Floating Hamster Ball: A locomotion method for free flight in virtual environments

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***Abstract*—3D navigation is an important task in many virtual reality applications. Several virtual reality locomotion techniques were introduced in the literature trying to obtain a navigation with high quality and comfort, avoiding cybersickness. In this work, we propose a hands-free locomotion technique which uses intuitive mechanics with a considerable level of accuracy. Our method is inspired in a hamster ball, where the user has to roll a sphere from its interior in order to move in a 3d space. We evaluate three variants of our method in order to obtain a desired configuration. Objective and subjective measurements were applied to compare efficiency, user experience and cybersickness.**

***Index Terms*—virtual reality, 3D user interaction, locomotion**

I. Introduction

Recent advancements in Virtual Reality (VR) technology strongly require the development of interaction methods in virtual environments (VE). In VR interaction, locomotion is an important component that allows users to navigate in a VE, updating their position from one point to another. VR locomotion is still a challenging problem due to the fact that the user usually is limited by a physical space, but it can be addressed in different ways depending on the application and the available devices. There is not yet a well-defined classification or benchmarking parameters for VR locomotion techniques because these devices are continuously evolving and most of them have been introduced in the last few years. In general, these techniques can be differentiated by the kind of interaction and the type of motion in the VE. Boletsis [1] tried to classify them in four main groups: (1) Motion-based, where the user uses physical motion to navigate without constraints in the VE. (2) Roomscale-based, where the user can move around inside a constrained physical space and have an equivalent motion in the VE. (3) Controller-based, where the user uses an artificial interaction to obtain continuous motion, i.e. without blinks, in the VE. (4) Teleportation-based, where the user is instantaneously positioned at the target position.

There are some important features that define the quality of navigation such as speed, accuracy, spatial awareness, ease of learning, ease of use, information gathering (obtain information during the navigation), presence, and immersion [2]. Interaction fidelity, defined as the exactness of real-world interaction reproduction in the VE, helps to increment the presence and the usability, as shown in [3].

In addition to these features, it is important to be careful with virtual reality sickness (cybersickness), which is a common problem in locomotion methods so far. That problem can be more serious in VEs that require the user to move in any 3D direction because this kind of motion is less common in a physical space. Flying [4], [5], diving [6] or floating in a zero gravity space [7] are actions that allow the user to perform this kind of locomotion. Also, controlled platforms such as ships, airplanes, flying boards [8], magic carpets or other flying objects, can be used to transport the user in the VE.

Several VR locomotion methods based on artificial interaction use joysticks [9], flysticks [10], tablets [11], keyboards or trackballs to perform the navigation in any 3D direction. According to the studies by Bowman et al. [12], and by Jaeger and Mourant [13], this kind of method reduces immersion [12] and increases the risk of inducing cybersickness [13], because they do not offer proprioceptive and vestibular feedback. Trying to improve this, methods using more complex devices were developed (e.g. [14], [15], [16]), however, most of these methods are not hands-free, preventing the user from doing another type of interaction while navigating. Also, they use expensive and very specific hardware that can not be easily obtained.

In this work, we propose a new VR locomotion method to navigate in any 3D direction. It is a hands-free method that uses physical interaction (i.e. gesture-based), generates a continuous motion in the VE, and has not physical space constraints. This method is based on the idea of a hamster ball that can float and roll in free space. The user is located inside a sphere and can apply friction forces to generate motion. We adopt the intuitive physics of rolling a sphere on the ground to define the mode of interaction of our method. We describe and evaluate different modes of our method using quantitative and qualitative metrics in order to enhance the importance of the visual feedbacks, i.e., the rolling sphere surface effect. We found that this feedback increases the usability without introducing too much discomfort.

The rest of this paper is organized as follows. In Section II we describe some related work relevant to this study. In Section III we explain how our method works and how it was implemented. In Section IV we describe the experimental evaluation of our method and the obtained results. In Section

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V we discuss our method and its features. Finally, in Section VI we present the conclusions.

II. Related Work

In this section, we focus on VR locomotion methods to navigate in the VE following any 3D direction, and locomotion methods based on a spherical interface. We do not consider walking methods or similar ones because they are out of our scope.

