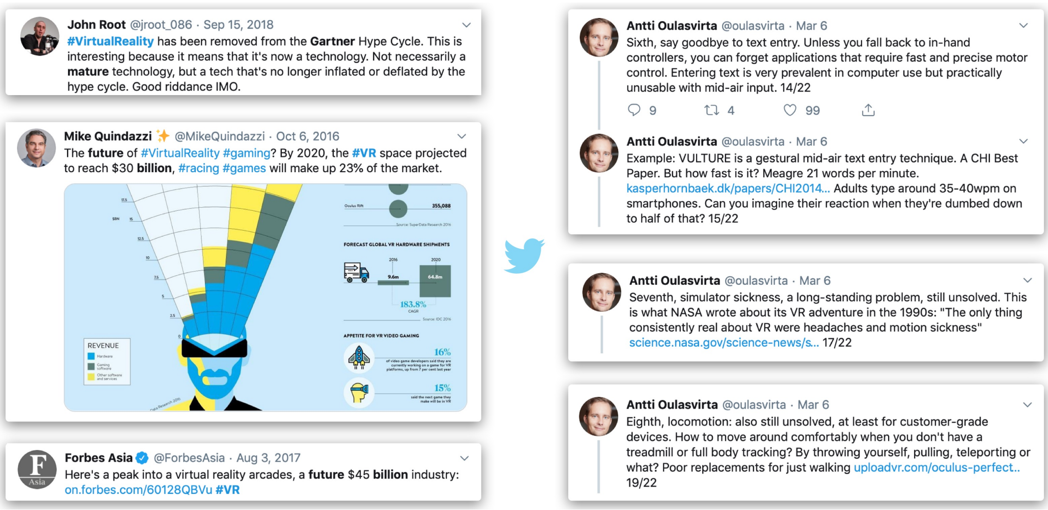

Fig. 1.1: Mixed voices on Twitter regarding the present and future of virtual reality.

Note that this is a cumulative dissertation. Hence, in contrast to traditional manuscripts, the present synopsis is a high-level pointer to published works, rather than a verbose in-depth elaboration of a particular research topic. The main objectives of such a synopsis are to establish a red thread through the conducted research, to familiarize the readers with the most important outcomes, and to draw final conclusions—in our case, conclusions related to the present and future of virtual reality.

1.1 Motives for Revisiting VR

One important argument among opponents of VR (research) is that the base approach of VR is not novel and has not evolved in the last decades. In fact, nearly all "VR booms" and associated promises failed, and many of us see no reason to believe the opposite regarding the current VR era. In the early nineties, we faced first commercial VR headsets, such as the Sega VR, and magazines predicted "affordable VR by 1994" [Eng92]. Now, more than twenty years later, VR is finally regarded as mainstream, arriving in the price range of consoles and high-end smartphones. Yet the idea remains the same: a stereo pair of images and head tracking form the base for an experience that is well-known and being studied extensively for decades—so why is it worth reconsidering it?

As always, the devil is in the details. While there was no major invention that revolutionized VR overnight, a number of subtle advances and incremental changes—both from a technical and psychological perspective—give us enough reason to revisit VR. In order to aid clarity, such changes can be aggregated in the following categories:

1.1.1 Hardware

As it comes to technology, the most striking progress was achieved regarding the three following characteristics of VR setups: *affordability*, *comfort*, and *features*.

Affordability. In general, the price tag is not all that important in research. However, easily available HMDs created a common base for VR experiments and increased reproducibility. Thanks to default setups, such as the HTC Vive ecosystem, researchers began to share their testbed implementations and best practices, which enhanced the overall robustness and transferability of the results.

Comfort. In the past, wearing a heavy and chunky HMD unavoidably introduced a bias due to discomfort and limited the potential of VR. Nowadays, HMDs have an overall weight around 500 grams and can be considered at least bearable for a prolonged period of time. More importantly, the show-stopping and dangerous cable clutter finally disappeared, be it in case of all-in-one solutions, such as the

Oculus Quest, or even in case of desktop VR variants, such as the HTC Vive Pro with a wireless adapter.

