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An Expandable Walking in Place Platform

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Advisor

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"Uma boa leitura."

— HERNANDI

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ABSTRACT

The control of locomotion in 3D virtual environments should be an ordinary task, from the user point-of-view. Several navigation metaphors have been explored to control locomotion naturally, such as: real walking, the use of simulators, and walking in place. These have proven that the more natural the approach used to control locomotion, the more immerse the user will feel inside the virtual environment. Overcoming the high cost and complexity for the use of most approaches in the field, we introduce a walking in place platform that is able to identify orientation, speed for displacement, as well as lateral steps, of a person mimicking walking pattern. The detection of this information is made without use of additional sensors attached to user body. Our device is simple to mount, inexpensive and allows almost natural use, with lazy steps, thus releasing the hands for other uses. Also, we explore and test a passive, tactile surface for safe use of our platform. The platform was conceived to be utilized as an interface to control navigation in virtual environments, and augmented reality. Extending our device and techniques, we have elaborated a redirection walking metaphor, to be used together with a cave automatic virtual environment. Another metaphor allowed the use of our technique for navigating in point clouds for tagging of data. We tested the use of our technique associated with two different navigation modes: human walking and vehicle driving. In the human walking approach, the virtual orientation inhibits the displacement when sharp turns are made by the user. In vehicle mode, the virtual orientation and displacement occur together, more similar to a vehicle driving approach. We applied tests to detect preferences of navigation mode and ability to use our device to 52 subjects. We identified a preference for the vehicle driving mode of navigation. The use of statistics revealed that users learned easily the use of our technique for navigation. Users were faster walking in vehicle mode; but human mode allowed precise walking in the virtual test environment. The tactile platform proved to allow safe use of our device, being an effective and simple solution for the field. More than 200 people tested our device: *UFRGS Portas Abertas in 2013 and 2014*, which was a event to present to local community academic works; during 3DUI 2014, where our work was utilized together with a tool for point cloud manipulation. The main contributions of our work are a new approach for detection of walking in place, which allows simple use, with naturalness of movements, expandable for utilization in large areas (such as public spaces), and that efficiently supply orientation and speed to use in virtual environments or augmented reality, with inexpensive hardware.

Keywords: Walking In Place, Virtual Reality.

Uma plataforma de *Walking in Place* expandivel

RESUMO

O controle da locomoção em ambientes virtuais 3D deveria ser uma tarefa simples, do ponto de vista do usuário. Durante os anos, metáforas para navegação têm sido exploradas para permitir o controle da locomoção naturalmente, tais como: caminhada real; uso de simuladores e imitação de caminhada. Estas técnicas provaram que, quanto mais natural à abordagem utilizada para controlar a locomoção, mais imerso o usuário vai se sentir dentro do ambiente virtual.

Superando o alto custo e complexidade de uso da maioria das abordagens na área, introduzimos uma plataforma para caminhada no lugar, (usualmente reportado como *walking in place*), que é capaz de identificar orientação, velocidade de deslocamento, bem como passos laterais, de uma pessoa imitando a caminhada. A detecção desta informação é feita sem o uso de sensores presos no corpo dos usuários, apenas utilizando a plataforma. Nosso dispositivo é simples de montar, barato e permite seu uso por pessoas comuns de forma quase natural, com passos pequenos, assim deixando as mãos livres para outras tarefas. Nós também exploramos e testamos uma superfície táctil passiva para utilização segura de nossa plataforma. A plataforma foi concebida para ser utilizada como uma interface para navegação em ambientes virtuais. Estendendo o uso de nossa técnica e dispositivo, nós elaboramos uma metáfora para caminhada redirecionada, para ser utilizada em conjunto com cavernas de projeção, (usualmente reportado como *Cave automatic virtual environment* (CAVE)). Criamos também uma segunda metáfora para navegação, a qual permitiu o uso de nossa técnica para navegação em nuvem de pontos, auxiliando no processo de etiquetagem destes, como parte da competição para o *3D User Interface* que ocorreu em Minessota, nos Estados Unidos, em 2014.

Nós testamos o uso da técnica e dispositivos associada com duas nuances de navegação: caminhada humana e controle de veiculo. Na abordagem caminhada humana, a taxa de mudança da orientação gerada pelo usuário ao utilizar nosso dispositivo, inibia o deslocamento quando curvas agudas eram efetuadas. No modo veículo, a orientação e o deslocamento ocorriam conjuntamente quando o usuário utilizava nosso dispositivo e técnicas, similarmente ao processo de controle de direção de um veículo.

Nós aplicamos testes para determinar o modo de navegação de preferencia para utilização de nosso dispositivo, em 52 sujeitos. Identificamos uma preferencia pelo modo de uso que se assimila a condução de um veículo. Testes estatísticos revelaram que os usuários aprenderam facilmente a usar nossa técnica para navegar em ambientes virtuais. Os usuários foram mais rápidos utilizando o modo veículo, mas o modo humano garantiu maior precisão no deslocamento no ambiente virtual. A plataforma táctil provou permitir o uso seguro de nosso dispositivo, sendo uma solução efetiva e simples para a área. Mais de 200 pessoas testaram nosso dispositivo e técnicas: no evento Portas Abertas da UFRGS em 2013 e 2014, um evento onde são apresentados para a comunidade local os trabalhos executados na universidade; e no *3D User Interface*, onde nossa técnica e dispositivos foram utilizados em conjunto com uma ferramenta de seleção de pontos numa competição.

As principais contribuições do nosso trabalho são: uma nova abordagem para detecção de imitação de caminhada, a qual permite um uso simples, com naturalidade de movimentos, expansível para utilização em áreas grandes, como espaços públicos e que efetivamente captura informações de uso e fornece orientação e velocidade para uso em ambientes virtuais ou de realidade aumentada, com uso de hardware barato.

Palavras-chave: walkign in place, realidade virtual.

LIST OF ABBREVIATIONS AND ACRONYMS

CAVE	Cave Automatic Virtual Environment
CoP	Center of Pressure
DOF	Degree of Freedom
HMD	Head Mounted Display
IMU	Inertial Measurement Unit
VE	Virtual Environment
VR	Virtual Reality
WIP	Walking In Place

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1 INTRODUCTION

The current research addresses the elaboration and test of a walking in place interface to be used for human-computer interaction. The control of locomotion in 3D virtual environments is an ordinary task. Several navigation metaphors have been utilized to control locomotion, such as: real walking, the use of simulators, and walking in place. These have proven that the more natural is the approach used to control locomotion, the more at-ease and immersed the user will feel inside the virtual environment.

In the present work, we studied devices and techniques, which allow the use of natural walking movements to control navigation in virtual environments. Based on the study of these works, we propose and develop a device capable of being utilized by ordinary people. Our device does not require the use of special hardware attached to the body, allowing for easy control of navigation in virtual environments. With the use of the device proposed in this work, a person can utilize walking in place to control navigation in virtual environments, keeping the hands free to be used for other interactive tasks.

Similar works developed to allow the control of the navigation in virtual environments attempt to evaluate and measure the devices conceived by their creators, either qualitatively or quantitatively, with regards to the level of immersion perceived during the use of the devices, the precision that the interface provides, the level of entertainment, among other characteristics (USOH et al., 1999; COHN et al., 2005).

Typically, devices in the field of navigation allow the user to mimic the walking process (SOUMAN et al., 2010; SCHWAIGER; THUMMEL; ULBRICH, 2007; LICHTENSTEIN et al., 2007), providing locomotion interfaces that capture the limb movements in real time. These movements are then replicated by an avatar in interactive time inside a Virtual Environment (VE). There is a myriad of devices that allow almost natural walking to be used as an interface.

There are four basic classes of work to control walking in virtual environments: devices that allow real walking to be developed by the user and translate real movements to virtual environment (WILLIAMS et al., 2007; SUMA et al., 2012), the ones that allow infinite bidirectional walking and free rotation over simulated infinite floors (DARKEN; COCKAYNE; CARMEIN, 1997), devices that allow the use of mimic patterns of walking, i.e., Walking In Place (WIP) over a restricted area (FEASEL; WHITTON; WENDT, 2008; MATTHIES et al., 2014), and devices that utilize virtual walking metaphors, such as surfing or pointing (VALKOV et al., 2010).

Some important factors for a walking interface are: learning time to use the devices, costs to build and maintain the device, and space required to accommodate them. A more detailed discussion will be presented in the next chapter, which will provide a full overview of the last twenty years of research in the field, classifying works accordingly to pertinent points (BOWMAN et al., 2004).

The aforementioned study of walking devices provides us with a set of criteria that helped to delimit our research ideas and define the type of device that could be made given our budget and time. The main criteria of our initial idea are enumerated below as the basis of our current work. The system should:

1. Allow the user to walk in a way as natural as possible
2. Be cheap to develop and easily scalable
3. Be simple enough to use and learn
4. Use the minimal amount of hardware attached to the body of the user
5. Be easy to setup
6. Allow the identification of natural movements as
    body orientation and rotation
    lateral walking
7. Allow for the control of velocity

This set of requirements worked as specific objectives, which we pursued during the development of our interface. Based on them, we elected the walking in place metaphor. We choose to capture the mimic pattern of walking in place of a user using a sensitive surface composed of scales. The proposal to identify the natural user movements is based only on the information captured from the scales, in real time.

After the analysis of the signals provided by our surface, we developed an algorithm to detect the basic locomotion movements of the user, such as: walking, rotation, and lateral walking. Furthermore, the analysis generates virtual position and orientation to be used as a control, for example in a VE. The details of the algorithm will be explained in Chapter 3. We proposed a set of user tests that helped to evaluate the system's usability and enhanced the quality of our technique.

Experiments revealed that our navigation device was easily usable by ordinary people with a fast learning curve and was efficient. Most of the users had a fun time testing our device, completing the tests in a short amount of time and achieving the goals defined in the tests, given useful feedback in both qualitative and quantitative data, which are reported in Chapter 5. Our technique proved to be easily expandable to larger spaces, without setbacks.

