Magic Carpet: Interaction Fidelity for Flying in VR

Daniel Medeiros, Maurício Sousa, Alberto Raposo, and Joaquim Jorge, *Senior Member, IEEE*

Abstract—Locomotion in virtual environments is currently a difficult and unnatural task to perform. Normally, researchers tend to devise ground- or floor-based metaphors to constrain the degrees of freedom (DoFs) during motion. These restrictions enable interactions that accurately emulate the human gait to provide high interaction fidelity. However, flying allows users to reach specific locations in a virtual scene more expeditiously. Our experience suggests that even though flying is not innate to humans, high-interaction-fidelity techniques may also improve the flying experience since flying requires simultaneously controlling additional DoFs. We present the Magic Carpet, an approach to flying that combines a floor proxy with a full-body representation to avoid balance and cybersickness issues. This design space enables DoF separation by treating direction indication and speed control as two separate phases of travel, thereby enabling techniques with higher interaction fidelity. To validate our design space, we conducted two complementary studies, one for each of the travel phases. In this paper, we present the results of both studies and report the best techniques for use within the Magic Carpet design space. To this end, we use both objective and subjective measures to evaluate the efficiency, embodiment effect, and side effects, such as physical fatigue and cybersickness, of the tested techniques in our design space. Our results show that the proposed approach enables high-interaction-fidelity techniques while improving the user experience.

Index Terms—Travel techniques, flying, virtual reality, user centered design, human computer interaction

1 Introduction

In this paper, we present a novel approach to improving flying in virtual reality (VR). As VR gear has become more widely available, effective travel techniques have also risen in importance. Generally speaking, travel in virtual environments (VEs) implies the translation of a person from an initial location to a target position along a given direction. In their classic survey, Bowman et al. [1] classified travel techniques on the basis of two main criteria: 1) whether movement is controlled virtually or physically, and 2) whether the action of motion is controlled actively or passively. In virtual techniques, travel is controlled via specific input devices, such as joysticks or handheld wands. By contrast, in physical techniques, people use their bodies to control their travel. In active techniques, the actions are performed by the users themselves, whereas the system is in control during passive travel. A more recent study relies on task decomposition to classify travel into three phases: direction indication, velocity specification and input conditions. These phases specify how the movement is started, continued and terminated [2]. A concept that is closely related to travel is interaction fidelity, which is defined by McMahan et al. [3] as "the objective degree of exactness with which real-world interactions can be reproduced". The closer a given travel technique is to real walking, the higher is its interaction fidelity. Thus, physical techniques provide higher interaction fidelity than virtual methods do because people can use their body poses to indicate direction [3], [4] and control the speed of movement [5], [6]. In this context, a fully embodied avatar is an important part of the user experience when a head-mounted display (HMD) completely occludes the user's body [7]. Indeed, such avatars are very important for effective high-interaction-fidelity techniques since such techniques use the movements of body parts as input, for which immediate visual feedback is required [8].

According to Bowman et al. [1], seven key factors affect the perceived quality of a travel technique: (1) its ease of use, (2) its ability to be learned, (3) the spatial awareness it affords, (4) its efficacy, (5) its appropriate use of speed, (6) its ability to support users in gathering information from the environment, and (7) its contribution to presence. Previous studies on interaction fidelity and quality factors [3], [9] have concluded that greater fidelity does not always translate into higher perceived quality. However, high-interaction-fidelity techniques have been shown to improve efficiency, efficacy, and presence in systems with high display fidelity, such as CAVE automatic virtual environments (CAVEs) [3] and close-to-real scenarios, in which locomotion is constrained to a ground plane. However, although it feels natural, walking is not very effective as a means of travel in large-scale VEs.

Flying provides a more efficient means of locomotion in unconstrained large VEs. However, limited work has been done on flying in VR as compared to other locomotion approaches. One possible explanation for this lack is that flying is unnatural to humans and difficult to control using state-of-the-art techniques since it requires simultaneously controlling many degrees of freedom (DoFs) for translation and speed control. It is unclear whether travel remains a simple task when additional DoFs are added. This may

- *D. Medeiros, M. Sousa, and J. Jorge are with the INESC-ID Lisboa, Técnico Lisboa, Universidade de Lisboa, Lisbon 1649-004, Portugal. E-mail: daniel.medeiros@tecnico.ulisboa.pt, jorgej@acm.org.*
- *A. Raposo is with Tecgraf/PUC-Rio, Rio de Janeiro 22451-900, Brazil. E-mail: abraposo@tecgraf.puc-rio.br.*

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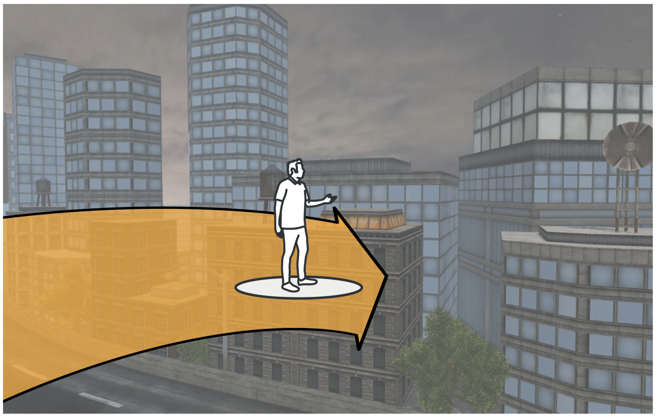

Fig. 1. Visualization of the explored design space.

require a complex equipment that emulates a machine, such as a paraglider [10] or virtual wings [11]. However, such equipment makes users uncomfortable and may hinder their ability to perform useful actions, such as virtual object selection and manipulation, since all their limbs are engaged in locomotion. One way to overcome this problem is to use gaze- [12] or hand-based steering [13] to indicate the direction of movement [1]. Preliminary work by Chen et al. [14] showed that physical techniques, e.g., gaze-based techniques, are more efficient than joystick-based virtual techniques. Thus, controlled flight in VEs remains a difficult task given the aforementioned issues. Our research suggests that this problem may be addressed by reducing the number of DoFs via task decomposition, a technique that improves precision in 3D object manipulation [15]. We argue that separating the DoFs can improve the travel quality factors. This separation also makes it possible to adopt metaphors that closely emulate how people walk in real life.

In this paper, we present our *Magic Carpet* design space, in which the user can apply close-to-real-walking metaphors to fly, as depicted in Fig. 1. *Magic Carpet* uses an informative proxy of the real physical ground on which the person is standing, matching its position and rotation to mitigate loss of balance, cybersickness, and vertigo. We render the proxy in the virtual scene below the user's feet and adopt a fully embodied representation for improved awareness. We evaluated this design space by conducting two complementary user studies, one for each phase of travel, namely, direction indication and speed control. This separation enables us to alleviate the most unnatural aspect of flying, i.e., the need to manipulate six DoFs to control the flight direction. To this end, we tested three techniques for direction indication – two of which are state of the art - and compared them with a novel technique based on 6-DoF separation [15]. In the second study, the best-performing technique for indicating direction was combined with three different techniques for speed control. As a result of both studies, we found that splitting flight into two separate components enabled techniques with high interaction fidelity that improve the travel experience. In what follows, we present the best techniques for use in our design space.

The main contributions of this research include 1) the introduction and exploration of a design space that improves the user experience during flying in VEs, 2) findings from a user study conducted to determine the most suitable direction indication technique for flying, 3) recommendations from a user study conducted to assess the influence of high-interaction-fidelity techniques for speed control, and 4) design considerations for future approaches to flying in VR.

2 Related Work

Travel activities in VEs can be classified into *exploration* and *search* activities. Exploration activities relate to navigation through a VE with no specific goal or target. In contrast, people engaged in search activities have a goal and may or may not rely on additional information, such as wayfinding, to assist them in reaching their desired locations [16]. Travel is also a form of manipulation, as users typically modify the positions and rotations of the virtual cameras, representing their own views within a VE [16]. Furthermore, travel can be decomposed into three subcomponents – i.e., 1) direction indication, which involves specifying how to move or where to move; 2) speed/acceleration control; and 3) input conditions – to prescribe how travel is initiated, continued, and terminated [1] .

Many classifications of travel techniques have been reported in the literature [12], [16], [17]. One of these [16] separates such techniques into active navigation tasks, in which users directly control their locomotion inside a VE, and passive tasks (such as target-based techniques [18]), in which users' movements are controlled by the system. Another taxonomic scheme classifies travel techniques based on the way the navigation occurs in the VE [12], i.e., physically or virtually. In physical navigation, users control their rotations and translations by moving their bodies, and their body movements are tracked by a dedicated 6-DoF system. In virtual techniques, the user's movement is controlled using a specific interaction device, such as a Flystick [19] or a tablet [20], that can be tracked to determine the direction of movement. According to LaViola et al. [2], these two classifications are complementary, making it possible to combine different techniques from either type of category in one system. For example, users can control their direction using a gaze-based technique while controlling their speed with a joystick.

