Embodied interface for levitation and navigation in a 3D large space

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ABSTRACT

We propose an embodied interface that allows both physical and virtual displacement within an Immersive Virtual Environment (IVE). It consists of a modular wearable used to control a mechanical motion base from which a user is suspended. The motion base is able to navigate in 3D through seven wires whose length is adjusted via a parallel link manipulator. Furthermore, an IMU-based body posture detection enables users to "fly" within the IVE at their own will, providing hands-free navigation, and facilitating other tasks' interactions. To assess the usability of this embodied interface, we compared it with a Joystick-based navigation control. The results showed that this interface allows effective navigation towards several targets located in 3D space. Even though the efficiency of target reach of the Joystick-based interaction is higher, a subjective assessment shows that the interface is comparable to the Joystick in hedonic qualities and attractiveness. Further analysis showed that with more practice, participants might navigate with a performance comparable with the Joystick. Finally, we analyzed the embodied behavior during 3D space navigation. This sheds light on requirements for further 3D navigation design.

CCS Concepts

•Human-centered computing → Interaction design theory, concepts and paradigms;

Keywords

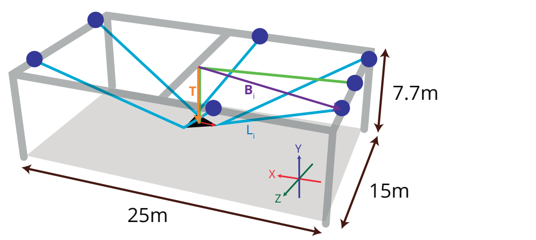
Embodiment, head anticipation, 3D space navigation

1. INTRODUCTION

Technology has allowed us to augment our innate human capabilities and fulfill ancient dreams, including that of flying. As land-based creatures, humans are not evolutionarily predisposed for controlling flight or position in 3D space. Human gait happens on a 2D plane, with moderate vertical displacement as allowed by the landscape. Levitating and flying introduce the possibility of vertical movement, which is not completely natural to us. In this sense, technology has opened the possibility for expanding our body-constrained limitations, and for challenging the physical laws. 3D navigation is already possible either using planes or Virtual Reality (VR) simulators. Both research about human navigation and training for movement in 3D spaces are done using these technologies.

Flying simulators are a popular VR application, both for training and entertainment, as they provide a risk-free environment where untrained users can experience flight. Beyond audiovisual factors, simulators can convey the feeling of vehicle movement. Given that VR flight simulators commonly mediate the control of a vehicle navigation; interfaces tend to mimic those of already existing vehicles. These include joysticks, buttons, or mouse pointing in a 2D plane translated to 3D navigation [2]. However, the possibilities expand beyond those. In 2001, [23] developed a taxonomy of the design space for navigation techniques. This taxonomy included differences according to the task selection, travel

(a) The LargeSpace and the Motion Base



(b) Motion Base wire diagram and LargeSpace coordinates. The green cable is the weight support cable. Dark blue circles correspond to each pulley. The vectors used for cable length calculation are also indicated

Figure 1: Motion Base of the LargeSpace

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control, and user interface. The variables in such user interfaces were the input mechanism, the control frequency, the control mapping, the type of display, simultaneous views, and simultaneous existence of objects. By proposing different interaction techniques, the authors capitalized on the VR visualization to compress, scale, and copy the VR world in order to facilitate navigation. However, these navigation control paradigms are heavily dependent on the visualization. It is important to notice that the used input mechanisms were only traditional button inputs. Nevertheless, as head-mounted displays (HMDs) become more affordable, opportunities increase to create new contexts where humans are able to experience individual flight. Furthermore, tracking and wearable technologies have also made it possible to explore new input modalities beyond buttons and thumbsticks. For instance, gestures tracked via motion capture systems are a popular interaction alternative that allows the user's body to be the controller of the virtual space.

One approach to gesture-based flight control has been to mimic birds, by using the arms as wings [18, 11]. Another approach to embodied interaction is to simulate horizontal gliding [9, 29]. Albeit intuitive, both wing-type or limb-extension type of interactions require to adopt a posture which is likely to cause tiredness very quickly. Additionally, the required movements do not allow users to freely use their hands for interaction with the Virtual Environment (VE). This problem is partially solved by providing a full body support wearable, and a button interface in the handles of such support. However, this does not allow to use other hand and limb gestures to do other tasks during navigation.

In a previous study, an exploration of multiple control modalities for embodied navigation pointed out to the fact that using subtle head movements had the potential to allow users to navigate in 3D space with a minimum effort [15]. Furthermore, previous research has explored anticipatory neural mechanisms that build predictions of future sensory and motor events during human gait; including gaze, head, and body movements. It has been shown that gaze anticipates head, and head anticipates body orientation to the gait direction of movement [6, 1]. Moreover, gravity restricts human displacements to 2D space. In this case, the head is stabilized to keep a continuously upright position with respect to gravity. Disorientation has been reported by astronauts when there is no such frame of reference, or when the head position is destabilized [27]. Despite the difficulties, professionals, whose work implies 3D navigation (e.g., astronauts or pilots), can master the task after a considerable amount of training. Even though there is a bodily optimization for terrestrial navigation using egocentric yaw rotations only; humans can deal and improve their spatial memory with allocentric reference frames in 3D-weightless environments [27].