The main contributions of our study are the development of a usable platform for detection of walking in place. It is stable for long-term utilization by users and detects lazy steps of walking in place. It proved to be easily expandable for large surfaces, as we utilize it from one to four independent devices, side by side, to capture pressure information. We also made available an efficient method for detection of orientation and inferring user speed. This can be utilized together with virtual environments. It is based on pressure sensors in the floor. Furthermore, we propose and test a tactile feedback approach to the usage of our platform. This tactile floor proved to be safe and effective for continuous utilization, together with head-mounted displays. The complete walking in place device presented is inexpensive and could be built at low costs. Our studies also developed a walking redirection technique for utilization in multi-display environments.

Our technique was also tested in other works, for instance, a virtual reality-based simulator that analyzes risk (JORGE et al., 2013). It also helped the navigation with greater freedom in point clouds (KRAMMES et al., 2014). The final result of the work was positive with the successful definition of an idea, the implementation of a device, execution of tests, and further ideas for new works in the field.

In this work, we start presenting an overview of techniques that allow a natural or near-natural walk in Chapter 2, followed by a summary presenting the positive and negative points of each technique. Then, we present how our technique contrasts with other techniques and how it works in details in Chapter 3. This is followed by a set of new uses of the technique in other works in Chapter 4. Chapter 5 explains the tests environments, procedures, the results and other findings, followed by a final discussion and our conclusions at Chapter 6.

2 RELATED WORK

Controlling locomotion in immersive VE is an active area of research. Works in the field of human-computer interaction that control locomotion using feet may be split mainly into four categories (BOWMAN et al., 2004; USOH et al., 1999):

- those that support real walking,
- those that support walking in a simulated surface,
- those that allow walking in place,
- and those that support virtual walking,

Given the amount of works in the field we identified two main avenues of works: the ones involving the development of physical devices or specialized techniques (SUMA et al., 2012; WELLS; PETERSON; ATEN, 1996); and the ones concerned with the user tests of devices and their psycho-physical effects as a learning tool (COHN et al., 2005; USOH et al., 1999). During the following sections we will use the term *device, interface* or *technique* to express the works in the field of walking interfaces.

The works of natural human-computer interaction attempt to capture the position and movements of the body's limbs and translate this information to be used inside the computer. Certain levels of real interaction guarantee a better experience for a specific task involving human-computer interaction, as presented by (RUDDLE; LESSELS, 2009; BOWMAN; FROHLICH, 2005). The user interfaces for VEs can be cheap and require a learning curve, or can involve a more complex (and expensive) hardware system to allow the capture of body movements. We are interested only in works where the feet are used to control locomotion using natural movements.

The human-computer interfaces can allow *physical travel* where the user actively moves and rotates his/her body and causes the viewport to move and rotate together. Or *virtual travel*, where the user stays stationary; but the viewport moves in a gaze-oriented manner. Usually the works on walking interfaces are a combination of both techniques (BOWMAN et al., 2004).

Feet interaction devices usually try to capture two categories of movements to allow motion in VEs: orientation (steering) and displacement of the user. These are the components of locomotion (TEMPLEMAN; DENBROOK; SIBERT, 1999). The field of feet interaction vary from capture of natural locomotion movements "free walking" (SUMA et al., 2012; COUVILLION W LOPEZ R, 2002; DE LUCA et al., 2012) using it as orientation and displacement, or indirect control through metaphors where small movements or orientation of the feet are used to control locomotion in VEs. Some studies about the accuracy of foot interaction points out that feet interaction can be successfully used to control *non-accurate tasks*, such as selecting objects in two dimensional (PAKKANEN; RAISAMO, 2004). However (LIMA FILHO et al., 2011) already proposed that feet can be used as accurate as hand controls.

The next sections summarize the four main classifications of walking devices, and highlights some interesting works in the field.

2.1 Walking Approaches

Accordingly to literature, *Real Walking* approaches can provide great sense of immersion if compared with WIP, Virtual Walking and cycles (USOH et al., 1999). Their use can be better targeted to Augmented Reality (AR) in mobile devices.

The use of real walking provides vestibular cues that improve the immersion feeling in virtual world spaces. However, real walking is not always possible due to space or constraints imposed by the length of the wires, and the need for efficiently tracking the user position and orientation. In open areas, GPS provides good tracking, but inside buildings there is a need for other techniques, such as: camera tracking, gyroscope, accelerometer, magnetometers, body markers and/or multi-lateration systems (GALATI; LEONARDI; TOSTI, 2008).

In works involving real walking, the user movements, such as displacement and orientation in the real world are translated in movements to the virtual, with or without some degree of manipulation in the mapping, from real to virtual. Works as (RUDDLE; LESSELS, 2009) provides tests in the field of real walking versus simulated walking, and points out that the little use of real movements, affect the abilities of users to remember object position in virtual environments.

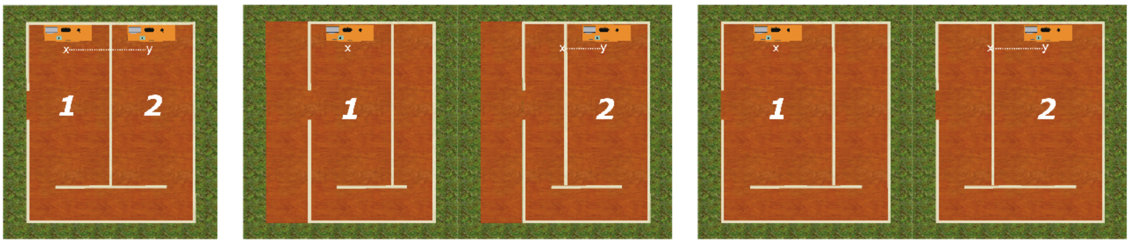
A common study in real walking techniques is the redirection of users unconsciously, in order to simulate bigger virtual environments than the physical space available to walk, maximizing the walking area. Works that manipulate this translation between real to virtual walking, usually are named redirect walking approaches. These manipulations usually fool the perception of space of the user by forcing little curved walking patterns (SUMA et al., 2012; BRUDER et al., 2012; SWAPP; WILLIAMS; STEED, 2010).

(SUMA et al., 2012) creates impossible spaces to maximize the natural walking in virtual environments with the use of overlapped real areas. With this work it was able to detect that up to 56% of a room can be overlapped before users perceive a strange space configuration. This technique uses cameras for user tracking. Figure 2.1 present the virtual overlap proposed.

(BRUDER et al., 2012) based himself on psycho-physical studies that revealed that our visual system dominates our vestibular system in detection of turning angles, or translation in space and then evaluate a *Redirect Walking and Driving Technique for VEs*. Their work tests again the human abilities to detect levels of walk redirection done with users walking or using an electric wheelchair. They found also that a user can be redirected in smaller circles when using the driving metaphor than when walking.

The latency in the translation of real movements to virtual movements is also a target topic, as a cyber-sickness factor. (FEASEL; WHITTON; WENDT, 2008) attempts to overcome the high-latency using sensors directly attached to the heels, knees, and chest (see Figure 2.2) of the users. With this approach, they were able to identify speed, orientation, and translation information with low-latency.

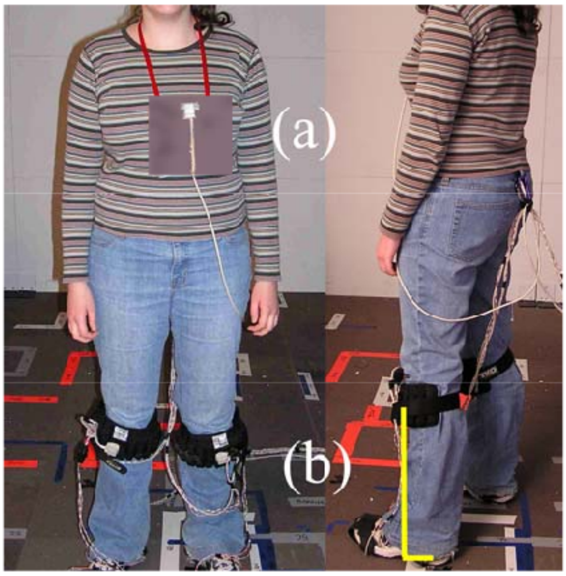
Figure 2.1: Impossible spaces. Real room configuration view displayed virtually as two individual rooms



(a) 0% Overlap (b) Fixed Room - 50% Overlap (c) Expanding Room - 50% Overlap

Source: (SUMA et al., 2012).

Figure 2.2: Walking in place sensor positions. Near waits, knees and ankles



Source: (WANG; LINDEMAN, 2011).

2.2 Simulated Walking Approaches

The walking simulator devices are *supposed* to allow the use of the legs more naturally, executing the walking gait with completeness of amplitude. This category provides better immersion to users than walking in place (USOH et al., 1999). However, the user is restricted to a small walking area, almost walking in place, or the use of some mechanical assistance.

The basic device for simulated walking is the treadmill and its counterpart, the omnidirectional treadmill. This type of device allows walking in any direction. The first ones were (DARKEN; COCKAYNE; CARMEIN, 1997; IWATA, 1999) which had some deficiencies, as identified in the literature, such as slow walking speeds; were loud to operate; and problematic to predict user movements, especially during rotations. These devices needed an arm to be attached to the user's center of mass to avoid falls. These kinds of devices were expensive to build. Most of the first omnidirectional treadmills had low precision to allow natural walking and problems with instant stops of the users. These are only the most visible points cited by the papers.

The CyberCarpet (SCHWAIGER; THUMMEL; ULBRICH, 2007; SCHWAIGER; THMMEL; ULBRICH, 2007) was a study to overcome the problems of the use of omnidirectional treadmills. It was done in order to allow high velocity displacement with high accuracy. The study utilized only a wheeled robot for the test. Souman et al. (2010) also tries to better control treadmill belts with the use of motion equations to estimate the best force against user feet and the inertia of the belts to achieve good response and immersion.

