Rock or Roll – Locomotion Techniques with a Handheld Spherical Device in Virtual Reality

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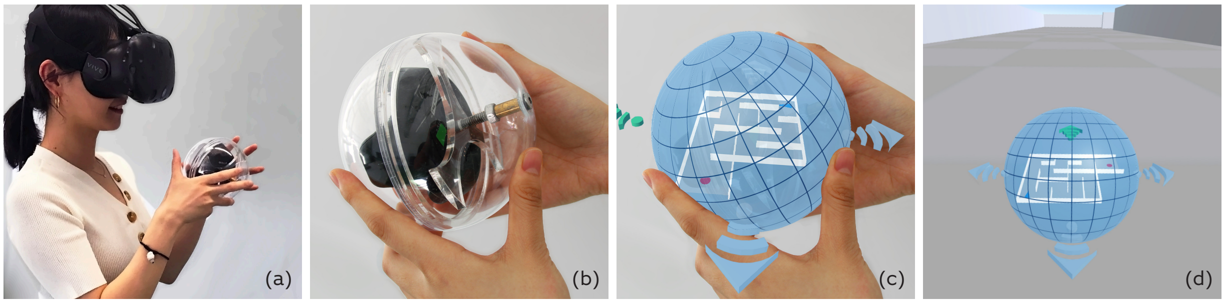

Figure 1: We show how a handheld (a), tracked spherical object (b) aligned with a visualization (c) can be used to control first-person locomotion (d) in virtual reality (VR) by means of rotation. We implement two different approaches (*Position Control*, *Velocity Control*) and compare them to two established methods using VR controllers. Our results show that the spherical controller in combination with the position control technique leads to both faster task completion and higher accuracy.

Abstract

We investigate the use of a handheld spherical object as a controller for locomotion in VR. Rotating the object controls avatar movement in two different ways: As a zero order controller, it is continuously rotated to the target position as if rolling a ball on the floor. As a first order controller, it is tilted like a joystick to determine the direction and speed of movement. We describe how our prototype was built from low-cost commercially available hardware and discuss our design decisions. Then we evaluate both locomotion techniques in a user study (N=20) and compare them to established methods using handheld VR controllers. Our prototype matched and in some cases outperformed these methods regarding task time and accuracy. All results were obtained without any usage instructions, indicating easy learnability. Some of our insights may transfer to interaction with other naturally shaped objects in VR experiences.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction devices—Haptic devices; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms— Virtual reality

1 Introduction

The design of interaction techniques for first-person locomotion in Virtual Reality (VR) is a demanding task: Virtual environments (VEs) commonly exceed the available physical space, but if our physical motion doesn't match our motion in the VE, cybersickness [15, 31] is likely to occur and familiar concepts such as controller-based input can not be used out of the box. As a result, a range of methods classifiable by the type of input (physical, artificial) and the type of movement (continuous, non-continuous) have emerged. Physical input relies on tracking natural motion cues and therefore, is primarily used to implement continuous approaches. The artificial paradigm describes any other form of input, for example, input devices such as handheld controllers. These devices also allow non-continuous techniques [5], such as the point and teleport approach [6, 8] that is widely used in VR.

Continuous techniques feel more realistic and immersive, but are often more susceptible to cybersickness caused by the noticeable disparity between real and virtual motion [14, 20, 47]. Methods using actual or redirected walking suffer from this problem to a lesser extent. However, they require a larger physical space, expensive hardware such as treadmills [42] or need to limit the VE. Non-continuous techniques are often faster and generally more comfortable to use, but they tend to reduce the level of immersion [23] or complicate orientation [6].

To address these issues, we see a great potential in simple physical interaction techniques known from the real world. For example, we learn to rotate objects in our hands to inspect them at an early age and we regularly and skillfully use it in many daily activities. A sphere is a well-known object that affords rotation in a very direct and natural way. The image of a ball rolling on the ground and thereby covering a corresponding distance is rooted in early childhood and provides an easily understood mental model clearly associated with continuous locomotion. The fact that synchronous visual and tangible feedback as generated by a sphere rotating in hands can enhance the sense of body ownership [29] provides an additional reason for exploring this concept in the context of virtual locomotion.

One main advantage of controller-based methods is the finite amount of physical space that is needed. Yet, the possibility to achieve persistent tangible feedback during movement is often limited. Therefore, a rotating sphere provides an interesting opportunity to create a novel type of feedback regarding both movement direction and velocity. We can classify our approach as continuous but as a hybrid approach between physical and artificial input. The handheld sphere, on the one hand, acts as a classical input device, but on the other hand, a physical motion associated with locomotion is transferred to the avatar. Accordingly, the technique can also be seen as a hybrid concept between gesture- and controller-based input. Building on the survey of Boletsis [5] we found that a majority of the ideas presented during the recent two years are of continuous nature, indicating a substantial demand for realistic locomotion.

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Spheres play a significant role as interaction devices, most prominently in the form of trackballs. These are closely related to our concept regarding the tangible feedback they provide. The rotation of the trackball is also felt by the fingertips, but since it has to rest on a socket, it can not be fully enclosed by the hands. Although trackballs can be used to control motion, they are primarily used for ergonomic reasons as a substitute for the mouse [27]. In first-person locomotion, the mouse commonly controls the rotation of the camera. However, since head-mounted displays (HMDs) allow a natural camera control by turning the head, a locomotion device such as our handheld sphere may be held and manipulated with both hands, controlling solely locomotion.

2 Background & Related Work

Since our implementation acts as an input device as well as a (virtual) display, we build on work in the fields of handheld spherical displays in AR and VR, handheld spherical devices in general, spherical devices as locomotion interfaces in VR, and continuous controller-based locomotion in VR.

2.1 Handheld Spherical Displays in VR and AR

Spherical interaction devices are not commonplace in VR. In the field of Augmented Reality (AR), a variety of projected spherical displays have been implemented, and more recent examples also allow to hold and rotate the display. Louis and Berard [4, 33] built a perspective-corrected display in AR and concluded that the rotation of a handheld sphere can very naturally be utilized to examine complex 3D objects displayed on the inside of the sphere. A comparison to a VR condition revealed benefits regarding the use of AR. Miyafuji et al. [36] showed a similar setup and extended the interaction methods from rotating to selecting, bouncing, and throwing.

Englmeier et al. demonstrated fully embodied spherical visualizations in VR [18] as well as a handheld sphere applied for 3D object manipulation in AR [17]. This application allowed for the rotation, translation and scaling of directly coupled virtual objects in an AR scene. Study results showed positive effects regarding the scaling of objects by rotating a handheld sphere around a horizontal axis. This may indicate possible advantages for an application in avatar locomotion requiring precise movement that is similarly controlled by rotating a spherical device around one or more axes.

Going back further, stationary AR spherical displays can no longer be picked up but provide rotation as a form of input. Benko et al. [3] explored multi-touch interaction simulating rotation. Other examples of stationary mounted spherical displays allow real physical rotation [13, 28] but often can not provide a fully spherical surface for visualization.