Physical navigation [17] aims to emulate the natural movements of the human body that are normally associated with active techniques. One of the first uses of such a technique was the real walking metaphor. Although this is the most natural form of navigation for humans, it presents several problems in VR, such as the limited physical space available to the user. Redirected walking techniques can be used to overcome this issue [21] by imperceptibly rotating the virtual scene around the users as they walk. However, such techniques normally need large spaces to guarantee an efficient travel experience without any break in the user presence inside the virtual space. This challenge was recently addressed by Yu et al. [22], who proposed a new travel technique in conjunction with a physical setup in which the scene was preprocessed in cells that occupied the available space in the physical room. Other approaches to this issue include omnidirectional treadmills using special hardware to enable a person to walk in any direction [23] and walking in place (WIP) [5], [24]. These techniques emulate the gestures of walking without any change in the user's position, thus

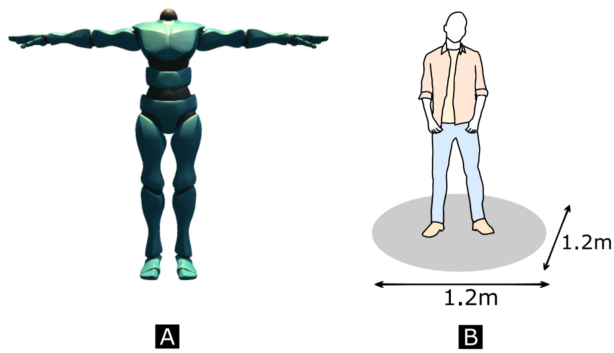

Fig. 2. User representation: A) avatar and B) Magic Carpet.

decreasing the physical space needed at the cost of diminished realism of interaction [25]. Steering techniques are another class of physical travel techniques in which the orientation of the user's body specifies the direction of movement inside the VE. In gaze-oriented techniques, the orientation of the head directs movement, while in hand-oriented techniques, movements are altered based on the direction of pointing. Torso-based techniques rely on the direction of the torso, and lean-based methods use the leaning of the torso or rely on hand and torso inputs to determine direction [26]. In the virtual-circle [6] approach, also known as the human joystick [3], the body is used in ways analogous to gamepad controls. When the user steps outside a virtual circle of a fixed radius, the user is translated in accordance with his or her walking vector. Although this approach is not as natural as WIP or a treadmill, it provides a smooth and efficient travel experience [3]. Another technique is the Virtusphere [27], which consists of a hollow sphere that works in similar manner to a treadmill, enabling the user to control the speed of movement and direction of walking inside the sphere. Studies indicate that because of the nature of these techniques, active travel techniques perform better than passive techniques. Ragan et al. [28] proved this by comparing teleportation with a hand-based steering technique. For this reason, we focused only on active techniques in this study.

Techniques with a high level of interaction fidelity are known to positively influence the travel experience for both exploration [17] and search tasks [29]. Suma et al. [9] demonstrated this by comparing real walking to steering techniques [4] such as torso-based, pointing-based, and gaze-directed translation techniques. While high-fidelity travel techniques can mitigate cybersickness [9], their use can be constrained by limited physical space and clutter. Additionally, during the execution of typical search tasks, the physical effort needed to reach the goal can be inconvenient and lead to exertion. The use of high-interaction-fidelity techniques as a replacement for real walking can lead to inefficiencies depending on the nature of the application. Users expect realistic locomotion, and when presented with an approximation, they need to adapt to it. This effect is observed in the Virtusphere [27], in which such techniques are outperformed by both joystick-based locomotion and real walking. However, McMahan et al. [3] have shown that the human joystick, a high-interaction-fidelity technique, outperforms a joystick-based low-fidelity technique in terms of efficiency and level of presence when high-display-fidelity technology is used (such as CAVEs and HMDs). Langbehn et al. [30] have also reported that a technique with a higher level of interaction fidelity (the redirected walking technique) produces better results in terms of spatial knowledge and presence and induces fewer cybersickness symptoms than a joystick-based technique – a virtual technique with low interaction fidelity – does. Thus, we can identify a positive correlation between the fidelity of the interaction and the travel quality in a ground-constrained scenario.

Regarding travel in VR setups, McManus et al. [7] reported that users performed locomotion tasks faster and with increased accuracy when an animated self-avatar was present in the VE. Moreover, a visible self-avatar is known to be effective for establishing embodiment [31]. Recent work by Nguyen et al. [32] also indicates that a real-world reference in the VE can improve one's spatial orientation in VR.

Virtual techniques and techniques with high interaction fidelity, such as real walking and redirected walking, are considered to elicit better results than flying. This advantage is observed only in human-scale environments [8] and in instances where the desired travel destination is in a ground-constrained location [33]. However, owing to the supernatural quality of some large VEs, such as multiscale VEs [34], travel targets may be out of reach, e.g., above ground, or in remote spots of the VE. Therefore, traditional, ground-based techniques alone are not sufficient to effectively support travel. Thus, flying metaphors provide the most flexible means of navigating arbitrary VEs. However, the flying metaphor is unnatural to humans. It requires the user to simultaneously control 6 DoFs related to movement (rotation/translation) while concurrently controlling the additional DoF related to speed. Such control is far different from what people are used to in real life. In previous studies, attempts have been made to mitigate this issue by employing complex contraptions to emulate flying machines, such as paragliders [10], spaceships,[1] or zero-gravity simulators [35], to allow users to indicate directions of movement using their bodies while controlling speed with additional buttons. By contrast, Birdly [11] uses a complex setup to enable users to fly by flapping mechanical wings, which also control the speed of movement. These devices offer efficient ways to fly in VEs. However, in instances where a certain location needs to be reached in more intricate scenarios, users need to further interact with the VE by either selecting, manipulating, or creating content, whereas these complex flying setups restrict users' actions to the flying task alone. Thus, such approaches are ill suited to contexts with rich interactions.

Techniques with a higher degree of interaction fidelity have been proposed to overcome this conflict. However, most studies have focused on the direction indication stage. Notably, work by Chen et al. [14] has shown that users perform better with a physical technique (gaze steering) than with a virtual technique for indicating direction in a flying scenario. Similarly, it has been shown that users can specify directions by using their bodies when they are either standing [36] or sitting down [37]. The point-and-fly technique, for example, uses the orientation of a 3D wand to indicate direction while using the horizontal distance between the

1. Icaros: Virtual Reality Fitness Experiences. Available at https://www.icaros.com/

head and hand to determine the speed of movement [33]. Separation of the DoFs has also been proposed to mitigate the unnatural aspects of the flying metaphor. This approach is a common strategy adopted to improve the precision of 3D object manipulation in VR [15]. Travel can be regarded as a form of manipulation, as discussed by LaViola et al. [2], as it involves the manipulation of the position and rotation of a virtual camera. Correspondingly, the DOF separation strategy constitutes a viable way to control the direction of movement in flying scenarios. An early attempt to implement this strategy was the ChairIO [37], which consisted of a stool that allowed the user to control rotation on the horizontal plane by rotating the stool or to lean in a chosen direction to control both the direction and speed of movement. Additional pressure sensors provided limited movement in both directions along the *Z*-axis [37]. However, no evaluation of the DoF separation strategy for flying in VEs was performed using the proposed device. Bowman et al. [1] compared both hand- and gaze-oriented steering in a 6-DoF translation environment and found similar performances in both cases, although the results were still preliminary owing to the lack of obstacles and the absence of user representation in the VE. Wang et al. [38] used a leaning approach and devised two different techniques, one using a frontal stance (with the user's feet facing the VE) and one using a sidewise stance, to fly in VR. The results of this study showed generally better results for the frontal-stance technique, but among the 12 tested participants, 3 (or 25%) left the test due to severe cybersickness side effects. A related approach by Sikström et al. also showed that physical techniques can offer an improved sense of embodiment [39] in a flying scenario as compared to joystick control [40] when a virtual body is present.

Because flying is not natural to humans, we propose to isolate the components of travel (as defined by Bowman et al. [1]) into two phases, namely, direction indication and speed control. By decoupling these phases, it is possible to isolate the most unnatural aspect of flying, i.e., the control of the additional DoFs involved in the direction indication phase. This separation enables the use of higher-interaction-fidelity techniques, such as WIP, to control the speed of movement.

3 Our Approach

As stated above, natural locomotion is not always suitable, and flying in VEs is not natural to humans. Furthermore, the increase in the number of DoFs creates more problems than it solves. Because flying is not natural to humans, we propose to isolate the components of travel into two phases, namely, direction indication and speed control. By decoupling these two phases, we enable the isolation of the most unnatural aspect of travel in this metaphor, namely, the control of the additional DoFs, and the use of techniques with a higher level of interaction fidelity for speed control.