One of the latest works in the omnidirectional treadmills is the CyberWalk (DE LUCA et al., 2009). The device was the largest found allowing a operation space at 25 square meters. This device implemented a very accurate prediction of user walking and the cinematics of the mechanics, being the safest reported up to date. However, most of these kinds of devices are expensive and prone to cause user falls.

We identify few devices able to simulate uneven walking surfaces. (IWATA; YANO; NAKAIZUMI, 2001) with the GaitMaster provided such a device. Composed of a complex mechanism, with 2 motion platforms, with 6 DoF each, it was able to supply complete walker feet movement, providing an infinite floor. The device, however, was insecure and required the foot to be safety strapped in order to prevent the fall of the foot off of the pads. The maximum velocity allowed on top of the device was 1.5 m/s. There were two implementations of the GaitMaster presented, as in Figure 2.3. The first proposal (a) uses a fixed base, allowing just one direction walk. The second version (b) utilizes a turntable base to allow any direction walk.

Another simulated floor was the CirculaFloor (IWATA et al., 2005), composed of movable tiles, which move to walking direction, filling the ground. Again, the max speed allowed was of 1.5 m/s, and depended on user walk prediction to move the tiles.

String Walker (IWATA; YANO; TOMIYOSHI, 2007) is a mechanical device which gives feedback to user feet. It utilized special shoes attached to motors by strings and that can slip on a low-friction surface being acted on by forces. A total of 3 DoF where allowed by the foot.

In the passive simulators, there is no force acting against the user feet. The usages of giant spheres, where a person can stand and walk freely were the first ones we identified. In these devices the user is enclosed inside a sphere. There are the *Virtual Sphere* (LATYPOV; LATYPO, 2003) and *CyberSphere* (FERNANDES; RAJA; EYRE, 2003).

The sphere movements are translated to direction and orientation to be utilized inside a VE. Figure 2.4 (A) presents the Virtual Sphere, which requires the use of wireless

HMD, while (B) the CyberSphere, where the image is projected in the outer surface. We were unable to identify test evaluation of these devices. However, these were commercial products and need large rooms to be operated.

Another passive device is frictionless surfaces. (SURYAJAYA; LAMBERT; FOWLER, 2009) proposed a mechanical device, composed of a curved platform filled with common ball bearings that have a fixed position and are free to rotate. The curved characteristic of the surface allows the feet to slide naturally to the center. The user's limbs are tracked by the use of markers and cameras. To use this device, the user's abdomen had to be constrained to avoid fall.

Most of the walking interfaces, either passive or active, require special expensive devices. Some of these devices need to be attachable to the body, such as mechanical arms to hold the user in place safely, as well as special rooms to be operated. We decided to avoid these kinds of constraints in our device.

2.3 Walking In Place Techniques

Walking in Place, as the name suggests, are techniques where the user mimics the pattern of natural human walking. Usually there is no change in position, only orientation. There is no complete walk gait in this kind of technique.

According to (BOWMAN et al., 2004) this type of technique is useful when there is a need for an increased sense of presence; but there is little room for real walking or a simulated walking device. (USOH et al., 1999) states that walking in place is not as effective as real walking or simulated walk to support immersion. However, it is better than a virtual walking device. We identified two main classes of devices in this field. Those who utilize sensors attached to the user limbs to generate walking and those that use platforms composed of sensors.

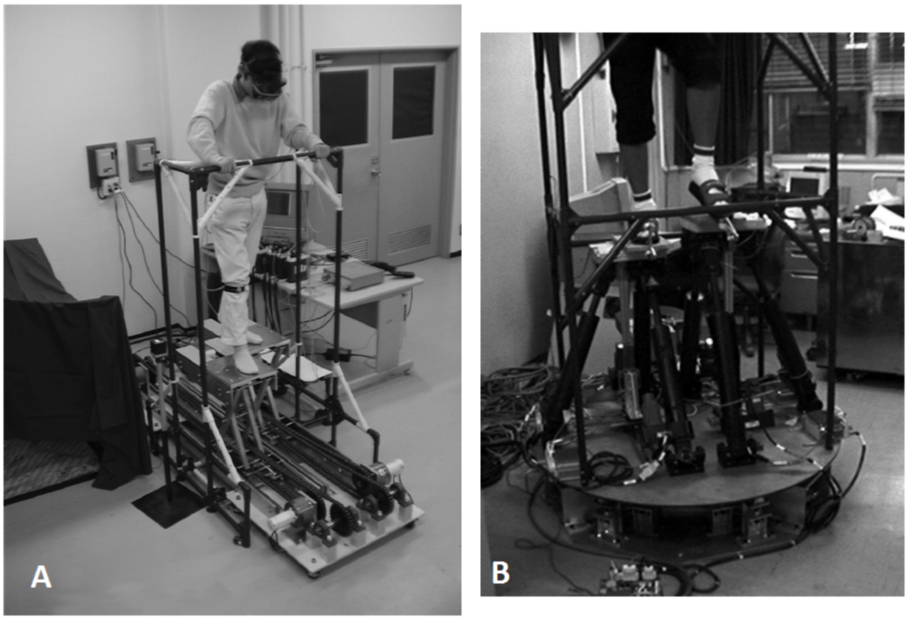
The work from Slater (SLATER; USOH; STEED, 1995) utilized magnetic sensors attached to the user body to capture head motion while the user mimics the walking pattern. The data captured was utilized to train neural networks, which identify walking patterns in the input signal. There were two problems with the technique: the detection of walk when the user was not walking, or undetected walking when the user was really walking. The article states this problem caused a negative impact and confusion to test users, as they preferred to use a virtual device (joystick) instead of the technique of walking in place.

The work of Templeman et al. (TEMPLEMAN; DENBROOK; SIBERT, 1999) proposed again, a WIP interface capable of identifying lateral walking, walking in place and orientation, based on special shoes with pressure sensors, gyroscopes and accelerometers attached to the knees and legs. The authors also provided several interesting details of study; but the device proposed was very complex as required many devices connected to the body.

Swapp et al. (SWAPP; WILLIAMS; STEED, 2010) proposed a device based on a low friction curved dish surface, where the user can slide the feet using special shoes, but without the use of a constraint around the user's abdomen. Due to the shape of the surface, the feet naturally slide to the center of the dish. Both rotational and displacement movements were inferred with this technique. The tracking was done with gyroscope and cameras. No pressure sensors were utilized.

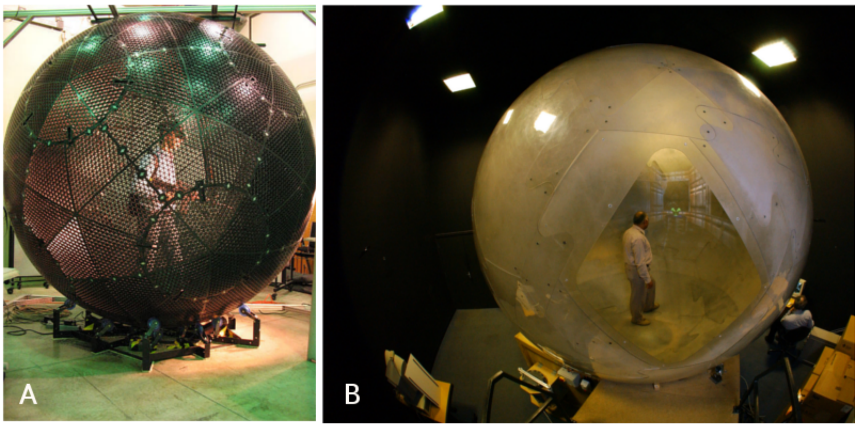
The work of Swapp (SWAPP; WILLIAMS; STEED, 2010) also make use of redirection techniques, together with a partial CAVE display. Small rotations in real world

Figure 2.3: GaitMaster devices. (a) the linear version. (b) the turntable version of device



Source: (IWATA; YANO; NAKAIZUMI, 2001).

Figure 2.4: In (a) Virtual Sphere and in (b) CyberSphere



Source: (LATYPOV; LATYPO, 2003; FERNANDES; RAJA; EYRE, 2003).

scenarios caused large rotations in VE. These were utilized to keep the user away from a lateral cave wall, redirecting the user to the center of the display wall. Figure 2.5 presents the device. Another device similar to this is the *Virtuix Omni* and was established in 2013. This one make the use of a rim to hold the user in place, inertial sensors to capture user orientation and Microsoft Kinect to capture user movements.

Figure 2.5: WIZDISH, low friction surface

Source: (SWAPP; WILLIAMS; STEED, 2010).

A system for tracking of the feet shadow under the floor was proposed and implemented by Zielinski et al.(ZIELINSKI; MCMAHAN; BRADY, 2011), as can be seen in Figure 2.6(a). The concept was developed to be used on CAVE. A camera was used in the ground, near the projector, and captures the interference in the light that comes from the surface caused by the user's feet. With some image processing, this technique allowed the identification of feet, and tracking of the user position and orientation. This technique allowed multiple users to be tracked in one surface.

No calibration was required for this system, but over-floor illumination could interfere with the identification of the feet.

Bruno et al. (2013) proposed a walking in place with variable speed based on amplitude (height) of leg movements. They employed IR tracking device and foot markers. It provides extensive comparative results against another technique that only uses the frequency of steps to control speed. The technique allows only for forward walking.

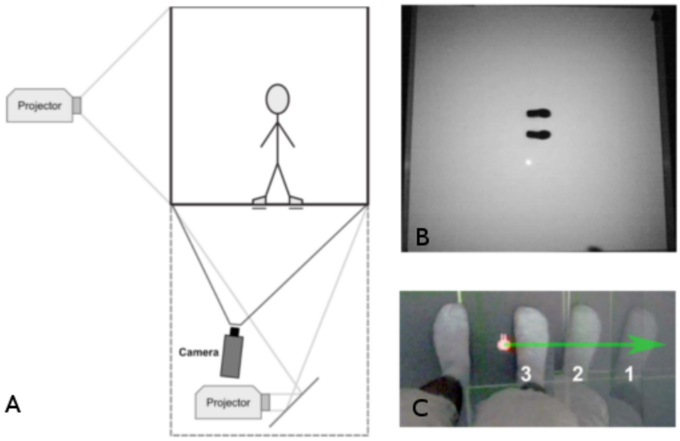
The devices built with platforms are commonly anchored or filled with sensors, which have their information captured, processed, and utilized to generate orientation and displacement information. The sensors detect the user pressure that represents the center of mass change.