2.2 Handheld Spherical Devices

As a distinguishing property, we discuss input devices using physical spheres by the degree to which the user's hands can enclose the sphere. Trackballs only allow to touch about one half of a sphere that is mounted in a socket [34] but can be used in a handheld way [16]. Trackballs are mainly used in the exploration of 3D objects on a 2D screen. The manipulation techniques needed for the camera have been outlined by Ware and Osborne [45] and often use an imaginary spherical space surrounding the object of interest.

In contrast, the concept of the 3D mouse offers six degrees of freedom (6-DOF) interaction. It is often implemented as an almost fully embraceable (potentially spherical) object mounted to a suspension or a socket. Froehlich et al. [22] realized such a setup by the name of *GlobeFish*. Equally interesting devices are the *Roly-Poly Mouse* [39] and the *TableBall* [24] that allow users to roll a spherical input device that adds three additional degrees of freedom to 2D translation. Interaction in mid-air [44] as demonstrated by Baudisch et al. [1] is primarily used for pointing instead of rotation [46].

Freely handheld devices with a fully spherical shape are rarely found. However, a recent example of a spherical game controller[1] aims at addressing users with disabilities. The capability to select virtual objects was demonstrated by Stoakley et al. [43] as they used a handheld sphere as a *Buttonball*. Generally, these concepts go back to the work of Hinckley et al. [25] that demonstrated positive effects of a handheld sphere on the usability of rotational tasks.

2.3 Spherical Devices as Locomotion Interfaces in VR

Since freely handheld spherical devices are so rarely used in VR, we include a discussion of locomotion interfaces in general, that in some way, utilize a physical sphere. Bozgeyikli et al. [7] have evaluated the use of a stationary trackball device for locomotion in VR for users with autism disorder. Results indicate that the trackball device could compete with a range of other methods. Schuemie et al. [40] used trackballs in VR therapy, which further documents that these devices can perform en par with other controller-based methods when placed in a stationary way. An early example of a spherical device used for VR locomotion is the patent of Beckman [2] that outlined the application of two spherical controllers for 6-DOF flight control. Another interesting approach is the *VirtuSphere* [35], a locomotion interface resembling a human-size hamster ball. Nabiyouni et al. [37] showed that the device was easily outperformed by a gamepad or a real walking technique and the findings of Skopp et al. [41] confirm this. Yet, their idea of mapping the rotation of a sphere to virtual locomotion is strongly related, although our approach relies on using hands rather than legs.

2.4 VR Locomotion by Hands

In this field, especially two areas are relevant for our work – continuous methods relying on indirect locomotion and hand gesture-based techniques. Indirect or artificial movement describes the concept of locomotion by using an input device [12]. Hand gestures are related because our technique automatically causes users to constantly perform physical gestures that imply locomotion, such as a finger-walking technique, introduced by Kim et al. [30]. As described by Frommel et al. [23] indirect locomotion is widely applied in VR applications and has been found to generate higher scores in enjoyment, presence and affective state but also leads to greater discomfort than non-continuous techniques. As stated by Wilson et al. [48] the mere imitation of walking gestures, for example, arm swinging or flapping [21] is inferior to more natural approaches [47] and even in some cases to controller-based strategies [9]. Cardoso et al. [11] confirm these findings by reporting on a hand gesture-based technique being outperformed by a controller. However, a comparison of two gesture-based methods for teleporting and joystick-based locomotion conducted by Coomer et al. [14] indicated superiority of gesture-based methods.

2.5 Implications from Related Work

The advantages of continuous locomotion in combination with the fact that the natural shape of a sphere elicits gestures associated with locomotion while simultaneously providing precise tangible feedback, make locomotion using a sphere a compelling use case. The fact that physical spheres also improve the perception of contained 3D visualizations suggests the idea of a sphere aligned with a visualization for navigation such as a *World In Miniature* (WIM) [43].

3 A Spherical Controller For VR Locomotion

Below, we will briefly describe how we built the handheld spherical VR controller from low-cost off-the-shelf hardware. Then we describe the theoretical foundation and design decisions regarding the two different locomotion paradigms (*Position Control* and *Velocity Control*) that we implemented for the device.

[1] https://bit.ly/2S7c6bT

3.1 Device Construction

The spherical device we had in mind had to meet two requirements: It had to provide fast and precise tracking and an orientation-independent, perfectly spherical shape to enable unhindered rotation in all directions.

Both can be achieved by simply placing a Vive Tracker[2] in a sphere made from infrared-transparent material such as acrylic glass [10, 17, 19]. To center the tracking device in the sphere we use a 1/4 inch threaded rod that is mounted to a threaded socket with a screw from the outside of the lower half as illustrated in Figure 2. The Vive Tracker is fitted with a matching thread at the bottom and can therefore simply be screwed to the top of the rod. To stably center the tracker, we insert a three-arm stabilizer piece just below the tracker that is held in place by the tracker pushing down on it. Once assembled, the input device is self-contained, perfectly round, relatively well balanced, and weighs about 190g in total. In comparison it is slightly heavier than Oculus Touch (150g) and lighter than a Vive Controller (309g).

3.1.1 Design Decisions

Our design is a trade-off between the factors of overall weight, tracking performance, and balance. We decided against the solution of placing two trackers [10] inside the device since this would have nearly doubled the weight of the sphere. Since the tracker is the heaviest part, in order to balance the construction, we aligned its center of gravity with the center of the sphere. We also found that the device would not properly perform without vertical and horizontal stabilization. This mainly happened when the device was fiercely rotated, which resulted in unintentional vibration of the tracker. We, therefore, applied the described stabilization measures, to prevent a negative impact on the tracking quality.

3.1.2 Limitations

Since our device is designed for easy reproduction using commercial hardware components we could not achieve a completely balanced sphere. To achieve perfect balance the tracking device would have to be spherical or the sensors would have to be mounted to the sphere itself. Also since the optical tracking requires an unobstructed line of sight we found that a sphere with a smaller diameter would greatly increase the risk of the sensors being covered by the users' hands. Lastly, the usage time of the device is limited by the Vive Tracker that allows for four hours of continuous use.

3.2 Locomotion Paradigms

Although an avatar can, in principle, move in 6 DOF in a VE, this only makes sense in specific scenarios, such as space flight. Locomotion in most VEs is more restricted and borrows from our experience of walking or driving in the physical world. Typical locomotion techniques map the four directions forward, backward, left, and right to controller-based input. Tracked controllers additionally allow movement in these directions relative to the orientation of the device. This method is well established, allows for subtle as well as distinguished adjustments of the movement direction and locomotion independent from the viewing direction of the HMD.

We identified two alternative paradigms for defining locomotion using a spherical device. The first borrows from the concept of a sphere that moves by rolling on the floor. The user has to perform a constant rotational motion. The second approach is borrowed from joystick interaction: Locomotion is triggered when the sphere is tilted in the desired direction and performed automatically until the controller is tilted back to its original position. Consequently, the first approach can be described as a *Position Control* technique that results in a direct translation of the input while the second method allows for changing the velocity of an automatically executed motion by manipulating the inclination angle (*Velocity Control*) of the device. According to the control theory defined by Jagacinski et al. [26], the first method can be classified as a zero order system and the tilt-based concept as a first order system.

