Isometric versus Elastic Surfboard Interfaces for 3D Travel in Virtual Reality

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Abstract

Three dimensional travel in immersive virtual environments (IVE) has been a difficult problem since the beginning of virtual reality (VR), basically due to the difficulty of designing an intuitive, efficient, and precise three degrees of freedom (DOF) interface which can map the user's finite local movements in the real world to a potentially infinite virtual space. Inspired by the *Silver Surfer* Sci-Fi movie and the popularity of the *Nintendo Wii Balance Board* interface, a surfboard interface appears to be a good solution to this problem. Based on this idea, I designed and developed a VR *Silver Surfer* system which allows a user to surf in the sky of an infinite virtual environment, using either an isometric balance board or an elastic tilt board. Although the balance board is the industrial standard of board interface, the tilt board seems to provide the user more intuitive, realistic and enjoyable experiences, without any sacrifice of efficiency or precision.

To validate this hypothesis we designed and conducted a user study that compared the two board interfaces in three independent experiments that break the travel procedure into separate DOFs. The results showed that in all experiments, the tilt board was not only as efficient and precise as the balance board, but also more intuitive, realistic and fun. In addition, despite the popularity of the balance board in the game industry, most subjects in the study preferred the tilt board in general, and in fact complained that the balance board could have been the cause of possible motion sickness.

Acknowledgments

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1 Introduction

Travel is one of the basic problems researchers want to solve in Virtual Reality (VR). More specifically,

> Travel is the motor component of navigation—the low-level actions that the user makes to control the position and orientation of his viewport. In the real world, travel is the more physical navigation task, involving moving feet, turning a steering wheel, letting out a throttle, and so on. In the virtual world, travel techniques allow the user to translate and/or rotate the viewport and to modify the conditions of movement, such as the velocity. (3D User Interface: Theory and Practice, Bowman, Kruijff, Laviola, and Poupyrev, 2004 [1])

Because in immersive virtual environments (IVE) physical rules in the real world do not necessarily need to be followed, travel is not limited to two dimensions in VR. However, due to the necessity of a third degree of freedom (DOF) and the extra cognitive load it carries to the users, more considerations need to be taken when designing a 3D travel interface.

This thesis presents an innovative 3D travel surfboard interface, inspired by the *Silver Surfer* Sci-Fi comics [2]. After discussing the motivation of the research in this chapter, Chapter 2 will introduce some related work. Chapter 3 will explain the methodology in detail, specifically, how the interface is designed to meet the requirements of 3D travel. Then, in Chapter 4, I will illustrate the hardware and the software development of a multi-model VR system which uses the surfboard as a travel interface to realize 3D navigation in IVEs. Chapter 5 will describe a user study we conducted to evaluate the travel interface. And finally Chapter 6 will conclude the thesis work by summarizing its scientific contributions, and introducing some future work.

What motivated me to work on 3D travel in IVEs is the big challenge to design a good interface for 3D travel, and the larger benefits it brings to the VR, game and data visualization communities. Because of the prevalence of board interfaces such as the *Nintendo Wii Balance Board*, my inspiration based on the *Silver Surfer* Sci-Fi comics and movies can be implemented and tested inexpensively.

1.1 The Challenge of 3D Travel

According to Bowman *et al.* [1], the main difficulty of travel in VR is due to the fact that users who take actions in a limited local real space are immersed in a potentially infinite virtual space. Although this is also the case in real life when we use vehicles to replace body movements, without vestibular cues, we will not achieve the same intuitiveness and efficiency by simply replicating the same metaphor in VR. And the fact that travel interfaces have to be designed so that immersed users can focus on meaningful tasks, such as 3D virtual object selection and manipulation, and not the travel interface, makes the problem even more difficult to resolve.

In some special VR applications the user's virtual avatar is confined to a relatively small space similar to the size of the real world space in which her real body exists. Simulating real walking has proven to be the best solution [3] in these scenarios. However, real walking is far more complicated than it appears to be in that a variety of actions such as walking, running, jumping, squatting, and turning could be initiated and stopped abruptly or gradually, independent or intertwined with each other. Limited by the current tracking technology [4], simulating real walking is still very hard for the time being.

Compared to 2D travel in which the user's virtual avatar is constrained on a terrain surface by gravity, 3D travel is even more challenging to implement. An extra DOF is required to allow the user to change her height in the IVE and not all DOFs are usable. For example, according to Vidal [5], roll[1]is much harder to be understood and controlled

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[1] as in "roll, pitch and yaw"

by humans and has a much higher possibility to cause motion sickness compared to pitch and yaw. In fact, a fundamental dilemma that challenges researchers in the area of 3D travel is that humans by nature cannot fly, but nevertheless are expected to fly naturally and efficiently in the IVE using a specifically designed interface.

1.2 The Importance of 3D Travel

Despite all the difficulties, a well designed 3D travel interface can enable some important applications, as listed, but not limited in the following sections.

Games

The release of the *Nintendo Wii* game console led to a phenomenal success. The core reason is the innovative controller—*Wiimote*—that brought the realism of gaming to a new level. The use of motion control for user input made games more accessible to audience who did not normally play, and enabled the game developers to focus the game design more on user experiences rather than technical constrains. However, the techniques used in *Wiimote* has existed in VR for a very long time before commercialization by *Nintendo*.

Recently, *Microsoft* released the *Kinect* controller for its *XBox 360* game console. The *Kinect* controller consists of a structured infrared light projector, an RGB camera and a depth camera and is able to track the user's full body motion inexpensively. The popularity of it impacted research in many areas, including human computer interaction, digital art, robotics and VR.

The success of the *Wii* and *Kinect* show the impact motion based controllers can have on the game industry. Similarly, it may be beneficial for the game industry if we can create an intuitivea and efficient motion based travel interface to replace the current interfaces such as the gamepad and joystick. In addition, such 3D travel interface can also be used by theme parks such as *Disneyland* or *SixFlag*, as they already have similar systems populated in their parks.

Virtual Tourism

With the idea of visualizing the world in 3D, more and more virtual tourism applications have been built in recent years, the most popular being *Google Earth.* According to *Wikipedia*, 3D virtual tourism (3DVT) refers to

> . . . the street-level navigation of virtual reality environments for purposes of exploring physical places in space and time without physically traveling there. (Wikipedia, Three-Dimensional Virtual Tourism)

In spite of the VR vocabularies in this definition, most 3DVT applications, including *Google Earth*, do not actually provide immersive navigation experiences to the users. Nonetheless, the capability of exploring the real world virtually made people's life much easier, especially when assistant information got overlayed on top of the real world images.

Although some hand held devices, such as the *SpaceNavigator* by *3DConnexion*, are built to allow the user to travel on the virtual earth efficiently, there is no appropriate interface yet for navigating these environments immersively and intuitively. Most 3DVT applications only allow the user to navigate in the virtual environment in a way similar to teleoperating a tourist. General actions users could take include moving forward/backward and turning left/right using buttons on a keyboard, and changing orientation of the viewport using a mouse. Some special actions allow the user to zoom out of the scene to get a perspective of viewing the world in the sky. But these actions easily break the presence constructed by the general locomotion, and make the experience very unrealistic. A well designed 3D travel interface could possibly solve the problem and also expand the current user community of such applications.

Possibly, 3D travel interface would make more sense if used to navigate in the universe rather than the earth where our locomotion in real life is limited in 2D. With this being said, 3D travel technique could potentially benefit more areas such as astronomy research and education, by motivating the students with the immersive and realistic space navigation experiences.

3D Data Visualization

In addition to traveling in IVEs similar to the real world, 3D travel techniques can also be used to navigate in abstract virtual worlds, such as the world of data, constructed by 3D visualization. Although this seems very untraditional for serious scientific researchers who prefer effectiveness much more than immersiveness, as the data grow exponentially in our world, we cannot assure a flat 2D screen would fit the "infinite virtual data world" forever. Besides, VR researchers believe the change from "data in my hand" to "me in the data" would make a significant difference in the way scientists perceive data and the patterns therein, especially in research areas such as biology or chemistry. To achieve this goal, a 3D travel interface would be necessary.

Based on the importance of 3D travel, it is my goal in this thesis to create an interface that would allow an immersed user to navigate in an infinite 3D IVE intuitively, efficiently and precisely. Chapter 3, Chapter 4, and Chapter 5 will cover the design, development and validation of the interface in more detail.

1.3 Inspiration

The *Silver Surfer* is a *Marvel Comics* superhero created by Kirby in [2]. Regardless of the background story, the most interesting point of *Silver Surfer* as for VR researchers is that his superpower to surf in the universe using a silver surfboard implies a 3D travel methodology, as shown in Figure 1.1.

In the 3D space, *Silver Surfer* controls the surfboard's direction of movement by leaning his body, and controls the speed using his superpower. The advantage of this metaphor for 3D travel is that it creates an experience very similar to real life snowboarding, skateboarding or surfing. This anchor to reality will make an interface based on the metaphor very intuitive, realistic and easy to learn for a large population of users who have surfing experiences in real life. However, the efficiency, precision and

Figure 1.1: The Silver Surfer in movie *Fantastic Four: Rise of the Silver Surfer*

other properties of it to fulfill 3D travel tasks in IVEs remain uncertain and are some of the questions we want to answer in this thesis. In Chapter 3, I will detail the design of the proposed interface.

1.4 The Nintendo Wii Balance Board

The *Wii Balance Board* is a special purpose gaming device designed by *Nintendo* to enable users to play games by balancing on the board. The development of the balance board is tightly coupled with the development of the *Wii Fit* game, in which the players copy actions of a game character to exercise, as shown in Figure 1.2.

Because of sales volume, *Nintendo* is able to sell the balance board for about eighty dollars, making it an inexpensive solution to realize the surfboard travel interface. And despite its low cost, the sensor data it provides are very precise and reliable, according to the reports of VR researchers who based their projects on the balance board ([6] and [7]).

To summarize, in this section I discussed the motivation of this thesis, specifically, the call of a 3D travel interface and the difficulties of creating it, and the inspiration from

Figure 1.2: The balance board in the *Nintendo Wii Fit* game

a Sci-Fi comic and the prevelance of a device that makes it possible to be realized inexpensively.

2 Related Work

In this chapter, I will introduce some related work to this thesis. Section 2.1 serves as a review of research milestones in VR travel, most of which focus on 2D travel for its closeness to reality. Using the *Wii Balance Board* as a travel interface is not a new idea, and in Section 2.2 I will point to some attempts by VR researchers, including a *Segway* simulator by Valkov [8]. And lastly in Section 2.3 I will talk about isometric, elastic and isotonic devices and how the differences can be applied to this research.

2.1 Travel Techniques

Many input devices have been proposed and evaluated as travel interfaces. Classic game controllers such as mice, keyboards, joysticks, and game pads were the first to be evaluated. Although the results show low presence and intuitiveness compared to motion based interfaces [3], some of them are fairly effective for certain travel tasks such as flight simulation. To make virtual travel more intuitive, several researchers tried to bring real walking into the limited lab space by developing different types of platforms or mounting orientation and acceleration sensors on the users body.

Inspired by the treadmills in fitness training, some research designed omni-directional treadmills and numerous prototypes were proposed. Among these the *Torus Treadmill* developed by Iwata [9] and the *Omni-directional Treadmill* developed by Darken [10] proved to be feasible, although they suffered from loud mechanical noise and slow rotation. Several updated versions were developed by other researchers featuring larger surfaces, which significantly reduced the safety threat for the users walking on them.

Templeman [11] designed and implemented the *Gaiter System* for walking-in-place (WIP) travel. Multiple tilt and pressure sensors were mounted on special locations on the users body to track gestures of in-place turning, stepping, and strafing. The system included a torso-mounted framework dropping from the ceiling to hold the user in a small area. Backward walking was implemented using an additional gesture because natural forward and backward walking in place are difficult to differentiate using sensor data.

The *HiBall* tracker developed by *3rdTech* based on an early project at the University of North Carolina at Chapel Hill allows a relatively large range for position and orientation tracking. Based on it, a real walking interface was proposed, in which the user wears a *HiBall* tracker and naturally walks in a larger lab space to travel in a virtual space. The researchers compared this technique with WIP and joystick flying and reported significantly higher intuitiveness, efficiency, and precision for the real walking technique ([12] [13] and [3]). To take this further and realize infinite virtual world travel, Razzaque [14] invented a redirected walking technique. The basic principle it relies on is an observation that humans can hardly walk in a straight line without vision from the real world, although they always believe they do. And most people do not notice small rotations of the whole world they are immersed in. Based on these they imperceptibly rotate the virtual world little by little when the user is walking and are able to redirect the user to walk in circles within a limited lab space.