Couvillion et al. (2002; 2005) utilized a matrix of resistor sensors to detect the pattern produced by foot pressure. This system was able to detect front, back, and lateral walking, as well as rotational movements with the use of a gyroscope in the user chest.

Bouguila at al. (2004) built a similar device, but instead utilized a matrix of switches over which the user stands on and simulates walking in place. Data captured in a sampling rate of 100hz was utilized to calculate orientation and walking patterns. Figure 2.7 shows some details of the system.

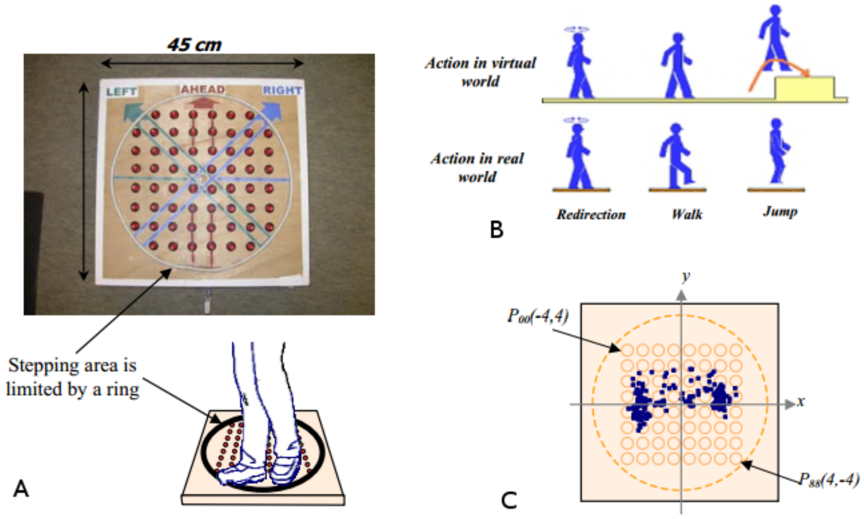
Williams at al. (2011) evaluated an approach using a Wii Balance Board in 2011. The

Figure 2.6: Shadow Walk. (a) Complete system idea. (b) View of beneath camera. (c) Example of strafe (lateral walking)



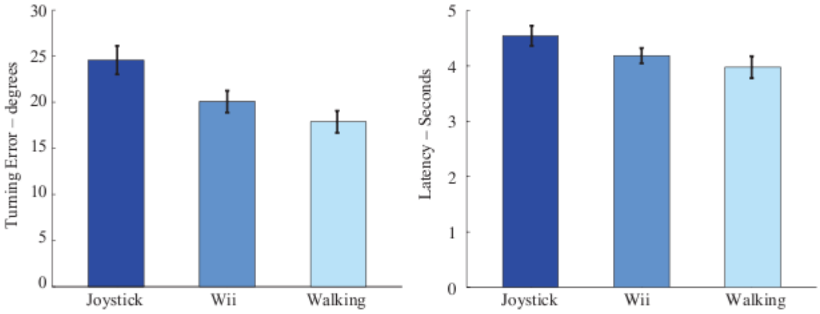
Source: (ZIELINSKI; MCMAHAN; BRADY, 2011).

Figure 2.7: Walking Pad. In (a) the sensor pad. (b) the possible movements detected by the system. (c) the calculated center of mass for several iterations of the system



Source: (BOUGUILA et al., 2004).

Figure 2.8: Two analysis for three approaches: Free walk, walking in place and joystick control. Error bar indicates error as mean. According to author, the condition has a significant effect on turning error. In Latency graph, the condition is not significant



Source: (WILLIAMS et al., 2011).

device is a platform anchored on top of four scales. The technique proposed was able to infer the speed of displacement. The orientation was captured with the use of a gyroscope attached to the waist of the user.

The test to evaluate the technique was done against real walking and joystick control. The tests were also done against real walking, using optical track of markers, and rotational sensors on the chest to detect position and rotation. Processing the signal from four sensors of WBB, the author got the step and intensity for displacement.

After user experiments, the author presented two graphs representing the turning error and latency for each approach as shown in Figure 2.8. The physical movement had the best responses. They had hypothesized that physical movement could prime the sensory motor system, which is more easily adapted in walking conditions as in WIP. However, the author highlights the limitations of previous works, such as Feasel, where the results using physical movement diverged from current work.

Twelve participants were tested in each mode. Resuming the graph and the reported results presented in the paper, the author states that the spatial awareness provided by the body use in physical movement, improved the movement in the virtual world, reducing the error in rotations. The use of WIP technique also had good results in rotational precision. The response time, presented as latency was insignificant across the conditions. The cost of the device is low, because WBB is a consumer product, and gyroscopes can be easily found at low cost.

Matthies et al. (2014) present a do-it-yourself WIP device using gym steeper and distance sensors with Infrared (IR) attached to legs and joystick to capture data. The device allowed the movement of legs in up and down movement on top of the stepper. The speed and orientation information were inferred, based on long term steering. The authors cite loss of equilibrium by users using the device with HMD. A CAVE display was opted for tests, together with a 3D mouse. One of the conclusions points out that the device was hard to use. Another author also (BARRERA; TAKAHASHI; NAKAJIMA, 2004) create a wearable device, which is attached to the user's leg. It could detect user steps and tilt. It used accelerometers to get this information and signal analysis for post-processing.

The majority of walking in place approaches rely on software or magnetometers, gyroscopes, and cameras to detect feet orientation and movement.

2.4 Virtual Walking

We are interested in virtual walking devices that utilize limbs, other than the hands, to control orientation. Works in this field use metaphor techniques, such as the experience of driving a car. Typical classification (BOWMAN et al., 2004) for steering devices are tracking head orientation (gaze-directed steering), pointing (that do not utilize the feet), and body leaning.

- gaze-directed steering: work by tracking the head of the user, and directing the displacement to that direction
- pointing: the user points to the direction which they desire to follow
- torso-directed steering: tracking the user's torso or sometimes waist, which determines the displacement direction
- camera-in-hand technique: the user can see the environment based on the direction and orientation of their hands
- physical steering props
- virtual motion controller
- semi-automated steering: displacement or orientation partially controlled by software

These techniques use hands, head, arms, or feet to indirectly control the direction and displacement. Many of the works in the simulated walking, real walking, or walking in place mix some of the steering techniques inside their functioning. The pressure sensor board provides an interesting interface to allow steering techniques.

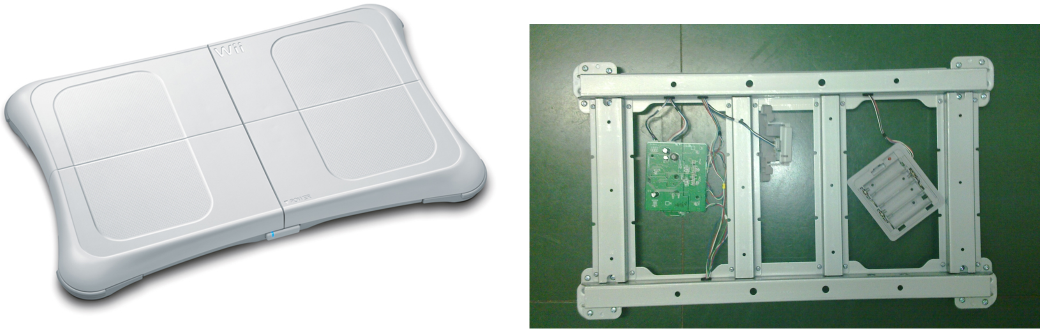
The first to propose the use of a surface where the user could stand on and lean their body to the desired direction of movement inside the VR environment was Wells et al. (WELLS; PETERSON; ATEN, 1996). The change in the Center of Pressure (CoP) of the feet was then captured by pressure sensors underneath the surface and processed. This is a physical-steering technique. (HAAN; GRIFFITH; POST, 2008) proposes the use of the Wii Balance Board (WBB) in three different configurations, to control action in VR. One of the techniques allows for 3 Degrees of Freedom (DoF), another for 2 DoF, and the final one for 1 DoF, respectively.

Thee work of Fikker et al. (2009) presented a comparative test between Wiimote and Wii Balance Board, for controlling displacement in a 2D Maze. The balance was used to allow movements in the lean mode, and the Wiimote was used to open doors in this method.

The results of the tests show that the use of Wiimote allowed faster navigation in the maze and was less prone to errors. However, the Balance Board provided more fun to users. This conclusion fits in with the (USOH et al., 1999) findings: that controls and simple techniques guarantee effective control in VR.

Valkov et al. and Wang et al. (VALKOV et al., 2010; WANG; LINDEMAN, 2011) proposed similar devices to Wells work (WELLS; PETERSON; ATEN, 1996), using the natural feet pressure and body lean (or tilting) techniques to control displacement in the environment. Both use the metaphor of surfing and flying in an environment. The device

Figure 2.9: Wii Balance Boards



Normal Open case

Source: the author.

proposed by Wang (WANG; LINDEMAN, 2011), utilized both a real balance board together with a pressure sensor board. He presented two modes of operation, which were isometric (fixed on the ground) and elastic (the base is movable), which required the user to keep their balance.

A common theme is accuracy of foot interaction. The author Lima et al. and Pakkanen et al. (LIMA FILHO et al., 2011; PAKKANEN; RAISAMO, 2004), presented studies of interaction in games, all using feet in different virtual walking modes. These works tracked the feet utilizing camera, printed markers, and sensor boards to capture information. Both point the usage of foot for precise walking. However, (LIMA FILHO et al., 2011) points out that foot interactions are as precise as hands for controlling spatial tasks.