Birdly [14] is a simulator of a bird flying where the user flaps his/her arms to fly and the device simulates wind and body positioning. In a similar way, Eagle Flight [17] is a video game that simulates the fly of an eagle where the user controls the flying direction using his/her head. AirtimeVR [15] simulates paragliding using an equivalent structure to a real paraglider. CharIO [16] is an adapted chair that allows a navigation with 6 degrees of freedom, where the rotation on the horizontal plane is controlled by the stool rotation and the other rotations are controlled by leaning the chair. Joyman [18] is a human-scale-based joystick platform that tries to preserve equilibrioception. Most of these methods are not hands-free, preventing the user from doing another type of interaction while navigating and use hardware of hard access.

In order to define the direction of motion, Mine [19] describes two different techniques: using the gaze (head-based controller) [2], [20]–[22] and using a hand pointing direction [2], [22]. As shown in [9], head-based controllers improve user performance and immersion reducing the risk of virtual reality sickness. Usually, when using this kind of techniques, the motion in reduced spaces and the speed control can turn into difficult tasks. Other locomotion techniques were developed by rotating the user around a central point or grabbing empty space [23].

Sphere based locomotion was introduced by using complex devices in two different ways: The VirtuSphere which is a device that allows the user to walk in place [24], and The Ultimate VR Vehicle which is a spherical platform that can navigate in any VE [25]. In a more abstract way, Mariancik [26] implemented a sphere that disappears while translating its position and appears in the target position. Based on the idea of a hamster ball, a locomotion technique that allows the user to move in the ground was discussed in [27]. Several comments about this technique describe that the method is funny and can be implemented for ball motion based games. In a similar way, our method adopts the physics of rolling a sphere from its interior, but the main difference is that our method follows a hands-free scheme and allows the user to navigate in any 3D direction. Also, we develop a user experience study evaluating quality and comfort features using different variants of our method.

III. Floating Hamster Ball

A. Description

Our method transfers the mechanics of rolling a sphere on the ground to a floating sphere that can roll in free space. It is inspired by a hamster ball toy where the user (hamster) can use all parts of its body to apply friction forces in the interior sphere surface rolling it. In our method, the user (human) is always inside the virtual sphere, as a hamster inside its ball. As he/she rolls the sphere, he/she moves as expected if the sphere was rolling on a plane under his/her feet. Forces are applied to the user using the vector created between the user head and the point where his/her hands collide with the sphere. This allows the creation of movement in any direction. Also, it is worth mentioning that the user never rolls with the sphere. He/she only translates, never rotates. These features result in three degrees of freedom interface, allowing the user to move the sphere in any 3D direction.

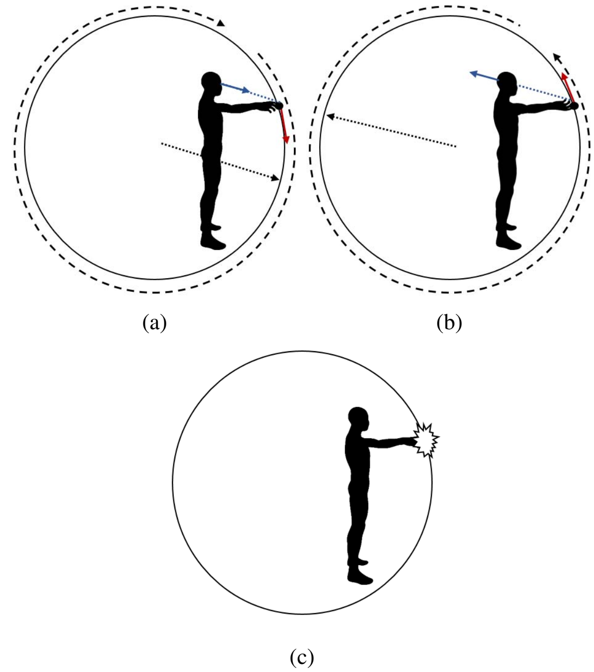


Fig. 1: Floating hamster ball interactions. Blue vector: pointing direction. Red vector: friction force direction. Doted arrows: translation direction of the sphere. Dashed arrows: torque applied to the sphere. (a) Move forward. (b) Move backward. (c) Stop.

It is worth mentioning that our method does not use whole body representation because it requires complex tracking systems that can introduce mismatching between physical and virtual motion. Therefore, we restrict the interaction to use hands only, so the virtual representation of the user is composed by an avatar with hands and vision. We use Leap Motion Controller[1], a hand motion-tracking device which has a high accuracy recognition. We also use Oculus Rift DK2[2], a head-mounted display which contributes to achieving a high level of presence and immersion.