Features. Affordable and comfortable HMDs compete on the market, and this competition ensures that manufacturers have to add unique features to their products. Hence, users finally receive acceptable display resolutions and an increased, yet still narrow, field of view. Moreover, VR setups now include sophisticated and precise controllers to enhance the interaction with VR content. And, perhaps most importantly, room-scale VR paved its way into production, which allows us to utilize the most realistic locomotion technique to explore virtual environments—natural walking.

1.1.2 Software

more sophisticated software (tracking and things from research that were merged into vr)

1.1.3 People

more digital people (less cs) –most important aspect maybe

these reasons have highest impact on aspects such as locomotion, interaction, and perception, so thats why we exactly revisit it and see what we can make out of it.

1.2 Scope and Contentual Boundaries

what is it about and what it is not about - what is scope, what is outside? - explain that there are not 7 paper, but much more - and that we subdivide the papers in walk, touch, and see - locomotion, interaction, perception

to have some sort of impression, we need some big picture, and need lot of areas. time limitations so we picked representatives (things that changed most maybe). main focus on walk, see, and touch.

describe what particular questions will be answered. - (antti) take look how to locomote in vr and present novel approaches. In particular, cybersickness and presence will be handled here (?)

- (annti) interaction in terms of gestures, haptics, representation, and software logistics

- what can we use vr for? differing perception is great

Limit to mainstream vr, no exotic setups. many studies are with vr games as example, as one of the most important motor of such setups.

examples of what is not inside but still important: text input, multi-user.

1.3 Structure of the Synopsis

how the big picture is collected. diff areas, ranging from vr techniques (locomotion) over interaction modalities and taxonomies to perception phenomena that make vr unique and beneficial.

1.4 anttis vr rant

Rant: Nine reasons why I don't believe in current VR/AR technology.

HoloLens, Magic Leap, and Oculus: Mind-blowing videos, and the market is estimated to explode to 200 billion by 2025 (Statista). So what's wrong?

HCI research tells why we haven't seen a killer app yet:

1.4.1 the gorilla arm

First, the gorilla arm. The videos show smiling users holding their arms up for extended periods. But that will cause shoulder pain. The Consumed Endurance model estimates that a user can hold arm up for just 90 seconds before starting to fatigue.

Anecdotally, when drsrinathsridha was working on a CHI paper, he could not find a comfortable posture for doing freehand gestures and had days of sore neck and arm. Well, you could try "gun slinging, but then you lose hand-to-display coupling and fall back to mouse-like input

So, either we lose hand input or we're limited to applications that that don't need more than 90 seconds of "air time".

1.4.2 hands have evolved for manipulating objects

Second, our hands have evolved for manipulating objects, not for poking in the air.

While vision-based tracking of hand movement has taken leaps forward, tracking of hands WITH objects hasn't. Here's a screencap from our ECCV paper from a few years back. Tracking works if you're slow and occlusions are bearable

So, it seems you can forget interactions with (arbitrary) physical objects. We're going to be designing poking-in-the-air applications for years to come.

1.4.3 poking-in-the-air is also inferior

Third, poking-in-the-air is also inferior as a means of interaction. Mechanoreceptive feedback is specialized and important for input. We don't want to lose it. Even pressing a button or hitting a virtual ball becomes hard.

Well, you could try 3 things: 1) forget applications where contact is needed (boo!), 2) wear gloves (clumsy, unhygienic), or 3) assume an instrumented environment. Ultrahaptics - as far as I have tried it - is too weak to replace real contact.

Users will miss real buttons.

1.4.4 gesturing is not "natural"

Fourth, gesturing is not "natural". There are few if any instinctual gestures. HCI research has sought for natural gestures for a decade, but found out that the gesture elicitation method artificially inflates claimed consensus:

So, either you forget "natural interaction", and assume that your users are willing to spend time learning new gestures, or you're stuck with simple pointing-and-pinching type gestures that users can transfer from the mobile device.

1.4.5 body misalignment

Fifth, body misalignment. This is my fav: The virtual and the physical body will never be perfectly aligned in time and space. The sensing+computation pipeline that mediates motion and display can only worsen alignment. Try petting a cat with Leap Motion. Ouch.

This is a serious issue for motor control, causing coordinate disturbance, temporal asynchrony, and poorer cue integration. Users cannot rely on their senses as they normally do when moving. Imagine tracking a bee in 3D space: Hard IRL, harder in VR

1.4.6 text

Sixth, say goodbye to text entry. Unless you fall back to in-hand controllers, you can forget applications that require fast and precise motor control. Entering text is very prevalent in computer use but practically unusable with mid-air input.