2.5 Pressure Boards

Pressure boards usually are platforms, anchored on the top of scales, or composed of pressure sensors like a matrix of resistor, which are able to detect the pressure changes of a person on top of them. The first of this kind for use in interaction using the feet was (WELLS; PETERSON; ATEN, 1996). A proposed and patented matrix of resistor sensors approach is presented by Couvillion (COUVILLION W LOPEZ R, 2002; COUVILLION et al., 2005).

The Nintendo Wii Balance Board (WBB) is a commercially available option since 2007 and sold with WiiFit kit. The boards are rectangular surfaces composed of 4 pressure sensors (or scales) installed in their corners, as seen in Figure 2.9. Each sensor can be read individually. The capture rate of sensor information can be made at a rate of up to 400hz.

The board size is approximately (20.5 x 13.2 inches), where a user can stand comfortably. This device is capable of sensing the Center of Pressure (CoP), or center of mass distribution of a user on top of the device. The device communicates with computer via Bluetooth, and for this model up to seven devices can be plugged in together.

Works in health area have been done with WBB to help people with impaired standing balance as (RA. et al., 2010), in substitution to specialized pressure boards. The device was used in different ways for locomotion control. In Walking in Place and Virtual Walking for VE we can cite (WANG; LINDEMAN, 2011; WILLIAMS et al., 2011; LIMA FILHO et al., 2011).

2.6 Safety

We identify that safety in the field of walking devices is a continuous concern. As users are typically immersed inside a Virtual Environment, using HMD or inside a CAVE utilizing stereo glasses, the real space identification is compromised. The three main fields of walking interfaces provide different ways to address this problem. Most works tend to use some virtual barrier when the user reaches limits of the real world space or device, warning visually.

In the field of real walk the technique of walking redirection (SUMA et al., 2012; BRUDER et al., 2012) requires continuous assistance while in use, to maintain a safe environment. Tactile feedback in the foot or visual feedback is utilized.

In the field of simulators, usual techniques include the restriction of user position by the use of mechanical arms in body chest (DARKEN; COCKAYNE; CARMEIN, 1997; IWATA, 1999), fixing the feet to the platform (IWATA; YANO; NAKAIZUMI, 2001), or constraining the area of walk by the use of circular abdomen rim and belts as in (SURYAJAYA; LAMBERT; FOWLER, 2009).

The Walking in place techniques typically provide few hardware protections, and utilize virtual isolating strips, which are show in the field of vision in case of real space danger.

2.7 Measurement, Evaluation, and Other Details

We identified in other works the use of the following set of techniques for analysis and validation: forms, sound recording, user position record, and posterior analysis. Some works deal with informal user tests, processing just qualitative information. Tests about psycho-physical effects and characteristic of the techniques are relegated to little exploration.

Qualitative tests typically carry tendencies, as reported by most of the works in this area. Subjects usually express good responses with the techniques due to the “new” effect to the use of alternative interfaces.

Quantitative tests usually compare the ability of using the interfaces proposed based on path following or object capture. Few tests analyze in-depth the techniques or device ability to detect correct orientation and displacement commands.

Usoh (USOH et al., 1999) made a comparison of the three main alternative walking navigation techniques, testing with users to detect the preference and immersion credibility. With this work he recreates a 1995 user test made by Slayer. The test results reinforce that real walking helps the sense of presence strongly, followed by Virtual Walk (some kind of walking in place) and Virtual Flying.

Cohn (COHN et al., 2005) also made an extensive study in the field of Virtual Environment locomotion interfaces, comparing real walking, WIP and Joystick flying. Each technique was tested with one of three visual conditions: HMD, unrestricted natural vision or field of view restricted natural vision.

Typical tests involve following trajectories with different techniques. The analysis of results is typically based on time spent to travel a known distance while following paths. The results are usually used to estimate the quality of technique/device as in (BOUGUILA et al., 2004).

We found tests that encompass use of behavioral (USOH et al., 1999) binomial logistic regression analysis for presence, behavior, and locomotion responses. However there are a complete set of works, as presented by Iwata that do not do extensively use tests or analysis to validate their techniques.

Iwata techniques and devices are only operated in informal user experiments and results are presented based on the accuracy response of sensors attached directly to the limbs of the user. The comparison are against natural walk with the use of each technique being studied. (DE LUCA; MATTONE; GIORDANO, 2007; DE LUCA et al., 2009, 2012) presents depth user tests and analysis, both qualitative and quantitative. There were several tests where the user position over the devices was recorded and compared with real travel path.

The test population for the area had been typically between 12 and 30 subjects, ranging from 20 to 40 years old. Typical analyses executed in the field are statistical One-Way repeated measure ANOVA, to detect significant differences between data-sets. This is the case in most tests, when equal participants are used in several tests. Some research results analysis was found to be done with Fisher Least Significant Difference, which provides mean comparison between groups.

The use of forms, with standard questions was common in tests. They use a typical Likert scale with five options to research qualitative information. The questions typically follow the details proposed by ISO 9241-400, *Principles and requirements for physical input devices*.

This ISO has suffered several changes in recent years. Old revision had the name ISO 9241-9 *Requirements for non-keyboard input devices*. There are also the ISO 9241-410 *Design criteria for physical input devices*. It defined standards such as measurement techniques and is based on Fitt's Law on human motor control. A set of questions is proposed to evaluate devices in user tests in ISO. They also define the details of direct tests (follow a path) to be applied in order to allow precise evaluation of some techniques.

(SUMA et al., 2012) registered that audio recording the tests helps to identify users feelings about the quality of the environment, as expression of frustration or other feelings through vocalizations gives information that could be used to determine the quality of the use. They also used white noise during the experiment. (BRUDER et al., 2012) utilized city sound noise to hide the laboratory noise. Both techniques provide users with vestibular cues and helped the feeling of immersion. The direct communication with users during tests is also avoided, and if need be, done via headphones, in a fixed virtual position in VE, or centered on the user's head (USOH et al., 1999).

The VE are typically displayed with Head Mounted Displays (HMD) or Cave Automatic Virtual Environment (CAVE). The utilization of either influences the usability of the technique (BOWMAN; FROHLICH, 2005; VALKOV et al., 2010). The specific use is also deeply attached to the kind of technique. HMD cables and sensors distributed in the body may generate undesirable loss of immersion, and should be avoided when possible (USOH et al., 1999).

Care should be taken at Walking In Place footstep distance in VE (COHN et al., 2005). Where discrete step recognition, with a fixed step size is generated, it may be difficult to detect the accuracy of displacement and may cause cyber-sickness and unnatural movement.

All techniques of Walking in Place (WIP) release the hands for other uses. Direction of walk may be defined by steering techniques as *head direction*, *waist direction* or even *arm orientation*. *Head direction* may constrain walk, since users cannot look around without being directed (BOWMAN; FROHLICH, 2005). The more natural seems to be waist changing the orientation of displacement inside the VE, according to our orientation of walk. As presented in Virtual Walking, some techniques rely on orientation of body center of mass over sensors, as in (WANG; LINDEMAN, 2011).

2.8 Summary of techniques

Table 2.1 presents a comparison between a set of techniques of walking in place, while Table 2.2 focused on the walking simulators found during the research. Works of walk redirection and of virtual walk were left outside these tables. Some works do not explicitly state as using HMD or CAVE, but we infer through indirect tips, as photographs or text. For some other works we could not evaluate this information, and it was left blank. We made subjective cost estimation for each device or technique.

For example, Omni-directional treadmills depend on special mechanical parts and hardware done by machinery. In this case we assume it as a high cost device. Works that use parts ready to use were considered low cost. All estimates do not assume the cost of the HMD or CAVE.

In Tables 2.1 and 2.2 it is possible to check the author, year of publication, the devices used in technique, cost and of WIP and Walk Simulator respectively. It is also possible to check some observations for each technique.

Table 2.1: WIP Techniques

Technique	**Author**	**Year**	**Active**	**HMD**	**Cave**	**Cost**	**Orientation**	**Translation**	**Main idea**	**Obs**
Neural Net	Slater	1995	no	yes		low	mag	mag	Neural Net recognized walk from head sensors	
Virtual motion controller	Wells	1996	no	yes	yes	low	not def.	not def.	surface with sensors	
Pressure Mat	Couvillion	2002	no	yes		med	giro	press sem	grid of pressure sensors	
Walking-Pad	Bouguila	2004	no	no	yes	med	giro	sig proc	switchs array activeted by user foots	
Low Latency WIP	Feasel	2008	no	yes		low	straingauge	straingauge	simple sensors attached to user knees and ankle	
Camera Based OBDP	Suryajaya	2009	no	yes		med	camera	camera	board filed with spheres where the user slip on	camera capture position
WIZDISH	Swapp	2010	no	yes	yes	low	giro	camera	curve dish where user split over	
Silver Surfer	Wang	2011	no	yes		low	straingauge	straingauge	Wii Balance board as tilt board	The use of legs, but not actually walking in place
Shadow Walking	Zielinski	2011	no	no	yes	med	camera	camera	camera capture user foots beneath cave	
WIP with Wii BB	Williams	2011	no	yes	no	low	giro	straingauge	user walk in place over wii balance board. Direction os obtained from giro in waits	

Table 2.2: Walking Simulators

Technique	**Author**	**Year**	**Active**	**HMD**	**Cave**	**Cost**	**Orientation**	**Translation**	**Main idea**	**Obs**
Omni Direction Treadmill	Darken	1997	yes	yes	yes	high	giro	accel.	omnidirectional treadmill	
VirtualSphere	Latypov	1999	no	yes	no	high	rot. Sensor	rot. Sensor	walk is captured based on sphere movement	
Omni Direction Treadmill-TorusMill	Iwata	1999	yes	yes	yes	high	giro	accel.	another omnidirectional treadmill	
GaitMaster	Iwata	2001	yes	no	yes	high	NA	NA	linear in first version, 6DoF in second.	
CyberSphere	Fernandes	2003	no	no	yes	high	rot. Sensor	rot. Sensor	walk is captured based on sphere movement. Image projected in sphere surface	
CirculaFloor	Iwata	2005	yes	yes		high	camera	accel.	movable robot tiles	movement through prediction
StringWalker	Iwata	2007	yes	yes		high			shoes with attached strings which apply forces in user foots	
CyberCarpet	Luca	2007	yes	yes	yes	high	camera	camera	surface full of ball bearings with move controled by a beneath treadmill	
CyberWalk	Luca	2008	yes	yes		high	camera	camera	treadmill with advanced algorithm	

2.9 Final Considerations

The works of Walking using devices are vast. The main researchers found are Iwata, that has been working in the field since 1989, Bowman which among other works has books on the area of interaction, devices, and techniques. Luca's main works focus on providing more natural walk simulation devices with mathematics tools. (USOH et al., 1999) provide a good evaluation between the three techniques: walking in place, walking simulators, and virtual walk.