The mechanics of our method can be described in three main movements (Fig. 1) as follows. (1) Move forward: occurs

[1]https://www.leapmotion.com/
[2]https://www.oculus.com/rift/

when the user collides his/her hands on the interior surface by applying a friction force from top to bottom. (2) Move backward: occurs when the user collides his/her hands on the interior surface applying a friction force from bottom to top. (3) Stop: occurs when the user continuously collides the hands at the same position applying static friction to the interior surface. The sphere stops its motion.

The friction forces can be applied at any point on the sphere interior surface. This point and the head-mounted display position are used to define the motion direction, i.e. the forward vector of the sphere. Since the sphere lies in a free space (without gravity) and has no friction, it lacks translational motion. Thus, a force is applied to the sphere center of mass to produce that motion, allowing the sphere to fly in a free space following any 3D direction.

B. Implementation

Our method was implemented using the game engine Unity3D[3] to control the virtual environment. The sphere is represented by a rigid body in which we can apply forces (acting through the center of mass of the sphere) or torque (acting with respect to a given axis). Aiming to facilitate user's hand collision with the sphere surface, we define atomic structures that we call contact points. These structures are just simple points that allow us to define collision positions and determine the friction force vector applied to the rigid body. We attach one contact point to each fingertip of the user's hands. So, the rigid body motion is influenced by the sum of all forces produced by the contact points.

The pointing direction for a single contact point which is colliding at position $\mathbf{x}$, is defined by the vector $\mathbf{u} = (\mathbf{x} - \mathbf{x}_c)/\|\mathbf{x} - \mathbf{x}_c\|$, where $\mathbf{x}_c$ represents the camera position. The friction force applied by each contact point can be represented as a tangent vector that lies on the sphere surface whose magnitude depends on the user's interaction speed. Given a constant time step where the position of the contact point at the initial time is represented by $\mathbf{x}_1$ and the position at the final time as $\mathbf{x}_2$, the tangent vector is defined as follows: $\mathbf{v} = \mathbf{x}_2 - \mathbf{x}_1$.

For each contact point collision, we can define a pointing direction and a friction force based on the previous point of collision. This tracking is filtered ignoring large distances that can disturb the interaction. We apply a torque to the sphere with respect to the vector $\mathbf{w} = \mathbf{u} \times \mathbf{v}$. The magnitude of the force is defined by $-\mathbf{up}_c \cdot \mathbf{v}$, where $\mathbf{up}_c$ is the up vector of the head-mounted display device (camera). An additional force is applied to the sphere's center of mass which follows the direction of vector $\mathbf{u}$. All forces are integrated and applied to the rigid body influenced by a damping factor. When the user tries to stop the sphere, these forces are dissipated.

The Floating Hamster Ball also provides the user with visual feedback about his/her interactions. When the user collides his/her hands on the sphere's interior surface, they change color and the sphere is illuminated. When the user is moving the sphere at a considerable speed, small particles are shown to define the direction of motion. While the user is stopping the sphere, small particles splashing show that the user is forcing to stop it.

[3]https://unity3d.com/

Fig. 2: User interacting with a VE using our navigation method (top). User visualization of the VE (bottom).

Aiming to identify the effects of our method on usability, user experience and reduction of cybersickness, we implemented three different modes as follows. Mode A: the sphere surface is totally transparent and the user can only perceive its presence by the visual feedback provided. Mode B: the sphere surface is transparent and can be perceived due that it has some relief patterns. The sphere surface remains static, i.e. not rolling, while moving in the space. Mode C: the sphere surface is transparent and has relief patterns. The user can perceive that it is rolling. Mode A and Mode B are variations of our concept, while Mode C is our concept without any modification. We hoped that the experiment would help us better understand and validate our design choices.