2.2 Balance Board Research

Since the release of the inexpensive *Nintendo Wii Balance Board* (BB), there has been a trend in the VR community to use it as a travel interface. The BB input device is a sturdy plastic panel that rests on four feet, each containing a pressure sensor that streams pressure values to the computer via Bluetooth. The four pressure values can be synthesized to obtain the user's center of gravity, which consists of X and Y components, as shown in Figure 2.1.

Most of the research based on the BB focuses on using it as a travel interface, by asking the user to face forward on the board and using the gravity center value along the Y-axis to move forward and backward, and that along the X-axis to turn left and

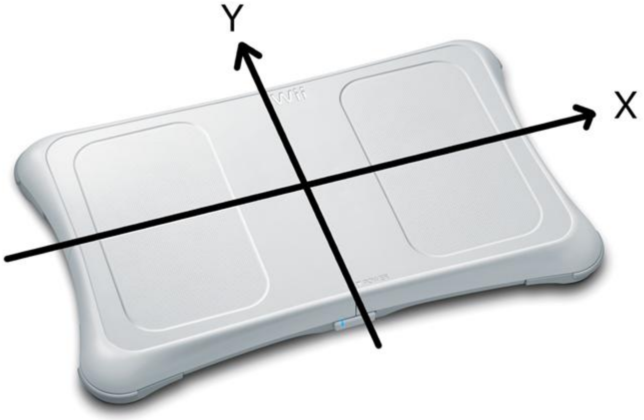
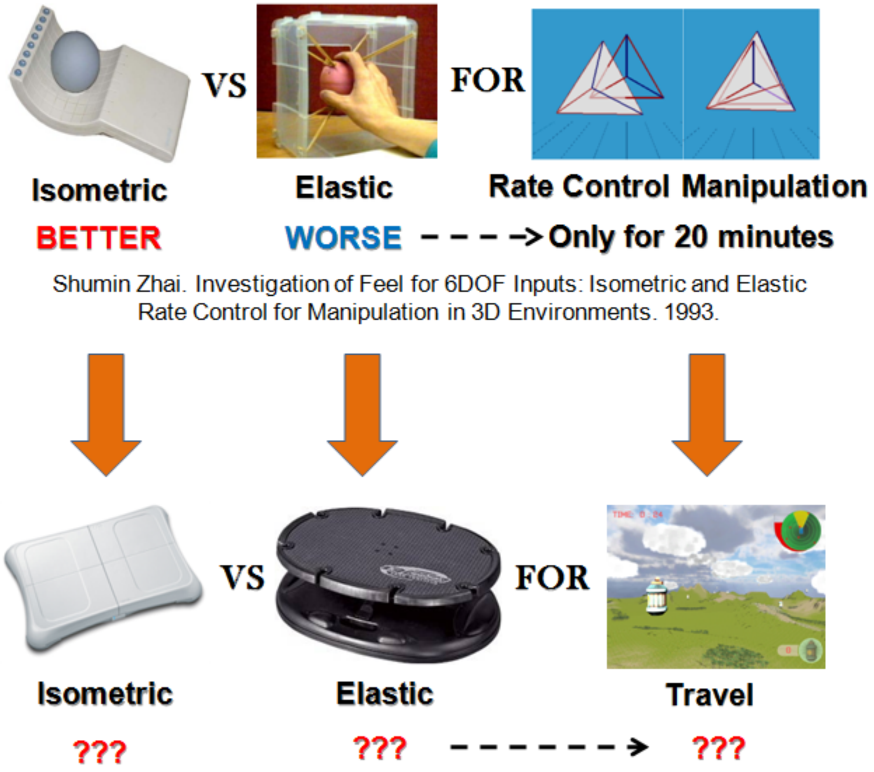


Figure 2.1: The coordinate system of the *Nintendo Wii Balance Board*

right in the virtual environment. The most recent implementation is Valkovs virtual *Segway Patroller* [8]. To extend the interface to navigate in 3-DOF, he programmed the BB to identify special foot gesture when the user leans one foot on its toe and the other on its heel. Depending on how much they differ from each other, the avatars position changes along the Z-axis at different rates. Though feasible, this approach is may not be intuitive and effective, and may be prone to undesired inputs, because the same foot gesture can be made when the user tries to maintain her balance on the board. In this thesis we also use the BB, but because of the 3D surfing metaphor we map the data from the X and Y axes to pitch and yaw of a virtual board.

2.3 Isometric, Isotonic and Elastic Devices

The terms isometric and isotonic came from exercise physiology. An isometric contraction happens when there is a tension on the muscle but no movement is made causing the length of the muscle to remain the same. On the other hand, in an isotonic contraction, tension remains unchanged and the muscles length changes[15]. In the context of human computer interaction, according to Zhai [15], an isometric device is a device that senses force but does not perceptibly move, such as the BB, while an isotonic device has zero or negligible resistance, but senses its own movement, such as the mice that are used with most of todays computer systems. Between the isometric and the isotonic, elastic devices refer to those whose resistive forces increase with displacement. For example, most re-centering joysticks are designed to be elastic.



Shumin Zhai. Investigation of Feel for 6DOF Inputs: Isometric and Elastic Rate Control for Manipulation in 3D Environments. 1993.

Figure 2.2: The relation between this research and Zhai [16]

In 1993, Shumin Zhai reported a series of user studies designed to investigate isometric, isotonic, and elastic devices for 6-DOF manipulation. In [17], subjects were asked to move a tetrahedron appearing away from the center of the screen as quickly as possible to align it with a target tetrahedron in the center, using a hand-held device that was either isometric or isotonic, under either the condition of position controlled or rate controlled data mapping. Results showed that by using isometric rate control and isotonic position control subjects took less time to complete the tasks than using other combinations. Two follow-on studies in [16] and [18] used the same experiment system to compare a hand-held elastic device with an isometric one for manipulating and tracking the tetrahedrons by rate controlled data mapping, and showed that the former has some superiority over the latter. However, all advantages vanished after 20 minutes of practice. This thesis, based on the virtual surfing metaphor, replaces the two hand-held devices with two surfboard interfaces and the manipulation tasks with 3D travel tasks as shown in Figure 2.2.

3 3D Travel Metaphor

In this chapter I will introduce the methodology that guides the design and development of the surfboard interface. Section 3.1 will introduce some background knowledge of travel interface design in VR. Section 3.2 gives a detailed description of how we designed the interface to meet the 3-DOF requirement of 3D travel. With the detailed design some research questions appear that need to be considered and inspected, including device directed direction control, position control versus rate control for virtual pitch and yaw, and isometric versus elastic interface for lower body interaction. All of these are discussed in Section 3.3.

3.1 Navigation = Wayfinding + Travel

According to [1], navigation in VR is a fundamental human task, that moves the virtual body of a user in and around an IVE. Navigation consists of travel and wayfinding. Travel is the motor component of navigation, which is the low-level actions that the user makes to control the position and orientation of her viewport in the IVE. Wayfinding is the cognitive component of navigation, which is the high-level of thinking, planning, and decision making related to user's movements. Clearly, travel and wayfinding are both parts of the same process and contribute toward achieving the same goals, and only in rare cases can one of them alone be used to fulfill the navigation task.

Wayfinding involves spatial understanding and planning tasks, such as determining the current location within the environment, finding a path from the current location to a goal location, and building a mental map of the environment [1]. Real-world wayfinding has been researched extensively, with studies of aids such as maps, directional signs, landmarks, and so on. In an IVE, wayfinding can also be crucial. If the user has no idea of where to go, the best travel interface would be useless. However, different than manipulation and travel techniques where the user perform actions in the IVE, wayfinding techniques support the performance of a navigation task only in the user's mind.

Travel is the task of performing the actions that move a user from her current location in the IVE to a new target location or in the desired direction. In the physical environment, travel involves unconscious cognition, that once we formulate the goal to move across the living room and through the door to the bedroom, our brain can instruct the necessary muscles to perform the correct movements to achieve the goal. The user's attention could be, and generally would be, focused on other events in the environment. In VR, we want to achieve the same level of intuitiveness and efficiency, and allow the user to reach infinity by her limited local actions. When we want to travel far distance in real life, we replace our simple body movements by vehicles, which is also achievable in VR by designing special interfaces. However, due to the absence of vestibular cues, the experience of driving a stationary vehicle will be much less intuitive and realistic, and may break the presence of the immersed user according to [1]. Therefore, to create a travel interface which is not only efficient and precise, but also intuitive and realistic is the main problem people are trying to solve in this area.

3.2 Surfing in 3D

General 3D space navigation consists of 6-DOF in two categories: pitch, roll, and yaw for orientation control and translations along the X, Y, and Z axes for location control. The fictional *Silver Surfer* can pitch, roll, and yaw his surfboard and use his "super charge" ability to speed up and move forward, giving him control of 4-DOF locomotion by which he can travel to any location in the 3D world. Because in essence three DOFs are sufficient to completely travel in 3D, and according to Vidal [5], roll (rotation around the forward direction) is against the human natural balance system and may lead to severe motion sickness and loss of orientation, we disabled roll of the virtual board in our design.

Because in real life surfing people prefer to define directions relative to the surfboard instead of the torso, I will redefine the four directions to prevent confusions. In the definition, I utilize two terms from skateboarding, snowboarding, and surfing for clarification purposes.

- Goofy: A stance of surfing, with the right foot in the front of the board's movement direction.
- Regular: The other stance of surfing, with the left foot in the front of the board's movement direction.

Based on these two terms, forward, backward, left and right are defined as follows. This definition will apply to the rest of the thesis, wherever I refer to directions.

- Forward: The forward direction when the board is moving. For a goofy surfer, "forward" here corresponds to the right side of her body; while for a regular surfer, it corresponds to the left side of her body.
- Backward: The opposite direction of "forward".
- Left: The direction when the board is turning left. For a goofy surfer, "left" here corresponds to the front side of her torso; while for a regular surfer, it corresponds to the back side of her torso.
- Right: The opposite direction of "left".

Figure 3.1 illustrates the design of the interface to satisfy the 3-DOF requirement of 3D travel. When a user stands on a board interface, she can balance her body to lean in four directions. Considering positive and negative values, this gives us two DOFs, which we can define as the X and Y axes. When she leans forward and backward, her center of gravity on the X-axis will change from negative (minimum) to positive (maximum). And similarly when she leans left and right, her center of gravity on the Y-axis will change from negative (minimum) to positive (maximum). In the IVE, the user will stand on a virtual board. And we map the center of gravity on the X-axis,

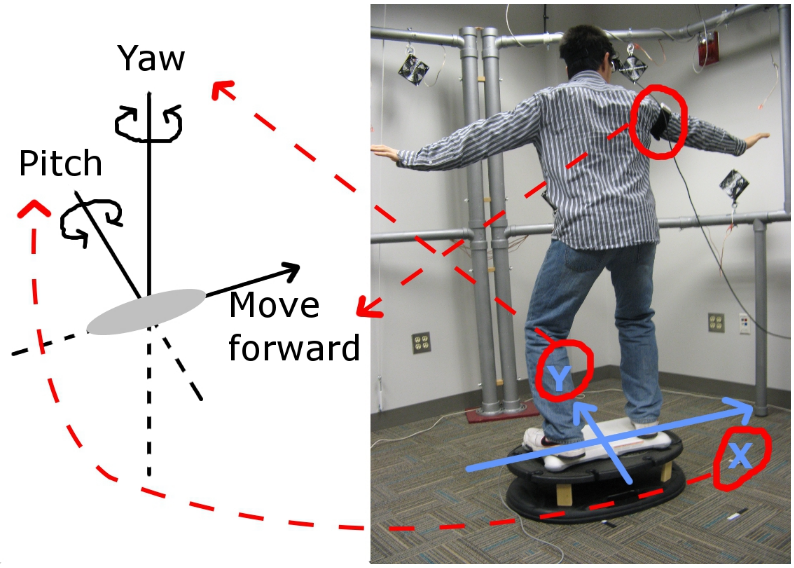


Figure 3.1: Implementation of 3-DOF travel

which is essentially the pitch of the board interface, to the pitch of the virtual board, and that on the Y-axis, which is the roll of the interface, to the yaw of the virtual board. In this way, the user can control the orientation of the virtual board in three dimensions.