The works in the walking redirection approach (SUMA et al., 2012; BRUDER et al., 2012) became an interesting idea to use when the technique should be tested in partial CAVE environment, where image is present in only three of four walls.

The use of camera trackers is common, as in (SWAPP; WILLIAMS; STEED, 2010; SURYAJAYA; LAMBERT; FOWLER, 2009; DE LUCA; MATTONE; GIORDANO, 2007; DE LUCA et al., 2009), but limit free walk to non obstructive environments and require a distributed number of devices. A set of works point the usage of sensors at user's waist (WILLIAMS et al., 2011) and/or in knees, feet, and joints (FEASEL; WHITTON; WENDT, 2008) (SLATER; USOH; STEED, 1995). Devices for Walk Simulation seem to be expensive, have problems, and are complex to implement. Some of them became commercial products such as CyberBall, CyberSphere WISDish and the Virtuix Omni.

Based on this, we found a gap for an inexpensive, large, and expandable surface that could detect user orientation and displacement, to allow easy VR navigation control and without many sensors or cables attached to the user's body. It should also be easy to mount, have a good response time, and have no perceptive lag. It should be usable either with HMD or CAVE, and be safe to use. A device with these characteristics could be used to guarantee some degree of immersion when utilized with VE. These assumptions pointed us to walking in place interfaces. Next chapter will present our solution based on these premises.

3 OUR PROPOSAL

This chapter will presents the details of our proposed idea to work with. The use of more natural controls for locomotion tend to guarantee better immersion (USOH et al., 1999; COHN et al., 2005). After the research of the field of walking devices for more natural human machine interaction, we take into account the shortcomings of the other techniques to control locomotion in VE like environments and elaborate the base for guiding the current work proposal.

The main points of our technique of walking in place are simplicity and naturalness, with the minimum amount of hardware attached on user body and the ability to be expandable to large physical environments. These items are enumerated below.

- To allow the use of natural reflexes for navigation and control skills
- To reduce the number of sensors attached to the body
- To be inexpensive to build in terms of hardware requirements
- To be simple: easy to use, reducing the stress of walking in place
- To be simple to mount by a person
- To allow Omni-Directional travelling to any direction
- To have the minimum delay in step and orientation detection
- To be expandable: flexible for use in bigger surfaces
- To be safe to use

We start with the idea of a technique to enable naturally utilization by a untrained person. It is common in other works the use of specialized hardware to achieve naturally walk, such as Omni-directional treadmills, which allow complete gait sequences, with low learning curve. However specialized hardware has high costs related to mechanics. This definition removed if most, all devices in the category of *walk simulators* leading us to a *Walking In Place* (WIP) category of devices.

The use of WIP sacrifices the immersion, compared to a physical device. However it still guarantees a short learning curve, as users already walk in the real world, some natural body feedback because of the use of walking mimicking and it is simple and we believe that is natural to ordinary people to utilize.

Another item to be accomplished is the setup simplicity to mount the device and easiness to use the technique, avoiding the use of any attached devices to the user's body, beyond HMD. Most of related techniques need several sensors to be attached to the user's body, of have the feet fixed in some way. We propose to reduce the tiredness of use of walking in place, with the use of lazy and small steps.

We choose to use in our work commercial Wii Platforms, which were used only as input interface to control locomotion and orientation for a user standing over it and mimicking walking in place. To achieve omni-directional travelling with naturalness, the user rotates and simulate walking.

We capture the signals from the balances, and elaborate a signal processing pipeline, capable of detect walk, speed, orientation and lateral walking of users. We enhance the pipeline via several small development and test procedures.

To achieve expandability of the device, we make it flexible enough to be used with multiple Wii Platforms, in any desired configuration, just by previously informing the platform position.

Safety for more natural navigation techniques is typically an issue in virtual reality, as the use of HMD removes or restricts the ability to get instantaneous visual feedback. Visual tips help in the stabilization of the body's balance. When full head tracking does not occurs (with 6 DoF), users depend heavily on their vestibular system for equilibrium and balance.

In case of our surfaces for walking in place, the set of boards utilized was small and had gaps between them when side by side. The users need to have the ability to detect the limits of the boards and gaps of the walking area with minimum influence on their behavior and the feeling of immersion. To achieve good safety levels, we rely on the use of passive foot tactile feedback.

Given this general overview of the aims of our work, the next section will cover the details of technique, how it was implemented, and safety details. The next chapter will contain extensions of the technique.

3.1 Overview of the Detection Process

To allow the natural spatial locomotion in 2D plane inside a virtual environment, 3 degrees of freedom have to be achieved: a displacement information (speed) (x, z) and rotation.

Our proposed work uses only the feet pressure information, generated by the mimic process of a person on top of a sensible surface with coarse spatial sensors. The position of the scales on the ground should be previously known. From the pressure information of these scales, after processing by our algorithm, we were able to detect orientation and infer the subjective speed of the user. This information can then be utilized to control a virtual camera inside VE.

Initial tests with the balances provide us with raw data from sensors. Based on the computation of the center of pressure used by (WILLIAMS et al., 2011), we initially used the Wii platform as a surf board, where a user can utilize the body lean for controlling the displacement and orientation. Furthermore, walk patterns were captured and tested as (WILLIAMS et al., 2011), and we were able to detect walking in place with fixed orientation.

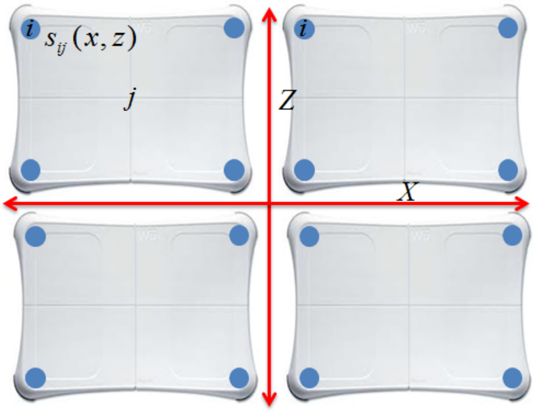
The walk patterns from users walking in place and rotating in place on top of one platform were captured and visually investigated. The first attempt was to train a hidden Markov field, to detect the user orientation. However, it was inefficient to detect correct orientation and walking patterns, often mixing them. It also had a slow response time.

We manually elaborated a processing pipeline, which was able to detect orientation and walking patterns. Sections below will present details about center of pressure, orientation, speed, and lateral walking detection. Most of this information is computed from the center of pressure captured previously.

3.2 Center of mass calculation

The initial tests were made with only one platform. Due to the small size of one platform, it was not suitable for rotational movements to be done safely by a person without training. The use of two or four platforms provided a more secure and comfortable surface for walking in place. Figure 3.1 shows a typical distribution of the balances in a rectangular shape.

Figure 3.1: Four balance boards. Each balance (j^{th}) have four pressure sensors (i^{th}) in their corners



Source: the author.

The center of pressure calculation is based on the Cartesian position of sensors (x, y) times the pressure value coming from the balance sensor. Multiple pressure surfaces (balances) can be used together to represent a final center of pressure of a user, on top of them, computed in a one step process 3.1. The time complexity for the computation is linear (O(n), where n is the number of sensors). The signal from balance sensors is captured continuously, as discrete samples, with range of $[0..65536]$.

Equation 3.1 provides the details of the calculation. This calculation is similar to (WANG; LINDEMAN, 2011) method. For simplicity we assume that all balances and sensors are around a common center position $(0, 0)$ and *sensor positions are represented by vectors*.

$$M(t) = \sum_{j=1}^{4} \sum_{i=1}^{4} \frac{s_{ij}(t) * W_{ij}}{\sum_{j=1}^{4} \sum_{i=1}^{4} s_{ij}(t)} \tag{3.1}$$

,where $M(t)$ is the discrete position of the center of pressure, in a moment in time. Each acquired sample information of sensor pressure is $s_{ij}(t)$, for each balance. Their respective position W_{ij} is a vector (x, y), which define the sensor in the space, for each balance i and each sensor j and which is fixed during the setup of the balances configuration.

The distribution of sensors can be sparse, and can even be placed under elevated floors in open areas, by only changing the (x, y) sensor information.

Since the $M(t)$ is the sum of all sensors positional vectors, it represent a two dimensional information: a vector. Thus, in the next sections, we can call $M(t)$ as vector. When we use the word "signal" for some variable, it means the instantaneous, discrete information – sample – captured in the time.

3.2.1 Center of mass normalization

Given that the Wii balances are placed all in the same orientation, with respect to each other, their position can be changed to any configuration. The only item that needs to be changed is the position of each balance, $(x, y)_{ij}$.

As can be seen in the formula, the total weight captured of the user on top of the platform is used to normalize the weight per sensor, adjusting the maximum value for scales between $[0..1]$. This way, the center of mass $M(t)$ remains similar between person and the next processing steps operate better.