Figure 2 shows a user interacting on the mode C of our implementation (top), and how the VE looks like when the user is immersed within it (bottom). The user does not need

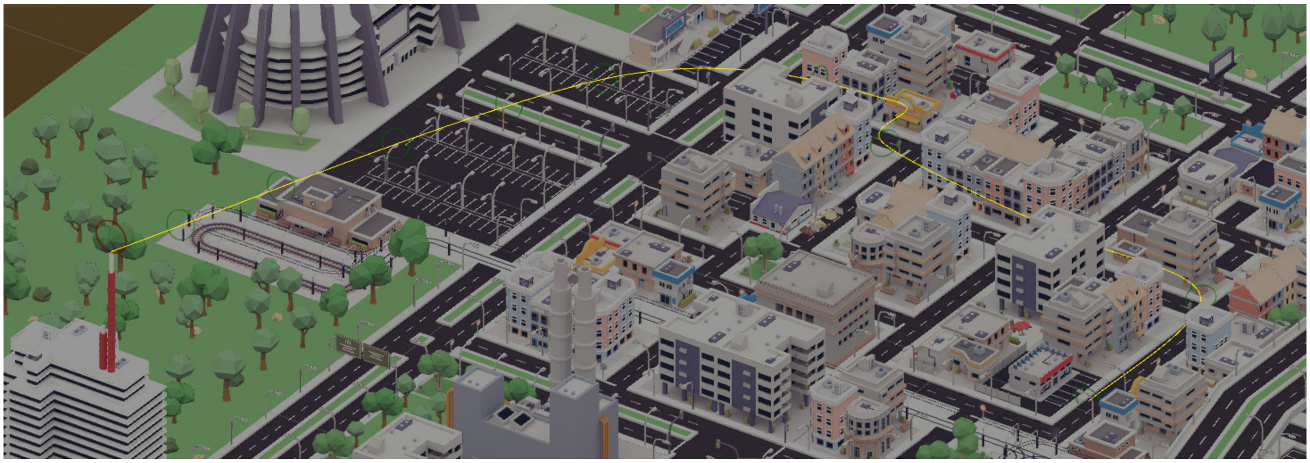


Fig. 3: Path used for experiments.

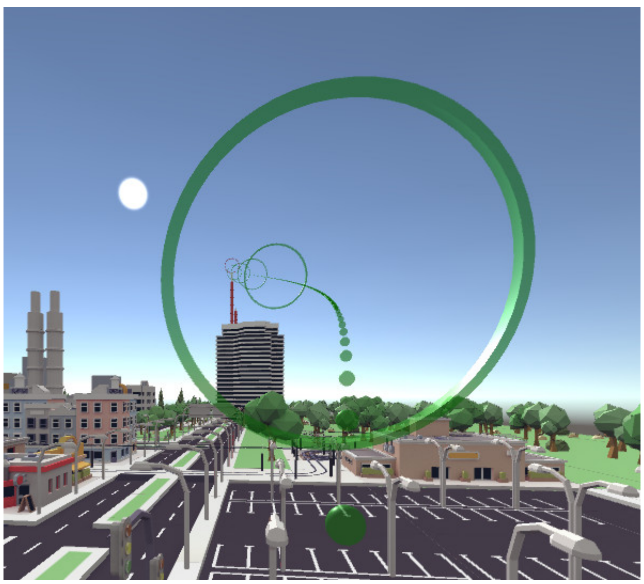


Fig. 4: First person view: Rings and points indicating the path to follow.

a controller to perform the locomotion interaction (roll the sphere) and has a small radius to perform another kind of interaction such as free movement of the hands. It is possible to see that when one hand collides with the sphere surface it generates a hand color change and an increase of sphere brightness. Also, we can see the relief patterns on the surface that are helpful to see that the sphere is rolling.

IV. Experiment and results

We conducted three evaluations of our locomotion method, one for each mode implemented (Mode A, Mode B, and Mode C) in order to identify their quality of navigation in terms of usability, user experience, and reduction of cybersickness.

A. Participants

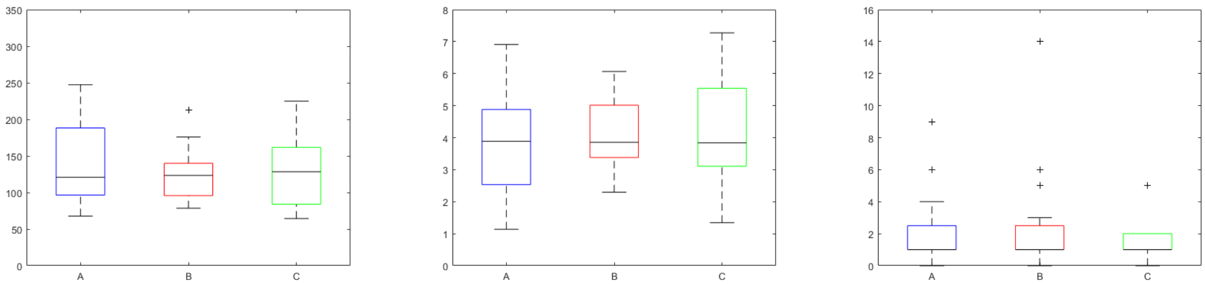
We recruited 16 participants, 8 of them had some experience with VR and 4 some experience using Leap Motion. The ages of 15 participants vary from 20 to 39 years, and one has 75 years. 2 participants are female.