Example: VULTURE is a gestural mid-air text entry technique. A CHI Best Paper. But how fast is it? Meagre 21 words per minute. Adults type around 35-40wpm on smartphones. Can you imagine their reaction when they're dumbed down to half of that?

Well, you could design a new open-loop gesture set, like a sign language. We tried exactly that (CHI'15), predicting that you might get up to 50 WPM with simple gestures and LeapMotion-level sensing. Downside? You need to practice around 10-20 hours

1.4.7 simulator sickness

Seventh, simulator sickness, a long-standing problem, still unsolved. This is what NASA wrote about its VR adventure in the 1990s: "The only thing consistently real about VR were headaches and motion sickness"

ut surely we have solved motion sickness by now with better hardware? No. Depending on task, up to 56 percent of participants felt motion sickness with Oculus Rift in a recent study:

1.4.8 locomotion

Eighth, locomotion: also still unsolved, at least for customer-grade devices. How to move around comfortably when you don't have a treadmill or full body tracking? By throwing yourself, pulling, teleporting or what? Poor replacements for just walking.

1.4.9 fov

Ninth, another persisting problem still with us: the narrow field of view. HoloLens had a notoriously narrow FOV "like a card deck".

When the HMD's FOV is narrower than your (real) peripheral vision, you lose visual context. Users need to turn and glance around to orient.

But peripheral vision is actually important in many visual tasks. NASA reported that pilots did better with traditional displays than with VR because of this.

1.4.10 summary

To sum up, definite progress has been made, but the scope of today's VR/AR technology is narrow. It is locked into applications where a few seconds of waving in the air is worth the hassle of putting on an HMD.

2 Locomotion in VR

Curiosity and the thirst for exploration are an important part of human nature. It is not surprising how easy we tend to lose ourselves in large, open game worlds, spending countless hours on roaming around unknown terrain. Hence, locomotion ever since had an important role in game design. And while this challenge is solved to a large extent in common digital games, locomotion techniques in virtual reality (VR) remain a large obstacle to this day.

This chapter discusses the challenges of VR locomotion and outlines a number of available solutions that allow the exploration of fictional worlds. We begin by looking at two important components of VR that one might also call the curse and blessing of such immersive setups: cybersickness and presence. In particular, we explain why common locomotion approaches, such as mouse and keyboard, are not viable in VR, and how the high degree of immersion allows the players to experience a feeling of being in the virtual world.

The main part of the chapter focuses on classifying the past and ongoing research on VR locomotion. We discuss a broad spectrum of possibilities to move in VR, ranging from stationary approaches relying on gamepads to advanced redirected walking techniques that trick our perception to enable unrestricted natural walking in a limited space. Finally, we propose a set of design guidelines to simplify the implementation of player locomotion in future VR games.

2.1 Presence and Cybersickness

At present, VR technology is considered mainstream, and more and more manufacturers are putting effort into creating head-mounted displays (HMDs) at affordable prices. Such HMDs are capable of rendering stereoscopic images at HD resolutions for each eye while maintaining a high refresh rate (90 Hz or above). The hardware also tracks the head orientation, which allows players to look around in VR like in real world and gather close-up experiences during gaming.

Players usually describe such impressions as a feeling of “being there” [Hee92; LD97]. Other popular wordings often include the two terms *presence* and *immersion* — sometimes in an interchangeable manner. Throughout the chapter, we utilize immersion [CCN14] when focusing on the technical quality of VR hardware [BD95; SC02]. In contrast, we use presence to describe how immersive setups affect our perception to make us believe that we are indeed in the virtual environment [Sla03].

Hence, (game) researchers and developers often target the increase of presence when coming up with novel VR approaches, and VR locomotion is a prominent advocate for such presence-enhancing research [SUS95]. To measure presence, the most common methods include the Presence Questionnaire (PQ) [WJS05] and the Igroup Presence Questionnaire (IPQ) [Sch03; SRF18]. In addition, the Immersive Tendencies Questionnaire (ITQ) [WS98] can be administered before the actual survey to check participants' individual tendencies to get immersed in an activity or fiction.