[2] `https://www.vive.com/us/vive-tracker/`

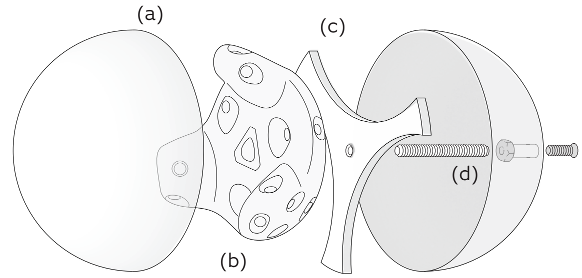

Figure 2: The spherical controller is constructed from a two-piece acrylic glass sphere with a diameter of 12 cm (a) that encloses a Vive Tracker (b). A stabilization piece (c) centers and stabilizes a 1/4 inch threaded rod that is screwed to the sphere from the outside (d).

3.2.1 Position Control

After a first implementation of the *Position Control* input paradigm, we discovered a dilemma: The direct mapping of the rotation allowed a very accurate control when the sphere was rotated slowly. However, a faster rotation into what was perceived as one clear direction would result in unintended secondary motion in other directions due to the imprecision of fast manipulation. As we did not want to sacrifice the intuitive, seamless adjustment of velocity, we decided to simultaneously support the direct mapping and the quick movement in one discrete direction. A simple detection algorithm based on previously executed rotations and rotational speed can recognize a fast movement and restrict it to the primary direction, as if putting the sphere on rails.

After careful testing during the pilot study we determined the average rotation speed for movement at running speed (10 m/s) at about 172.8 °/s, and for walking speed (5 m/s) at about 84.8 °/s. We translated rotation speeds to the desired locomotion speed by multiplying with a simple constant. We did not apply restrictions regarding movement speed, which is therefore limited only by the speed at which the user can turn the physical device.

Once the limit for walking speed is exceeded, we lock the direction to the one in which the user was moving within a time frame of 0.25 seconds prior to exceeding the threshold. With this simple auxiliary function, we could provide a relatively steady motion when moving at running speed while allowing completely unrestricted and precise movement at lower speeds. The transition between free and locked movement can barely be noticed because faster rotation is generally perceived as a motion in one of the four main directions. The facts that the sphere has to be physically slowed down to change rotation direction and the dependency of the movement direction from the orientation of the device supports a smooth transition between both states.

3.2.2 Velocity Control

With the *Velocity Control* paradigm we found a similar issue as with *Position Control*. When the locomotion used the exact direction in which the sphere was tilted, this often did not correspond with the user's intended movement direction, which usually coincided with the four basic directions. We, therefore, decided to limit the possible movement directions to those four and left subtle adjustments to the orientation of the device relative to the HMD position. We also did not limit the maximum movement speed which increases linearly with the inclination angle of the device. As a consequence, fast locomotion speed can easily be achieved by rotating the device several times into the desired direction.

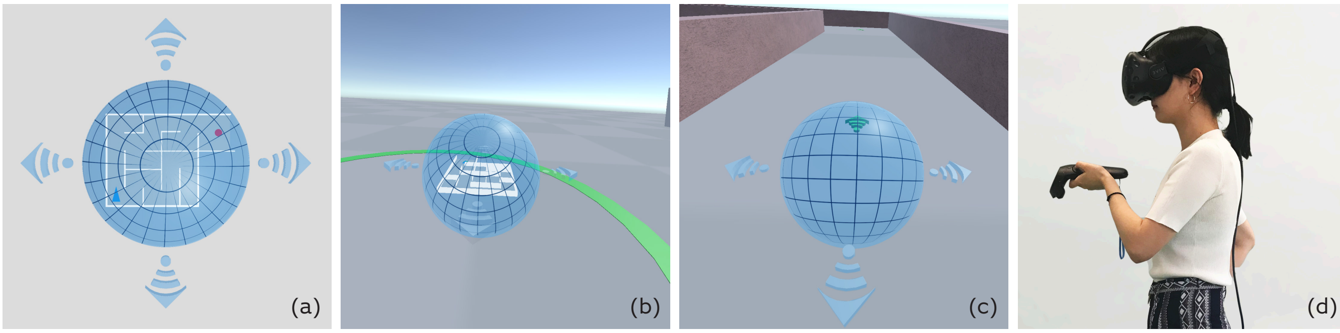

Figure 3: To realize the visual concept of following a rolling sphere we provided a rotating grid, directional arrows and a WIM (Task 3) as navigation aid (a). After each trial, users had to place their avatar as precisely as possible in the center of a circle (b). For the second task users had to follow a narrow path (c) while avoiding collisions with the walls. Comparison methods were based on a handheld controller equipped with a touchpad (d).

Rotation in the opposite direction resulted in a decrease of speed and eventually, a complete stop. Similarly to the rotation technique, we analyzed numerous trials of test users and found common ground at an average inclination angle of about 45°. This may, in comparison to previous research [39] appear as a rather large value but is a result of the test users consistently performing quite large and clearly defined rotations showing the intent to start or stop moving. Therefore, at this angle, movement is initiated with walking speed while further rotation in the same direction linearly increases the locomotion speed.

Control theory tells us that first order controllers should provide a clear zero point to which they can return to stop motion [32]. Since the sphere did not provide such a clear zero position, movement could not be easily stopped. We, therefore, implemented a detection of rapid opposite rotation (exceeding 172.8 °/s), which regardless of the current rotation angle would reset the system to zero. This enabled abrupt stopping, which improves precision for hitting a target. In this technique, frequent changes of direction result in a rocking motion (hence the title).

4 Experiment

In order to evaluate our design and to learn about the performance of our approach, we conducted a user study comparing the two locomotion paradigms for the spherical controller to related strategies using VR controllers.

4.1 Study Design

The study was designed as a single-factor within-subjects experiment, in which each subject used four different input techniques to complete a total of six tasks per technique (three different navigation tasks, twice each). The four conditions were presented in (incompletely) counterbalanced order using a balanced Latin Square and two permutations of its rows that were repeated five times per task to prevent unwanted learning or fatigue effects. Including two follow-up questionnaires, the study took about one hour, and the subjects were granted a break between tasks to recover from possible cybersickness. To investigate the learnability of the methods, we did not supply any usage instructions apart from the hint that a new technique was used whenever a new condition started.

4.2 Apparatus

The construction of the prototype for our study was described in the previous section. Below, we will provide more detail of the hardware we used and give a description of how we implemented the software and what design decisions and observations shaped the implementation. According to the previously defined paradigms we describe details of the implementation of both locomotion strategies.

4.2.1 Hardware

As a VR display, we used an HTC Vive HMD[3] with a 110° field of view, a screen refresh rate of 90 Hz and a latency of about 20 ms. Its built-in tracking system provides an accuracy of 0.5 mm in a room-scale environment [38]. For the two sphere-based techniques we used a spherical controller as described above. The tracking system provided a low latency experience while tracking errors due to obstruction of the sphere were hardly noticeable. The existing locomotion techniques, which formed our control conditions, use the Vive Controller[4] and in particular its touchpad. In all implementations, locomotion was constrained to movement on the ground, and the user's perspective was limited to the first person view. We provided a visual representation of the currently used controller but no tracking of the hands.