Therefore, we propose an embodied system, that allows individuals to levitate and navigate in 3D space using head and body rotation as input mechanisms for 3D navigation in a real space. This is achieved with the support of one of the world's largest immersive virtual environment with full-surround and floor projections, named LargeSpace. While stereo projection displays are able to create the illusion of a virtual world larger than the actual size of the projection space; a cable-driven Motion Base supports the movement of a user in 3D space, providing a somatic sensation of flight.

The contributions of this paper are:

- The system design and implementation of an embodied interface that augments human 2D navigation to 3D real space movement.
- The assessment of the performance, usability, and hedonic qualities of the proposed embodied passive interface; relative to an active, button-based interface such as a Joystick.
- The behavioral assessment of human body posture during 3D navigation to inform future designs.

This system distinguishes itself from other flight simulation technologies in that: (1) it can augment human capability by allowing real-flight in a large space; (2) the user is able to experience it in an individual vertical position; (3) the proposed embodied control method for levitation allows for hands-free control with subtle movements.

2. RELATED WORK

There exist a number of flight simulators and 3D navigation techniques. First, we provide examples of cable-driven flight simulators similar to the Motion Base used in this study. Second, we describe in detail the most prominent embodied interaction techniques developed to navigate in 3D. Most of the mentioned works focus on virtual displacement only. The LargeSpace allows for both virtual and real displacements. In this work, we mainly focus on 3D real-displacement control. Its coupling with virtual displacement is left for future work. Therefore, previous work focusing on 2D virtual displacements or redirected walking to achieve unlimited virtual displacement sensation with a minimal real-world displacement (e.g., [21]) are not extensively mentioned here.

Since their first conceptualization in the 80s, cable-driven robots have become popular in applications where loads are to be transported over wide areas of space, for sports training, planar haptic interfaces, locomotion interfaces, and air vehicle simulators [14].

The "Seilroboter mit Passagier" or Cable-robot simulator [3], developed at the Tübingen-based Max Planck Institute for Biological Cybernetics (MPI) is among the first cable-driven parallel robots able to transport humans. It consists of a carbon fiber frame suspended by eight steel cables that can simulate vehicle trajectories in six directions.

More modest cable-based flight simulators include the Iron Man Flight Simulator [9], which is a mounting device made with a hang glider harness and a small crane. This system integrated a HMD with Google Earth images; a Wii remote to control the flight; and a wind machine to increase immersion. Furthermore, they used Ironman-like movements to steer the flight. Also, earlier work by Ars Electronica has the user suspended by a harness, combined with VR and force feedback to convey the sensation of flying [29]. Inspired by the practice of paragliding, flight is controlled by body rotation and limb movement. More recently, Krupke et al. [11], constructed a flight simulator with a climbing harness, a set of climbing ropes, a motor winch, and a Thera-Band sling for load reduction. With this arrangement, up to 400kg can be suspended from the ceiling from three points offloaded via pulleys. Users can be suspended while wearing a HMD, and their movements can be tracked from the floor to control a VR-simulated flight. Moreover, they designed two different types of control for the navigation. The first

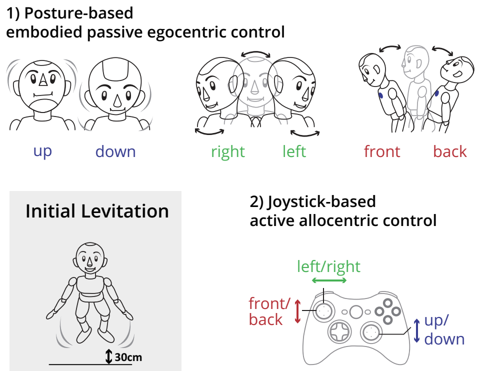


Figure 2: Overview of the interactions

one was simulating that of a bird, by moving the arms imitating wings. The second one was the so-called "Superman" method which solely used the orientation of one of the arms of the participant to steer the navigation. Finally, a user evaluation showed that both control methods were similar in usability, level of presence, and task load. However, participants reported that the bird method feels more natural.

Other alternatives to enhance the physical sensation of flying are moving body supports. This is illustrated by Birdly, which implements a moving base where the user can lie down, combined with rich audiovisual and haptic feedback elements to provide an embodied experience of flying [18]. Another example of a moving base attached to the ground to provide individual flight experience is the ICAROS project [19]. The proposed moving base provides support for legs and arms in a platform that allows pitch and roll movement. It includes a button controller to start and stop a flight application in a phone Application that can be visualized with the Samsung Gear VR. Flight control signals are obtained from the Smartphone Inertial Measurement Unit.