Each participant experimented the three modes in different test sessions spaced by at least 15 minutes, only if the previous cybersickness symptoms are dissipated.

B. Procedure

Using each mode, the user has to follow a flying path around a city. The user starts at a ground level position and has to move through the city to reach the top of a big building. We used the same path for all modes and all participants in order to maintain uniformity in the experiments. This path is described by a set of points and rings inside the VE, and its corresponding shape is shown in Figures 3 and 4. As we can see, it starts in a street at ground level followed by several smooth and hard curves in a narrow space between buildings. These curves are helpful to test maneuverability. Then, it has a large free space with a high slope that allows the user to experience high speed and probably arm fatigue. The path ends in the top of a building where the user can experience vertigo sensation.

Before the test sessions, one for each mode, we explain the concept and the mechanics of the floating hamster ball. Then, using the corresponding devices and running the application, we show the mechanics again in more detail. After that, the participant is positioned to start the experiment without having a training time. We guide the participant if he/she gets lost or has problems with the interaction. We only follow this pipeline for the first session because the next sessions use the same mechanics. Due to the learning effect that a previous session can introduce in the next ones, we opted to use different session orders for different users. We used all possible permutations of the modes at least two times, trying to preserve



(a) time (b) speed (c) collisions

Fig. 5: Efficiency metrics boxplot

an equilibrium. After each session, the participant has to answer user experience and simulator sickness questionnaires.

C. Methodology

We evaluate the user experience efficiency according to the following aspects: the time the user takes to finish the path, the length of the user's trajectory, the speed of the sphere translation, and the number of sphere collisions. These metrics are helpful to define if the user succeeds in completing the experiment.

We also evaluate the user experience in two dimensions: pragmatic quality and hedonic quality-stimulation. Pragmatic quality (PQ) allows describing the usability of the method and the success of the interaction. Hedonic quality-stimulation (HQ-S) indicates the level of user interest in the method. We adopted the questionnaire proposed by [28] which measures PQ and HQ-S based on paired adjectives. These adjectives have opposite meanings and must be selected in a scale from -3 to 3, where -3 corresponds to the worst adjective and 3 to the best one. Hassenzahl et al. [28] assigned a score of each pair of words to compute PQ or HQ-S. We also adopted this score to compute PQ and HQ-S in our evaluations.

In order to measure cybersickness, we adopted the Simulator Sickness Questionnaire (SSQ) proposed by [29] and updated by [30]. The questionnaire allows us to define the levels of nausea, oculomotor disturbance and disorientation based on a set of more specific symptoms. These symptoms are weighted by the scores described in [30].

D. Results

All results described here compare the three modes that we propose. In the graphs, we use blue color to represent mode A, red color to represent mode B and green color to represent mode C.

In Table I, we show for each mode the average values obtained for time, distance, speed and number of collisions. We can see that mode A takes more time than the others, and mode C more time than B. The average trajectory length (distance) of mode C is higher than the trajectory length of mode B, resulting in similar average speeds. The average speed of mode A is considerably lower than the others. The speed can influence in the number of collisions, for this reason, mode A has a lower value than mode B. Nevertheless, the value of mode C is lower than the value of mode A, and the maximum number of collisions for modes A and B are 9 and 14 respectively, while for mode C the maximum is 5.

TABLE I: Efficiency metrics

Mode	Average Time	Average Distance	Average Speed	Average Collisions
A	155,149	479,998	3,796	2,063
B	123,512	479,904	4,197	2,563
C	140,256	480,646	4,196	1,813

In Figure 5 we show the corresponding boxplots where the top and bottom of the colored box are the 25th and 75th percentile, the line in the middle of the box represents the median, the plus sign marks represent the outliers, and the lines extending above and below the box are the whiskers. An observation is considered outlier if its value is more than 1.5 times the interquartile range, i.e. the range between top and bottom of the box. Whiskers are positioned to contain maximum and minimum values without considering outliers.