4.2.2 Software

In order to create the VE for our study, we used the Unity Engine[5] and C# as a programming language to realize the three navigation tasks. For detecting the relative rotation direction of the spherical object, we calculated the difference between its absolute rotations in a quaternion representation for subsequent frames. To make the sphere rotate visually and to match the intended metaphor of a rolling sphere we added a grid (as seen in Figure 3) to the surface and four directional arrows that indicate the current moving direction and also help to illustrate that the direction in which the device is pointing influences this direction. While moving, a user can always adjust the movement path by pointing the device in the desired direction. For example, while moving forward on a straight line, the movement direction can additionally be adjusted if the handheld device is shifted to left or to the right. In general, the visual concept also can be seen as a third-person camera observing the virtual sphere that appears during rotation to roll on the floor, but without actually touching the ground.

4.2.3 Pilot Study

For a preliminary lab study, we recruited ten test users and logged their usage of the spherical device while performing both related locomotion strategies. Users were asked to rotate the device to start and stop movement under the *Velocity Control* paradigm or to imagine to move at normal pace or at running speed under the *Position Control* paradigm while rotating the sphere. We logged the resulting rotational angles and speeds in order to determine the parameters for the implementation. For the four parameters, each user had to repeat ten trials.

[3] https://www.vive.com/
[4] https://www.vive.com/us/accessory/controller/
[5] https://unity.com/

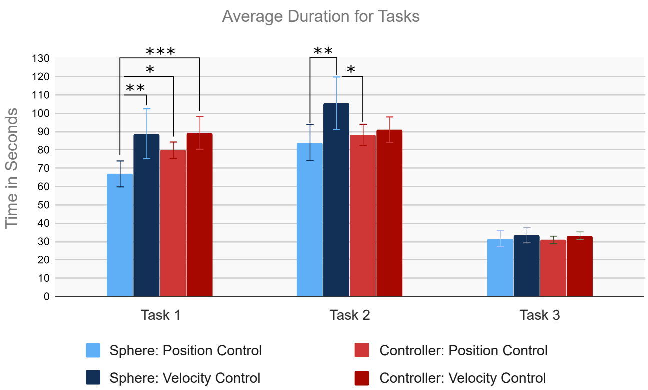

Figure 4: Task duration for the four conditions. Values are given in seconds with 95% confidence intervals.

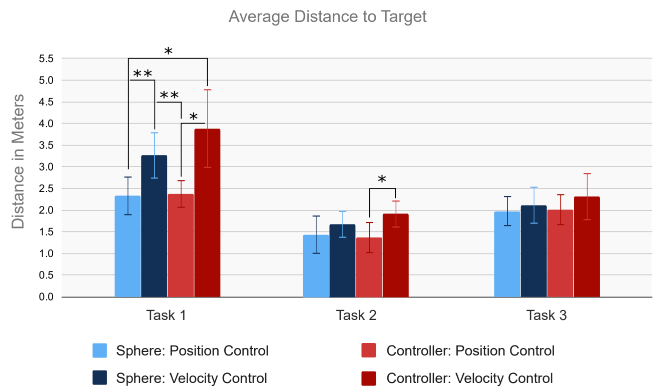

Figure 5: Accuracy for navigating to the center of a target for the four conditions. Values are given in meters with 95% confidence intervals.

4.3 Experimental Conditions

For each condition relying on the spherical controller we chose a related technique using VR controllers that resembled the main characteristic of the corresponding sphere strategy. Since both sphere-based approaches rely on the four main directions, the well-established controller technique of pointing the controller to one direction and using the touchpad to change direction accordingly represents a *Position Control* technique. We mirrored the automatic movement inflicted by sphere's *Velocity Control* method by implementing constant locomotion initiated by a directional click on the touchpad. We regard this design as closer related to second sphere-based technique than a joystick-based approach that would automatically return to its neutral state upon release. As a positive side effect we also did not need to introduce an additional piece of hardware to the setup. Due to our focus on continuous locomotion techniques that appear as the appropriate choice to compare to our intended concept of a metaphorical rolling ball, we did not draw a comparison to discrete locomotion approaches.

While the first controller-based method is widely applied [23] the latter is more uncommon but matches the sphere's velocity rate control technique. For all conditions, we used the regular walking and running speed of $5\,\mathrm{m/s}$ and $10\,\mathrm{m/s}$ defined by Unity's first-person controller. We added a threshold to ignore rotations below $0.25°$ to prevent small unintended movement. In conjunction, while the device is not rotating, a detection of a larger change in the sphere's position ($> 2\,\mathrm{cm}$ per frame) allows for re-positioning the device without accidentally moving the avatar.

4.3.1 Sphere: Position Control (SPC)

The first sphere condition implements the guidelines set out in Section 3.2.1. To guarantee responsive and fluent locomotion we compute any position change caused by rotating the device on a per-frame basis.

4.3.2 Sphere: Velocity Control (SVC)

The second sphere condition implements the guidelines set out in Section 3.2.2. As with the previous condition, interaction (adjustment of the velocity rate) is implemented in real-time.

4.3.3 Controller: Position Control (CPC)

Similar to *Sphere: Position Control* the first controller-based method requires continuous input. As it is widely used in VR application, we implemented this by means of touchpad input. To adjust the speed we scaled it linearly from running to walking speed according to the users' finger position: a constant button press near the outside of the pad results in full running speed ($10\,\mathrm{m/s}$) while sliding a finger to the center reduces the speed up to a minimum of $5\,\mathrm{m/s}$ (walking speed). Releasing the touchpad then triggers an immediate stop. To prevent unintentional movement when the center of the touchpad was pressed we added a small dead zone with a radius of 0.5 cm.

4.3.4 Controller: Velocity Control (CVC)

To complement the automatic movement induced by the sphere's *Velocity Control* technique, we realized a controller-based implementation requiring discrete input (clicking the touchpad) to start as well as to stop moving. In accordance with the previous VR controller method, locomotion speed could be regulated by swiping on the touchpad (against the direction of travel). Therefore, a click on the outermost point of the touchpad results in full running speed ($10\,\mathrm{m/s}$) while a click at the center was again ignored using the same dead zone as in the previous condition.

4.4 Participants

We recruited 20 participants, 10 of which self-identified as male and 10 as female with an average age of 25.5 years. They rated their VR experience on average at 2.8 (on a scale from 1 = none to 5 = expert) and their experience with first-person locomotion in general at 3.25 (on the same scale). None of the subjects had prior experience with the spherical device.

4.5 Tasks

We presented a total of three locomotion tasks with different goals in mind. The tasks were executed in ascending order of difficulty. Before starting a new task we asked participants to read and confirm a short task instruction. In terms of visual representation, we chose a minimalist VE to avoid visual distractions. While the main focus of all tasks was to observe completion time and accuracy of movement, we decided for situations that should also resemble scenarios that are likely to occur in exploratory VR applications, such as: quickly moving from one point to another, following a defined path, or building a mental concept of a VE using a WIM.