3. THE LARGESPACE

The LargeSpace is one of the largest immersive displays in the world. It covers a space of 7.7m height, 25m width, and 15m length.

3.1 Projection system

Stereo images are seamlessly projected on the walls and floor of the LargeSpace by twelve Mirage series projectors made by Christie Digital Systems [22]. Furthermore, objects within can be precisely tracked via twenty OptiTrack Prime infrared cameras.

3.2 The Motion Base

The Motion Base is a triangular-shaped structure that allows to suspend a user in the air (Figure 1). This is achieved by attaching a harness to the Motion Base, allowing users to be lifted and displaced, to be able to move their body and to make use of their limbs while in the air. The used harness is fabricated by Moritoh Corporation and can support a maximum of 560kg (100kg guaranteed). This harness lifts the users by the waist, and partly from the thigh.

3.2.1 Hardware

The wire-drive Motion Base is composed of a carbon-iron base and seven wires and seven pulleys that control wire length. Each wire is connected from a pulley installed in the top of the LargeSpace to the vertices and to the center of the base, in a Stewart Platform mechanism arrangement. Figure 1(b) shows placement of the wires in the LargeSpace. The aforementioned wires are SUS wires of 3mm thickness; except for the weight support wire hanging from the ceiling, which is 4mm thick. The maximum load supported by the wires is 3.5kN, and the maximum length is 30m, although only 20m are necessary for 6DoF movement around the LargeSpace. The motors are Panasonic MEME502SCH servomotors with 5.0 kW output, 15.9Nm torque, and 3000 guaranteed r/min. The diameter of the wire rod is 85cm, with a 2.5cm groove where the cable fits. The motors use an HPtec controller HCRTEX, and communicate with RTEX, which has 5msec latency [5].

3.2.2 Wire length and position calculation

The motion base is controlled by the rotation of the pulley and adjustment of wire length. Rotation is achieved with a parallel link manipulator [10]. Using this method, the wire length is calculated with Equation 1, by considering three vectors. First, the mounting position of the rope from the center position of the base to each of the Motion Base's vertices (P). Second, the vector indicating the position of the center of the base from the center of the ceiling of the LargeSpace (T). Third, the vector indicating the mounting position of each rope from the center of the space (B). For more details check figure 1(b). This system design allows the user to move around a 3D space of 10m width, 6m height, and 5m depth. The maximum speed is 2.5 m/s.

$$\mathbf{L}_i = \begin{bmatrix} X_L i \\ Y_L i \\ Z_L i \end{bmatrix} = R(\phi, \theta, \psi)\mathbf{P}_i + \mathbf{T}(X_T, Y_T, Z_T) - \mathbf{B}_i \quad (1)$$

3.2.3 Safety assurance

Security during movement is ensured by considering five factors. First, by constraining the maximum load of the system according to the vendor's safety indications. Second, by the implementation of a hardware emergency stop switch. Third, by an infrared sensor for excessive reel detection and prevention. Fourth, by a software blocking of out-of-range movements. Finally, by constraining the interaction design to avoid sudden human pulling of the harness, and by securely attaching to the body all control wearables or devices that might fall.

4. SYSTEM DESIGN

4.1 Interaction design

The so-called Levitas interface explores embodied movement control for 3D space navigation. Embodied interaction embraces the fact that human minds are not completely abstract or independent of a bodily existence; but rather, that cognitive and motor capabilities have developed together through biological evolution [4, 28, 16, 12].The body is emphasized as locus of interaction and the result of the user's actions affect the state of the whole body at every instant.

As humans do not possess any natural means to float in the air, the ability to fly using only our own body constitutes a completely new experience. Thus, an embodied control is a challenge. Our focus has been in interaction modalities

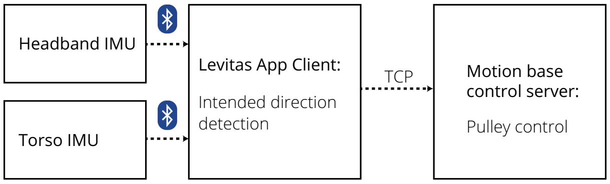


Figure 3: System overview

which are closer to natural action, even if levitation or flight are not natural capabilities of humans. Therefore, we consider body postures which take advantage of innate human motor characteristics; and we explore how they expand to 3D movement. We capitalize on the head anticipation phenomena during locomotion in 2D displacements [7, 1], and expect to see it generalized in 3D navigation.

Contrary to other flight simulators, the Motion Base allows individual flight in a vertical position, similar to floating or levitating. Previous work has shown the possibility of using a wing-type interaction to navigate in the LargeSpace with the use of the motion tracking system [5]. However, they did not propose a method to go backwards. Furthermore, the use of the limbs for additional interaction purposes is limited while moving the arms as wings; and the broad nature of the gestures may cause untrained users to quickly become tired. Therefore, subtler body movements like waist rotations and head orientation were preferred to indicate navigation direction.