The time boxplot shows that mode B has the lowest median and the smallest box, indicating that it can be the fastest mode to perform the task. Notice that mode C has the minimum value while mode A the maximum. The speed boxplot shows that all modes have a similar median but different distributions. Mode B presents a smaller box and more centered whiskers, so the speeds are more balanced for this mode. Mode C presents the highest speed while mode A the lowest one. Collisions box plot shows 2, 3 and 1 outliers for modes A, B and C respectively. It is possible that these users had some difficulties to avoid collision with buildings. All modes have users that followed the path without colliding. Even so, mode C has a smaller box and without a value above the box. Unfortunately, these results are not statistically significant to define if one mode is better than other.

For each mode, Figure 6 shows word pairs average values included in user experience questionnaire. Bolded words are more related to PQ while not bolded are more related to HQ-S. It is clear that mode C has the higher average for most cases that define the PQ. In the case of HQ-S, word pairs

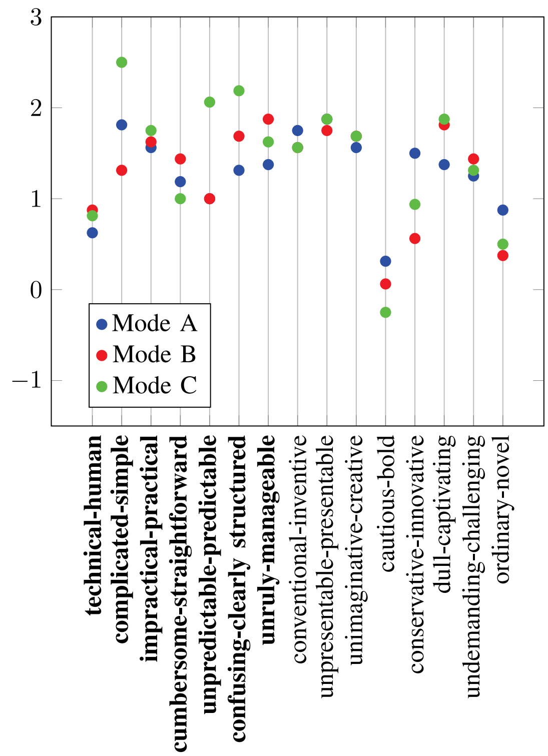


Fig. 6: Word pairs average values.

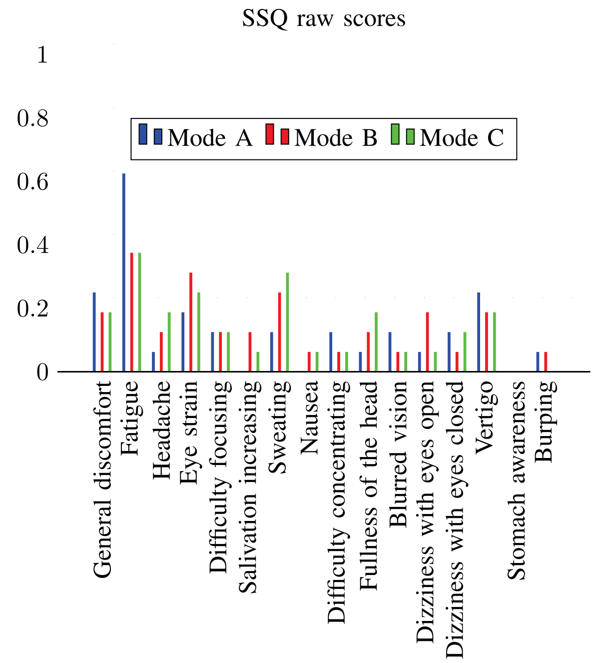


Fig. 7: SSQ raw data average

average values are more balanced. Based on this information we obtain the global values for PQ and HQ-S which are shown in Table II. It is more clear that mode C has a better PQ than the others, and mode B has better PQ than mode A.

We found that users with experience with VR performed the task using mode B and C in a reasonable amount of time, while mode A presented some difficulty. Some of them described that it is easier to use mode C than the others because they receive more visual feedback. In counterpart, some of them found mode C more uncomfortable to visualize the environment. Most of the users suffered too much trying to move the sphere in mode A, claiming that they had arm fatigue.