Unfortunately, the increase in players' perceived presence is not the only thing that an immersive setup entail. The produced realism imposes high demands on VR software and hardware regarding the human perception. Minor faults or technical issues, such as slightly offset locomotion or a sudden frame rate drop, can have severe consequences regarding the players' well-being and result in *cybersickness* [SKD97; LaV00]. Other prominent terms often used in this context are *simulator sickness* [Kol95] and *motion sickness* [Mon70; HR92; Ohy+07]. In contrast to the manifold reasons of cybersickness, the main cause of simulator sickness is an incorrectly adjusted simulator [Ken+89] and can be regarded as a rather technical problem.

Cybersickness involves symptoms such as nausea, eye strain, and headaches. Roughly spoken, the main reason behind that negative phenomenon is a mismatch in our vestibulo-ocular system. Our vestibular system senses acceleration that ideally matches the visual input. When these signals do not match, the aforementioned symptoms are likely to occur [RB75]. There exist three popular explanations [LaV00] for such an unwanted body reaction: poison theory, postural instability theory, and—the most prominent—conflict theory.

Hettinger et al. [Het+90] also mentioned vection as a possible reason behind cybersickness. Vection describes the feeling of movement that relies only on our visual system and can be experienced when, e.g., we sit in a standing train and observe another train that is currently accelerating. Vection is influenced by several factors, including the field of view (FOV), the alignment and proximity of moving objects, and the optical flow rate. For instance, the combination of a large FOV and fast objects that account for a large proportion of players' view amplify the perceived vection and smooth the way to cybersickness. Hence, limiting the FOV is one of the possible approaches to reduce cybersickness [FF16; Lin+02].

To conclude, we suggest keeping cybersickness in mind and to avoid cognitive mismatches where possible — however, not at all costs, as "sickness-save", stationary scenes without any locomotion would potentially miss out on a wide range of benefits that VR has to offer. And sometimes, as shown by von Mammen et al. [VKE16], games might even benefit from an artificially induced cybersickness.

2.2 VR Locomotion Landscape

We have seen that locomotion in VR is not just a way of transporting the player from A to B. Rather, locomotion strives to provide realistic, immersive experiences that increase the player's presence while working around cybersickness. In recent years, research [Bol17] and the game industry [Hab+17] created a plethora of varying locomotion approaches. As often the case, there is no "right" answer which one to pick for your upcoming VR game. Hence, the main purpose of the following sections is to provide a rough overview and classification of available approaches and to serve as a starting ground for further research and development. In particular, we start by considering locomotion approaches that do not involve a physical movement of the player, before moving on to techniques that evolve around the idea of natural walking in VR.

2.2.1 Stationary Approaches

Although HMDs can track head movements, only a subset of them is capable of tracking the global position of a player in the room. One also says that such setups support *room-scale tracking*. One common approach is to utilize a set of base stations that emit infrared pulses, which are captured by the HMD to estimate the global position. Conversely, there is a considerable amount of HMDs that comes without room-scale support. Main reasons to omit such tracking are the lower costs and the increased portability. As such devices do not support the physical movement of the player, stationary locomotion techniques are required to allow the exploration of game worlds. Another reason for stationary approaches is the reduced fatigue, as players might even remain seated during a gaming session.

Traditional I/O Approaches

Existing games are sometimes ported to VR, be it to promote the title or to build on the success of the original game. In such cases, developers tend to take over the controls including locomotion to reduce the turnaround time and keep the familiar game UI. Hence, VR players are pushed towards desktop I/O, be it a keyboard [AM16], a joystick [Boz+16a], or a gamepad [FF16]. The advantage of the method is, without doubt, its simplicity regarding implementation and the familiarity to experienced players.

However, as we pointed out before, a cognitive mismatch between our vision system, i.e., seeing the motion via the HMD, and our vestibular system, i.e., remain stationary or even seated, can easily lead to cybersickness when using such approaches. Hence, we recommend to pay close attention to this issue when relying on traditional methods. As a partial remedy, developers might want to reduce the FOV, as, e.g., was done in Skyrim VR [Bet17]. Another way would be to limit or disable continuous in-game player motion in favor of quick or discrete player movements [Hab+17] to reduce vection. The work of Medeiros et al. [Med+16] and Yao et al. [Yao+14] also confirmed the benefits of short, fast movements with no acceleration as one measure to combat cybersickness in such cases.