4.5.1 Straight Line

The first task also served as a training task, and therefore, the time users needed to get comfortable with the locomotion techniques is included in the measurement. To complete the assignment, subjects needed to acquire a sequence of four targets, located in a distance of 100 m in a straight line from the starting position. After reaching the circular target (indicated by a large arrow), participants had to move to the center of the target (Figure 3 b) as precisely as possible within five seconds and were subsequently reset to the starting position.

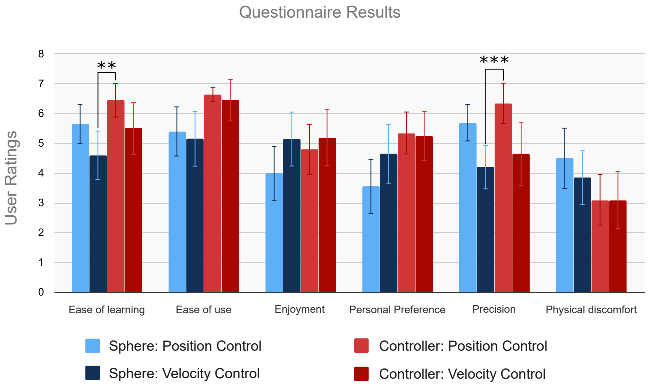

Figure 6: Users' perception ratings with 95% confidence intervals. Apart from physical discomfort a higher rating marks a better result.

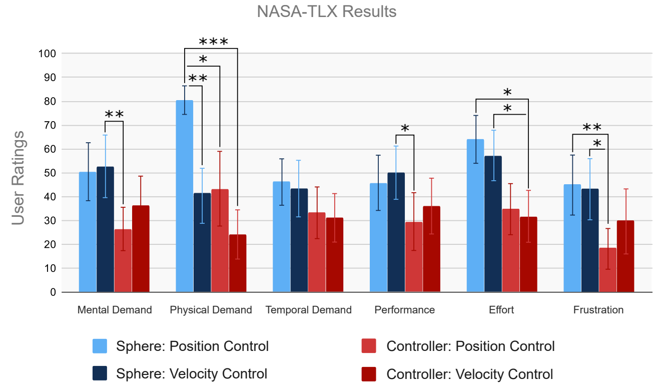

Figure 7: Average values for users' NASA-TLX ratings with 95% confidence intervals. Higher ratings represent a worse result.

4.5.2 Path

In the second task, participants had to follow a narrow path indicated by low walls (Figure 3 c). The description stated that users had to avoid contact with the walls but at the same time should place themselves in the center of a circular target (located at the end of the path) as fast as possible. To avoid a visual learning effect, we presented mirrored and/or rotated variants of the same path. The complete course had a total length of about 800 m.

4.5.3 Maze

For the last task, users had to find their way out of a simple maze (Fig. 3 a). They were supported by a WIM [43] that was attached to or enclosed by the virtual representation of the controller. The WIM showed the avatar as a blue arrow and the target as a red dot. Again, to counter learning effects, we presented a succession of mirrored and/or rotated versions of the same maze.

5 Results

We present quantitative data on task performance and accuracy as well as results from two post-experiment questionnaires followed by qualitative insights we gathered during the study.

5.1 Quantitative Results

For all three tasks, we measured completion time. The first task (Straight Line) took participants about 60-90 seconds, while the second (Path) took about 80-110 seconds. The maze took less time, and users finished it in about 30 seconds. As a measure of accuracy, we recorded how precisely users managed to acquire a target presented at the end of each task, as well as the average deviation from an ideal line for tasks one and two. For the second task, we also counted collisions with walls. In addition to these measurements, we present results from a self-designed questionnaire (7 point Likert scale) and a NASA-TLX survey. In favor of a broader investigation, we decided not to run a specific questionnaire on simulator sickness, but tried to cover this topic within our own questionnaire.

5.1.1 Task Completion Time

Fig. 4 gives an overview of task completion times for the four conditions. We ran a repeated measures ANOVA with multivariate tests (Pillai's trace and Wilk's lambda) that consistently revealed statistical significance for the four input conditions for the first and second task: $F(3,17) = 26.95$, $p < \mathbf{0.001}$ and $F(3,17) = 7,32$, $p = \mathbf{0.002}$. Then, we completed pairwise t-tests with Bonferroni-correction. Comparing the sphere to controller conditions revealed a significant difference between *SPC* and all other conditions: $p = \mathbf{0.004}$ (*SVC*), $p = \mathbf{0.03}$ (*CPC*) and $p < \mathbf{0.001}$ (*CVC*). This indicates a significantly faster task completion for *SPC* in Task 1. For the second task pairwise comparisons revealed significant differences between *SPC* and *SVC* with $p = \mathbf{0.002}$ as well as between *SVC* and *CPC* with $p = \mathbf{0.045}$. Again, *SPC* induced significantly lower completion times than *SVC* which itself was significantly slower than *CPC*. For the results of the third task we discovered no significant differences: $F(3,17) = 2,07$, $p = 0.143$ demonstrating that the sphere-based controller performed roughly on par with the VR controller.

5.1.2 Accuracy

In order to evaluate the accuracy with which the subjects acquired the target we used the same procedure as for task duration. Again, the repeated measures ANOVA with multivariate evaluation (Pillai's trace and Wilk's lambda) revealed significant differences for the first task $F(3,17) = 7.14$, $p = \mathbf{0.003}$. As for task time we consider the differences involving the sphere conditions. A significant difference was found between *SPC* and *SVC*: $p = \mathbf{0.005}$ and *SPC* and *CVC* with $p = \mathbf{0.013}$. This indicates advantages in accuracy for *SPC* while again the measures for condition *SVC* were surpassed by those for the condition *CPC* with $p = \mathbf{0.008}$. Regarding sphere-based input, the analysis revealed no significance for the second and third task $F(3,17) = 2.67$, $p = 0.08$ and $F(3,17) = 0.59$, $p = 0.63$. This confirms the assumption that for target acquisition the sphere-based approaches would keep up with the results of the VR controller conditions. Fig. 5 gives a complete overview of average precision and significant differences. The higher average values for the first task result from the succession of four targets that users had to acquire in one trial while in the other tasks, only one target had to be reached.

The analysis of collisions resulted in general statistical significance for the controller conditions: $F(3,17) = 8.12$, $p = \mathbf{0.001}$. This was a result of the condition *SPC* causing clearly more collisions than all other conditions: $p = \mathbf{0.002}$ (*SVC*), $p < \mathbf{0.001}$ (*CPC*) and $p = \mathbf{0.001}$ (*CVC*). These findings are also supported by the observation that users of sphere-based techniques could not follow a path or a line as precisely as with the controller strategies.

As demonstrated by the exemplary walking patterns in Fig. 8 *SPC* achieved a higher precision for specific line segments than *SVC* regarding mean values. In terms of individually deviating patterns and average deviation in general (euclidean distance to ideal line) the sphere-based techniques generated a higher average deviation in comparison. However an analysis of the complete walking patterns for the first and second task did not reveal significant deviation for the conditions: $F(3,17) = 2.58$, $p = 0.087$ and $F(3,17) = 2.03$, $p = 0.147$.