TABLE II: User experience

Mode	PQ	HQ-S
A	6,702	7,552
B	7,446	6,479
C	8,914	6,201

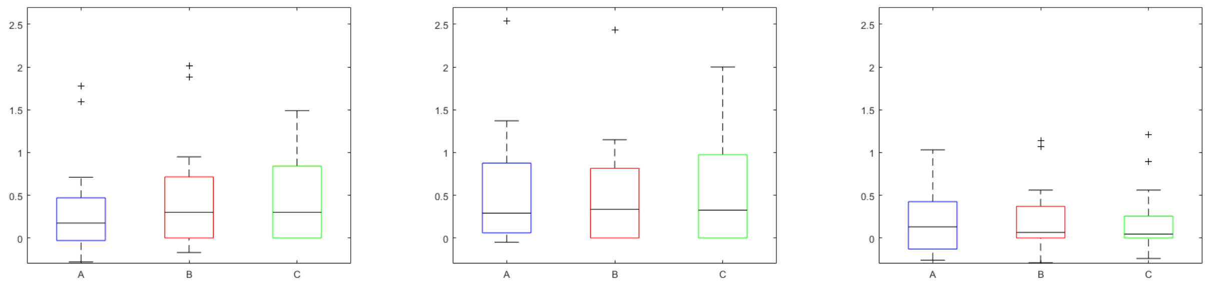
Measuring cybersickness, Figure 7 shows SSQ average values for each symptom. In general, fatigue is the most common symptom when using all modes, but mode A presents a considerably higher value than the others. The latter happens due that mode A is more difficult to use as shown by user experience experiments. General discomfort is an important symptom in this experiment because it summarizes other symptoms. Mode A has the higher value for this symptom. Mode A produces more vertigo than others because when the user sees the ground from the top of the building it has the sense that it is floating in the air, while in the other cases the user has the reference of the sphere that works as a ground. Mode C has higher values for headache and fullness of the head because seeing a rolling object all the time can be uncomfortable for the user.

Table III shows the average values for each dimension of the SSQ: nausea, oculomotor disturbance, and disorientation. We can see that mode A produces less nausea and disorientation than the others, but this can be induced by the low speed obtained by the users. In the case of oculomotor disturbance, mode A has the highest value while mode B has the lowest one.

TABLE III: Simulator sickness symptoms summary

Mode	Nausea	Oculomotor	Disorientation
A	0.342	0.568	0.186
B	0.493	0.518	0.219
C	0.436	0.535	0.199

Figure 8 we show the corresponding boxplots where the boxplot of nausea shows that mode A has the smallest median and a small size of the box (interquartile range). Also, whiskers are closer to the box. Oculomotor boxplot shows that the three modes have a similar distribution where the maximum value of mode C can be considered an outlier if we modify the criteria of outlier detection. In the disorientation boxplot, we can see that the quartile range of mode C is smaller than the others, resulting in a higher level of confidence. Its median is lower than the others and the outliers are disturbing the



(a) nausea (b) oculomotor (c) disorientation

Fig. 8: SSQ boxplot.

previous average value. As shown in [31], disorientation is more common in virtual reality applications, so the results of this dimension have a more important consideration.

V. Discussion

We introduced a VR locomotion method for free flying in general VE using a gesture-based scheme. This kind of method tends to be more immersive because it does not need an artificial interaction. The method generates a continuous motion inside the VE, avoiding spatial jumps such as teleport, resulting in a more realistic motion. Users have a small radius in the physical space to perform interactions while its representation in the VE has no space constraints. The locomotion depends on a simple interaction that allows the user to control the speed and direction of motion at the same time. Several flying techniques lack speed controlling or use different types of interaction to address both tasks. In the next subsections, we discuss some important topics related to navigation quality and cybersickness, considering some characteristics perceived during the experiments.

A. Navigation quality

Speed control is an important task to define the quality of navigation. Using our method, the user can acquire both high and low speeds by applying friction forces to the virtual sphere surface. Because the rigid body accumulates the applied forces, the user can speed up the translational motion performing faster arm movements or large armfuls. Due to the high PQ and the average speed reached by mode C, we found that the users have a better speed control when using this mode.

The sphere works as a vehicle that can follow any 3D direction. Combining this feature with speed control, we can acquire a navigation with high accuracy. In our experiments, all users achieved the path following task, that gives us some indication that the navigation accuracy of our method was enough to perform this task.