To this end, we present a new interpretation of the *Magic Carpet* metaphor that combines a fully embodied user representation with a virtual floor proxy to improve spatial awareness and the sense of embodiment and to prevent side effects such as cybersickness, fear of heights, and imbalance issues. In each phase of travel, we use continuous input control, where the start and end of movement are specific to each technique, as described below.

We performed two user studies, one for each phase, to ascertain the most suitable combination of methods. In the first study, to choose the best-suited technique for indicating direction, we evaluated three different techniques. The first technique tested for this phase was the novel technique "Elevator+Steering", which uses the DoF separation strategy. This is a common way to improve the accuracy of 3D object manipulation [15]. In accordance with this technique, the control of the DoFs was decoupled into a horizontal translation, based on the projection of the user's gaze onto the horizontal plane, and movement along the *Z*-axis, based on the concurrent use of additional buttons. The second technique was a gaze technique, in which the indicated direction is controlled by the user's gaze, and the third was a hand technique, in which the user's hands are used to indicate where to go. In contrast to the work of Bowman et al. [1], the presence of a full-body representation and obstacles in the scene enabled an in-depth investigation of various travel quality factors, namely, efficiency, cybersickness and, most importantly, spatial awareness. In the hand technique, the user indicates direction with his or her hands while still being able to use his or her head to inspect other parts of the VE. During the execution of the second study, to assess speed control, we used three different techniques with varying levels of interaction fidelity. In order of increasing interaction fidelity, the tested techniques for speed control were a joystick-based technique, the speed circle technique – a novel technique for controlling speed based on previous work [3], [6] – and the WIP technique [5]. Both the speed circle and WIP techniques can be regarded as high-interaction-fidelity techniques. Because of the number of tested techniques, we employed the best-performing direction indication technique identified in the first study in conjunction with the tested techniques for speed control.

In the following sections, we present the common test design for both studies, followed by descriptions of the techniques implemented for each trial and by a detailed analysis and discussion of the elicited results.

4 Study 1: Direction Indication

In this first experiment, we evaluated three different techniques for direction indication in a flying task.

The test followed a within-subject design with one trial per participant. We recruited 18 participants for this experiment; two of the participants were female. The participants' ages varied from 21 to 35 years. The majority of the participants had previous experience with 3D applications, such as games and modeling systems, and with HMDs (83.3 percent or 15 participants), while 77 percent of them (14 participants) had previous experience with Kinect usage.

In the following subsections, we present the techniques implemented for direction indication and the results obtained in terms of qualitative and quantitative metrics, followed by a detailed discussion. The qualitative metrics were obtained based on questionnaires issued to evaluate user preferences and comfort issues. Additionally, the questionnaires allowed us to evaluate the sense of embodiment and its subcomponents, including agency (the feeling of

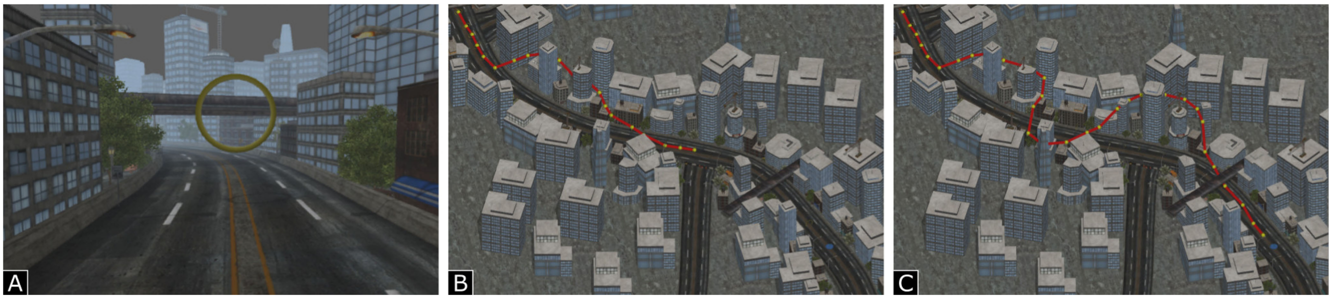

Fig. 3. User tasks in the virtual environment: (a) A ring marking a target. (b) Path used in the first experiment, with 22 rings and a total length of 180 m. (c) Path used in the second experiment, with 34 rings and a total length of 350 m. The red line indicates the path for each experiment, and the yellow dots indicate the positions of the rings.

having control of the virtual body), body ownership (the feeling that the virtual body was the same as the user's), and the sense of self-location (the feeling that the virtual body was located at the same place as the real body) [39]. To evaluate task performance, we gathered data based on logs and collected the total task time, total collision time, and user path length.

4.1 User Representation

The user was mapped onto an abstract humanoid avatar (Fig. 2A). This representation was chosen for both male and female participants. The user's joint positions and rotations as obtained from the Kinect sensor were mapped directly onto the avatar using direct kinematics. Because of the Kinect's hand tracking limitations, we attached a reflexive rigid body to the control wand to enable rotation tracking using the OptiTrack optical system.[2] The collected data were then mapped onto the avatar's hand to represent the dominant hand of the participant.

A ground-plane circle was rendered and placed below the feet of the participant so that he or she could walk on top of it (Fig. 2B). This circle represented the reliable subarea of the available tracking space, with dimensions of 1.2×1.2 m^2. The planar orientation of this circle was fixed and was the same as that of the real floor, that is, perpendicular to the body of the participant.

4.2 Implemented Techniques

Two different techniques were implemented that differ in how the user uses his or her body to indicate the direction of movement with his or her head or hands, as described in previous studies [1], [33]. This work extends the work of Bowman et al. [41] by placing obstacles in the virtual scene and by using a fully embodied representation to improve the spatial awareness of the user. In addition, we developed the novel technique referred to as Elevator+Steering, which uses the DoF separation strategy commonly employed in 3D object manipulation [15]. Because travel is a form of manipulation, this approach can facilitate the control of additional DoFs that is necessary when flying in a virtual scene.

4.2.1 Elevator+Steering Metaphor

In this technique, the direction of movement is based on the projection of the participant's gaze orientation onto the horizontal plane. Additional buttons control the direction of travel in the vertical plane (Fig. 4A) during travel. Another additional button is used to trigger movement.

4.2.2 Gaze-Oriented Steering

In this technique, the direction of movement is based on the rotation of the head of the participant (Fig. 4B). An additional button is used to trigger movement.

4.2.3 Hand Steering

In this technique, the direction of movement is based on the orientation of the dominant hand of the participant (Fig. 4C). An additional button is used to trigger movement.

4.3 Methodology

First, we presented the participants with short descriptions of the tasks and the techniques used. To collect user profiles, we asked the participants to fill out a pretest questionnaire about their backgrounds and experience with navigation methods in VR settings.

Furthermore, we presented each user with a calibration task. For the execution of the calibration procedure, each user was positioned at a fixed location in our laboratory and was asked to raise one of his or her hands. This procedure was performed to calibrate the tracking system between the HMD and the depth sensors, thus associating the user's movements with the virtual avatar. To familiarize the users with the procedures, each user performed a training scenario in which he or she could freely explore the VE. This training scenario was presented before the testing of each of the techniques, and no time limit was imposed. After performing the training task, each user performed the calibration procedure and then the test task. To assess user preferences, fatigue,

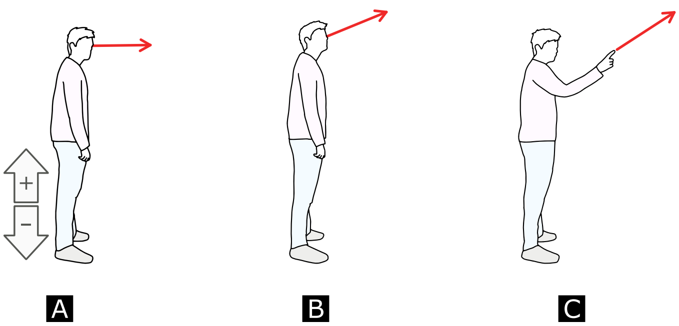

Fig. 4. Direction indication techniques implemented : (a) Elevator+Steering technique, (b) gaze technique and (c) hand technique.

2. https://www.optitrack.com

and the sense of embodiment, we asked each user to fill out a post-test questionnaire.

These steps were conducted for each combination of test conditions. The order of the test conditions was changed in every test following a balanced Latin square arrangement to avoid biased results.

4.4 Task Description

During this experiment, the user was asked to fly through rings, indicating the direction of movement using one of the proposed techniques. The selected environment was based on a city scene obtained from the Unity3D Asset Store.[3] This scene was modified to remove visual clutter.