Our proposed interface uses two Inertial Measurement Units (IMU) integrated in a headband and a pin for the clothes. They are used to detect head and torso rotations which are intended to act as passive control inputs. Passive modalities are those that require no explicit input command. This design choice was made in an effort to create a perceptual interface based on body movements and states which people inherently perform [24].

Users are allowed to navigate in three axes. The X axis corresponds to front and back; the Z axis to left and right; and the Y axis to up and down (Figure 1(b)). These movement directions were mapped to multiple control inputs. Figure 2 summarizes the proposed movements for navigation control. For navigation in a horizontal plane, head and torso orientation are used. By leaning forwards and backwards, the motion base also moves in those directions. Looking left or right steers the Motion Base sideways. Finally, looking up and down grants the user the power to ascend or descend. The selected movements are subtle, and unlikely to cause tiredness.

4.2 System architecture and wearable design

The Motion Base is controlled by two PCs, one of which functions as a client and hosts the control application; the second PC is a server, which effectively controls the Motion Base's pulleys and wire length. The system overview is provided in Figure 3.

The sensing system consists of a modular wearable device that includes two custom Inertial Measurement Units (IMUs) implemented with a Bosch BNO055 chip in UART configuration and a RN41 Bluetooth SMD module which relays the data to the host of the software control application (Levitas App). The Levitas App receives and aggregates sensor data, computes the resulting motion, and sends commands to the Motion Base via TCP.

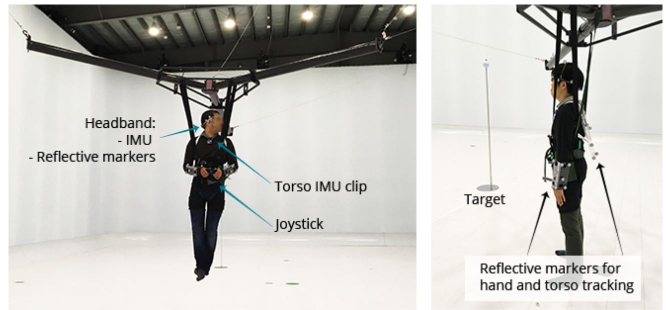


Figure 4: Wearable for 3D navigation and body posture tracking. An example of the 3D-real target, and the Joystick used for the user evaluation are also shown.

To allow prototyping iterations we opted on an unobtrusive, modular wearable design. It consists of a headband with an IMU, and a clip with a second IMU for the torso. The headband is fairly easy to put on and does not cover the face. One IMU is attached to it in order to measure head movement. A second IMU is implemented on a clip that can easily be attached to the user's clothes on the chest area. Each IMU is equipped with a Li-on battery, encapsulated in a box of 5 x 3.5 x 2 cm. The maximum size and weight is mainly due to the battery. Smaller pins could be achieved considering the trade-off with battery life.

For evaluation purposes, a set of hand-bands and a back-marker board were also designed. They consist of rigid structures of acrylic, with several markers attached. The intention is to track the user's body posture with the Motion Capture system of the LargeSpace (Figure 4). The motion tracking system maximizes tracking accuracy, and facilitates calculations by using the same calibration and reference frame.

4.3 Software

The Levitas App is written in C++ and acts as mediating layer between sensor data and the Motion Base control. Based on the sensor data, it computes the intended direction of movement, which is then sent to the Motion Base software via TCP. Smoothing is performed using a moving averaging window of 10 samples, to avoid jerky movements. The movement speed is set-up to a fixed rate of 20 cm/s.

The control of the Motion Base is done according to three states: (1) standing on the ground, (2) levitating, and (3) flying. The users always start on the ground, and they need first to achieve a state of levitation before they can fly around. The levitation is achieved by moving upwards 30 cm. After the user has reached the levitating state, the flying state is activated. While flying, the user can control his position in 3D space.

The IMUs require calibration at the beginning of each session, by recording the user's baseline position. The baseline position is a relaxed straight posture, with the head facing straight along the X axis of the LargeSpace in the West direction. Sensor readings after the calibration were subtracted from the baseline, to obtain only the rotation from it. If readings in any of the input channels rise above each respective direction threshold, then the user starts to move

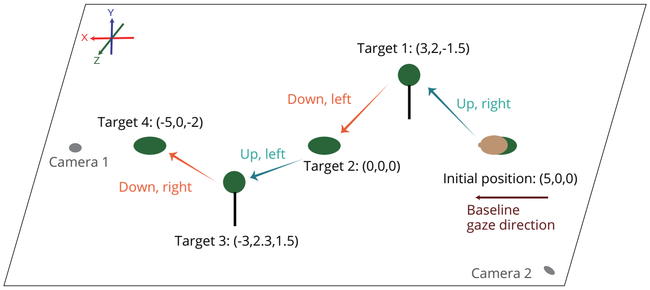


Figure 5: Target location during the user evaluation. The targets were tangible marks in the LargeSpace.

in that direction. Thresholds were defined after testing comfortable postures for several users, and adjusted slightly for each individual. Furthermore, they were mutually exclusive to the opposite direction of movement.