The third DOF, the control of the travel speed along the forward direction, is implemented by mounting an accelerometer on one of the users arms. To eliminate the possible confusion of moving forward while pointing backwards, the accelerometer is always mounted on the users forward arm as shown in Figure 3.1. In another word, for a regular surfer the sensor is mounted on her left arm and for a goofy surfer it is mounted on her right arm. The accelerometer senses the tilt of the arm as it is raised or relaxed and feeds data to the system in real time to control the travel speed intuitively. However, when the user leans her body on the board to control the moving direction, she may unintentionally raise or lower her arm simultaneously, which will be detected by the accelerometer to update the speed. To deal with this side effect, the board sensors are consulted to see if the user is leaning or not when the data from the arm sensor are processed. And if necessary, the data from the board sensors will be used to compensate the surfing speed. In addition, to simulate real life skateboarding, snowboarding and surfing experiences and eliminate possible confusions, the system does not allow moving backwards when the user attempts to raise her arm at the opposite direction.

3.3 Research Questions

The design of the surfboard interface brings about some interesting research questions. In this section, I will define each of them in the contexts of related research.

3.3.1 Device Directed Control

Bowman *et al.* [19] categorized travel interfaces into three classes based on how the direction of movement is controlled.

- Gaze-directed interfaces: The user moves in the direction she is looking at.
- Pointing-directed interfaces: The user moves in the direction she is pointing at.
- Torso-directed interfaces: The user moves in the direction her torso is facing.

The surfboard metaphor belongs to a fourth category—device-directed interfaces—because the virtual board, whether pitched or yawed or kept still by the actions on the board interface, always moves towards its front like a vehicle, which is also the front of the real board from the immersed users perspective.

Because the virtual locomotion is decided completely by the board interface, when the users head is tracked, it is possible for her to travel in one direction while looking in another. However, the users viewport direction should not be completely independent of the board interface because in the virtual world, the users body is attached to the virtual board and pitching or yawing the board should naturally impact the body as well. This is similar to the experience of sitting on a swiveling chair. Because the body has a fixed connection to the chair, the viewport of the person will also be influenced. However, the impact will not dominate the viewport because of the existence of the neck. Although the surfboard interface does not turn in the real world, keeping the viewport in the IVE partially dependent on the turning of the virtual board will make a more realistic simulation of real life experiences.

In the swiveling chair example, when the seated person focuses her viewport on a target to her left or right side and the chair starts moving forward, the vestibular cues will tell the person that she is moving in a direction different from the direction of her viewport. However in the IVE, when the surfer focuses on a target different than the movement direction of the virtual board, because of the absence of the vestibular cues, the difference cannot be intuitively perceived and understood. The user's mind has to undergo additional processing of the visual information to understand what is going on and why she is not moving towards the target. This cognitive load may confuse or frustrate the user if not clarified beforehand. In a public demonstration of the *Silver Surfer* VR system (described in Chapter 4) at the 2011 IEEE VR & 3DUI conference, the cognitive overload confused many users. However, after some training, the cognitive load got reduced and the user got more efficient at travelling in the IVE using the surfboard interface.

3.3.2 Position Controlled versus Rate Controlled Yaw

In VR, position control and rate control are two approaches to map data from the device to a variable in the virtual environment. In position control, the user performs actions on the device to control a variable in the virtual environment directly; while in rate control, the same actions control how fast the value of a variable changes gradually, until the action is released by the user. For example when we navigate a web page, we can either drag the bar at the very right side of the screen to navigate directly to a certain part of the webpage, or press down the middle button of the mouse, and move the mouse up and down to control how fast the webpage gets scrolled up and down. Using the previous definition, the former approach belongs to position control and the latter belongs to rate control.

For the surfboard metaphor, the concept of rate control and position control can be applied to the pitch and yaw of the virtual board. In rate control, the pitch and roll data from the real board are used to control how fast the virtual board pitches or yaws; while in position control, they are mapped directly to where exactly the virtual board pitches or yaws. Intuitively, the pitch of the virtual board should be controlled by position, because by rate controlled pitch, the virtual board will possibly become upside down, which will confuse and nauseate the user whose body is always upright in the real world. However, rate controlled yaw and position controlled yaw can both be implemented to turn the board left and right. Although turning is by rate control in real world snowboarding, skateboarding and surfing, there is no clear proof that we should not consider position controlled yaw in virtual space surfing.

3.3.3 Isometric versus Elastic Surfboard Interfaces

Figure 3.2 shows two devices that can be utilized as the surfboard interface. The left one is the *Wii Balance Board* introduced in Chapter **??**, and the right one is a *Reebok Core Board* which tilts around two axes in a limited range. The balance board is isometric because its surface keeps stationary and senses the user's center of gravity by four pressure sensors. The tilt board is elastic because as it tilts in a limited range and the rubbers underneath the surface push it back to the center, giving the leaning user elastic resistance feedback.

Figure 3.2: Isometric versus elastic boards

Intuitively, the balance board is more stable and the tilt board is more realistic. Yet which one is better for the space surfing metaphor remains a question that needs to be examined by a comparative user study.

The last two research questions were investigated by a comparative user study, in which the users were asked to fulfill a 3D travel task in an IVE using either the tilt board or the balance board, and using either the rate controlled or the position controlled yaw. As mentioned in Chapter 2, the design of the user study is similar to that presented in Zhai [16] in the sense that we replaced the hand-held devices by two surfboard devices, and the manipulation tasks by 3D travel tasks, as shown in Figure 2.2.

The major differences between this thesis and Zhai [16] are listed as follows. The user study design will be detailed in Chapter 5.

- Muscle groups: Zhai [16] focused on hand-held trackball devices while this thesis focuses on board devices—the difference between hand interaction and lower body interaction.
- Rate and position control: In Zhai [16], the data mapping from the device to the IVE are by rate control. While in this research, we investigate both position controlled and rate controlled yaw.
- Tasks: The task users are asked to fulfill in Zhai [16] is 3D object manipulation, while in this research, the task is to travel to target positions in a 3D IVE.

To summarize, in this chapter I described the design of the 3-DOF surfboard interface to fulfill 3D travel tasks, and discussed three research questions it brings about. The last two questions formed a comparative user study which is very similar to Zhai [16]. The user study design motivated the development of the *Silver Surfer* VR system, which will be presented in the next chapter.

4 System Implementation

In this chapter I will present the *Silver Surfer* multi-model VR system, as shown in Figure 4.1. Section 4.1 will list all the devices involved and Section 4.2 will detail the virtual environment. The system implementation as well as the interface methodology are published in [20].

Figure 4.1: The *Silver Surfer* VR system

4.1 Hardware System

As shown in Figure 4.1, I utilized several input and output devices to set up the multi-model VR system. In this section I will discuss the functionality of each device.

4.1.1 Input Devices

Based on the metaphor in Section 3.2, I need several input devices (sensors) to implement the surfboard interface, and to track the user's head orientation so that I can utilize a Head-Mounted Display (HMD) to provide immersive vision of the virtual environment.

The surfboard interface is expected to work in two modes—the balance board mode and the tilt board mode—for us to conduct a comparative user study. For the balance board mode, we use the *Nintendo Wii Balance Board*. As mentioned in Section 2.2, the *Nintendo Wii Balance Board* is able to sense the center of gravity of a user standing on it and stream the data in X and Y components to the computer it is paired to using *Bluetooth*. According to a simple test using the *WiimoteLib* developed by Brian Peek [21], the data from the balance board are precise, responsive and reliable to be used as an ideal isometric board interface.

For the tilt board mode, we use the *Reebok Core Board*. It is an exercise board which tilts in four directions. The rubber underneath the surface resists tilt to keep it parallel to the ground which makes it an elastic device. However, because it is not designed as a human computer interface, a tilt sensor needs to be mounted underneath its surface to sense the tilt. We selected the *B-Pack Compact Wireless Accelerometers (Model WAA-001)* produced by *Wireless Technology Inc.* The accelerometer is *Bluetooth* enabled and streams 3-axis acceleration data at a maximum frequency of 50Hz to the computer. These data can be synthesized to get the pitch and roll of the sensor, and therefore can be used to sense the tilt of the board surface it is attached to.

Because the height and surface size of the two boards are very different, I combined the two into a single board interface which works in either tilt mode or balance mode to ensure an unbiased comparison. Figure 4.2 illustrates the idea. We fixed the balance board on top of the tilt board using industrial-strength *Velcro* hook and loop fastener, and put a piece of wood on each of the corners below the tilt board to disable the tilt if necessary. So when we want the combined board interface to work in the tilt mode, the wood pieces will be removed so that leaning on the balance board will tilt the board, and the data from the *B-Pack* sensor will be used to control the virtual board. On the other hand, when we want it to work in balance mode, we will mount the wood pieces underneath the tilt surface so that the balance board will be stationary and the data from the pressure sensors of it are used to control the virtual board similarly. By doing this, we can focus the comparison exclusively between the tilt and the balance features of the board interface.

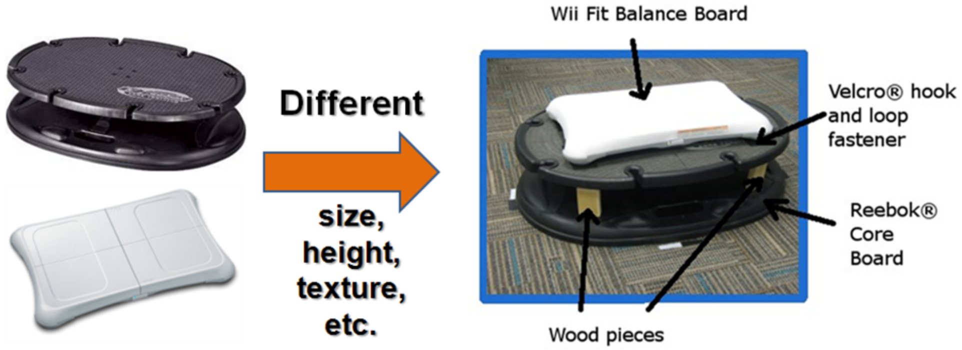


Figure 4.2: Combined board interface

To control speed, another *B-Pack* accelerometer is mounted by a neoprene wrap on the triceps of the user's forward arm.

To track the head orientation of the user, we use the *SpacePoint Fusion Sensor* produced by *PNI Sensor Corporation.* The *SpacePoint Fusion Sensor* is an inexpensive 9-DOF sensor (three axes each of magnetometer, accelerometer, and gyro) with a Kalman filter to calculate a smooth quaternion. It is recognized by the computer as a USB HID device. We convert the quaternion data to Euler angles so we can update the orientation of the viewport in the IVE. A simple test showed that the data from the sensor is very responsive, precise and reliable when used locally but may drift when its location is changed. Therefore we programmed the software system to ask the user for re-calibration when the user initially put on the HMD.

4.1.2 Output Devices

For the visual output, we use an *eMagin z800 HMD*. It consists of two OLED screens with a resolution of 800x600 and a diagonal field of view (FOV) of 40 degrees. There is a gyroscope and a headset coupled to the HMD but because of their low quality, we replaced them with the *SpacePoint Fusion Sensor* and a noise-proof headset. Although the HMD is capable of rendering stereovision on its two screens, we decided to provide monoscopic vision by rendering the two screens with the same picture, because the IVE we developed features more faraway objects and terrains, which do not make obvious differences in stereoscopic view. Because of the limited FOV of the HMD, to make the user more focused on the task and to increate immersiveness, we attached a black mask on the HMD that blocks light from the outside world.

Figure 4.3: The *TactaCage* wind simulation system

In addition, we use our *TactaCage* system to simulate wind as shown in Figure 4.3. This system was designed for an immersed user to stand in the middle and allow fans mounted around the perimeter to provide wind feedback under computer control. Seven muffin fans mounted in front of the user are used in the *Silver Surfer* system.

The speed of the fans depends directly on the speed of the virtual board, which is controlled by the arm-mounted *B-Pack* accelerometer. According to users' feedback from the public system demonstration, the wind simulation system makes the space surfing experience much more intuitive, realistic and fun. The only drawback of this system is that the fans make a lot of noise when spinning which is the reason that we replaced the build-in headset of the HMD with a noise-proof headset. The headset is proven to be very effective in shutting noises from the real world. And when the system is used to conduct a user study, the experimenter can still communicate with the subject through a microphone.

4.2 Software System

This section presents the software development to realize the surfboard interface in an infinite IVE. Section 4.2.1 describes the IVE we developed using the *Unity3D* game engine. Section 4.2.2 introduces a standard input/output(IO) framework called *Virtual Reality Peripheral Network* (VRPN) and a middle-ware called *Unity Indie VRPN Adapter* (UIVA) we developed to connect the devices to the IVE through *VRPN*. Finally, Section 4.2.2 explains how the raw data from the devices are processed to realize the surfboard interface.