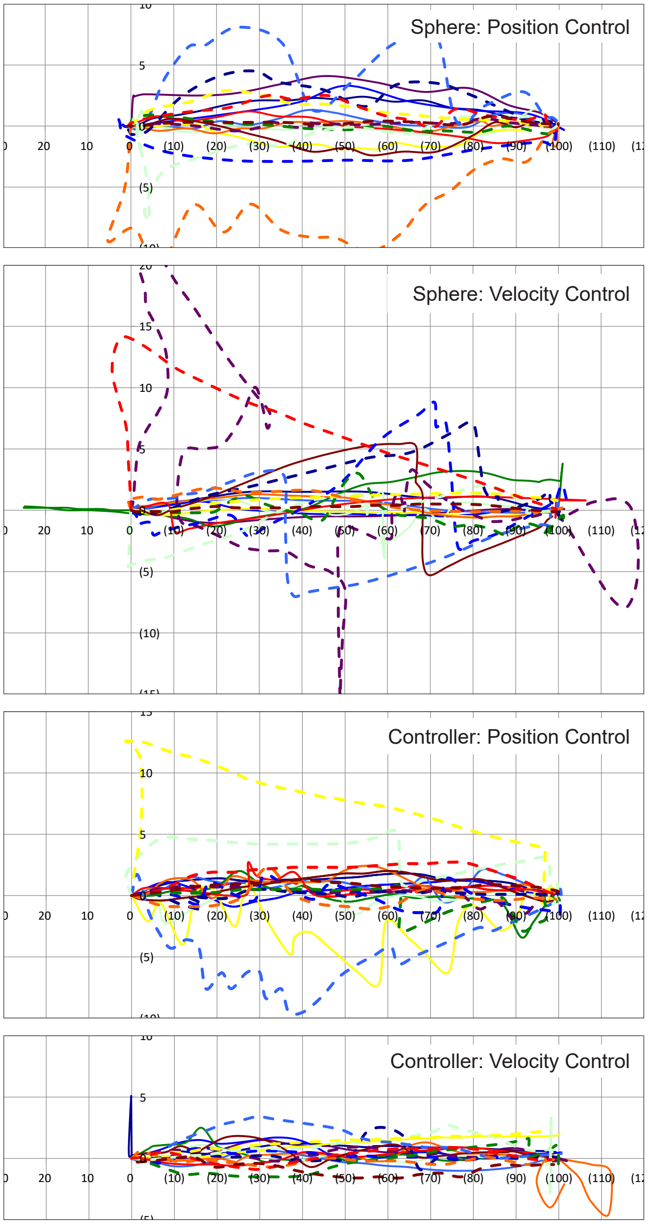

Figure 8: Visualization of locomotion patterns extracted from the straight line task for all four conditions. Units are given in meters. The start point is located at (0,0) the target at (100,0). Each color represents one user's moving pattern.

5.1.3 Questionnaire Results

To analyze our device subjectively participants were asked to answer a post-experiment questionnaire. Fig. 6 gives an overview of the results. We completed a Friedman test on the given ratings. We discovered no significant influence of the conditions for questions regarding enjoyment ($\chi^2(3) = 3.52$, $p = 0.329$) and personal preference ($\chi^2(3) = 7.34$, $p = 0.062$). For ease of learning ($\chi^2(3) = 15.46$, $p = \mathbf{0.001}$), ease of usage ($\chi^2(3) = 16.71$, $p = \mathbf{0.001}$), precision ($\chi^2(3) = 20.75$, $p < \mathbf{0.001}$) and discomfort ($\chi^2(3) = 10.42$, $p = \mathbf{0.015}$) we found a statistically significant influence. Subsequently, we ran Dunn-Bonferroni post-hoc tests for pairwise comparisons. Subjects felt that *SVC* was significantly harder to learn than *CPC*: $z = 3.55$, $p = \mathbf{0.002}$. While the controller conditions were perceived as easier to use according to mean values, the post-hoc test revealed no pairwise significances. *CPC* was regarded significantly more precise than *SVC*: $z = 4.04$, $p < \mathbf{0.001}$. Although the mean values for discomfort indicate advantages for the controller methods, the post-hoc test found no significances for pairwise comparisons.

5.1.4 NASA-TLX

As illustrated, in Fig. 7 subjects completed a NASA-TLX questionnaire for each locomotion technique to provide subjective insights about the mental and physical demands. A Friedmann test followed by the Dunn-Bonferroni post-hoc test uncovered significant differences between conditions for each question. For mental demand ($\chi^2(3) = 16.46$, $p = \mathbf{0.001}$) *SVC* received significantly higher scores than *CPC*: $z = -3.73$ $p = \mathbf{0.001}$. In the case of physical demand ($\chi^2(3) = 29.70$, $p < \mathbf{0.001}$), *SPC* was rated significantly higher than the three other conditions: *SVC* with $z = -3.30$, $p = \mathbf{0.006}$, *CPC* with $z = -2.75$, $p = \mathbf{0.035}$ and *CVC* with $z = -5,20$, $p < \mathbf{0.001}$. For temporal demand the condition was significant ($\chi^2(3) = 7.89$, $p = \mathbf{0.048}$) but the post-hoc test did not reveal abnormalities. However, in the case of performance ($\chi^2(3) = 10.7$, $p = \mathbf{0.013}$) we found significant differences between *SVC* and *CPC*: $z = -2.75$, $p = \mathbf{0.035}$, indicating inferior subjective performance for the methods utilizing the handheld sphere. The same picture showed for effort ($\chi^2(3) = 14.12$, $p = \mathbf{0.003}$) and frustration ($\chi^2(3) = 13.8$, $p = \mathbf{0.003}$). Regarding effort *CVC* was rated significantly lower than both sphere-based conditions: $z = -2.81$, $p = \mathbf{0.024}$ and $z = -2.87$, $p = \mathbf{0.029}$. For frustration we discovered a similar pattern. Again, both sphere-based conditions were rated higher, this time with a significant difference to *CPC* with $z = -2.75$, $p = \mathbf{0.035}$ and $z = -3.18$ $p = \mathbf{0.009}$.

5.2 Qualitative Results

With comments during the study or in the remarks section of the questionnaire, users stated that *SPC* required greater effort but, in general, was more natural to use than *SVC*. Suggestions and comments, in general, indicated that users preferred the controller-based methods, although interaction with the sphere seemed to provide a certain entertainment factor.

We found no remarkable difference in rotation strategies between the majority of participants. They all rotated the sphere using two hands; only one participant tried to switch to one-handed rotation, which did not work well for *SPC* but was occasionally used for *SVC*, once the movement speed was set.

In terms of learnability, all participants figured out how to use both sphere-based techniques within the first few trials of the first task. We observed a slight advantage for *SPC* regarding quick understanding. We could not attribute comments revolving around cybersickness to either sphere- or controller-based methods. The tasks, in general, appeared to be somewhat susceptible to this phenomenon due to the disparity of real and perceived locomotion.

Additionally, we could clearly observe a positive reception of the higher physical involvement that the condition *SPC* elicited. Although in the perspective of long term use, such greater physical demand may be seen as a negative effect, some users stated a greater feeling of presence within the virtual scene due to constant physical involvement and respective tangible feedback.