5. USER EVALUATION

A user evaluation was conducted to investigate (1) user's understanding, performance, and enjoyment of the proposed control system; and (2) to assess whether human head anticipation occurs in 3D navigation even when using other control methods non-dependent on this embodied characteristic.

We evaluated the effectiveness and efficiency of Levitas. Also, we conducted a subjective assessment of pragmatic and hedonic qualities of the interface. Being a hands-free embodied interface designed to match natural navigation movements, and even though reaching the activation threshold is slower than pressing a button; we hypothesized our system to have good enough performance, usability and to be enjoyable to use. As a reference, we compared the proposed system to a basic Joystick navigation interface. Joysticks are ergonomic, highly responsive, and the button pressing has inherent haptic feedback, therefore they are the VR control interface per excellence. Despite these advantages, having a joystick limits the hand usage for other types of interaction, and is often reported as less fun than gesture-interaction [26]. Moreover, we explored the user's body posture during usage to investigate whether the expected embodied control movements happen even if the user controls the navigation with a Joystick. For these purposes, an XBOX controller was implemented through the Levitas App, using the interactions described in figure 2.

5.1 Methods

1. **Experiment design.** Participants explored two interaction type conditions (Levitas and Joystick) in a within-subjects design. The conditions were presented in a counterbalanced order. Cable-length change speed was fixed to 40cm/sec in both conditions, and no VR visualizations were projected on the surrounding screens. Participants controlled their translation around the real 3D space as described in figure 2.

2. **Participants.** Fourteen participants voluntarily joined the study (average age=26.4 years old, SD=3.82; 3 female). Although some of them had previous experience riding the Motion Base, none of them used the proposed interface before. From these participants, the first one gave valuable qualitative feedback to quickly improve calibration and wearable comfort. The next three participants were considered as a pilot, and the remaining 10 participated during the full experiment as described below.

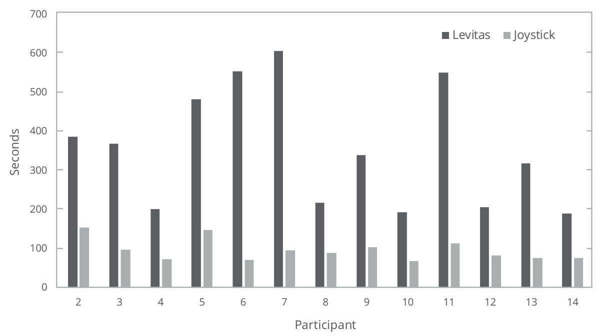
3. **Task.** Participants were provided with graphical instructions on what type of commands were available to navigate in a figure similar to figure 2. Afterwards, the system was calibrated to their preferred head and torso rotations. Next, they were invited to explore different postures to control their flight during three minutes of practice. After practicing, they were asked to fly to four position markers placed around the LargeSpace. Two of those markers were placed at 2 and 2.3 m above the ground, and two were placed directly on the ground (figure 5). The start and goal markers were located at the extremes of the X axis, and two-equally distanced intermediate goals at the extremes of the Z axis. They were given as much time as they needed to complete the task. Afterwards, each user was asked to fill in a questionnaire to assess the condition experienced right before.

4. **Measurements.** Data from all sensors was logged as well as the commands received by the server. Additionally, six reflective markers were attached to the headband, six to a back acrylic board, and seven to wrist boards as shown in Figure 4. This was intended for head, torso, and hand tracking during the trials. The subjective assessment questionnaire included: (1) the AttrakDiff questionnaire to assess pragmatic and hedonic qualities, in its online version [8, 25]; (2) a question about the degree of sense of agency in a 5-point Likert scale; (3) the Net Promoter Score (NPS) question in a 10-point Likert scale to assess how likely users are to recommend the system to friends or colleagues [17]; and (4) demographic and Joystick experience control questions.

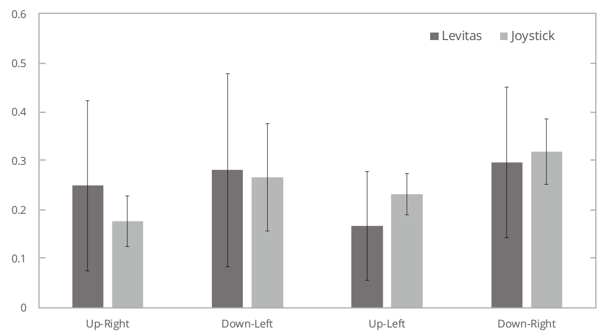
5.2 Analysis

The video recordings were analyzed to visually inspect whether subjects were able to complete the task or not. The motion tracking data of the head, torso, and arms was used to identify in detail the users' translation and rotation. Based on this information, the efficiency, or the time to complete the task, was estimated. The moment when the user reached the target was defined as the point in which the Euclidean distance between the user and the target is minimized. Additionally, we calculated the percentage of the total task time that each participant took to reach each one of the targets. This allowed us to test if the efficiency was dependent on the direction of movement, and therefore, on the posture required to control the flight.