4.2.1 The Silver Surfer Game

Based on the surfboard interface metaphor and the design of the comparative user study, we designed and developed a virtual environment using the *Unity3D* game engine, which is shown in Figure 4.4.

The virtual world is made infinite by rolling the same basic terrain tile in the direction the user travels. To elaborate, for example, in Figure 4.4, the virtual world contains nine identical terrain tiles that repeats in eight directions (north, south, east, west, northeast, northwest, southeast, southwest) based on the current location of the

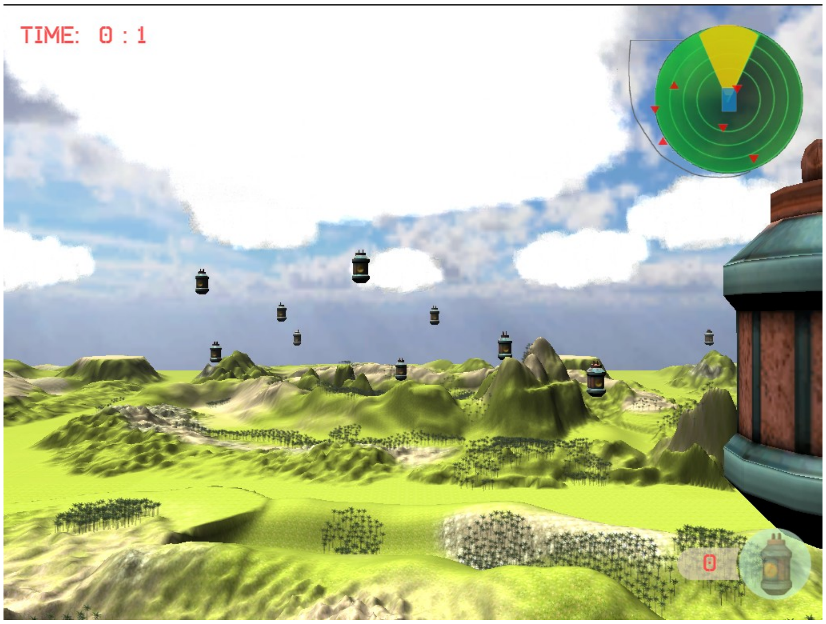


Figure 4.4: The virtual environment

Silver Surfer avatar. The avatar stands on a silver board which is rendered underneath her feet, whose direction is controlled by the board interface, either in the tilt mode or the balance mode. Above the infinite terrain, there are infinite green canisters floating in the sky at random locations. The user can fly through these targets to collect them by controlling the board interface. And when it happens, the virtual *Silver Surfer* will yell a cheering sound and the corresponding target will explode into particles to indicate that the target is successfully collected. To increase realism, clouds and trees are added to the virtual environment, both of which the avatar can fly through naturally without collision. When the user fails to maneuver the interface well and crashes into the terrain, she will be stopped by the terrain and no hurt or penalty will be applied.

To facilitate wayfinding, a radar is rendered at the top-right corner of the screen as a graphical user interface (GUI) component so the user can locate the targets near her avatar, as shown in a zoomed view in Figure 4.5. The red triangles indicate the targets locations relative to the virtual board. The virtual board is represented as a blue rectangle in the middle, and always faces up on the radar. So when the virtual

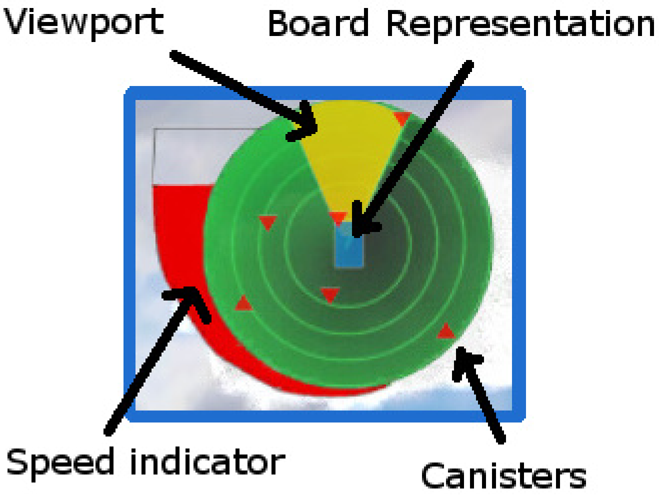


Figure 4.5: The radar

board yaws, all objects on the radar except the board rotate in the opposite direction around the center point of the radar. In another words, the radar is designed to be forward-up instead of north-up. The yellow sector corresponds to the users viewport whose direction depends mainly on the user's head orientation and partially on the yaw of the virtual board. The red bar to the left of the radar indicates the user's current surfing speed, based on the data from the arm-mounted accelerometer.

In addition to the radar, the timer on the top-left corner shows how long the user has been immersed in the system, and the number next to the canister icon in the bottom-right corner indicates how many canisters the user has collected.

At last, a background elevator music is added to the virtual environment to damp the noises of the fans, and to add more fun as well.

4.2.2 Connecting Devices

In this section I will explain how the devices introduced in Section 4.1 are connected to the virtual environment (the *Unity3D* game engine). All the input devices are connected directly to *VRPN* as servers and the game engine as a client polls the latest data by sending a request. The communication between the game engine and the

VRPN servers is realized by the *UIVA* middle-ware.

B-Pack

The *B-Pack* accelerometer is mounted on one of the user's arms to enable the user to control her travel speed by simply raising/lowering her forward arm, which simulates the experience of real life skateboarding, snowboarding and surfing when the surfer raises two arms to keep balance. In *VRPN*, the accelerometer is recognized as an analog device with three channels corresponding to the acceleration along the three (XYZ) axes. These three values are synthesized on the client side to get the angle of the pitch and roll of the sensor. The data is generated by the device and streamed to the *VRPN* server every 60 milliseconds and the latest data gets sent to the client from the server upon request.

The B-Pack accelerometer is mounted in a way that its pitch value will range from 0 to 90 degrees when the user lifts her arm from waist-side to horizontal. We use the *go-go* technique [1] to map the raw data to the speed of the virtual board. Specifically, the pitch data is mapped linearly from 0 to 45 degrees, and exponentially from 45 to 90 degrees so that the user has both precise slow speed control which allows her to fine-tune her position in the IVE when she gets close to a target and large range high speed control which allows her to travel large distances across terrains more efficiently.

As mentioned in Section 3.2, there is a side effect of using arm to control speed. When the user shifts her center of gravity on the board to control her direction, her arm may go up and down with her body unintentionally. For example, when the user leans backwards on the board to pitch the board up, she may lift her arm to more than 90 degrees, and will find her avatar moving much faster than she has expected. And because she is immersed in the virtual world, she may not understand the reason.

To solve this problem, we took the pitch of the board into consideration to determine the travel speed. In another words, the pitch of the board is used to estimate how much the user inclined her arm unintentionally, and is subtracted from the arm sensor pitch data to make the speed control more usable.

SpacePoint Fusion

The SpacePoint Fusion sensor is attached to the HMD to track the user's head orientation to provide immersive visual feedback. It is also recognized as an analog device by *VRPN* with four channels corresponding to the four quaternion values representing the orientation of the sensor. These four values are transformed to three Euler angle values according to Shoemaker [22] on the client side to update the orientation of the viewport.

Wii Fit Balance Board

The user stands on the *Wii Balance Board* and shift her center of gravity to control the direction of her virtual locomotion in 3D. It is also recognized as an analog device by *VRPN* with four channels corresponding to its four pressure sensors. These four values are synthesized on the client side to get the center of gravity on the XY plane it defines.

Because of the height, weight, and balance skill differences, different users may have different center of gravity ranges. Therefore a calibration procedure needs to be carried out before the user interacts with the system. In the user study, the user follows the picture instructions shown in Figure 4.6 to calibrate the board interface, for both the tilt mode and the balance mode.

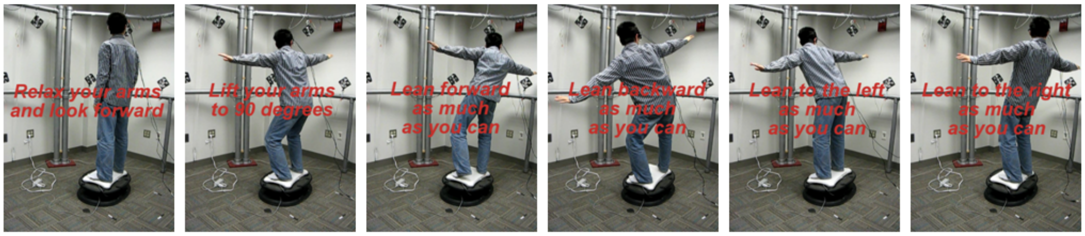


Figure 4.6: The calibration procedure

In the original design, the tilt board was tracked using the *B-Pack* accelerometer which is mounted underneath its surface. However, the balance board can also be used for the same purpose because the user will stand on it and shift her center of gravity when she tilts the board. If calibrated correctly, the tracking of the tilt board using the balance board data can be equally precise, responsive and reliable. In fact, we compared both solutions and most users reported that using the balance board data to track the leaning of the tilt board feels more usable. This may be because of the hardware advantages of the pressure sensors over the accelerometer.

In the IVE, the center of gravity data along the X-axis is used to control the pitch of the virtual board by position control, and that along the Y-axis is used to control the yaw of the virtual board by either position control or rate control, as a parameter to be evaluated by the user study. Figure 4.7 shows how the board data get processed.

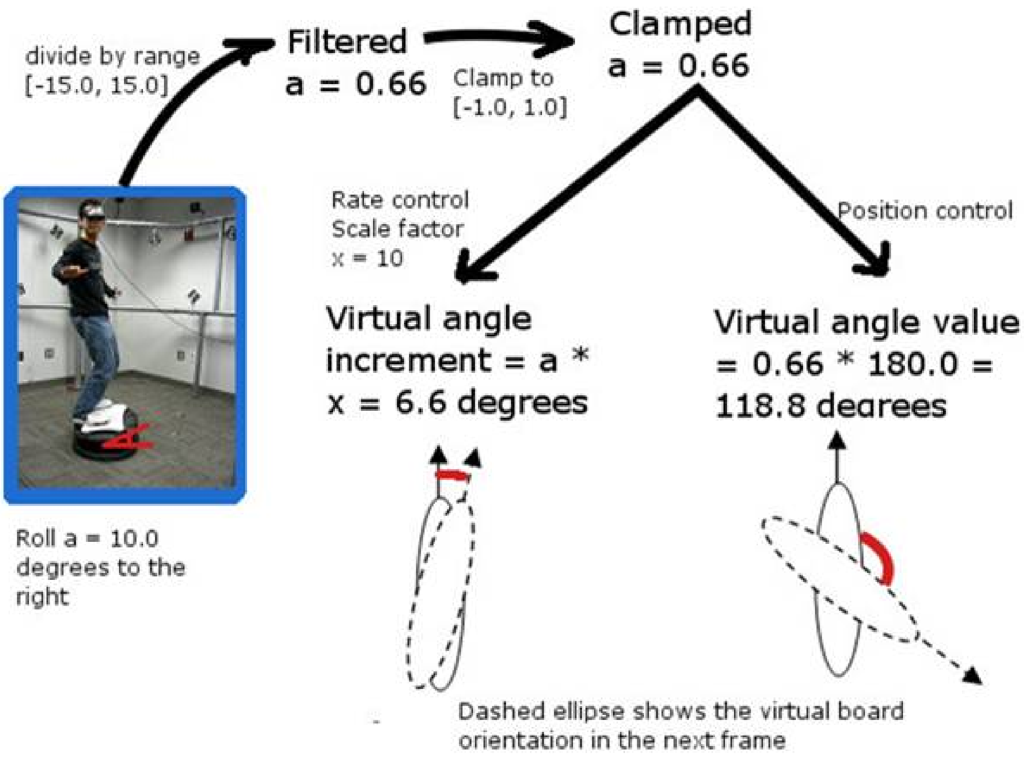


Figure 4.7: Data processing of the board interface

The range values used to divide the raw data from the board are obtained from the calibration procedure. In rate control, the data from the real board (clamped to [-1.0, 1.0]) are used to control how fast the virtual board yaws, namely, the rate of the yaw; while in position control, it is mapped directly to where exactly the virtual board yaws to, namely, the position of the yaw.