To guide users through the scene, we positioned rings to indicate the desired path. Only one ring was shown at a time, and once crossed – successfully or not – that ring disappeared, and a new ring appeared (Fig. 3). If the new ring was not visible to the user, an arrow was shown in the middle of the screen to indicate the next ring's position. This test consisted of 22 rings along a path with a length of 180 m and included abrupt changes in the Z-coordinate to best evaluate the users' attention and the effectiveness of direction indication for each of the tested techniques (Fig. 3B). Once the direction had been chosen, the user pressed a button on the control wand and was then translated in the chosen direction at a constant speed of 3 m/s. The user could also modify his or her direction while traveling. To stop moving, the user needed to release the trigger button.

4.5 Setup

For visualization, we employed an Oculus Rift DK2 HMD. We used a button on the control wand to trigger movement. The wand used was the Sony Playstation Move Navigation Controller. The body movements of the participants were tracked with the Creepy Tracker toolkit [42] using five Kinects connected to a central application through the local network. The Creepy Tracker was chosen because of the ability to track the entire body without utilizing additional markers. Furthermore, to minimize the effects of network communication, both the central hub application and the client applications were executed by the same desktop computer.

The five sensors were fixed on the walls of the laboratory where the study was being held and covered an area of approximately 4×4 m^2. We chose a subregion of the tracking area of each Kinect with a size of 1.2×1.2 m^2 to ensure more reliable tracking outcomes and arranged the Kinects using a wide-baseline arrangement.

Because of the Kinect's limitations in terms of tracking hands and head rotations, we also used 10 Flex3 OptiTrack cameras, which were placed on the ceiling and operated at 100 FPS. The Creepy Tracker had an average delay of 76 ms relative to the OptiTrack system because of the Kinect's limitations. Although this latency might hinder real-time performance in VR without some mitigating factor, combining the tracker's positional data with the orientation provided by the HMD appeared sufficient to satisfy the illusion of being present in the VE. Additional markers were placed on the wand to enable the tracking of the hand rotation with three DoFs.

3. Unity3D Store: http://unity3d.com/store

4.6 Results

In this section, we present the main observations made during the first experiment as well as difficulties and suggestions from participants regarding the test task. To assess the differences among the three techniques for direction control, we collected both objective and subjective data in the form of logs and questionnaires, respectively, during the evaluation sessions. For the continuous variables (collision time, total time, and users' total traveled path lengths), we used the Shapiro-Wilk test to assess data normality.

Because the samples were not normally distributed, we used the Friedman nonparametric test to identify the main effects. Once the main effects had been found, we performed additional Wilcoxon signed-rank post hoc tests with Bonferroni correction to assess the statistical significance between each pair of variables. For the questionnaires, we also used the Friedman nonparametric test to identify the main effects and Wilcoxon signed-rank post hoc tests with Bonferroni correction for each pair of variables.

In the following subsections, we present the analysis of the results from the questionnaires and log files obtained during the tests.

4.6.1 Subjective Responses

By analyzing the data from the questionnaires, we identified statistically significant differences regarding the ease of indicating direction (Q2: $\chi^2(2)$=25.24, $p<0.001$), moving around the VE ($\chi^2(2)$=11.677, p=0.003) and reaching the rings (Q4: $\chi^2(2)$=19.24, $p<0.001$).

We can infer that the users found it easiest to indicate the direction of movement (Q2) using the hand-steering technique and found it most difficult with the elevator technique. This is explained by the statistical significance results found by comparing the gaze and hand techniques (Z=-2.414, p=0.016), the elevator and hand techniques (Z=-3.601, $p<0.001$), and the elevator and gaze techniques (Z=-2.635, p=0.008). Statistical significance was also found for Q3 with regard to the finding that users felt it was more difficult to move using the elevator technique than using the hand (Z=-3.286, p=0.001) and gaze (Z=-2.919, p=0.004) techniques. The participants found it more difficult to reach the rings (Q4) with the elevator technique than with the gaze technique (Z=-2.810, p=0.005). Additionally, statistical significance was found with regard to avoiding obstacles (Q5); users found it easier to avoid them with the hand technique than with the elevator technique (Z=-3.397, p=0.001).

Regarding embodiment (Q8Q10), we did not identify any statistically significant differences among the tested techniques. Additionally, we did not identify significant differences between the tested pairs of techniques in regard to the ease of walking inside the circle (Q1), feeling of safety (Q6), or fear of heights (Q7). However, the participants felt that the elevator technique significantly affected their fear of heights compared to the gaze technique and significantly affected their sense of self-location compared to the hand technique. The questionnaire results are summarized in Table 1.

4.6.2 Task Performance

To assess differences in user task performance among the different representations, we collected data based on logs.

TABLE 1
Results Obtained from the Questionnaires in the Direction Indication Experiment, Presented as Median (Interquartile Range) Values

	It was easy to...	Elevator	Gaze	Hand		I felt...	Elevator	Gaze	Hand
Q1.	...walk inside the circle.*	5 (1)	5 (1)	5.5 (1)	Q6.	...safe inside the circle.*	5.5 (1)	6 (1)	6 (1)
Q2.	...indicate the direction of movement.	4 (1)	5 (1)	6 (0)	Q7.	...a fear of heights.	1 (2)	1 (1)	1 (1)
Q3.	...move around the VE.*	5 (1)	6 (1)	6 (0)	Q8.	...a sense of agency.	5 (2)	5.5 (1)	5 (1)
Q4.	...reach the rings.*	5 (2)	6 (1)	6 (1)	Q9.	...body ownership.	4.5 (2)	5 (0)	5 (2)
Q5.	...avoid obstacles.*	5 (1)	5 (1)	6 (1)	Q10.	...a sense of self-location.	5 (1)	5 (0)	5 (1)

*Here, * indicates statistical significance.*

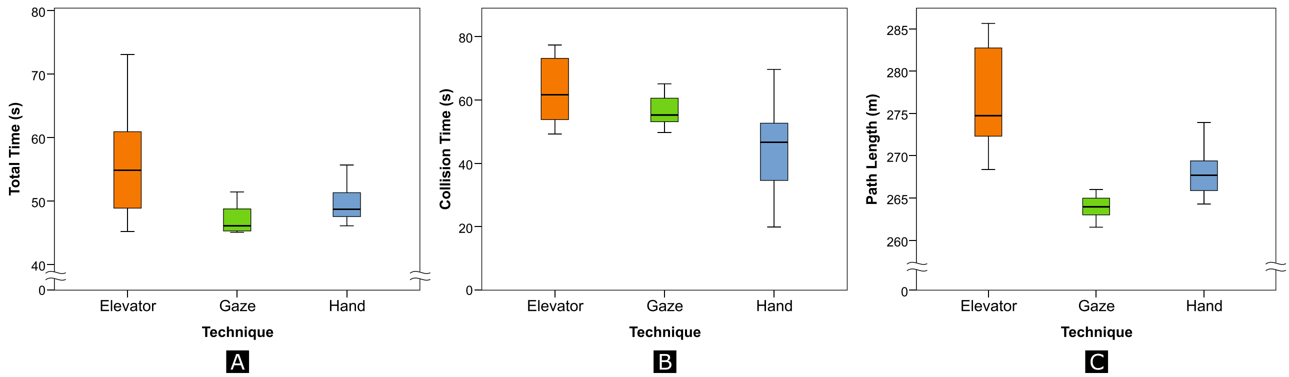

Fig. 5. Results obtained from the direction indication experiment for (A) total time, (B) collision time, and (C) path length. In each plot, the Elevator +Steering technique is represented in orange, the gaze technique in green, and the hand technique in blue.

The data collected in this phase included the total task time, total collision time with objects, and path length. We chose the chest point as the reference point for calculating the total distance traveled because this is the most reliable joint provided by Kinect sensors.

Regarding the total task time, we identified statistically significant differences ($\chi^2(2)$=8, p=0.018). Specifically, significant differences were noted between the gaze and elevator techniques (Z=-2.621, p=0.009), with the gaze technique requiring a shorter amount of time to complete the task, and between the hand and gaze techniques (Z=-2.417, p=0.016), with the hand technique showing an advantage. The data regarding the total path length can be found in Fig. 5A. Regarding the total collision time, we also found statistically significant differences ($\chi^2(2)$=17.33, p<0.001), with the hand technique showing a clear advantage compared to the elevator technique (Z=-3.461, p=0.001) and the gaze technique (Z=-3.201, p=0.001). A summary of the total collision time results can be found in Fig. 5B.

We also found a statistically significant difference regarding the path length ($\chi^2(2)$=21.53, p<0.001) (Fig. 5C) between the gaze and elevator techniques (Z=-3.574, p<0.001), with the gaze technique being associated with the shorter path length. Statistically significant differences were also found between the hand and elevator techniques (Z=-3.101, p=0.002), with the hand technique having the shorter path length, and between the hand and gaze techniques (Z=-3.337, p=0.001), with the gaze technique having the advantage.