Based on calibration data, we also determined the most comfortable head and torso rotations consciously chosen by the users. Next, we used the motion tracking data to analyze the actual head and torso rotations during the flight in both conditions. Questionnaire data was analyzed using standard statistic methods for repeated-measures. Finally, observations from the video recording and verbal comments from the participants are also reported.

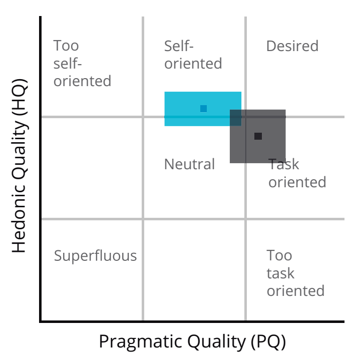


(a) Task completion time per participant (n=13)

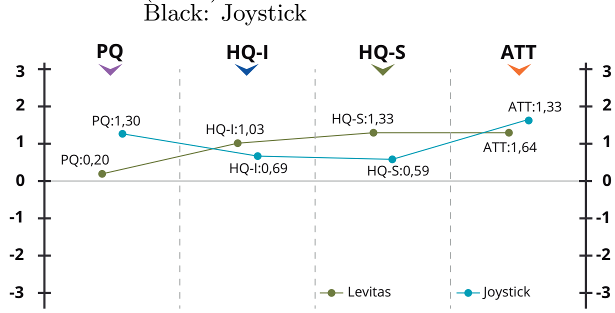


(b) Target reach normalized time per trajectory direction of movement (n=12)

Figure 6: Effectiveness completing the proposed task per input interface



(a) AttrakDiff Portfolio (n=10). Blue: Levitas. Black: Joystick



(b) AttrakDiff average values (n=10).

Figure 7: Subjective assessment

5.3 Results

5.3.1 *Task performance*

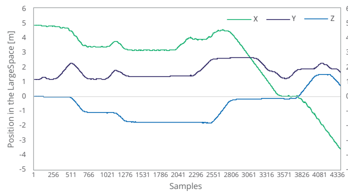
All participants finished the task, and reached all targets with both interaction techniques. Whereas variables in Levitas were participant ability and personal calibration, for the Joystick the main variable was previous gaming experience. 13 participants have used a Joystick before, and most considered themselves as beginner gamers. 12 of the participants played 0 to 5 hours per week, and only two played from 5 to 10 hours per week. Furthermore, 42% of the participants considered themselves as beginner gamers, and the rest considered their ability as intermediate.

Figure 6 shows task completion times per participant, interface, and direction of movement. The overall completion time with the Joystick was significantly shorter than with Levitas ($t(13) = -5.8719$, $p<0.05$). Completion times ranged from participant to participant, with wider variations in the Levitas control (mean =5.49 , SD=2.91) than with the Joystick control (mean =1.485, SD=0.62). A repeated measures two-way ANOVA with task completion time as dependent variable; and gaming experience and control type as independent variables was performed. There were no significant main effects of gaming experience ($F(2,14) = 1.193$, $p>0.05$); and the interaction between gaming experience and control type ($F(2,14) = 1.112$, $p>0.05$). Additionally, the time spent to reach each individual target yielded to no significant difference on controller type ($F(1,95)=0.003$, $p>0.05$). On the other hand, the movement direction ($F(3,95) = 3.71$, $p<0.05$), and the interaction between movement direction and controller type ($F(3,95) = 3.23$, $p<0.05$), were significant. Pairwise comparisons with Bonferroni correction showed no further significant differences. Figure 6(b) shows the time per direction of movement and per interface.

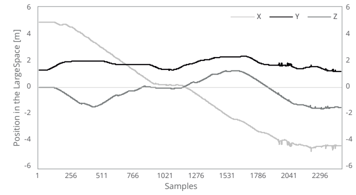
5.3.2 *Body posture*

Comfortable head and torso rotations reported by the participants during calibration were minima of 15° for head pitch upwards, 20° for head pitch downwards; 40° for both head yaw to the left, and for head yaw to the right; 4° for torso pitch forwards; and 3° for torso pitch backwards. These were well below the maximum described as normal human movement. The common values are 50° for head hyperextension (up), 40° for head flexion(down); 55° head rotation both to the left and right; and 70° torso flexion (front) and 30° torso hyperextension (back) [13]. Especially the torso rotation was very limited during calibration, due to the movement constraints imposed by the harness. However, during the actual flight, participants tended to do wider movements than the commonly observed in other contexts, and visibly apply more force while doing them. Even if they were reminded that it was not necessary. Finally, the sensor placement was different for some participants due to their hairstyle, which significantly changed the calibration values.