TactaCage

To increase immersiveness and add more locomotion cues, the *TactaCage* wind simulation system is used to render wind based on the user's travel speed. It is driven by the *TactaBox* which is essentially a PCB programmed to control the voltage of up to 16 outlets. The *TactaBox* is connected to the computer at the serial port and allows the computer to control the 16 voltage values by sending formatted commands. Each outlet is indexed by an ID and its voltage ranges from 0 (no wind) to 255 (strongest wind). The serial communication is programmed in C# and compiled to a DLL file which is included in the asset folder of the game so that a script can be written on the engine side to update the voltage values of one or more fans. Using this approach the wind speed can be easily updated in each frame of the game.

UIVA

The *UIVA* middle-ware is developed to connect *VRPN* and the *Unity3D* game engine. The framework in Figure 4.8 explains the functionality of the middle-ware.

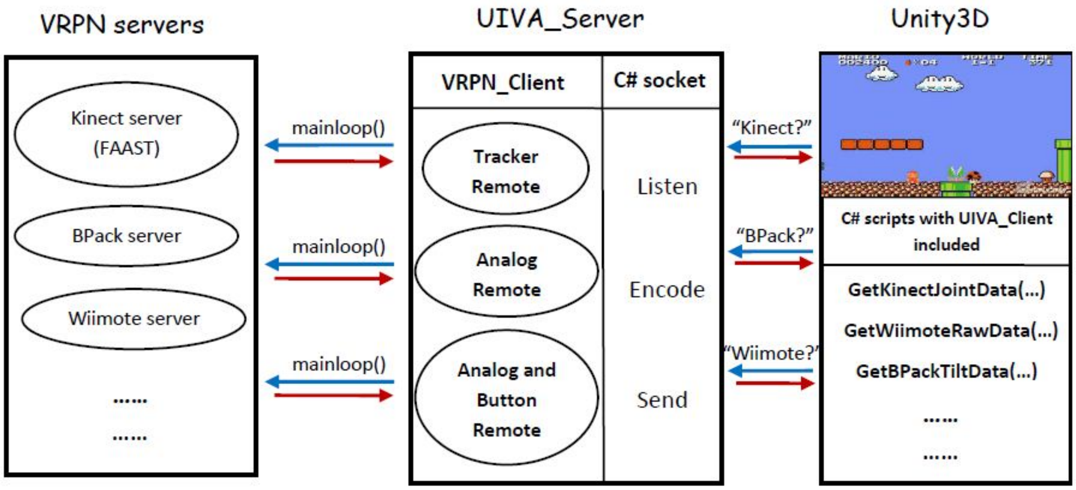


Figure 4.8: Unity Indie VRPN Adapter

UIVA is written in C# and consists of two parts: an executive file which is launched by the user after the *VRPN* servers are running and a DLL file which resides in the *Unity3D* game engine. In Figure 4.8 "UIVA_Server" refers to the executive and "UIVA_Client" refers to the DLL file, from the standpoint of the *Unity3D* game engine. When the executive is executed, it reads in a configuration file and creates a *VRPN* client for each device that is active on the *VRPN* server side. Then it creates a socket to talk to the DLL file in the game engine. In the perspective of the *VRPN* servers, the *UIVA* executive is a client. And in the perspective of the *Unity3D* game engine, the *UIVA* middle-ware is a device server. By this approach the data from the *VRPN* servers can be requested by *UIVA*, upon request of the *Unity3D* game engine.

To summarize this chapter, I explained the implementation of the *Silver Surfer* VR system. Specifically, I discussed the choice of input and output devices, the design and development of the virtual environment, and how the devices are connected to the *Unity3D* game engine to allow the user to interact with the IVE.

5 Evaluation

To evaluate the surfboard interface, a user study is conducted based on the *Silver Surfer* VR system. In this chapter, I will describe how I designed, tested and conducted the user study in detail. I will also present some results from the analysis of performance and questionnaire data collected in the study.

5.1 Purpose and Hypothesis

The purpose of the user study is illustrated in Figure 5.1. There are two research questions to answer for the surfboard travel interface.

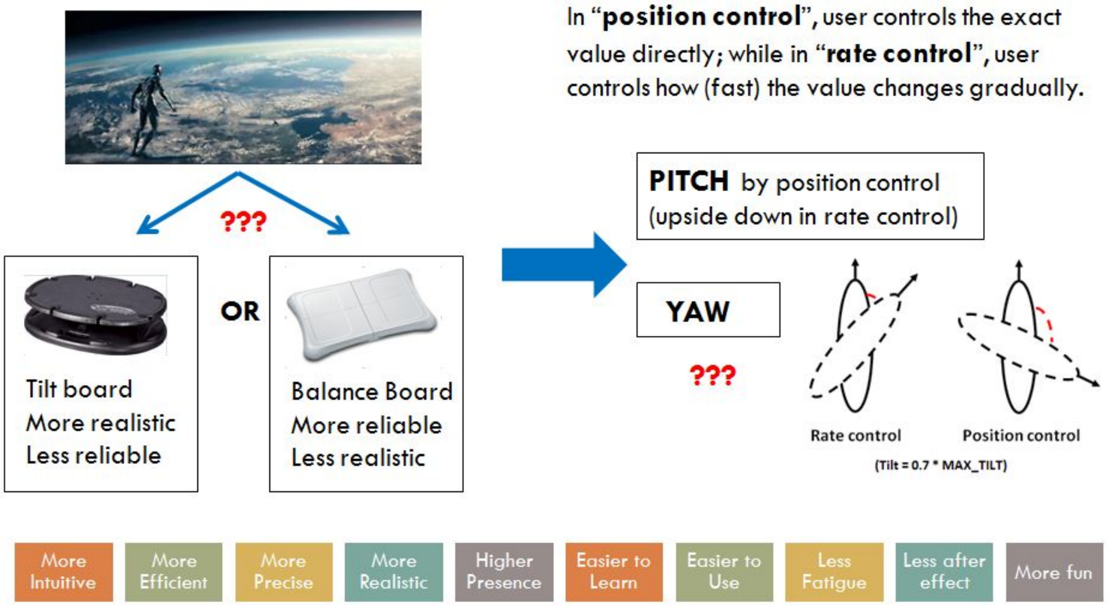

In “**position control**”, user controls the exact value directly; while in “**rate control**”, user controls how (fast) the value changes gradually.

Figure 5.1: The research questions

1. Which board is more preferable by the users, the isometric balance board or the elastic tilt board?

The balance board rests on a fixed surface and is therefore more reliable and requires less effort to keep balance. As a result using the balance board the user may be more efficient and precise to fulfill travel tasks, feel it easier to learn and use and suffer less from fatigue and after effect. On the other hand the tilt board tilts in a limited range and provides elastic resistance feedback, which creates an experience closer to real life snowboarding, skateboarding and surfing. And as a result the user may feel the tilt board more intuitive, realistic, fun and may experience a higher level of presence.

2. There are two methods to map the roll of the real board to the yaw of the virtual board—position control and rate control. Which approach is more preferable by the users?

   The pitch to pitch mapping should always be position control because using rate control the virtual board may be upside down while the user is still standing upright in the real world, which will cause confusions and motion sickness. However, the roll to yaw mapping is not as intuitive to decide. In real life skateboarding, snowboarding and surfing, yaw is by rate control which means when the surfer leans to her left, the board will keep turning left until she returns to the center position. However, because using position control the user is able to turn to a direction instantly, it may be more effective and precise than rate controlled yaw.

The purpose of the user study discussed in this chapter is to answer these two questions. By the user study we wanted to discover the optimal combination of the two parameters so that the corresponding travel interface will optimize the following factors as much as possible:

- Intuitiveness: how intuitive or natural the user feels of the board interface.
- Efficiency: how efficient the user can travel using the board interface.
- Precision: how precise the user can travel using the board interface.
- Realism: how realistic the surfing experience is using the board interface.

- Presence: how much presence can the user experience using the board interface.
- Ease of learning: how easy is it to learn how to use the board interface.
- Ease of use: how easy is it to use the board interface once the user has learned how to use it.
- Fatigue: how much fatigue the user feels using the board interface.
- After effect: how much after effect, such as loss of balance, does the user feel using the board interface.
- Fun: how much fun does the user experience using the board interface.

Because the balance board rests on a fixed surface and never tilts, it may be easier to keep balance on. As a result, we hypothesize that the balance board is easier to learn, easier to use, more efficient, more precise, and cause less fatigue and after effect. On the other hand, because the tilt board provides elastic resistance feedback and is closer to real life surfing experience. Based on this, we hypothesize that the tilt board is more intuitive, realistic, and fun, and will lead to a higher level of presence than the balance board.

5.2 User Study Design

To investigate our hypotheses, we designed a user study which compares the two board modes and the two methods of data mapping. The study consists of three main experiments—the pitch experiment, the yaw experiment and the combined experiment—so we can evaluate the two DOFs separately and comprehensively. Figure 5.2 shows the virtual environments in these three experiments. Larger images can be found in Appendix B.


Pitch Experiment
Yaw Experiment
Combined Experiment

Figure 5.2: The three main experiments

5.2.1 The Pitch Experiment

In the pitch experiment, the virtual board's yaw is disabled and the user only controls the pitch of the virtual board to travel up and down across a valley by leaning on the board backwards and forwards. The pitch of the virtual board is always by position control and ranges from -60 to 60 degrees so the user cannot travel backwards in the virtual environment. The virtual valley is infinite and the task is to collect the targets distributed at different heights. This experiment includes two treatments to compare the tilt board and the balance board, as shown in Table 5.1.

Table 5.1: Design of the pitch experiment

Board Mode
Tilt Board
Balance Board

5.2.2 The Yaw Experiment

In the yaw experiment, the virtual board's pitch is disabled and the user only controls the yaw of the virtual board to travel left and right by leaning on the board to the left and to the right. The yaw of the virtual board can be implemented by either rate control or position control, as described in Section 4.2.2. The virtual world is infinite and the task is to collect canister targets distributed at different horizontal locations. This experiment includes four treatments by a factorial design comparing board modes and the mapping methods, as shown in Table 5.2.

Table 5.2: Design of the yaw experiment

	Mapping Method	
Board Mode	Position Controlled Yaw	Rate Controlled Yaw
Tilt Board	PCTB	RCTB
Balance Board	PCBB	RCBB

5.2.3 The Combined Experiment

In the combined experiment, the virtual board is no longer limited and the user controls both the pitch and the yaw of it to travel in three dimensions. Again, the yaw of the virtual board can be implemented by either rate control or position control. The virtual world is infinite and the task is to collect canister targets distributed at different 3D locations. This experiment includes four treatments by a factorial design comparing board modes and the mapping methods, as shown in Table 5.3.

Table 5.3: Design of the combined experiment

	Mapping Method	
Board Mode	Position Controlled Yaw	Rate Controlled Yaw
Tilt Board	PCTB	RCTB
Balance Board	PCBB	RCBB

At the beginning of the study, the experimenter collected some general information of the subject regarding her height, weight, age, gender and surfing experiences (in real life or video games), after which the user was required to calibrate both the balance board and the tilt board. Then the user went through a general training session for up to eight minutes to get familiar with the interface, the virtual environment and the travel task. In this session the user controlled both pitch and yaw, by the first condition (board mode and mapping method) in the first pitch and yaw trials that are assigned to her randomly by Latin square. After the training the user was allowed to ask the experimenter questions and inform the experimenter when she was ready to start the study.

In the study, the user played all 10 trials. To guarantee the same basic skill set for each treatment, each trial started with a pretest. The user had to collect a certain number of targets in 50 seconds to pass the pretest. The number of targets required are eight, four and two in the pitch, yaw and combined experiment, respectively. After each main experiment, the user was asked to complete a questionnaire to rate the balance board and the tilt board, coupled with either position controlled or rate controlled yaw, in a scale from one to six, for all the 10 questions listed in Section 5.1 based on her experience in the corresponding experiment. She was also asked to choose a board for her general preference and to give some comments of the experiment. The user study procedure was recorded by a video camera as a reference for data analysis as shown in Figure 5.3.

Figure 5.3: Snapshot of video record

5.3 Pilot Study

To test the design of the user study, a pilot study was conducted. The subjects were nine lab members, two of which had tried an early version of the *Silver Surfer* system. Two subjects dropped the pilot study. From their feedback and our observation as the experimenters we discovered the following problems.

High Attrition Rate

The formal user study based on this design may result in a high attrition rate, because of the following reasons:

1. Long duration

   By the with-in subject design, each subject has to go through all 10 trials, which takes about 2.5 hours in total. Subjects may get very tired in some later trials and results may be biased consequently.