4.7 Discussion

We found that the Elevator+Steering technique elicited the worst results in our tests. It was the least efficient technique (in terms of total time) because the users spent most of their time colliding with objects. It was also the technique with the longest traveled distance among the three tested techniques.

The results for the gaze- and hand-oriented steering techniques were similar to those found by Bowman et al. [1]. The hand technique had the advantage in terms of efficiency (total time), and the gaze technique the advantage in terms of the distance traveled. The users indicated that the hand technique allowed them to be more aware of the presence of a virtual body. This was attributed to the fact that the users spent a shorter amount of time colliding with objects with the hand technique. With this technique, they had increased awareness of their virtual bodies and could focus on performing the task, but they encountered difficulties in avoiding obstacles. The participants also found it easier to indicate the direction of movement and to navigate in the VE using the hand technique, as indicated by the questionnaires. Another advantage of the hand technique was that it provided the possibility of traveling in a different direction than the direction in which the user was looking, thus enabling him or her to inspect the virtual scene while traveling.

5 Study 2 : Speed Control

In the second study, we assessed the impact of the use of close-to-real techniques for controlling speed when flying in VEs. The test design and methodology used in this test were similar to those in the previous study. We also used the same VE and presented a task similar to that in the previous experiment but following a different path (Fig. 3C). This path was longer, measuring 330 m, and contained abrupt changes in the Z position. We also incorporated more complex maneuvers, such as U-turns, to force users to carefully control their speeds while they flew. Similar to the previous experiment, the subjective SSQ was used to assess cybersickness. Based on the results of the previous evaluation, we employed the hand technique as the technique for indicating direction in combination with all the proposed speed control techniques.

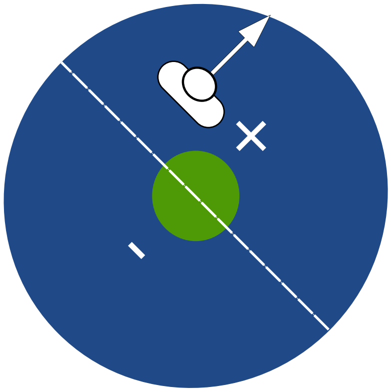

Fig. 6. Division of the speed circle into positive and negative halves. This division was updated according to the orientation of the user.

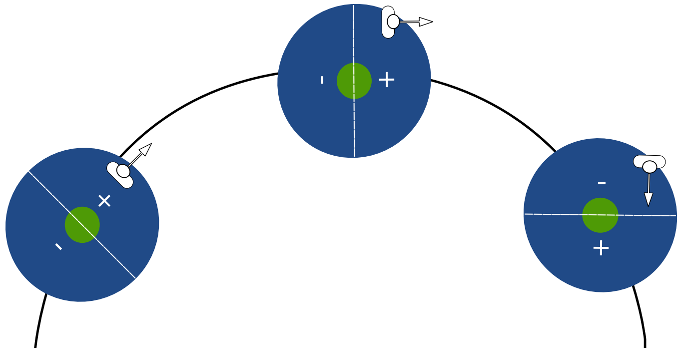

Fig. 7. Example showing how the movement stops when the user is performing a U-turn.

For this experiment, we recruited 18 participants; four were female. The ages of the users varied from 21 to 35 years, with an average age of 25. Regarding experience, the majority of the users had previous experience with 3D applications, such as games and modeling systems. The majority also had previous experience with HMDs (88.8 percent or 16 participants) and with Kinect usage (72.2 percent or 13 participants).

In the following subsections, we present the implemented techniques and outline the details of the obtained results, followed by an in-depth discussion.

5.1 Implemented Techniques

We tested the speed control capabilities of three different techniques. The techniques ranged from a low level of interaction fidelity (joystick) to a high level of interaction fidelity (speed circle and WIP). To indicate the direction of movement, we used the hand technique, which elicited the best results in the previous study, in combination with all of the tested speed control techniques. For all techniques, the speed was constrained to a maximum of 5 m/s.

5.1.1 Joystick

In this technique, the speed was controlled with an analog stick similar to those traditionally used in games. The vertical axis of the joystick was used to control the speed of movement. At the middle of the stick, the speed was zero, and when the stick was moved along the vertical axis, the speed increased until it reached its upper limit. For the comparison of the outcomes elicited with the different techniques, we chose to include only movements along the positive axis of the joystick.

5.1.2 Speed Circle

The speed circle technique is an adaptation of the virtual circle metaphor [3], [6], in which the human body is used as an analog stick. We utilized a mapping identical to that in the joystick technique but used the position of the hip joint as the input for controlling the user's speed. In the neutral zone, which was represented by a green circle in the middle of the speed circle, the movement speed was zero. Outside the neutral zone, the movement speed was determined by the projected distance of the user from the center of the circle. To prevent negative speeds, the circle was divided into two different halves relative to its center, which were updated according to the user's projected forward direction. When the user stepped in the negative half of the circle, the movement stopped (Fig. 7). Additionally, in U-turn-like movements, the user could adjust his or her position while turning or walking toward the opposite side of the circle. This limitation was explained to the users during the pretest and training scenarios. Despite the use of the torso position as the input to control the speed of translation, we used the orientation of the hand as the means of indicating the direction of movement, as in the joystick technique.

To avoid users stepping outside the ground plane circle when their bodies were within the maximum speed zone, we extended the spatial extent of the zone by 0.5 m in instances when participants reached the border of the circle. This extended circle was rendered in yellow to differentiate it from the conventional circle.

5.1.3 Walking in Place

Our WIP approach was adapted from that of Bruno et al. [5], which is optimized for data gathered from commodity depth cameras, because this approach employs the knee movements of the user to determine the gait speed. However, in contrast to Bruno et al., we used the hand orientation of the user to determine the overall travel direction because this evaluation scenario was not restricted by a large-scale wall display. To reduce fatigue, we limited the movement needed to reach the maximum speed. To accomplish this, we set a maximum threshold speed of 5 m/s.

5.2 Results

Similar to the first experiment, we used both objective and subjective data to compare the three techniques for speed control.

We used the the Shapiro-Wilk test to assess data normality. We then applied a repeated measures ANOVA test with Greenhouse-Geisser correction to identify significant differences in normally distributed data and Friedman's nonparametric test with a Wilcoxon signed-rank post hoc test for non-normally distributed data. In both cases, Bonferroni correction (corrected significance = significance x 3) was used in the post hoc tests.

5.2.1 Subjective Responses

The results showed statistically significant differences regarding the ease of walking inside the carpet (Q1: $\chi^2(2)=10.61$,

TABLE 2
Results from the Questionnaires Collected in the Second Experiment, Presented as Median (Interquartile Range) Values

It was easy to...	Joystick	Speed circle	WIP	I felt...	Joystick	Speed circle	WIP
Q1. . . .walk inside the circle.*	6 (0)	5 (2)	5 (3)	Q8. . . .safe inside the circle.*	6 (1)	6 (1)	4.5 (3)
Q2. . . .indicate the direction of movement.	6 (1)	6 (1)	6 (1)	Q9. . . .a fear of heights.	1 (2)	1 (1)	1 (4)
Q3. . . .control the speed of movement.*	6 (0)	5 (1)	3 (2)	Q10. . . .fatigue.	1 (1)	1 (2)	3 (4)
Q4. . . .move around the VE.*	6 (1)	5 (1)	4.5 (2)	Q11. . . .a sense of agency.*	6 (1)	6 (1)	5 (3)
Q5. . . .reach the rings.*	6 (0)	6 (1)	4.5 (2)	Q12. . . .body ownership.	6 (1)	5.5 (1)	5 (2)
Q6. . . .avoid obstacles.*	6 (1)	5 (2)	4.5 (3)	Q13. . . .a sense of self-location.	6 (1)	5.5 (1)	5 (2)
Q7. . . .coordinate movements.*	5 (1)	5 (1)	4 (3)				

*Here, * indicates statistical significance.*

p=0.005), controlling the speed (Q3: $\chi^2(2)$=25.34, p<0.001), moving around the environment (Q4: $\chi^2(2)$=21.55, p<0.001), reaching the rings (Q5: $\chi^2(2)$=16.74, p<0.001), avoiding obstacles (Q6:$\chi^2(2)$=14.52, p=0.001), and coordinating movements (Q7: $\chi^2(2)$=10.67, p=0.005). There were also statistically significant differences related to feeling safe inside the circle (Q8: $\chi^2(2)$=17.53, p<0.001), the sense of agency (Q9: $\chi^2(2)$ =7.190, p=0.027), fatigue (Q12: $\chi^2(2)$=9.8, p=0.007), and the fear of heights (Q13: $\chi^2(2)$=15.056, p=0.001). We also found statistically significant differences regarding the cybersickness score (F(2,50)=4.378, p=0.018).