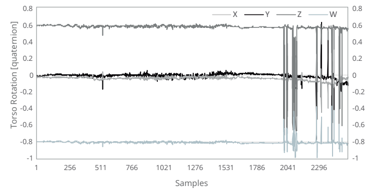
The motion capture data revealed that participants tended to keep their torso in the baseline position during the Joystick interaction, and that they rotated it just enough to move forwards and backwards in the Levitas interaction. Furthermore, they constantly reported that torso movement was challenging due to the harness structure, which supported all weight from the waist. Some participants opted for strategies such as extending the arms and legs to adopt a more horizontal position. However, this movement required



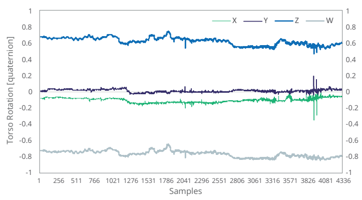
(a) Levitas translation



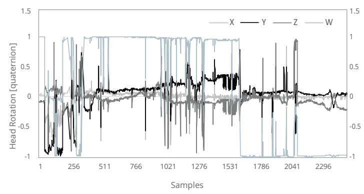
(b) Joystick translation



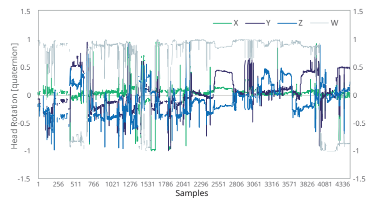
(c) Joystick torso rotation



(d) Levitas torso rotation



(e) Joystick head rotation



(f) Levitas head rotation

Figure 8: Body posture and moving trajectories for participant 4. Translations are represented in meters. Rotations are represented in quaternions. Both use the coordinate system of the LargeSpace. From the plots, it can be seen that users took more smooth trajectories with the Joystick than with Levitas. With Levitas, there were small torso rotations, whereas with the Joystick the torso was maintained straight. Finally, head rotations happened both in the Joystick and Levitas conditions.

visible effort.

On the other hand, head rotation occurred in both Levitas and Joystick conditions. During the Joystick condition, participants locked their gaze to the target, which helped them to achieve the task more effectively. With Levitas, the interactions were intended to move the head towards the desired movement direction, but participants often overshoot or undershoot the target. Probably because they were doing wider head movements than they would usually do while only looking at the target (Figure 8). Furthermore, some rotation combinations such as going forward and upwards; or backwards and downwards were reported as unnatural. As a strategy to cope with this, participants moved first on one direction, and then on the other, describing staircase-like trajectories (Figure 8(a)). In contrast, while using the Joystick, the moving trajectories were smoother, and allowed for diagonal movement (Figure 8(b)).

5.3.3 Subjective assessment

Subjective assessment ratings showed that whereas the Joystick interaction (PQ=1.3,HQ=0.64) has more perceived pragmatic qualities, the Levitas control (PQ=0.2,HQ=1.18) appears as attractive, and with slightly better hedonic qualities and attractiveness (figure 7(b)). This suggests that the Joystick interaction is more task-oriented, and the Levitas interaction is rather self-oriented. Even though the performance of the joystick is perceived as superior to the Levitas one, there is a trend indicating that the Levitas interface is more fun. The mean agency reported for Levitas was 3.2 (SD=1.1) on a 5-point scale. Similarly, the mean agency felt during the Joystick manipulation was 3.8 (SD=0.9). A paired t-test showed no significant difference ($t(12)=1.74$, $p>0.05$). Finally, the Net-Promoter Score for Levitas was 0.29, as opposed to the 0.14 score given for the Joystick interface.

6. DISCUSSION

The chosen interactions allowed for a fully controllable hands-free embodied interface for 3D navigation. 100% completion rate was achieved in the proposed task with fairly good usability scores. Despite participants taking longer completing the task than with a traditional Joystick, there is a trend indicating that Levitas has higher hedonic qualities; i.e., it is more fun to use. Moreover, we observed that head rotations towards the desired direction of movement were present in both conditions, which suggest that these movements are performed unconsciously, and have the potential to reduce mental load when using Levitas to navigate. Moreover, Levitas could be used for hands-free 3D navigation while a Joystick, or other type of interactions, are used to interact with the virtual environment.

Even though interaction with Levitas is slower, the time seems proportionally distributed in all movement directions. This is contrary to what we expected, given some uncomfortable posture combinations such as moving up-forward, or down-backwards. These postures are difficult because leaning forward naturally implies looking down, and leaning backwards implies looking up. Furthermore, wide head movements to the sides imply a lack of gaze contact with the targets. A possible result of this was the stair-like navigation paths adopted during the Levitas control. These navigation paths, in combination with target-gaze decoupling lead to frequent overshoots and undershoots in the Levitas condition.

Although performance did not depend on self-reported gaming experience, the participant's experience using a Joystick partially explains why they were so much better with it than with Levitas. Some of them even asked to stop the practice before its allotted time passed.