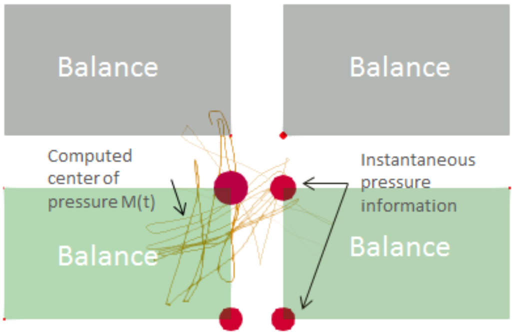
3.3 Orientation calculation

When a user walks and rotates his/her body on top of the walking surface, the center of pressure information $M(t)$, changes in time, for their components (x, y). Once sensors are read and the center of mass is calculated, we compute the orientation of the user.

Typically during the text, the expression *signal* refers to discrete, sampled data, acquired from the hardware in fixed time intervals, representing the sensors information or processed data.

The visual inspection in Figure 3.2, presented that the center of mass changes more or less in the direction of the feet pressure, as users stand on top of the platform and mimic walk. This variation is perpendicular to the walk direction. We evince that the speed information $M(t)$ could be used as a partial direction information to determine the orientation of the user.

Figure 3.2: Typical variation of the center of mass in orange during the execution of WIP. The balances are also projected



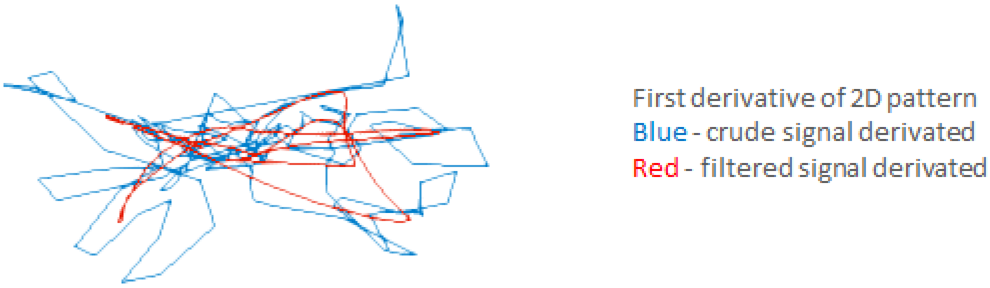
Source: the author.

Taking the nomenclature from Digital Signal Processing (DSP) techniques, we decide to apply on $M(t)$ an impulse response filter (some researchers may call it a derivative filter) to capture the changes of the center of pressure, which represents the speed information. A more formal definition can be set as

$$S(t) = \frac{dM(t)}{dt} \tag{3.2}$$

The first order derivative gave us the ability to identify when a user rests their body weight on top of the platforms, as this is a high speed event. This event provided the partial information about walk direction. The Figure 3.3 illustrates the signal after crude derivation (in blue), and after some low pass filtering, the signal becomes the red line in 3.3. The derivative signal contains orientation correspondent to the foot pressure direction.

Figure 3.3: Typical $S(t)$ during the execution of WIP. Blue - signal without filtering. Red - signal with filtering



Source: the author.

As seen in the previous figure, $S(t)$ is also over-imposed with noise that damages the identification of the interest signal. Figure 3.4 illustrates a better evolution over time of the $M(t)$ and $S(t)$. At left image, the center of pressure $M(t)$ with filtering applied, and the right image the derivative of the $S(t)$

We detected that small changes of the user balance, when using the platform, generate variation on all these signals. We defined a set of vectors that will be presented further, to keep track of individual foot position and that are utilized to compute user orientation.

We performed tests and found that a low pass of the derivative signal could offer a good way to cut off undesirable noise signals and small changes of the user balance, in order to only detect the steps. A simple mean filtering was utilized. It guaranteed minimum delay in detection and produced good step response. A small study found that in 100hz capture rate, a mean of 10 and 20 averaged samples for each sample of $M(t)$ offered the good step detection with low noise.

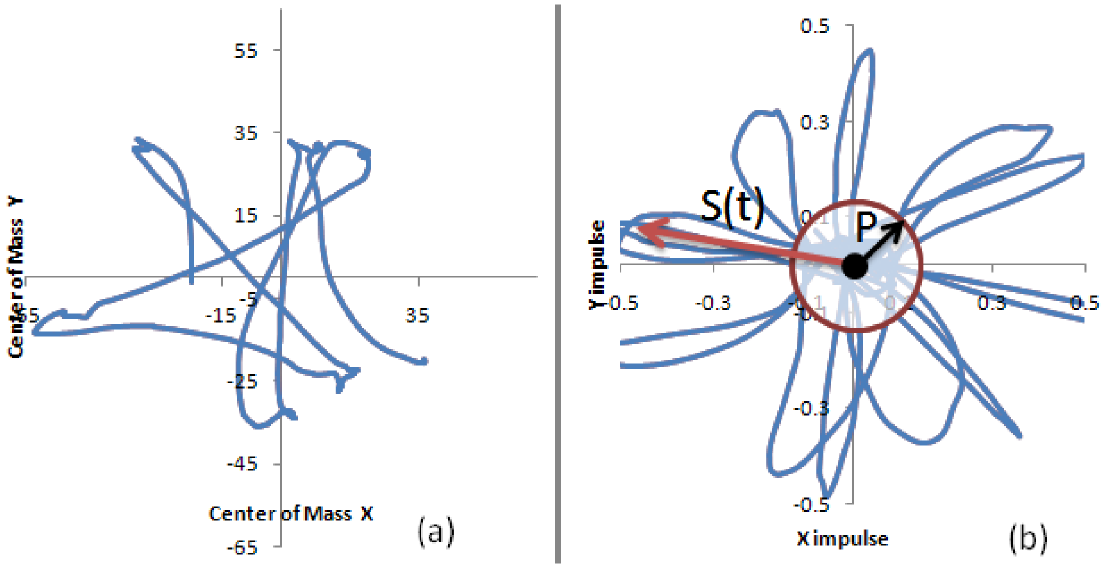
From now on, we will refer to the $S(t)$ as a vector, thus $\vec{S(t)}$

Based on this derived signal $\vec{S}$, we chose to limit their further processing when their modulus is greater than p.

$$\|\vec{S(t)}\| > p \tag{3.3}$$

where p is a threshold defined after informal tests, to allow good separation to discern between user step and natural body balance which preferably should not cause step movements. When the $\vec{S(t)}$ is above this threshold, it is processed by what we called "a vector lock system."

Figure 3.4: Filtered center of pressure $M(t)$, in the left, during the execution of WIP. In the right, derivative signal and $S(t)$. Both represent some seconds of sampled data



Source: the author.

The threshold was used to avoid that small changes – noise – on the pressure sensors interfered with the orientation detection for the next steps. The vector lock system is used to track the orientation of the user on top of the surface.

The use of this threshold proved to not influence the identification of even small footsteps over the platform. We identify that small steps generate enough variance to be detected and processed efficiently. This allowed the use of our device with lazy steps.

3.4 Vector Lock System

When visualizing the previous derived $\vec{S(t)}$ in the Cartesian place, over time, it is possible to identify that it varies in alternated directions more or less around 180 degrees as an user mimic walking in place and change their orientation.

We assume that the next processing only applies when $||\vec{S(t)}|| > p$

We track the variation of $|\vec{S(t)}|$ over time, for the local maximum value in a sample window, which represents the inflection point of $\vec{S(t)}$ over a short time. When this condition is achieved, the sample $\vec{S(t)}$ is compared against a reference unitary vector $\vec{R}$ which contains the last inflection point.

$$\vec{S(t)} \cdot \vec{R}$$

The final, individual, foot position is represented by the use of two other auxiliary vectors, $\vec{A}$ and $\vec{B}$

If the arc-cosine's of the dot product between the detected inflection point of $\vec{S(t)}/t$ and $\vec{R}$ is bigger than 90 degrees, then a auxiliary vector $\vec{A}$ receives the content of $\vec{S(t)}$ and $\vec{R}$ receive a mirrored copy of $\vec{S(t)}$.

Otherwise a vector $\vec{B}$ receives the content of $\vec{S(t)}$ and $\vec{R}$ receives a copy of $\vec{S(t)}$.

As the user walks, the vectors $(\vec{A}, \vec{B})$ converge on the possible direction of each foot, respectively, on top of the platform. These are used to determine the body orientation of the user on top of the platform.

Then we define the body orientation as a unitary vector $\vec{C}$, which is calculated as the mean of the perpendicular vectors $\vec{A}$ and $\vec{B}$.

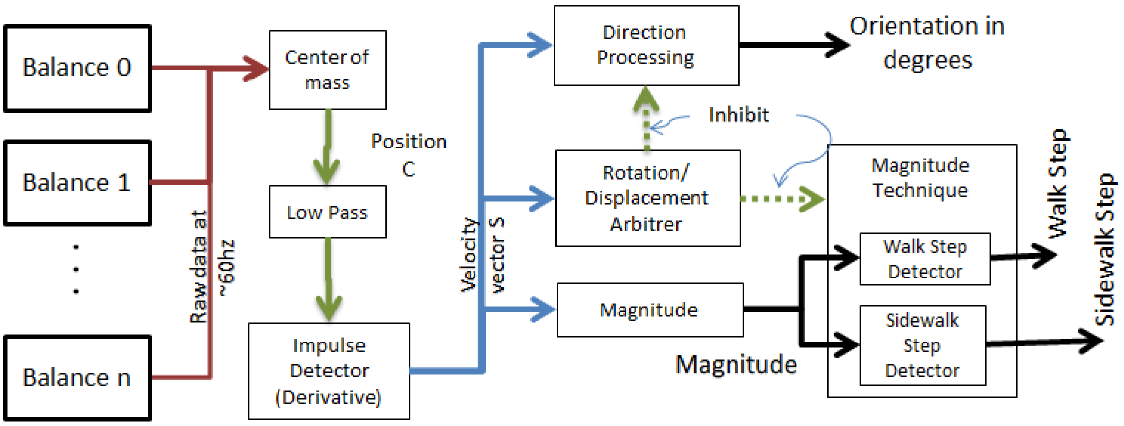
$$\vec{C} = (\perp \vec{B} + \perp \vec{A})/2$$

This vector $\vec{C}$ is assumed as the most probable orientation of the user on top of balances.