Regarding the use of the Magic Carpet, the participants found it easiest to walk around the carpet (Q1) using the joystick technique (Z=-2.899, p=0.004) and felt less safe within the carpet when using the WIP technique in comparison to both the joystick (Z=-2.979, p=0.003) and speed circle (Z=-2.915, p=0.004) techniques. When asked about speed control (Q4), the participants reported finding it easier with the joystick than with the WIP (Z=-2.750, p<0.001) and speed circle (Z=-2.750, p=0.006) techniques and more difficult overall with the WIP technique compared to the speed circle (Z=-3.016, p=0.003) and joystick techniques.

Using the WIP technique, the users also found it more difficult to move around the environment (Q4) (joystick: Z=-3.471, p=0.001; speed circle: Z=-2.593, p=0.01) and to reach the rings (Q5) (joystick: Z=-2.822, p=0.005; speed circle: Z=-2.946, p=0.003). For obstacle avoidance (Q6), the users overall preferred the joystick technique over the speed circle (Z=-2.547, p=0.011) and WIP (Z=-3.095, p=0.003) techniques. Regarding embodiment (Q11-Q13), we found statistically significant differences only with regard to the sense of agency with the WIP technique, with which users felt they had less control over their virtual bodies compared to the speed circle technique (Z=-2.555, p=0.011). We did not find statistically significant differences among the tested techniques with regard to the fear of heights (Q9). The users also felt more fatigue with the WIP technique (Q10) than with either the joystick (Z=-2.699, p=0.007) or speed circle (Z=-2.840, p=0.005) technique. Additionally, they found it more difficult to coordinate movements (Q7) with the WIP technique in comparison to the joystick technique (Z=-2.609, p=0.009). The elicited results are summarized in Table 2.

Regarding cybersickness issues, the users indicated additional side effects related to the user experience with the WIP technique (average score=88.12), with severe cases of “Stomach Awareness”, “Vertigo”, “Dizziness with Eyes Closed”, “Nausea”, and “General Discomfort” (one instance of each). This finding could be explained by the statistically significant differences found in comparison with the joystick (average score=39.52, t(17)=-3.265, p=0.005) and speed circle (average score=43.84, t(17)=-3.021, p=0.008) techniques.

5.2.2 Task Performance

In addition to the previously described data (total time, total collision time, and path length), we gathered additional information, such as the speed variation, the percentage of time spent in translation (flying time), and the percentage of time during which the carpet remained stationary (idle time).

Based on the analyzed results, we found statistically significant differences with regard to the total time ($\chi^2(2)$=27.11, p<0.001), flying time percentage ($\chi^2(2)$=13.765, p=0.001), idle time percentage ($\chi^2(2)$=10.53, p=0.005), and path length ($\chi^2(2)$=14.33, p=0.001).

Regarding time, the users completed the task in a shorter time with the joystick (average time=64.9 s) than with either the speed circle (average time=97.73 s, Z=-3.724, p<0.001) or WIP (average time=81.7 s, Z=-3.724, p<0.001) technique. We also noted that the movement was less fluid using the WIP technique (average flying percentage=71.2%, average idle percentage=8.18%), as indicated by the smaller idle time percentage compared to the speed circle (average=88.35%, Z=-3.053, p=0.002) and joystick (average=92.7%, Z=-3.124, p=0.002) techniques and the higher flying time percentage compared to the speed circle (average=11.65%, Z=-3.053, p=0.002) and joystick (average=8.18%, Z=-3-385, p=0.001) techniques. Moreover, we found that the joystick technique resulted in a shorter path length (average length=479.57 m) compared to both the speed circle (average length=494.77 m, Z=-2.765, p=0.006) and WIP (average length=492.6 m, Z= -3.201, p=0.001) techniques (Fig. 10).

5.3 Discussion

In previous studies on ground-constrained scenarios, researchers have reported improvements when using higher-interaction-fidelity techniques [3] in VR setups. However, the use of techniques with moderate interaction fidelity tends to impact performance [27]. From our results, we can infer that WIP was the least suitable technique in terms of task performance in comparison to the other tested approaches. However, we can still consider it efficient in terms of collision time, path length, and total task time. In our tests, we noticed that users experienced more difficulty in coordinating the direction indication and speed control phases with this technique. Consequently, more participants stopped the speed control movement when they reached a ring, then pointed to the next

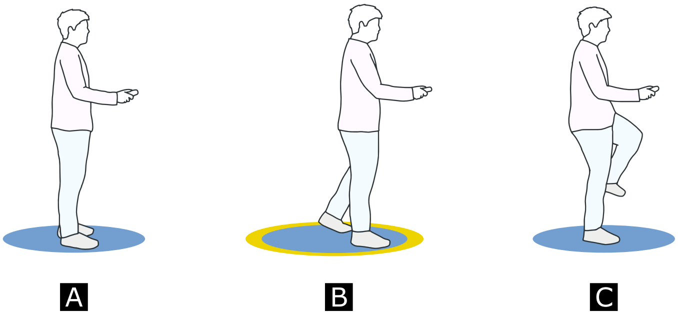

Fig. 8. Implementation of the speed control techniques: (A) joystick, (B) speed circle, and (C) walking in place. An extra circle (shown in yellow) was rendered when the user reached the border of the default circle.

ring, and then flew to it. This behavior explains the increased amount of idle time observed with this technique (Fig. 8A). The users also stated that with WIP, it was more difficult to control the speed, and they reported more cybersickness and balance issues during the experience. Regarding embodiment, as seen from the results of the questionnaires, the users also felt less control over their virtual bodies (less sense of agency) with the WIP technique. This may be attributed to the noise in the depth sensor signals. Another interesting point reported by the participants was that they lost balance in some cases because of the weight compensation that occurred naturally during their gait in real life, for which the emulated experience did not entirely match the actual experience.

The joystick technique was found to be generally the most efficient technique for flying in immersive environments. This may be explained by the familiarity the users already had with video games. However, in most cases, the users did not finely control the speed, as indicated in Fig. 9E, but instead maintained the maximum speed most of the time.

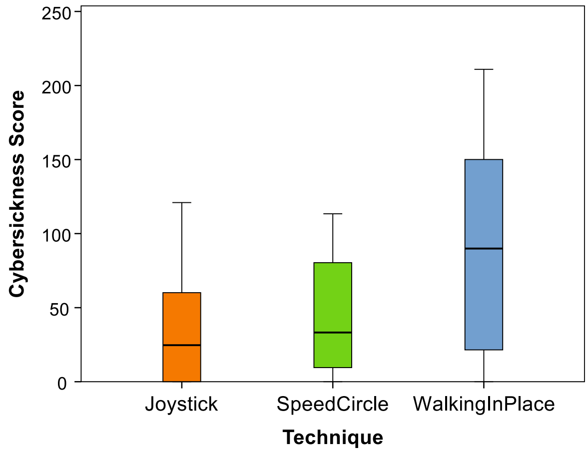

Fig. 10. Summary of the cybersickness scores with the three tested techniques for speed control. Orange represents the joystick technique, green represents the speed circle technique, and blue represents the walking-in-place technique.

From observing the behavior of the participants during the test, we can infer that the participants mostly controlled their speed while they flew based on the speed circle technique (as shown in Fig. 9E), especially when executing abrupt movements, such as U-turns. The participants often reported that they were lost within the circle. However, they quickly compensated for this issue by recentering themselves before restarting their intended travel actions. They also stated the