2. Frustrating pretests

   The pretests were commented to be very frustrating by many subjects. The user had to collect the required number of targets within 50 seconds, otherwise the pretest will restart. As the experimenters, we observed that some subjects kept failing the pretests and by the time they have passed it they did not care about the actual study anymore. Some subjects even got angry as they felt the repetitive failures offended their confidence.

3. Motion sickness

   In the pilot study, a black mask was attached to the HMD to block the light out of the subject's field of view to increase immersiveness and eliminate distractions. However, the extra weight of the mask as well as the less of ventilation made several subjects felt nauseous. Another reason of motion sickness is that the system transits from level to level abruptly without any fading in and out. For some subjects, this transition made them discomfort especially when they concentrated on the travel tasks.

To reduce the possibility of attrition, we applied the following solutions to the problems above.

1. The pretests were refined to have no time limits. Instead, the system requires the subject to get a certain number of targets, and the last two targets need to be collected within a certain amount of time. The pretests will automatically move

on to the actual trial when the subject meets the requirements. However, the subject is not aware of the existence of such requirements and can therefore relax and get trained more effectively. The new approach was tested by two previously frustrated subjects and they commented the new pretests served much better as trainings instead of challenges. In the pitch pretests, the user will pass when they collect 20 targets and the last two take no more than five seconds. In the yaw pretests, the numbers are 10 and 8. And in the combined pretests, the numbers are 8 and 12.

2. The black mask was removed from the HMD and fading in/out was added to the level transitions. Motion sickness disappeared for the subjects who reported nausea in the pilot study.

Position Controlled Yaw Dilemma

From the pilot study, position controlled yaw did not seem to make much sense. It was neither understandable or controllable by most subjects because the roll of the real board as the input data had a very small range, but was mapped to a big range of 360 degrees (turning at most 180 to the left and right) yaw of the virtual board. Most of the time in position controlled yaw, the virtual board as well as the viewport shifted left and right abruptly and frequently because the user could not control the board precisely by shifting her center of gravity. Many subjects got very frustrated and dizzy and refused to move on. When we changed the yaw range of the virtual board to 240 degrees (turning at most 120 degrees to the left and right), it became controllable. However, by doing this, we sacrificed the ability of the virtual board to go backwards and there are some targets in the world that the user, no matter how hard she tries, is incapable to collect. Because using rate control the user could keep turning the board to go backwards, the comparison between the two mapping methods are biased.

At last, we decided to remove this parameter in the formal user study, and only compare the two board modes instead. In Chapter 6, I will introduce another user study as a future work to investigate the advantages and disadvantages of the position controlled yaw.

Useless General Training

When the user was exposed to the complete 3D travel in the eight minutes' general training, there were too many DOFs for her to understand, let alone to control. In fact, most subjects got frustrated and chose to skip the general training. Because the refined pretests serve as a very well training solution, we removed the general training from the user study. This also reduced the duration of the user study by eight minutes.

Tiring Speed Control

The user has to keep her arm raised to keep a constant speed. Most subjects in the pilot study reported the speed control to be very tiring. To keep the speed control in place for intuitiveness without tiring the subject too much, we mounted the *B-Pack* accelerometer on the user's wrist instead of the triceps in the formal user study so that when the user gets tired, she can rest her upper arm and just control the speed by raising her lower arm.

5.4 Formal User Study

The formal user study was approved by the Institutional Review Board (IRB). The subjects were undergraduate students from Worcester Polytechnic Institute (WPI). The total number of participants were 30 and six dropped out. The general information are summarized as follows.

- Gender: 16 males and 8 females.
- Surfing Stance: 13 regular surfers and 11 goofy surfers.
- Age: mean = 20.7 years, standard deviation = 1.8.

- Height: mean = 174.2 centimeter, standard deviation = 11.1 centimeter.
- Weight: mean = 161.5 pounds, standard deviation = 29.0 pounds.
- Real surfing experience: 10 no experience, 8 yearly, 1 monthly, 5 once.
- Game surfing experience: 19 no experience, 1 yearly, 4 once.
- Claimed balance skill (1 to 10): mean = 6.2, standard deviation = 1.8.

Of the six dropped subjects, five of them dropped because of motion sickness. The reason of motion sickness (feeling nausea), as reported by four of those five subjects was that

> "The balance board made me sick. I felt so much movement in the virtual environment but the balance board always keeps stationary. This inconsistency made me feel nauseous."

Another possible reason of the motion sickness is lunch. All five subjects came to the study at around 12:00pm. Although we did not ask them whether they had lunch before the study, this could have been a reason that they got nauseous rather than the subjects in other time slots.

5.5 Data Analysis

The results of the data analysis will be presented in this section. The data from the questionnaire and the performance records were analyzed using single factor ANOVA.

5.5.1 Questionnaire Analysis

The results of the subjective evaluation of the board interface (the questionnaire) are presented in this section. Each of the three questionnaires is answered by the subject according to her experience from the corresponding main experiment. A sample questionnaire is included in Appendix A.

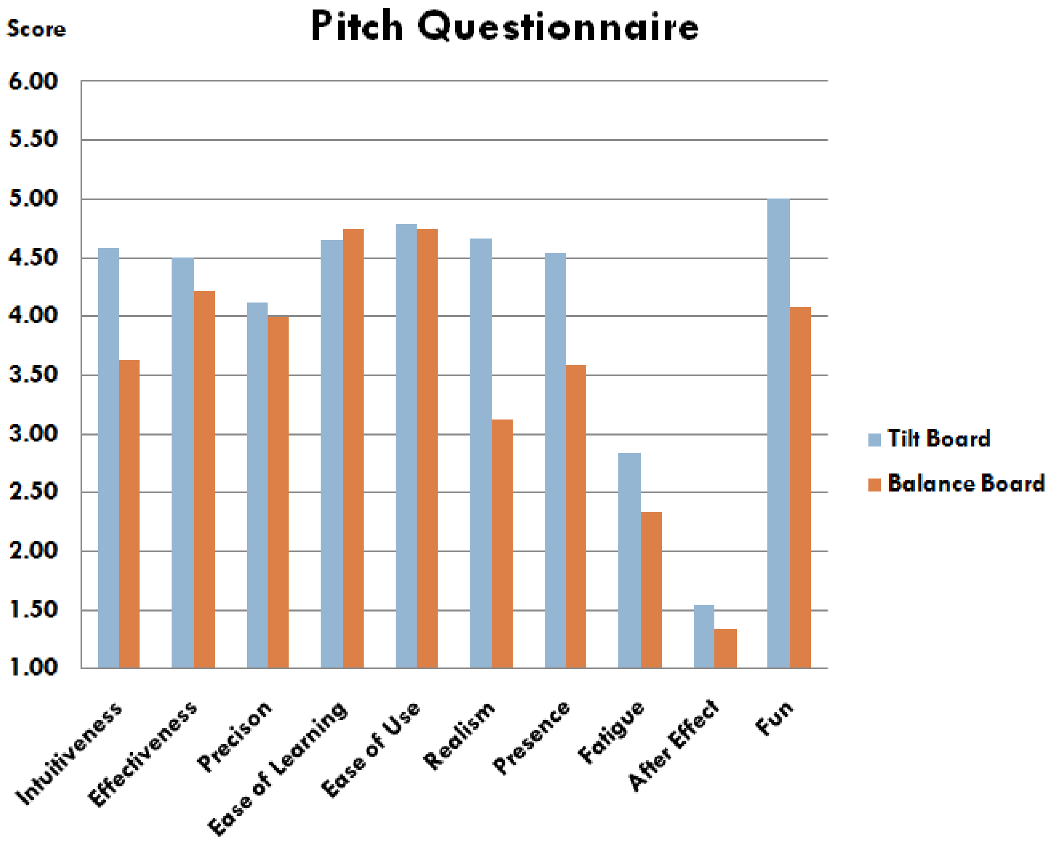


Figure 5.4: Results of the pitch questionnaire

Table 5.4: Pitch questionnaire results summary

	Mean		Standard Deviation		
Question	Tilt Board	Balance Board	Tilt Board	Balance Board	p-value
Intuitiveness	4.6	3.6	0.8	1.3	.002**
Effectiveness	4.5	4.2	1.2	1.0	.337
Precision	4.1	4.0	1.6	1.5	.728
Ease of Learning	4.7	4.7	0.9	0.7	.745
Ease of Use	4.8	4.7	0.6	1.1	.875
Realism	4.7	3.1	1.6	1.7	.000***
Presence	4.5	3.6	1.0	1.4	.004**
Fatigue	2.8	2.3	1.6	1.8	.192
After Effect	1.5	1.3	1.3	0.8	.489
Fun	5.0	4.1	0.7	1.7	.006**
Preference	Tilt Board	20	Balance Board	4	

$^{+}$p-value $<$ 0.1 (trending) *p-value $<$ 0.05 (weakly significant)
**p-value $<$ 0.01 (significant) ***p-value $<$ 0.001 (highly significant)

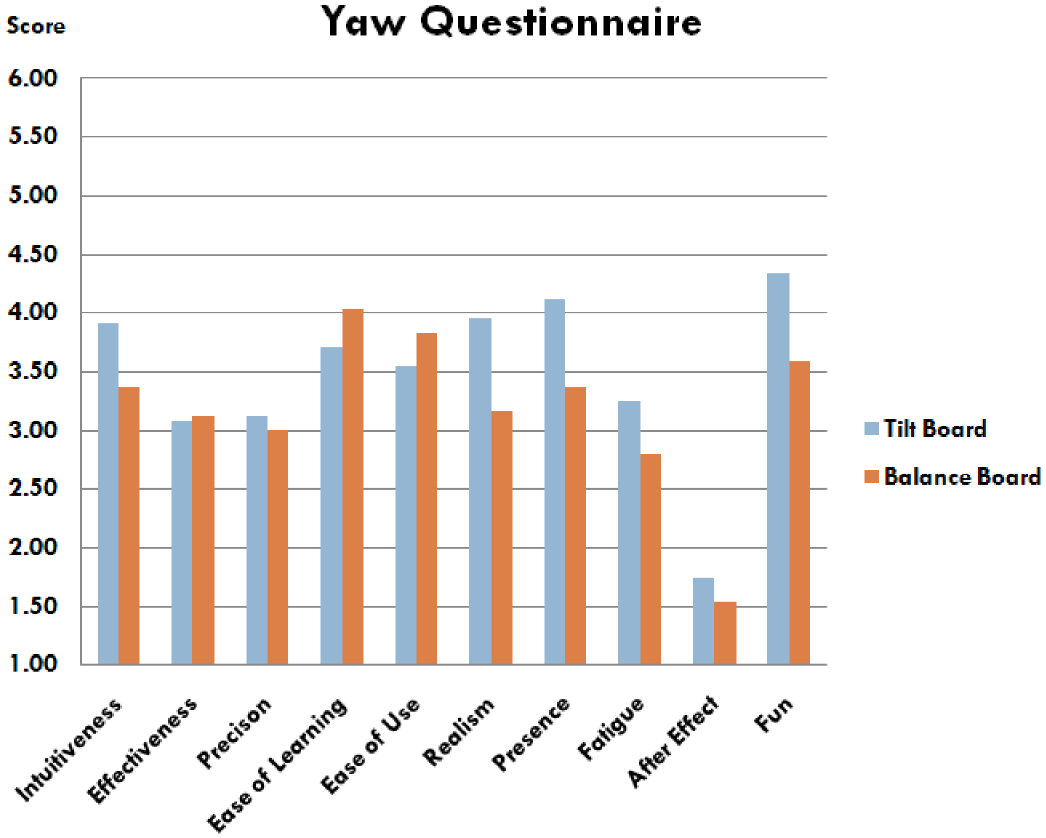


Figure 5.5: Results of the yaw questionnaire

Table 5.5: Yaw questionnaire results summary

	Mean		Standard Deviation		
Question	Tilt Board	Balance Board	Tilt Board	Balance Board	p-value
Intuitiveness	3.9	3.4	1.8	0.9	.111
Effectiveness	3.1	3.1	1.5	1.1	.899
Precision	3.1	3.0	2.0	1.4	.742
Ease of Learning	3.7	4.0	1.7	1.2	.340
Ease of Use	3.5	3.8	1.3	0.9	.344
Realism	4.0	3.2	1.6	1.3	$.027^*$
Presence	4.1	3.4	1.1	0.9	$.013^*$
Fatigue	3.3	2.8	1.3	1.9	.218
After Effect	1.8	1.5	1.2	0.7	.456
Fun	4.3	3.6	2.0	2.0	$.071^+$
Preference	Tilt Board	18	Balance Board	6	