In our implementation we sum small friction forces during a collision with the interior surface of the sphere. So, the resulting sphere motion depends on the collision time and the amount of displacement during the collision. For that reason, not desired motion resulting from a wrong interaction or detection is amortized. The main difficulty occurs when the user is continuously touching the sphere with one hand, without the intention to stop it, while trying to move it with the other hand. In our experiments, we guided the users to take care about this phenomena.

Due that the VE physics works over the sphere, the user's motion is limited by the sphere's radius. This can be considered a disadvantage for navigation accuracy but it is helpful to avoid that the user passes through walls for example. Also, the physics over a sphere is simple and avoids abrupt motion changes that can generate discomfort for the user.

Because the motion direction of our method is not dependent on the user's gaze, he/she can look around while the sphere is moving. This is not possible using methods such as [17] where the user can not look around without modifying the navigation direction. During our experiments, we saw that some users using modes B and C, started to see around without stopping the sphere. This was possible because they had the sensation that they are inside a vehicle. In the case of mode A, it is more difficult to see around while the sphere is moving because it can cause vertigo or loss of equilibrium.

We found that the participants in our experiments did not need too much time to be adapted to our locomotion method. Our mode of interaction is more intuitive than methods that require a more complex learning such as the usage of a joystick. Mode C was the easiest to learn and use and this is evidenced in the user experience results (PQ). In counterpart, users found more interesting the mode A because it is bolder. The latter is shown by the HQ-S reached by this mode. During the experiments participants presented several problems while using the mode A, requiring more guidance than using the other modes. The absence of visual reference of the sphere surface disturbs the interaction.

Due that the locomotion is performed only when the user is colliding the sphere surface, there exists a free interaction space in the interior of the sphere that can be used for simultaneous task execution. For example, if an application requires the user's movement while throwing objects, our method can address this problem.

The user that has 75 years, started with some problems with the interaction because it was his first experience with VR. He tested mode C as the first experiment. Due to the simplicity of the proposed interaction, the adaptation was fast and the user reached the end of the path colliding just two times with an average speed of 2.26, which is not the minimum for this mode. No cybersickness symptoms were registered for this user. In the case of other modes, this user registered a similar speed but with some cybersickness symptoms. It is important to note that users that we expect to have more problems with the interaction got adapted rapidly.

B. Cybersickness

It is difficult to compare cybersickness results between the three modes. Mode A can be considered a special case because it has a poor usability and its average speed is considerably lower than the other modes. This can cause the user to perceive less visual movement and in consequence reduce the intensity of the symptoms measured in the SSQ.

Comparing modes B and C, mode C produces less average values for nausea and disorientation. Intuitively, we found that the direct feedback of the success or failure of a collision and the force that was applied, improves interaction fidelity. So, there exists a possibility that the continuous movement of the sphere surface can induce the user to avoid focusing on a specific point and for this reason, the perception of motion in the VE is decreased. In counterpart, we also found that this movement increases the oculomotor disturbance as shown by the average value.

VI. CONCLUSION AND FUTURE WORK

We proposed a hands-free gesture-based VR locomotion technique that allows the user to navigate in any 3D direction inside an arbitrary VE without constraints. Our method adopts several features that increase the quality of navigation keeping a simple mode of interaction. Using the same mechanics, the user can increase his/her speed and define the direction of movement. All these features are difficult to find in flying methods.

Rolling a sphere from its interior, such as a hamster in its ball, is an action that is easy to imagine. Considering this motion in a flying manner does not require a high level of abstraction because the same mechanics are used. All modes reached high levels of PQ and for this reason, we can say that our method is intuitive and easy to use.

Summarizing the advantages and disadvantages of modes that we proposed in this work, we can say that the low usability of mode A disturbs the locomotion efficiency and generates fatigue. Mode B and mode C are more easier to use do to the sphere surface reference but in the case of mode C the sphere surface rolling can introduce oculomotor disturbances. However, we recommend the usage and improvement of mode C because we think that the sphere surface rolling is an important feedback for usability and it can be helpful to reduce cybersickness symptoms.

Using mode A, we found that users showed more fear when the sphere collides with buildings and felt more vertigo when they reach a high altitude. The fact that the sphere works as a vehicle gives the user some security.

We consider further investigating the sphere surface rolling effect considering different speeds and textures. Also, the other feedbacks can be improved to obtain a better usability and help in the reduction of cybersickness symptoms.

In addition to visual feedbacks, we can explore different mechanics such as rotating on the current sphere's up axis. We perceived that most users tried to rotate the sphere movement direction applying a horizontal friction force.

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