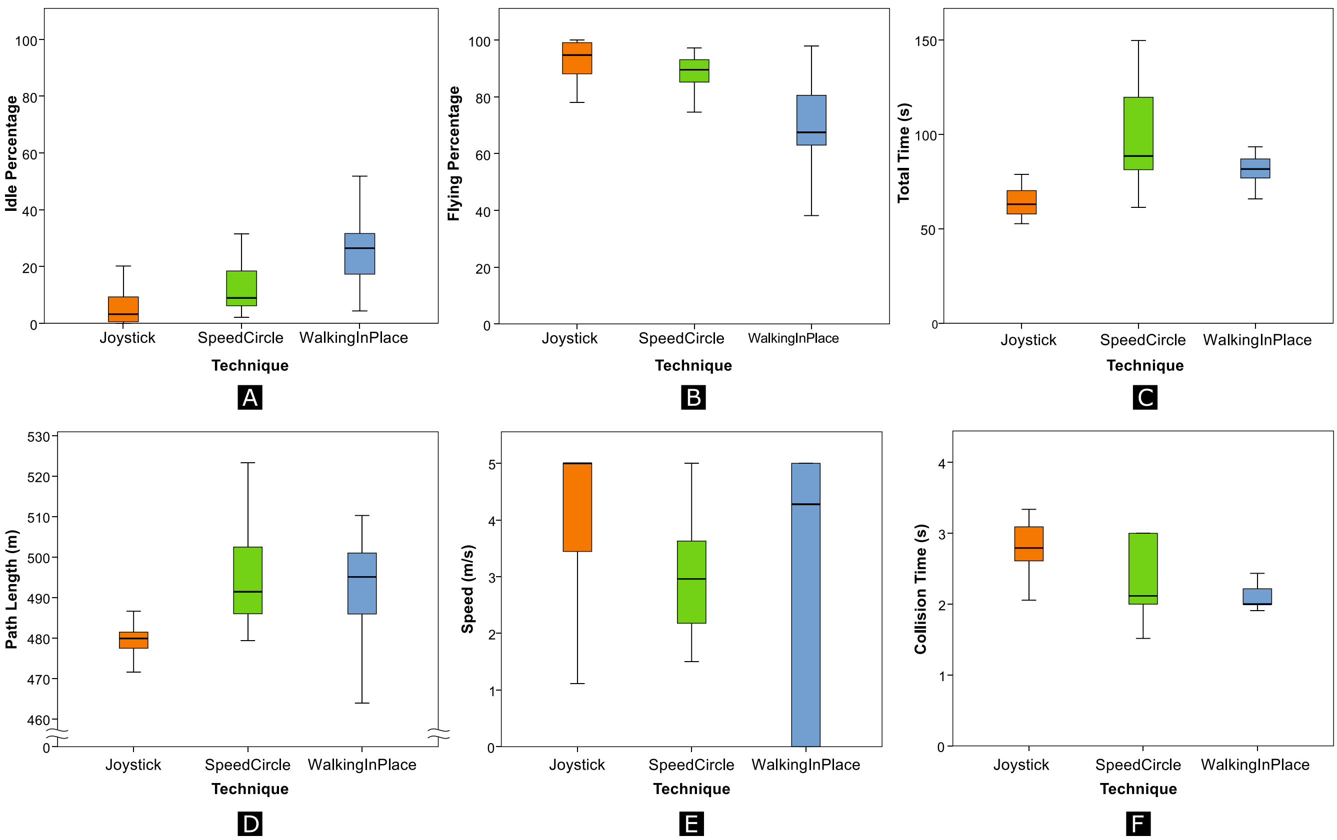

Fig. 9. Results obtained from the speed control experiment for (A) idle time, (B) flying time, (C) total time, (D) path length, (E) speed variation, and (F) collision time. In each plot, the joystick technique is represented in orange, the speed circle technique in green, and the walking-in-place technique in blue.

need to periodically look down at the circle. This, however, had a negative impact on their performances in comparison to the joystick technique. They also stated that more training could improve their performance.

Ultimately, we can state that the use of high-interaction-fidelity techniques is not always the best option for flying in VR. Although the joystick technique has been proven optimal for use in such applications based on our tests, we can still identify the speed circle technique as a good alternative when more precise speed control is required. We can also report that joystick rotation does not induce increased cybersickness in flying tasks, as opposed to room-scale VR [30].

6 Conclusions

Choosing the most appropriate travel technique is essential when designing a VR experience. Previous research has suggested that close-to-real floor-constrained techniques provide a comfortable user experience. However, in some specific cases, the user needs to fly to explore the VE more effectively and to be able to reach remote locations. Although flying differs considerably from the natural way in which people move in real life and requires the simultaneous control of multiple DoFs, the supernatural qualities of some environments render flying the most efficient travel method.

In this work, we presented the "Magic Carpet" approach to flying in VR, which enables a fully embodied representation of the user with a floor proxy. Furthermore, it improves the sense of presence and avoids side effects such as imbalance and cybersickness. Our proposed design space enables the use of high-interaction-fidelity techniques, which leads to improvement in various quality factors (namely, presence, efficiency, and efficacy) in ground-constrained scenarios when a high-display-fidelity setup is used. We introduced this design concept by conducting two separate user studies, one for each phase of the flying experience, namely, direction indication and speed control. In the first study, we focused on direction indication by assessing two state-of-the-art techniques, namely, the gaze technique (which uses the orientation of the head) and the hand technique (which uses the dominant hand orientation), for specifying the direction of travel. Additionally, we proposed a novel technique referred to as Elevator+Steering, which uses DoF separation for direction control. The second study focused on speed control, for which we evaluated three different techniques. Among them, we proposed the speed circle technique, a high-interaction-fidelity technique for controlling speed in flying scenarios. This approach was based on previous work on ground-constrained travel [3], [6] and enables the user to use his or her body as the joystick to control the speed of movement.

The results from the first study show that the Elevator +Steering technique elicited the worst performance among the tested techniques. The hand technique proved to be a more natural technique for this purpose because it improves the participants' awareness of their bodies and thus is more appropriate for scenes with increased complexity. Another advantage of this technique is that the movement and the camera are controlled separately, enabling the user to inspect the scene while traveling. In the speed control study, we found that the joystick technique elicited the best performance; however, the participants remained physically stationary and thus seemed not to control their speed but rather maintained the maximum speed most of the time. We can also conclude that the speed circle technique is a good option for speed control because the users could exert effective control with this method, even during the execution of abrupt movements and tight trajectories. The results from the second study also suggest that the WIP technique is not a viable option for flying in VR since the participants often stopped moving to specify a direction. Regarding the integration of both techniques in our design space, we can infer that the participants seemed to have difficulties except with the WIP technique. Finally, our results show that Magic Carpet provides a novel and viable way to fly in VEs, with increased flexibility. It also contributes a design space to foster novel, more effective high-interaction-fidelity techniques for flying in VR.

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References

[1] D. A. Bowman, D. Koller, and L. F. Hodges, "Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques," in *Proc. Virtual Reality Annu. Int. Symp.*, 1997, pp. 45–52.
[2] J. J. LaViola Jr, E. Kruijff, R. P. McMahan, D. Bowman, and I. P. Poupyrev, *3D User Interfaces: Theory and Practice*. Reading, MA, USA: Addison-Wesley Professional, 2017.
[3] R. P. McMahan, D. A. Bowman, D. J. Zielinski, and R. B. Brady, "Evaluating display fidelity and interaction fidelity in a virtual reality game," *IEEE Trans. Vis. Comput. Graph.*, vol. 18, no. 4, pp. 626–633, Apr. 2012.
[4] D. A. Bowman, E. Kruijff, J. J. LaViola Jr, and I. Poupyrev, "An introduction to 3-d user interface design," *Presence: Teleoperators Virtual Environ.*, vol. 10, no. 1, pp. 96–108, 2001.
[5] L. Bruno, M. Sousa, A. Ferreira, J. M. Pereira, and J. Jorge, "Hip-directed walking-in-place using a single depth camera," *Int. J. Human-Comput. Studies*, vol. 105, pp. 1–11, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1071581917300460
[6] P. Dam, P. Braz, and A. Raposo, "A study of navigation and selection techniques in virtual environments using microsoft kinect®," in *Proc. Int. Conf. Virtual Augmented Mixed Reality*, 2013, pp. 139–148.
[7] E. A. McManus, B. Bodenheimer, S. Streuber, S. De La Rosa, H. H. Bülthoff, and B. J. Mohler, "The influence of avatar (self and character) animations on distance estimation, object interaction and locomotion in immersive virtual environments," in *Proc. ACM SIGGRAPH Symp. Appl. Perception Graph. Vis.* 2011, pp. 37–44.
[8] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks Jr, "Walking > walking-in-place > flying, in virtual environments," in *Proc. 26th Annu. Conf. Comput. Graph. Interactive Tech.*, 1999, pp. 359–364.
[9] E. A. Suma, S. L. Finkelstein, M. Reid, S. V. Babu, A. C. Ulinski, and L. F. Hodges, "Evaluation of the cognitive effects of travel technique in complex real and virtual environments," *IEEE Trans. Vis. Comput. Graph.*, vol. 16, no. 4, pp. 690–702, 2010.
[10] L. Soares, L. Nomura, M. Cabral, L. Dulley, M. Guimarães, R. Lopes, and M. K. Zuffo, "Virtual hang-gliding over rio de janeiro," in *Proc. IEEE Virtual Reality Workshop "Virtual Reality Public Consumption"*, 2004, pp. 112–115.
[11] M. Rheiner, "Birdly an attempt to fly," in *Proc. ACM SIGGRAPH 2014 Emerging Technol.*, 2014, Art. no. 3.
[12] M. Mine, "Virtual environment interaction techniques," UNC Chapel Hill, Chapel Hill, NC, US, Tech. Rep. TR95–018, 1995.
[13] M. Nabiyouni, B. Laha, and D. A. Bowman, "Poster: Designing effective travel techniques with bare-hand interaction," in *Proc. IEEE Symp. 3D User Interfaces*, 2014, pp. 139–140.