Figure 5.4 shows the results drawn from the questionnaire of the pitch experiment. The X-axis corresponds to the ten questions and the Y-axis corresponds to the score

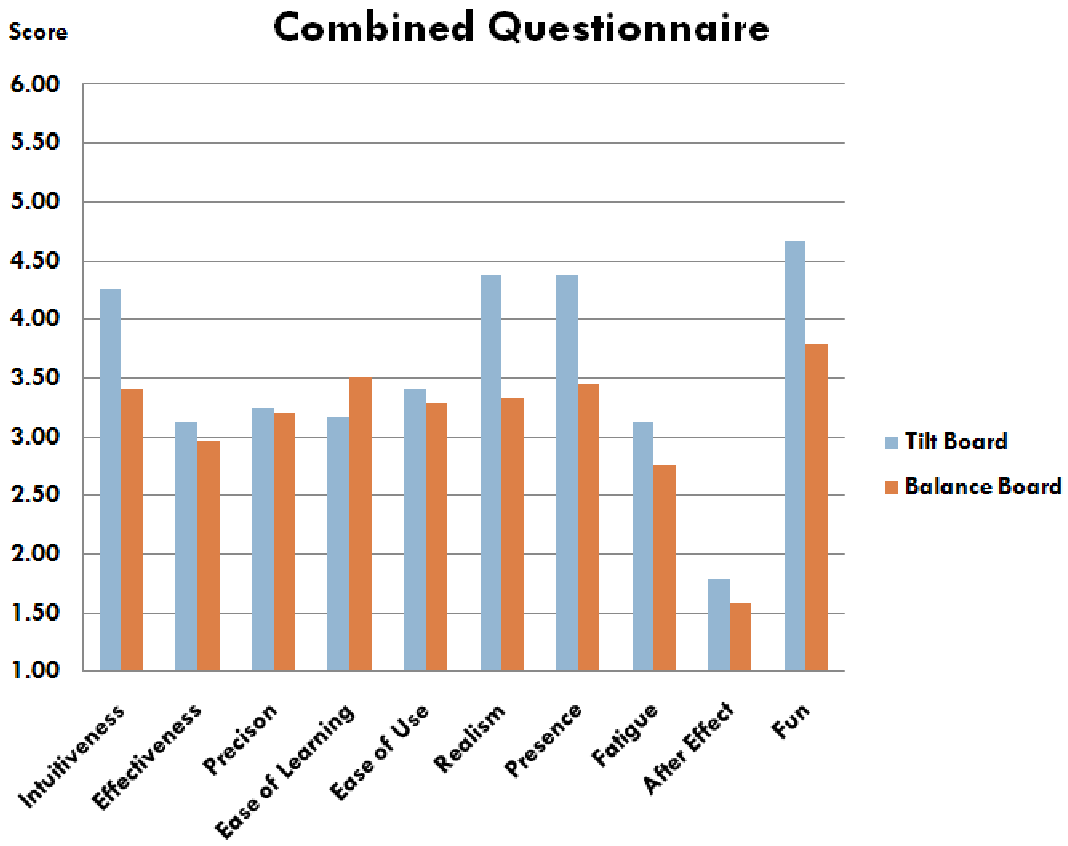


Figure 5.6: Results of the combined questionnaire

Table 5.6: Combined questionnaire results summary

	Mean		Standard Deviation		
Question	Tilt Board	Balance Board	Tilt Board	Balance Board	p-value
Intuitiveness	4.3	3.4	1.7	0.8	.012*
Effectiveness	3.1	3.0	1.2	1.3	.608
Precision	3.3	3.2	1.9	1.3	.910
Ease of Learning	3.2	3.5	1.3	1.7	.352
Ease of Use	3.4	3.3	1.7	1.5	.736
Realism	4.4	3.3	2.2	1.5	.012*
Presence	4.4	3.5	1.8	1.1	.012*
Fatigue	3.1	2.8	1.7	2.1	.350
After Effect	1.8	1.6	1.3	0.9	.491
Fun	4.7	3.8	1.9	1.8	.031*
Preference	Tilt Board	20	Balance Board	4	

each board mode got for the ten questions averaged over the 24 subjects, which ranges from one (not at all) to six (very much). In general, the results show that the tilt board is significantly more intuitive (p-value = 0.0021), realistic (p-value = 0.0001), and fun (p-value = 0.0060) and leads to higher level of presence (p-value = 0.0036). There is no significant difference between them for efficiency, precision, ease of learning, ease of use, fatigue, and after effect. In addition, 20 of the 24 subjects (83.3%) preferred the tilt board in this experiment, while the other four subjects preferred the balance board. The detailed results including the standard deviation and the p-value are shown in Table 5.4.

Figure 5.5 shows the results drawn from the questionnaire of the yaw experiment. In general, the results show that the tilt board is significantly more realistic (p-value = 0.0270) and leads to higher level of presence (p-value = 0.0128). There is also a trend of the tilt board being more intuitive (p-value = 0.1113) and more fun (p-value = 0.0714). Again, there is no significant difference between them for efficiency, precision, ease of learning, ease of use, fatigue, and after effect. Eighteen of the 24 subjects preferred the tilt board (75%), and the other six subjects preferred the balance board. The detailed results including the standard deviation and the p-value are shown in Table 5.5.

Figure 5.6 shows the results drawn from the questionnaire of the combined experiment. In general, the results in the combined questionnaire show that the tilt board is significantly more intuitive (p-value = 0.0122), realistic (p-value = 0.0117), and fun (p-value = 0.0310) and leads to higher level of presence (p-value = 0.0119). And there is no significant difference between them for efficiency, precision, ease of learning, ease of use, fatigue, and after effect. Twenty of the 24 subjects (83.3%) preferred the tilt board, and the other four subjects preferred the balance board. The detailed results including the standard deviation and the p-value are shown in Table 5.6.

5.5.2 Performance Analysis

During the user study, the system kept a record of how many targets the user collected in each trial, and how long it took her to pass each pretest. The former serves as an indicator of the efficiency of the board interface and the latter can be used to estimate the ease of learning of the interface. This section will show the results drawn from these data in the three main experiments.

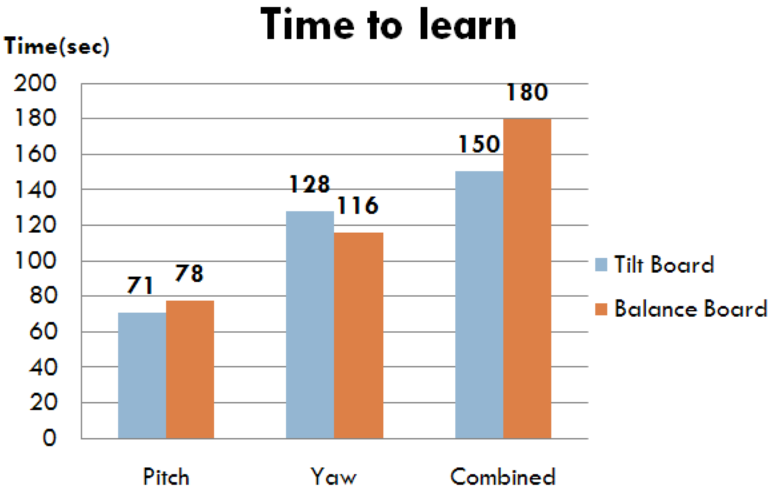


Figure 5.7: Results of learning the interface

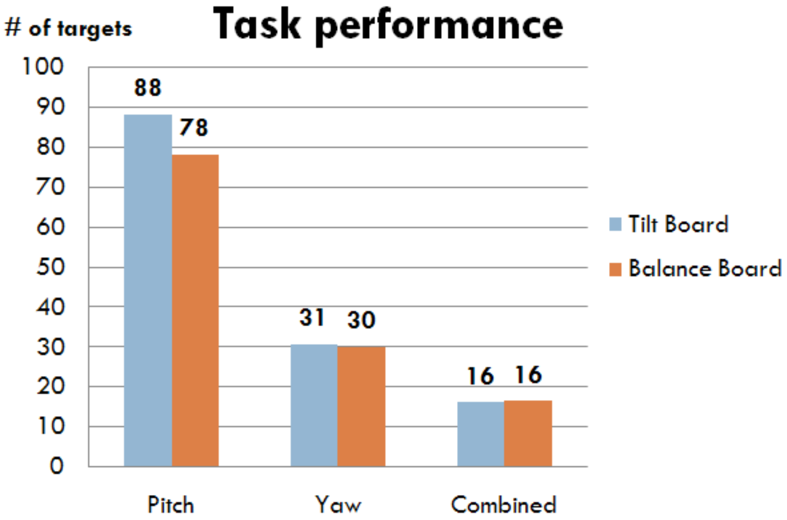


Figure 5.8: Results of number of targets collected

Figure 5.7 shows the statistic of the time users spent on learning the interface (meet the pretest's requirement) in each trial. The p-value for the pitch, yaw, and combined experiments are 0.178, 0.431 and 0.208 respectively, so there is no significant ease of learning difference between the tilt board and the balance board. The detailed data is shown in Table 5.7.

Figure 5.8 shows the statistic of the number of targets users collected in each trial. The p-value for the pitch, yaw, and combined experiments are 0.025, 0.831 and 0.858 respectively. In the pitch scenario, the tilt board is significantly more efficient than the balance board, while there is no difference in the yaw and combined scenarios. The detailed data is shown in Table 5.8.

Table 5.7: Time (sec) to learn results summary

	Mean		Standard Deviation		
Experiment	Tilt Board	Balance Board	Tilt Board	Balance Board	p-value
Pitch	71.0	77.7	298.6	274.5	.178
Yaw	128.2	115.8	3739.0	2065.5	.431
Combined	150.4	180.1	4315.0	7584.7	.208

Table 5.8: Number of targets collected results summary

	Mean		Standard Deviation		
Experiment	Tilt Board	Balance Board	Tilt Board	Balance Board	p-value
Pitch	88.3	78.3	236.6	203.7	.025*
Yaw	30.6	30.1	69.5	61.5	.831
Combined	16.1	16.5	26.4	55.6	.858

5.5.3 A System Mistake

The analysis in the previous section shows that the tilt board is more efficient than the balance board in the pitch scenario. However, this result may have been biased. In the data analysis, we discovered a mistake we made when we refined the user study which may threatens the validity of the result. The mistake is illustrated in Figure 5.9.

The picture shows a small portion of the travel path in the pitch experiment for two trials in which the user controls the tilt board or the balance board. The problem, as revealed in the picture, is that the targets distribution for the balance board trial is harder than that of the tilt board, because there are two targets next to each other

Figure 5.9: A mistake in the user study

that have a larger height difference. For the balance board trial, when the user has reached the first target, it is harder to get to the second target than in the tilt board trial. And because the virtual world extends infinitely (to the right in the picture) by repeating the same terrain tile in the pitch experiment, this effect could have been accumulated and have caused the efficiency difference between the two boards.

The original consideration of adding different target distributions is to have the tilt board and balance board trials both take half of each distribution across all subjects, in a random way, so that we can understand the user's virtual locomotion using the surfboard interface better. However because of this mistake, the result that the users got more targets in the pitch experiment may have been biased. Actually, the yaw and combined experiment also have the same problem, but because the users have a larger infinite virtual world which extends in nine directions (instead of one in the pitch experiment), the influence is much smaller.

Without re-conducting the user study, we decided to predict what the unbiased result would be based on our expert knowledge. As shown in Figure 5.8, the difference in the number of targets collected is very small (88 versus 78). Therefore we tend to believe that without the influence of the mistake, the number of targets collected using the tilt board and the balance board will be the same.

5.6 Discussion and Conclusion

In the beginning of this chapter, we hypothesized that the balance board, due to its reliability, will be more efficient and precise, easier to learn and use, and cause less fatigue and after effect. However, the results from the user study did not show any difference regarding these questions. Here we present some possible reasons based on our knowledge.

First of all, unlike the trackball devices in Zhai's research [16], the surfboard we used in the *Silver Surfer* system is a lower body interface which relies on the user's ability to shift her weight. Compared to hand interaction, it is much less precise to control. As a result, the difference between the isometric balance board and the elastic tilt board may have been dominated by the general difficulty of this interaction metaphor. Because in Zhai's research, the advantage of the isometric device over the elastic device disappeared after 20 minutes of training, the lack of difference in terms of efficiency and precision between the two boards is not as strange as it seems to be.