5.3 Results Summary

We did not expect the spherical controller to be able to keep up with the established controller-based techniques. This hypothesis was widely affirmed but, surprisingly, *SPC* could outperform the VR controllers in measures regarding task completion time and accuracy in terms of target acquisition. The observation that this strategy could compete with the compared methods for these measures in general was as unexpected as the general ability of the sphere-based techniques to follow a path without significant deviation. When comparing the two sphere-based strategies *SVC* was inferior for the most part but managed to score significantly fewer collisions in the path task. Questionnaire results and qualitative evaluation showed users' preference for the VR controllers. For the concept of the fully contained WIM we could neither find advantages nor disadvantages.

6 Discussion and Future Work

To our own surprise, we found that *Sphere: Position Control* could keep up with controller-based methods in terms of task completion time. This finding can not only be attributed to higher possible movement speeds since with *Sphere: Velocity Control*, high movement speeds could be achieved more easily, yet, no similar effect could be observed.

Since we almost exclusively found beneficial effects of the spherical controller for the *Sphere: Position Control* paradigm, the control of velocity rate can clearly be seen as inferior. The seamless adjustment of movement speed by tilting the sphere did not provide any advantages for our tasks and also the potentially infinite velocity had no positive influence on task times. The zero order system, without doubt, represents the better concept for our handheld spherical controller.

However, both concepts could be extended by adding functionality to the rotation around the central axis (up) that can be implemented independently. This was not needed for locomotion, but it is evident that the controller, in general, could support a variety of additional interaction techniques such as selection or gesture-based input or quick reorientation by rotating the camera around the up-axis. The fact that the device needs both hands to be operated certainly limits its current usability. Yet, developments in hand pose estimation enabling multi-touch support could mitigate this limitation opening up additional interaction techniques or new application fields such as mobile VR. Such advances could allow for greater hardware independence, in our case, from the Vive Tracking system. Exploring multi-touch input on a handheld spherical device in conjunction with locomotion or specialized use cases such as ball-rolling games could provide an exciting opportunity for future work as well as an extension allowing for 3D object manipulation. Our implementation could allow for moving objects from a distance while this was not supported in previous work [17].

Accuracy results can be interpreted in two ways: On the one hand, the seamless transition, and direct feedback of constantly rotating a sphere supported target acquisition significantly. On the other hand, the less steady movement had adverse effects on the collision with walls while consistency in path tracing was also given for the spherical device. Combined with the findings regarding task completion time, this indicates that the current implementation does perform well when a user does not need to follow an exact path without collision but instead needs to acquire a precise position in a possibly less restrictive VE. This is not surprising given our stabilization tweaks in the software.

The fact that subjects with mediocre VR experience partially outperformed familiar VR-controllers with a completely unknown, unexplained device is interesting in its own right. We can deduce, that the concept of a spherical controller is almost intuitively understood, in particular, when considering the zero order system. This makes the controller not only an exciting alternative for novice users or applications in public spaces but the interesting fact that people with autism spectrum disorder are naturally drawn to spinning objects [7] may hint at other interesting future use cases and potential exploration of the performance of novice users not having any experience in virtual locomotion.

Another interesting observation was the overall positively received higher physical involvement that users consistently reported especially for the first sphere condition. These reports coincide with observations of tangible feedback enhancing the feeling of embodiment and self-location within a VE [29]. While this was somewhat expected for a tangible device, a future exploration could clarify to what extent this effect can be attributed to the shape or the general interaction paradigm of locomotion by rotating a handheld object.

In the case of the enclosed WIM, we can only find the advantage of less used screen space (in comparison to the controller attachment). However, the concept of a fully enclosed visualization associated with the locomotion process also seems to provide an interesting topic for future research.

Lastly, the subjective ratings of participants clearly show that the handheld spherical device is not yet on par with controller-based input but possible extensions could help to close this gap. Especially in terms of path precision and collision avoidance, a perfect balance in weight, as well as a more sophisticated detection of the intended movement direction, could help to remedy existing deficiencies.

7 Summary and Implications

We have demonstrated how the rotation of a handheld spherical object can be translated to first-person locomotion in VR. Our prototype implementation exclusively relies on low-cost, commercially available hardware. It is not entirely clear, to what degree the observed positive effects in task time and accuracy can be attributed to the novel type of tangible feedback created by the handheld, rotating sphere. However, the opportunities provided by a zero order input system resting in the user's hands and the apparent advantages in learnability and physical involvement in combination with the flexibility of VR invite further investigations of the outlined prototype.

The ease with which our subjects understood the device and its operation promises benefits for novice users, but could also indicate future use cases with children or, in general for users who have to rely on natural, uncomplicated interaction concepts. As we have tried to demonstrate, such an interaction concept is especially compelling if it can be transferred effortlessly from the real to the virtual world by a simple metaphor such as a rolling ball.

References

[1] P. Baudisch, M. Sinclair, and A. Wilson. Soap: a pointing device that works in mid-air. In *Proceedings of the 19th annual ACM symposium on User interface software and technology*, pp. 43–46. ACM, 2006.

[2] B. C. Beckman. Virtual reality flight control display with six-degree-of-freedom controller and spherical orientation overlay, Feb. 14 1995. US Patent 5,388,990.

[3] H. Benko, A. D. Wilson, and R. Balakrishnan. Sphere: multi-touch interactions on a spherical display. In *Proceedings of the 21st annual ACM symposium on User interface software and technology*, pp. 77–86. ACM, 2008.

[4] F. Berard and T. Louis. The object inside: Assessing 3d examination with a spherical handheld perspective-corrected display. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 4396–4404. ACM, 2017.

[5] C. Boletsis. The new era of virtual reality locomotion: a systematic literature review of techniques and a proposed typology. *Multimodal Technologies and Interaction*, 1(4):24, 2017.

[6] D. A. Bowman, D. Koller, and L. F. Hodges. Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality*, pp. 45–52. IEEE, 1997.

[7] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey. Locomotion in virtual reality for individuals with autism spectrum disorder. In *Proceedings of the 2016 Symposium on Spatial User Interaction*, pp. 33–42. ACM, 2016.

[8] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey. Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*, pp. 205–216. ACM, 2016.

[9] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey. Locomotion in virtual reality for room scale tracked areas. *International Journal of Human-Computer Studies*, 122:38–49, 2019.

[10] L. Bozgeyikli and E. Bozgeyikli. Tangiball: Dynamic embodied tangible interaction with a ball in virtual reality. In *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion*, pp. 135–140. ACM, 2019.

[11] J. Cardoso. Comparison of gesture, gamepad, and gaze-based locomotion for vr worlds. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, pp. 319–320. ACM, 2016.

[12] W. Cockayne and R. Darken. The application of human ability requirements to virtual environment interface design and evaluation. *The handbook of task analysis for human-computer interaction*, pp. 401–421, 2004.

[13] R. Companje, N. van Dijk, H. Hogenbirk, and D. Mast. Globe4d: time-traveling with an interactive four-dimensional globe. In *Proceedings of the 14th ACM international conference on Multimedia*, pp. 959–960. ACM, 2006.