Interestingly, a couple of participants tried super hero postures to increase forward and backward torso rotations. More generally, participants tried to excessively compensate using movements for which the interface was not calibrated. Some of them guessed that wider-slower movements would help, but others opted to apply more force, which just made them more tired. It seemed that they expected force-speed coupling, which might be a hint for future design. As mentioned before, the movement of the Motion Base was set to a constant speed. This was somehow expected when using the Joystick, but for the body, participants seemed to expect a change. Furthermore, we would like to point out that in between trials, the users' position was reset from the final target to the initial one. This was done at the Motion Base maximum speed, while the user was still riding it. We observed that participants were not urged to hold the harness when they were in control and at a low displacement rate; but they tended to hold the harness more when they were not in control or when the speed became "scary". Thus, future designs should explore in more detail the role of acceleration in the users' behavior.

At a constant speed, head rotations happened in both the Joystick and the Levitas interactions. As observed, and reported by some participants, looking at the target destination is very important for navigation. However, the wide head movements during Levitas interaction made it difficult to always look at the targets. This is probably why participants took more time reaching the targets with the new interface.

Finally, we would like to point out that whilst the Joystick-based interaction was advantageous in this particular context, participants experienced some confusion when trying to reach the targets with their hands and they found them busy holding the Joystick. In these situations, the risk of dropping the controller was high. Therefore, we decided to physically tie the control to the user's wrist; which in turn made it difficult to change the hand holding the controller. This issue might be enhanced in more complex tasks with variable speed. In those situations, users would tend to either hold the harness, or to use their hands for more complex manipulations in the VR environment. All in all, instead of a competitor strictly speaking, the Joystick might be a good complement for embodied navigation.

This is reflected in the subjective assessment. Although the performance was superior with the Joystick, the perceived hedonic qualities and attractiveness of Levitas seems moderately higher. The NPS score was 15% above for Levitas. General usability is comparable for both interfaces, and the higher challenge in the Levitas might be explained by the lack of experience using this type of interfaces, as opposed to using joysticks. An alternative explanation is the wide-movement usage, which made it difficult to look at the target all the times. We expect that as people get used to the threshold interface, they would do more efficient movements.

6.1 Limitations

As this work outlined, embodied technologies pose new challenges. Different system requirements and behavioral reactions are expected from using our body as the control. Albeit small, the more salient limitation of our system is the actual, and the subjective delay between the command and the Motion Base reaction. The limited feedback available in Levitas, and the embodied nature of the interaction made it difficult for the participants to create an adequate mental model of the expected outcome of each movement. Furthermore, although head and torso anticipation were described as body posture passive inputs, the participants' tendency was to pay unnatural attention to them. While using Levitas, they became active movements. In fact, most users did use their head as a Joystick. Further research is needed to determine whether this effect would be alleviated with practice.

Another constraint was that the participants had many rigid bodies attached to track their body posture. These were used only for evaluation purposes, and might have constrained the movement of the participant. Without them, interactions might improve. Finally, the number of participants in the study was limited. More measurement would be necessary to confirm the preferred hedonic qualities of Levitas as embodied interface, when compared to a Joystick.

7. CONCLUSION AND FUTURE WORK

The proposed embodied interface for levitation and navigation in 3D space, called Levitas, was successfully implemented to drive the LargeSpace's Motion Base. The Motion Base is a cable-driven parallel robot that allows 3D translations in real space, and moderate rotations. When compared with previous work, the provided movement experience is unique, as it allows the user to ride in vertical position, respecting the natural reference frame for movement orientation. Levitas aimed to explore such advantage. Thus, the available control commands were designed to extend natural egocentric locomotion in 2d space to 3d space navigation. A user evaluation showed that Levitas is capable to obtain 100% task completion in a simple navigation and target reach task. Furthermore, it was rated as having good hedonic qualities, and fairly good usability: participants felt in control of their movements and enjoyed the flight. However, the efficiency and efficacy of the interface were not as high as that expected of navigation using a Joystick. Despite the aforementioned limitations, we uncovered evidence that even if a controller is used, people tend to redirect their gaze, and partially their heads to the desired target direction. Showing the potential of an embodied navigation paradigm in combination with other control modalities to interact with the surrounding virtual environment. Finally, we reported the average head and torso rotations when navigating in 3D. This information could be used to inform future interaction designs. In future work, we would like to assess the learning curve to such interfaces. As discussed by [27], the human body is not optimized for 3D navigation; however, we have the potential to improve with practice. Furthermore, a more accurate mental model of how the embodied interface reacts to the body movements could be supported by providing bodily feedback upon command activation. Other potentially interesting research directions include the usage of this interface in combination with the surrounding VR environment to increase the perceived navigated distance. Previous research already investigated how the psychophysical limitations of the human body can be used to give the user the perception of unlimited navigation although they did not move beyond a small room in the real world [21, 20, 30]. Finally, by integrating the virtual view in the system, more complex tasks where hands free navigation is important could be explored. In those contexts, Levitas might have a more prominent advantage to the Joystick's performance.

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