[14] W. Chen, A. Plancoulaine, N. Férey, D. Touraine, J. Nelson, and P. Bourdot, "6dof navigation in virtual worlds: comparison of joystick-based and head-controlled paradigms," in *Proc. 19th ACM Symp. Virtual Reality Softw. Technol.*, 2013, pp. 111–114.

[15] D. Mendes, F. Relvas, A. Ferreira, and J. Jorge, "The benefits of dof separation in mid-air 3d object manipulation," in *Proc. 22nd ACM Conf. Virtual Reality Softw. Technol.*, 2016, pp. 261–268.

[16] D. A. Bowman, E. Kruijff, J. J. LaViola Jr, and I. Poupyrev, *3D User Interfaces: Theory and Practice*. Reading, MA, USA: Addison-Wesley, 2004.

[17] R. Ball, C. North, and D. A. Bowman, "Move to improve: promoting physical navigation to increase user performance with large displays," in *Proc. SIGCHI Conf. Human Factors Comput. Syst.*, 2007, pp. 191–200. [Online]. Available: http://doi.acm.org/10.1145/1240624.1240656

[18] D. Medeiros, E. Cordeiro, D. Mendes, M. Sousa, A. Raposo, A. Ferreira, and J. Jorge, "Effects of speed and transitions on target-based travel techniques," in *Proc. 22nd ACM VRST*, 2016, pp. 327–328. [Online]. Available: http://doi.acm.org/10.1145/2993369.2996348

[19] G. Cirio, P. Vangorp, E. Chapoulie, M. Marchal, A. Lecuyer, and G. Drettakis, "Walking in a cube: Novel metaphors for safely navigating large virtual environments in restricted real workspaces," *IEEE Trans. Vis. Comput. Graph.*, vol. 18, no. 4, Apr. 2012.

[20] D. Medeiros, F. Carvalho, L. Teixeira, P. Braz, A. Raposo, and I. Santos, "Proposal and evaluation of a tablet-based tool for 3d virtual environments," *SBC J. Interactive Syst.*, vol. 4, no. 2, pp. 30–42, 2013.

[21] G. Bruder, F. Steinicke, and K. H. Hinrichs, "Arch-explore: A natural user interface for immersive architectural walkthroughs," in *Proc. IEEE Symp. 3D User Interfaces*, Mar. 2009, pp. 75–82.

[22] R. Yu, W. S. Lages, M. Nabiyouni, B. Ray, N. Kondur, V. Chandrashekar, and D. A. Bowman, "Bookshelf and bird: Enabling real walking in large vr spaces," in *Proc. IEEE Symp. 3D User Interfaces (3DUI)*, 2017, pp. 116–119.

[23] D. Swapp, J. Williams, and A. Steed, "The implementation of a novel walking interface within an immersive display," in *Proc. IEEE Symp. 3D User Interfaces*, 2010, pp. 71–74.

[24] M. Slater, M. Usoh, and A. Steed, "Taking steps: The influence of a walking technique on presence in virtual reality," *ACM Trans. Comput.-Hum. Interact.*, vol. 2, no. 3, pp. 201–219, Sep. 1995. [Online]. Available: http://doi.acm.org/10.1145/210079.210084

[25] M. C. Whitton and T. C. Peck, "Stepping-driven locomotion interfaces," in *Human Walking in Virtual Environments*. New York, NY, USA: Springer, 2013, pp. 241–262.

[26] C. Lai, R. P. McMahan, and J. Hall, "March-and-reach: a realistic ladder climbing technique," in *Proc. IEEE Symp. 3D User Interfaces*, 2015, pp. 15–18.

[27] 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 *Proc. IEEE Symp. 3D User Interfaces*, 2015, pp. 3–10.

[28] E. D. Ragan, A. Wood, R. P. McMahan, and D. A. Bowman, "Trade-offs related to travel techniques and level of display fidelity in virtual data-analysis environments," in *Proc. ICAT/EGVE/EuroVR*, 2012, pp. 81–84.

[29] R. A. Ruddle and S. Lessels, "The benefits of using a walking interface to navigate virtual environments," *ACM Trans. Comput.-Human Interaction*, vol. 16, no. 1, 2009, Art. no. 5.

[30] E. Langbehn, P. Lubos, and F. Steinicke, "Evaluation of locomotion techniques for room-scale vr. joystick, teleportation, and redirected walking," in *Proc. Virtual Reality Int. Conf.*, 2018, Art. no. 4.

[31] V. I. Petkova, M. Khoshnevis, and H. H. Ehrsson, "The perspective matters! multisensory integration in ego-centric reference frames determines full-body ownership," *Frontiers Psychology*, vol. 2, 2011, Art. no. 35.

[32] T. Nguyen-Vo, B. E. Riecke, and W. Stuerzlinger, "Simulated reference frame: A cost-effective solution to improve spatial orientation in vr," in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces*, Mar. 2018, pp. 415–422.

[33] S. Freitag, D. Rausch, and T. Kuhlen, "Reorientation in virtual environments using interactive portals," in *Proc. IEEE Symp. 3D User Interfaces*, Mar. 2014, pp. 119–122.

[34] J. McCrae, I. Mordatch, M. Glueck, and A. Khan, "Multiscale 3d navigation," in *Proc. Symp. Interactive 3D Graph. Games*, 2009, pp. 7–14.

[35] D. Krupke, P. Lubos, L. Demski, J. Brinkhoff, G. Weber, F. Willke, and F. Steinicke, "Evaluation of control methods in a supernatural zero-gravity flight simulator," in *Proc. GI-Workshop VR/AR*, 2015.

[36] X. Tong, A. Kitson, M. Salimi, D. Fracchia, D. Gromala, and B. E. Riecke, "Exploring embodied experience of flying in a virtual reality game with kinect," in *Proc. IEEE Int. Workshop Mixed Reality Art*, 2016, pp. 5–6.

[37] S. Beckhaus, K. J. Blom, and M. Haringer, "Chairio–the chair-based interface," *Concepts Technol. Pervasive Games: A Reader Pervasive Gaming Res.*, vol. 1, pp. 231–264, 2007.

[38] J. Wang and R. Lindeman, "Leaning-based travel interfaces revisited: Frontal versus sidewise stances for flying in 3d virtual spaces," in *Proc. 18th ACM Symp. Virtual Reality Softw. Technol.*, 2012, pp. 121–128. [Online]. Available: http://doi.acm.org/10.1145/2407336.2407360

[39] K. Kilteni, R. Groten, and M. Slater, "The sense of embodiment in virtual reality," *Presence: Teleoperators Virtual Environ.*, vol. 21, no. 4, pp. 373–387, 2012.

[40] E. Sikström, A. de Götzen, and S. Serafin, "Wings and flying in immersive vr – controller type, sound effects and experienced ownership and agency," in *Proc. IEEE Virtual Reality*, Mar. 2015, pp. 281–282.

[41] D. A. Bowman, E. T. Davis, L. F. Hodges, and A. N. Badre, "Maintaining spatial orientation during travel in an immersive virtual environment," *Presence: Teleoperators Virtual Environ.*, vol. 8, no. 6, pp. 618–631, 1999.

[42] M. Sousa, D. Mendes, R. K. D. Anjos, D. Medeiros, A. Ferreira, A. Raposo, J. a. M. Pereira, and J. Jorge, "Creepy tracker toolkit for context-aware interfaces," in *Proc. ACM Int. Conf. Interactive Surfaces Spaces*, 2017, pp. 191–200. [Online]. Available: http://doi.acm.org/10.1145/3132272.3134113

Daniel Medeiros received the BSc degree in computer science from UFPB/Brazil and the MSc degree in informatics from PUC-Rio/Brazil. He is a researcher with INESC-ID Lisboa. He is working toward the PhD degree in the Instituto Superior Técnico, University of Lisbon. His current interests include virtual reality, human-computer interaction and 3D user interfaces.

Maurício Sousa received the BSc and MSc degrees in information systems and computer engineering from ULisboa. He is a researcher with INESC-ID Lisboa. He is working toward the PhD degree in the Instituto Superior Técnico, University of Lisbon. His current interests include interaction design, 3D user interfaces and collaboration using multiple surfaces.

Alberto Raposo received the DSc degree in electrical/computer engineering from Unicamp, Brazil. He is an associate professor with the Department of Informatics/PUC-Rio, a project coordinator with Tecgraf/PUC-Rio and a FAPERJ researcher. His current interests include virtual reality, 3D interaction, HCI and computer graphics, and he has authored or coauthored more than 120 publications in these areas.

Joaquim Jorge coordinates the VIMMI research group at INESC-ID and is a full professor with the Instituto Superior Técnico, University of Lisbon. His research interests include virtual reality and multimodal user interfaces. He is an editor-in-chief of the *Computers and Graphics Journal*, a dellow of the Eurographics Association, a distinguished speaker and member of ACM and a senior member of the IEEE.