Secondly, although the balance board does not tilt, the user still needs to keep balance on it. The fundamental difference lies in the type of muscle contractions between the two boards. The most active muscle groups using the surfboard metaphor are the toes (when a goofy surfer tries to turn the virtual board to the left), the waist (when a goofy surfer tries to turn the virtual board to the right, by leaning her upper body backwards) and the calves (involved in almost all actions). Using the balance board, the muscles are doing isometric contractions while using the tilt board, the muscles are doing semi-isotonic contractions. These two types of muscle contraction may cause difference in perceived level of fatigue for different users, and there is no clear evidence that one will cause less effort than the other in general. Another reason of the equally rated fatigue may be that subjects did not feel the board interface tiring to use, as can be observed from the results of the questionnaires. Because using the surfboard to travel 3D virtual environment is not considered to be tiring in general, it may not matter whether to use a balance board or a tilt board. The low rating effect may also be used to explain the lack of difference for the after effect caused by the interface, in a sense that because the users do not feel much after effect in general, it does not matter which board they are using.

Thirdly, the ease of learning and ease of use of the interfaces vary among users. Some users may feel standing on a fixed surface more reliable, and therefore easier to catch up and use; while others may feel standing on a tilt platform much closer to the real life experience, and is therefore easier to learn and use by transferring their skills from the real life.

However, as hypothesized, the tilt board is reported to be significantly more intuitive, realistic, fun and leads to a higher level of presence. The reason is clear, as commented by most subjects, that by providing the elastic resistance feedback, the tilt board experience is closer to real life skateboarding, snowboarding and surfing. The opposite is the balance board, which does not provide any feedback and has a higher possibility to cause motion sickness.

To summarize, our conclusion is that the isometric balance board and the elastic tilt board are equally efficient, precise, easy to learn and easy to use, and lead to equally minor fatigue and after effect. So to fulfill 3D travel, either of them can be selected to implement the surfboard interface. However, in VR, we prefer the tilt board, because the balance board may cause motion sickness in immersive virtual environments and the tilt board is more intuitive, realistic, fun and leads to more presence, all of which are considered to be critical for VR applications.

6 Conclusion

In this thesis, I discussed the design and development of an innovative surfboard interface for 3D travel tasks in IVEs based on the *Silver Surfer* Sci-Fi comics and movies. I described the methodology in detail to show how the interface is designed to meet the three DOFs requirement of 3D travel, and some extra cognitive load coupled with this design. I also talked about isometric versus isotonic devices, and position controlled versus rate controlled yaw, which are research questions that need to be investigated by comparative user studies. To validate the interface, we designed and developed a multi-model *Silver Surfer* VR system. Based on this system, we conducted a user study and concluded that to serve as a surfboard travel interface in VR, the elastic tilt board is significantly more intuitive, realistic, fun and leads to a higher level of presence. However, the efficiency, precision, ease of learning, ease of use, after effect and fatique of the interaction showed no difference between the tilt board and the balance board. We also discovered that when used as a travel interface in an immersive virtual environment, the balance board has a higher possibility to cause motion sickness, because the virtual locomotion is not reflected by the haptic feedback of the interface.

Regarding future work, I will propose two further user studies based on the surfboard interface. The first user study will reconsider position controlled yaw which is removed from the original user study design. The position controlled yaw suffered from mapping small input range of the board's roll to large range of the virtual board's yaw. However, it is possible to combine position controlled and rate controlled yaw to a hybrid solution, so that we may benefit from the precision of position control and the larger range of rate control. Assume the board interface can roll up to 30 degrees to the left and right. When the value lies in the small center range, for example, -10 to 10 degrees, we map it by position control to -50 to 50 degrees of virtual board's yaw. And when the value exceeds this range, we apply rate controlled yaw. In this way, we hypothesize the user will be able to travel in large scale terrains by rate controlled yaw, and apply position controlled yaw when they get closer to the targets. With this hypothesis, we plan to compare this new mapping method with the rate controlled yaw, for both the balance board and the tilt board. Table 6.1 describes the design of the user study. The user study will consist of a yaw experiment and a combined experiment with four treatments for each.

Table 6.1: Evaluation of the hybrid solution

	Mapping Method	
Board Mode	Hybrid Controlled Yaw	Rate Controlled Yaw
Tilt Board	HCTB	RCTB
Balance Board	HCBB	RCBB

The second user study will compare the surfboard interface with Valcov's [8] *Segway* travel interface. The *Segway* simulator is an interface based on the *Wii Balance Board*. Compared to the surfboard interface, the user stands on the board facing forwards, and lean forward (of her body) to gain speed, and leans to her body's left and right to turn the virtual *Segway* left and right. Their original design only supports 2D travel. In a later design, another DOF is added to enable elevation and descending vertically, by programming the balance board to detect a special foot gesture. We are interested in comparing the surfboard metaphor with the *Segway* metaphor in both 2D and 3D travel scenarios, to see if there is any difference in terms of usability between standing on the board facing forward versus facing to the left/right (the front side of the board), and using leaning forward/backward to control speed and arm raising/relaxing to control elevation, versus the opposite, which is using leaning forward/backward to control the pitch of the virtual board and arm raising/relaxing to control the speed.

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A A Sample Questionnaire

Please rate the tilt board and the balance board for each of the questions below based on your experience from the experiment you just completed.

1. Intuitiveness: How natural, realistic, or intuitive do you feel each mode was to use? (1 = not intuitive, 6 = very intuitive)
2. Efficiency: How efficiently could you reach your targets? (1 = not efficient, 6 = very efficient)
3. Precision: How precisely could you move to hit your targets? (1 = not well, 6 = very well)
4. Ease of Learning: When you first started, how easy was it to learn how to use the travel interface? (1 = not easy, 6 = very easy)
5. Ease of Use: Once you learned how to use the interface, how easy was it to use the travel interface? (1 = not easy, 6 = very easy)
6. Realism: How much did you feel like you were actually surfing in the sky like Silver Surfer? (1 = not realistic, 6 = very realistic)
7. Presence: How much did you feel like you actually existed in the virtual environment, rather than in the lab? (1 = in the lab, 6 = in the virtual environment)
8. Fatigue: How tired did you feel using the interface? (1 = not tired, 6 = very tired)
9. After Effects: How much did each of the travel interfaces affect you after you stopped (e.g., loss of balance)? (1 = no after effects, 6 = strong after effects)
10. Fun: How much fun did you have when using the travel interfaces? (1 = no fun, 6 = lots of fun)

11. In general, which board do you prefer, the tilt board or the balance board?
12. Following the last question, please provide any comments about each board mode. What do you like about it? What do you dislike about it?
13. Do you have any comments about the experiment in general?

B The Virtual Environments

Figure B.1: The IVE of the pitch experiment

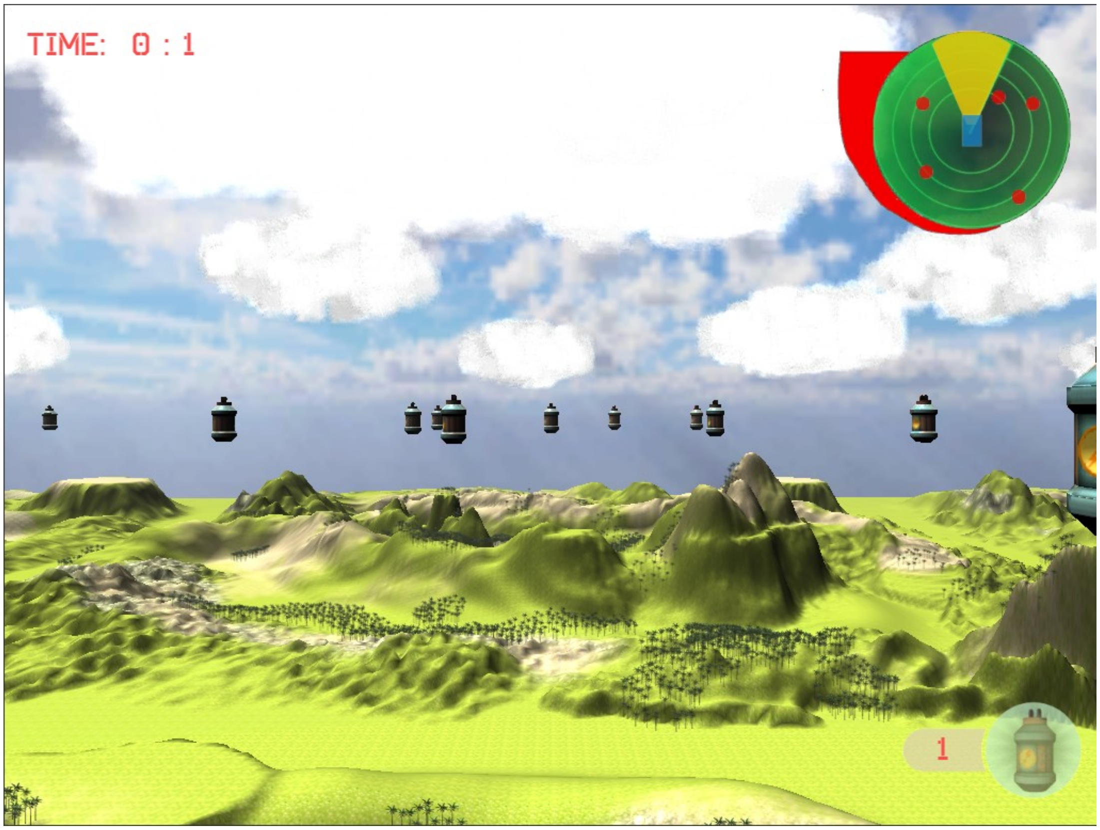

Figure B.2: The IVE of the yaw experiment

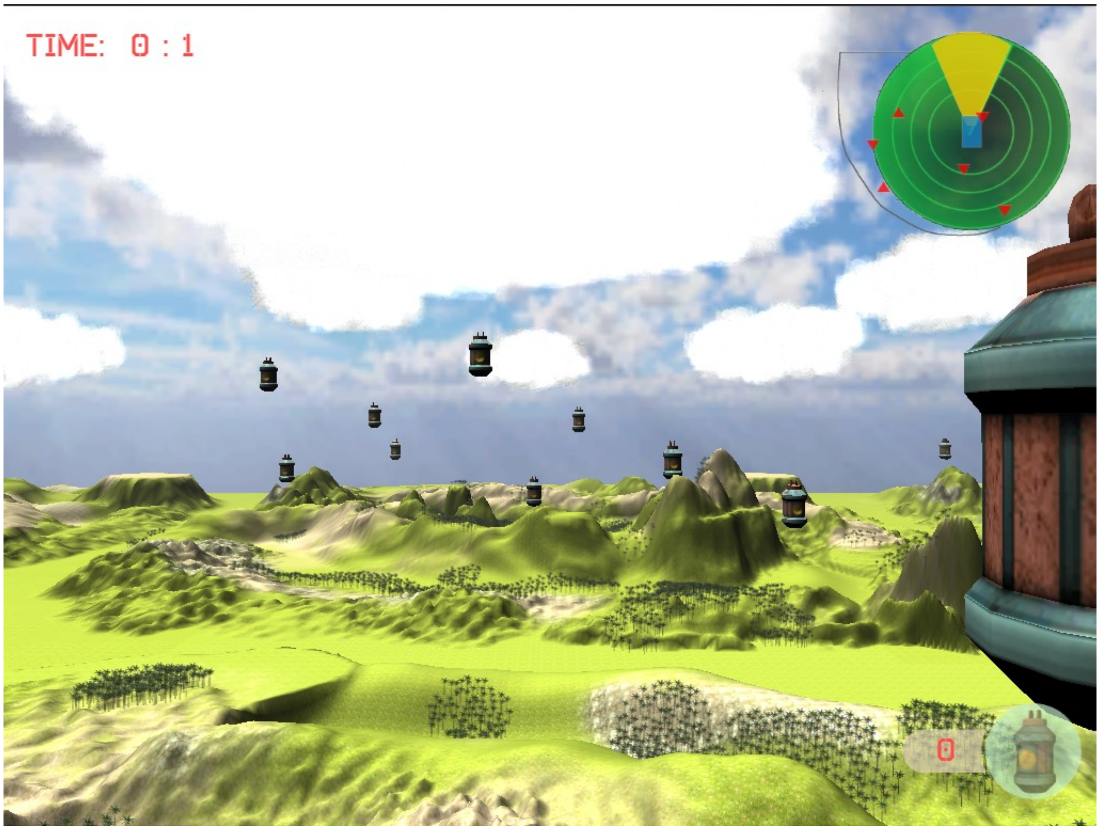

Figure B.3: The IVE of the combined experiment