Teleportation

If we take the idea of fast and short movements to the extreme, we will end up with a technique called the point and teleport locomotion approach [Boz+16b]. Players select a destination using a pointing device, e.g., a controller [XMS17], and are instantly teleported to that place, thus entirely removing the vection issues. Regarding cybersickness, this technique is more robust than traditional gamepad locomotion [FSW17] and is being strongly encouraged by the majority of established VR systems such as the HTC Vive.

The targeting is often visualized by an arc that starts at the controller or the virtual hand representation and ends at the planned destination. On the one hand, the targeting is considered intuitive and robust. On the other hand, however, such implementation limits the travel distance to visible places that are not far away, and certain virtual environments might further limit the travel distance by exposing obstacles, such as trees or walls, that prevent players from targeting more distant locations. In addition, the displayed teleportation arc itself is a rather obstructive interface element that covers parts of the game world and might decrease players' perceived presence, if it does not blend in well with the setting. Another issue to be considered is the limited precision when teleporting to very close areas, as the displayed arc gets too compressed and is not very helpful for predicting the outcome. This uncertainty often results in numerous relocation attempts until the desired position is finally achieved.

The last drawback of teleportation is the reduced spatial orientation of players, which might also impact their experienced presence. Players need to reorient themselves after a relocation, which imposes an additional cognitive load. To overcome this obstacle, researchers propose to render previews of the destination area, or, as proposed by Bruder et al. [BSH09], utilize such previews as virtual portals where players have to pass through to reach their target.

The described arc-based teleportation, although being recommended by hardware manufacturers, is still relatively uncommon in VR games. A more widespread variation of the technique is known as node-based teleportation [Hab+17]. This technique is based on predefined points of interest that could be represented by, e.g., an icon. In contrast to the arc-based method, players cannot pick their destination freely and can only travel between such nodes. The node selection is usually implemented by looking at a node and pressing a button. The subsequent teleportation process is often accompanied by a fading animation. This feature, in combination with a clever choice of node locations, allows to reduce player disorientation, but obviously limits the perceived freedom of exploration.

Redirected Walking

In contrast to walking in place techniques, which address the room-scale limitation by completely avoiding that the player moves through the real room, other approaches enable natural walking by applying redirection or reorientation. The idea of redirected walking is to manipulate the player's movement in the virtual world by creating a mismatch between the real world locomotion and the translation in the game world. As a result, the perceived movement in the virtual world is more extensive than the player actually moves in the real world space [RKW01; Raz05; Ste+10]. While players do not notice the manipulation, they unconsciously compensate the offset by slightly repositioning and reorienting themselves. Hence, by manipulating translation, path curvature, and rotation, reorientation techniques can be used to keep players inside the boundaries of the tracked space without making them aware of the fact that they are actually walking in circles. Nescher et al. [NYK14] and Paris et al. [Par+17] discuss different redirection methods and algorithms, providing further information how such techniques can be applied to VR games.

Redirection and reorientation techniques maintain the advantages of natural walking regarding high perceived presence, intuitiveness, and a low risk of cybersickness. However, though current approaches tackle the issue of space limitation to some extent, they still require a much larger space than is given in common living rooms and, thus, require further adaptations in that regard [Gre+16; Eng+08; LBS16; BSH09]. The demands of such techniques in terms of the VR setup and the implementation are considerably high.

Multiscale Navigation

Until now, the approaches we considered usually perform on a 1:1 ratio between the physical and the real world. In other words, the travelled distance in the physical room roughly corresponds our virtual footprint. An alternative way to deal with the room-scale limitation is rescaling of players and/or their motion [BTF17]. Note that world rescaling is equivalent to player rescaling. However, we strongly discourage altering the world size, i.e., the size of all objects, due to obvious performance reasons and, in worst case, floating point precision issues.

In research, the dynamic scaling of virtual environments is mostly used within multiscale virtual environments (MSVEs) [ZF02]. For instance, such approaches can be utilized to explore the inner organs of virtual human representations [Kop+06]. Hereby, the current scale can be set either manually by the player or computed automatically based on current task or location. As shown by Argelaguet et al. [AM16], automatic scaling is often more predictable for developers and allows to optimize rendering parameters to reduce diplopia or cybersickness.