[14] N. Coomer, S. Bullard, W. Clinton, and B. Williams-Sanders. Evaluating the effects of four vr locomotion methods: joystick, arm-cycling, point-tugging, and teleporting. In *Proceedings of the 15th ACM Symposium on Applied Perception*, p. 7. ACM, 2018.

[15] S. Davis, K. Nesbitt, and E. Nalivaiko. A systematic review of cybersickness. In *Proceedings of the 2014 Conference on Interactive Entertainment*, pp. 1–9. ACM, 2014.

[16] T. L. Dellinger. Hand-held trackball computer pointing device, Nov. 9 2004. US Patent 6,816,151.

[17] D. Englmeier, J. Dörner, A. Butz, and T. Höllerer. A tangible spherical proxy for object manipulation in augmented reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2020.

[18] D. Englmeier, I. Schönewald, A. Butz, and T. Höllerer. Feel the globe: Enhancing the perception of immersive spherical visualizations with tangible proxies. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1693–1698, March 2019.

[19] D. Englmeier, I. Schönewald, A. Butz, and T. Höllerer. Sphere in hand: Exploring tangible interaction with immersive spherical visualizations. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 912–913, March 2019.

[20] A. S. Fernandes and S. K. Feiner. Combating vr sickness through subtle dynamic field-of-view modification. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 201–210. IEEE, 2016.

[21] A. Ferracani, D. Pezzatini, J. Bianchini, G. Biscini, and A. Del Bimbo. Locomotion by natural gestures for immersive virtual environments. In *Proceedings of the 1st international workshop on multimedia alternate realities*, pp. 21–24. ACM, 2016.

[22] B. Froehlich, J. Hochstrate, V. Skuk, and A. Huckauf. The globefish and the globemouse: two new six degree of freedom input devices for graphics applications. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*, pp. 191–199. ACM, 2006.

[23] J. Frommel, S. Sonntag, and M. Weber. Effects of controller-based locomotion on player experience in a virtual reality exploration game. In *Proceedings of the 12th international conference on the foundations of digital games*, p. 30. ACM, 2017.

[24] M. Hancock, O. Hilliges, C. Collins, D. Baur, and S. Carpendale. Exploring tangible and direct touch interfaces for manipulating 2d and 3d information on a digital table. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, pp. 77–84. ACM, 2009.

[25] K. Hinckley, J. Tullio, R. Pausch, D. Proffitt, and N. Kassell. Usability analysis of 3d rotation techniques. In *Proceedings of the 10th annual ACM symposium on User interface software and technology*, pp. 1–10, 1997.

[26] R. J. Jagacinski and J. M. Flach. *Control theory for humans: Quantitative approaches to modeling performance*. CRC Press, 2003.

[27] L. Karlqvist, E. Bernmark, L. Ekenvall, M. Hagberg, A. Isaksson, and T. Rostö. Computer mouse and track-ball operation:: Similarities and differences in posture, muscular load and perceived exertion. *International Journal of Industrial Ergonomics*, 23(3):157–169, 1999.

[28] S. Kettner, C. Madden, and R. Ziegler. Direct rotational interaction with a spherical projection. In *Creativity & Cognition Symposium on Interaction: Systems, Practice and Theory*, 2004.

[29] K. Kilteni, R. Groten, and M. Slater. The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, 2012.

[30] J.-S. Kim, D. Gračanin, K. Matković, and F. Quek. Finger walking in place (fwip): A traveling technique in virtual environments. In *International Symposium on Smart Graphics*, pp. 58–69. Springer, 2008.

[31] J. J. LaViola Jr. A discussion of cybersickness in virtual environments. *ACM Sigchi Bulletin*, 32(1):47–56, 2000.

[32] J. D. Lee, C. D. Wickens, Y. Liu, and L. N. Boyle. *Designing for people: An introduction to human factors engineering*. CreateSpace, 2017.

[33] T. Louis and F. Berard. Superiority of a handheld perspective-coupled display in isomorphic docking performances. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*, pp. 72–81. ACM, 2017.

[34] I. S. MacKenzie, T. Kauppinen, and M. Silfverberg. Accuracy measures for evaluating computer pointing devices. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 9–16. ACM, 2001.

[35] E. Medina, R. Fruland, and S. Weghorst. Virtusphere: Walking in a human size vr "hamster ball". In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 52, pp. 2102–2106. SAGE Publications Sage CA: Los Angeles, CA, 2008.

[36] S. Miyafuji, T. Sato, Z. Li, and H. Koike. Qoom: An interactive omnidirectional ball display. In *Proceedings of the 30th annual acm symposium on user interface software and technology*, pp. 599–609. ACM, 2017.

[37] M. Nabiyouni, A. Saktheeswaran, D. A. Bowman, and A. Karanth. Comparing the performance of natural, semi-natural, and non-natural locomotion techniques in virtual reality. In *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 3–10. IEEE, 2015.

[38] D. C. Niehorster, L. Li, and M. Lappe. The accuracy and precision of position and orientation tracking in the htc vive virtual reality system for scientific research. *i-Perception*, 8(3):2041669517708205, 2017.

[39] G. Perelman, M. Serrano, M. Raynal, C. Picard, M. Derras, and E. Dubois. The roly-poly mouse: Designing a rolling input device unifying 2d and 3d interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pp. 327–336. ACM, 2015.

[40] M. Schuemie, B. Abel, C. van der Mast, M. Krijn, and P. Emmelkamp. The effect of locomotion technique on presence, fear and usability in a virtual environment. In *EUROMEDIA*, vol. 2005, p. 11th. Citeseer, 2005.

[41] N. A. Skopp, D. J. Smolenski, M. J. Metzger-Abamukong, A. A. Rizzo, and G. M. Reger. A pilot study of the virtusphere as a virtual reality enhancement. *International Journal of Human-Computer Interaction*, 30(1):24–31, 2014.

[42] F. Steinicke, Y. Visell, J. Campos, and A. Lécuyer. *Human walking in virtual environments*. Springer, 2013.

[43] R. Stoakley, M. J. Conway, and R. Pausch. Virtual reality on a wim: interactive worlds in miniature. In *CHI*, vol. 95, pp. 265–272, 1995.

[44] P. Touma, H. Murr, E. Bachaalany, and I. Maalouf. 3d mouse and game controller based on spherical coordinates system and system for use, Mar. 23 2010. US Patent 7,683,883.

[45] C. Ware and S. Osborne. Exploration and virtual camera control in virtual three dimensional environments. *ACM SIGGRAPH computer graphics*, 24(2):175–183, 1990.

[46] C. Ware and J. Rose. Rotating virtual objects with real handles. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 6(2):162–180, 1999.

[47] M. C. Whitton, J. V. Cohn, J. Feasel, P. Zimmons, S. Razzaque, S. J. Poulton, B. McLeod, and F. P. Brooks. Comparing ve locomotion interfaces. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pp. 123–130. IEEE, 2005.

[48] P. T. Wilson, W. Kalescky, A. MacLaughlin, and B. Williams. Vr locomotion: walking¿ walking in place¿ arm swinging. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry-Volume 1*, pp. 243–249. ACM, 2016.