In games research, a recent example of player rescaling is a locomotion technique called *GulliVR* [Kre+18]. The approach allows players to turn into giants on demand and cover large distances in just a few steps. At first glance, the idea is similar to a common flying approach, as both variants share the same camera position and velocity. However, flying is known for its severe cybersickness due to the cognitive mismatch of physical and virtual movement speeds. In contrast, GulliVR increases the interpupillary distance as part of the whole-body rescaling process, which has two effects. First and foremost, the cybersickness is removed as players feel like they are walking as giants (no mismatch) and not like they are artificially floating or flying. Second, players perceive the environment from above as a miniature world, which opens up novel design possibilities [CKK19].

2.3 Design Implications

Locomotion in VR has a huge impact on the failure or success of a game. A well-chosen technique is able to enhance the player experience and help players to immerse even more in the fictional worlds. On the downside, technical issues or cognitive mismatches can easily render a game unplayable due to a significant amount of introduced cybersickness. Not surprisingly, our high-level recommendation is to design locomotion in a way that minimizes the risks of cybersickness and maximizes the perceived presence. Ideally, we would choose natural walking for most cases, but, unfortunately, the room-scale limitation forces us to consider alternatives and handle respective trade-offs.

For that reason, we recommend enforcing a decision regarding locomotion quite early in the development process, as certain approaches have a considerable interplay with other game mechanics, such as object interaction, quest locations, world size, etc. As a starting point for such decision making, we summarized the mentioned locomotion methods in Figure 2.1. Please note that such overviews rely on certain over-generalizations, e.g., not all gamepad-based techniques are causing cybersickness. However, we feel that a condensed summary might be helpful, especially when designing a VR game for the first time. Furthermore, we propose the following questions to be asked during the VR game design process with respect to locomotion:

	natural motion	cybersickness	intuitiveness	hardware reqs	short distances	long distances	fatigue
traditional I/O	-	-	○	+	+	○	+
teleport/node	-	+	-	+	○	+	+
gestures	-	○	○	○	+	○	○
natural walking	+	+	+	○	+	-	-
walking in place	○	○	+	○	+	○	-
treadmills	+	+	+	-	+	○	-
redirected walking	+	+	+	-	+	○	-
multiscale nav	+	+	○	○	-	+	-

Fig. 2.1: An overview of VR locomotion techniques including their benefits and drawbacks. Green color (+) means that this attribute is a known advantage of the technique, yellow (○) stands for limited value, and red (-) is rather a disadvantage.

What is my target audience? The canonical question for almost any kind of decision making. We emphasize three aspects of this question. First, how exhausting is the locomotion allowed to be? This depends on age and the overall target group, as well as the type of the game, i.e., it might be an exergame or something meant for relaxation/recovery. Second, how long are the players meant to play the game at a time? This aspect also determines how physically straining the locomotion is allowed to be. Third, what hardware setups do our players have? In other words, are we designing for Google Cardboard that only tracks head orientation or can we assume room-scale tracking? In particular, we are limited to stationary approaches if we do not have access to the player position.

How important is exploration? In general, games with a heavy focus on exploration and player movement benefit a lot from realistic, well-constructed locomotion approaches that allow a free and natural journey through the virtual world. Conversely, if the main emphasis of the game is on aiming and shooting, a node-based teleportation technique with carefully predefined locations might be more efficient. Furthermore, the overall size of the virtual world should be considered, as some of the techniques excel at short distances, whereas other approaches are designed to cover large distances in a short amount of time. Taken to the extreme, certain game genres, such as escape rooms, might even consider to rely only on natural walking by fitting the virtual environment completely into the living room.

What else happens during locomotion? This question is also related to the main focus of the game. Certain techniques, such as gaze-based locomotion, limit the amount of concurrent activities and are less suited for games in which players need to perform additional interactions while walking. The overall effort required for locomotion—be it mental or physical—also impacts the general pace of the game. In other words, fast-paced games might rather benefit from an instant, node-based teleportation rather than forcing players to physically run through their living rooms or spending precious seconds while aiming with the arc-based teleportation approach.

Again, these questions are meant as a starting point. In combination with the overview in Figure 2.1, this kind of reasoning might be helpful to establish a well-suited locomotion technique early on and to take full advantage of virtual reality gaming.

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Declaration

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City, October 4, 2015

Andrey Krekhov