As we test this approach, we detect that the orientation vector $\vec{C}$ may have fast changes as the user rotates on top of the platform, leading to unwanted shaking of the orientation (camera), which caused cyber-sickness during the pre-test phase.

A mean filter again was applied on $\vec{C}$ to smooth orientation changes. We tested and defined empirically the filter value to minimize shake effects and maintain the responsiveness in orientation changes. The complete pipeline is presented in Figure 3.5.

Figure 3.5: Complete pipeline to detection of orientation, walk steps and strafe



Source: the author.

The above details are the orientation detection. The lateral walk (strafe) will be presented in next's sections.

3.5 Step Detection and Displacement Generation

The module of step detection is able only to infer a virtual speed information from the user simulating the walking gait with walking in place on top of the boards. As the user really does not complete the walk gait, we infer a walk speed based on step per time or step intensity (pressure intensity). Either of the two techniques of step generation are applied on top of signal $\vec{S}(t)$, after it is trimmed by threshold previously defined as p. The speed of the generated steps and their duration are presented below as possible techniques to control displacement velocity.

3.6 Walking Speed

We detect that we could generate speed information in two different ways:

- using step frequency to generate speed variation
- using step intensity to generate speed variation

Both ideas are applied on top of the intensity of the previous vector $|\vec{S}|$. This information is more or less within a known range, for any user of the device, as $|\vec{S}|$ is a normalized value that takes the total weight of user of the device during their processing (see Subsection 3.2.1). Both speed ideas were tested initially without limit velocity, and we chose to use ranged velocities.

For velocity control, as step frequency variation, we integrate the step frequency, every time signal $\vec{S(t)}$ is detected, clamping this integrated signal to a max value. To these ranges are attributed minimum and maximum speeds.

For velocity control as step intensity, we kept track of the signal intensity up to their maximum peak value on the step. This intensity is integrated, and is translated to a speed, which is defined between ranges of minimum and maximum speeds.

The tests without speed limit demonstrated that some users could cheat the speed generation and walk much faster than others. The speed range limits provided good control over this variability. In both options of processing, the velocity is used as the base to generate the displacement information by integration. For further references, we will call this velocity as $Walking_{speed}$.

3.7 Walk Inhibitor

After detection of steps events, they could be used to generate the inferred displacement. A problem arises from this fact: as users step, these steps affect both the displacement and the orientation. We manage this situation with two different approaches:

- allowing displacement occur during rotational movements
- avoiding displacement occurring during rotation

The exact behavior, used for stop displacement and then rotate, was based on visual inspection of the natural human walk. After visual inspection we determined that users tend to keep walking while making light curves, but typically stop walking when making sharp changes in direction. We try to replicate this behavior.

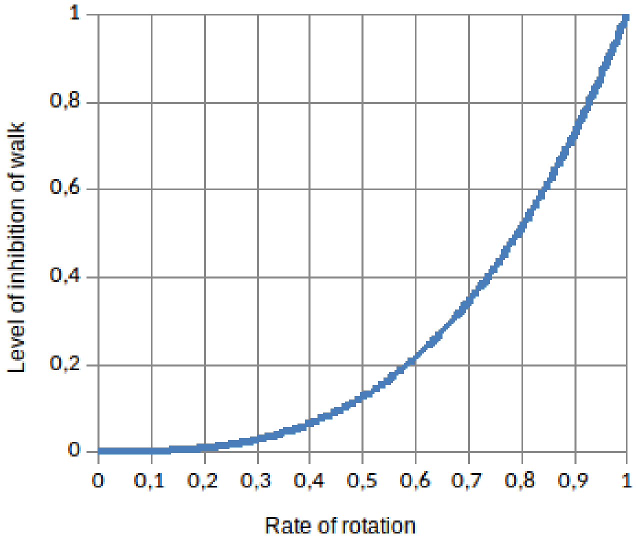
The natural behavior of our technique was to allow walking during rotation. As for the second behavior, we decided that would be more correctly inhibit walking during rotation. The first attempt was to restrict displacement when any change in orientation occurs. This proved problematic, as small orientation changes happen when we WIP, causing several breaks during the walk.

We define a threshold to restrict displacement only when rotation is greater than a certain level. Again, this proved inefficient, as the displacement ceases in strokes in this configuration, being severally unnatural.

In order to overcome these problems, we define a variable inhibitor, based on the rate of change of the rotation value ($\vec{C}$) that actuate on the displacement speed. The displacement signal is attenuated gradually in function of the rate of rotation. Initially a linear inhibition gradient was utilized. After basic tests, we detect that a good response was obtained with the use of a non-linear response. We choose an exponential inhibition gradient.

This allowed smooth transition between walking and halt walking, giving the user the ability to executes curves, while rotating or make big orientation changes, which were only rotational, without strokes. Low rotation deltas do not inhibit walk. As the delta of rotation become higher, the greater the inhibition on the displacement. The maximum displacement attenuation was defined as occurring above 40 degrees, causing the rotation to occur in place. The transfer curve, in Figure 3.6 illustrates the behavior of the inhibition versus rotation.

Figure 3.6: Inhibition response. The longitudinal axis represents delta rotation. Latitudinal axis represent the inhibit value



Source: the author.

The final inhibition can be calculated as:

$$\begin{aligned} I &= (Clamp(0, 45, \Delta_R)/45)^3 \\ IWalking_{speed} &= Walking_{speed} * (1 - I) \end{aligned} \tag{3.4}$$

Where Δ_R is the instantaneous variation of the rotation between samples, from the orientation detection 3.3, $Walking_{speed}$ is the displacement speed, from the walking speed modules 3.5, I is the intensity of inhibition, $IWalking_{speed}$ is the the final displacement speed to be utilized inside the VE, with the inhibition applied.

3.8 Lateral Walking Detection

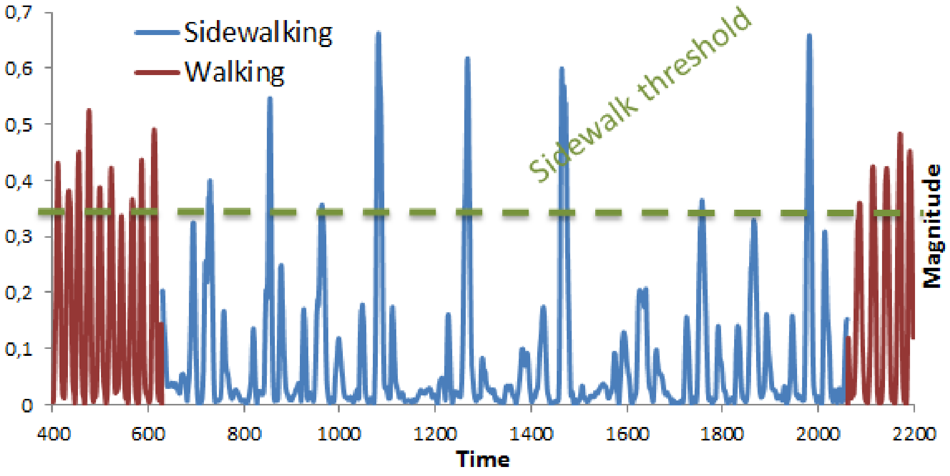
The detection of lateral walking was done on top of the previous derived vector $\vec{S(t)}$. Again, analysis of this vector over time reveals that when users make lateral walking movements, the signal presents a well defined pattern, which allowed us to define a threshold for detection of lateral steps. More than one approach was attempted to detect lateral walking, with varying levels of success.

To efficiently detect lateral walking, we defined two threshold levels. Let's call the threshold of walking p and the threshold of lateral walk q, always with $q > p$. If the inflection point of the signal is greater than a second threshold q, then lateral walking step is generated. Otherwise, if this inflection point is above of only p, then a step is generated.

When the user walks laterally, a pattern is identified in the evolution of $\vec{S(t)}$ over time. Figure 3.7 shows the pattern. In our initial tests we defined the threshold q as 0.5 (green horizontal line), which when crossed, generates a lateral walk in the direction perpendicular to $\vec{S(t)}$ and into the same quadrant of $\vec{M}$. That was a simple method to detect lateral walking, but it was ineffective and had a low success rate.

An analysis based on 170 known samples – with 41 lateral walking steps and 129 walking steps – generated 80% succeeded detections for lateral walking, and 99% succeeded detections for walking in place. Among the 41 lateral walking steps, 20% were considered as walking. In the same way, among the 129 walking steps, 1% were identified as lateral walking.

Figure 3.7: Magnitude of $\vec{S(t)}$ with details of walking (red) and lateral walking (blue) patterns in a typical use of the device. Threshold for lateral walking detection is represented in green



Source: the author.

We tried different techniques of walking, with different results, but all had problems. We tried filtering techniques to better detect lateral walking and neural networks, but all very unsuccessful at accurately measuring lateral walk. Further investigations must be done in this field.

3.8.1 Safety

The initial tests of our WIP technique and device were performed with only one balance. This setup provided basic data for analysis. However the inclusion of the Head Mounted Display, for basic tests, reduced the ability of users to watch their feet and keep safe on top of our sensor surface. This setup proved to be a dangerous configuration for continuous use of the device, as users could step outside the platform and fall.

As a measure to allow safer usage we then utilized two platforms. This configuration increased the walking area, but was not too safe for users. The users had to use very small steps and feel the Wii border with their feet, in order to not step out and fall. However, with small steps, users were able to detect the lack of surface area.

We then increased to four platforms, as in Figure 3.1, creating a bigger walking surface. Again, without a way to warn the user about the surface border, the use of this setup was insecure as can be seen on figure 3.8. We opt to not use guard rails or hold users by the chest to limit the walkable area. Also, we opt to not insert alerts on the screen to limit the walkable area. As users utilizing the device are immersed, with HMD, we chose a tactile barrier, detectable by the feet. The tactile barrier was a slightly elevated floor around the balances.

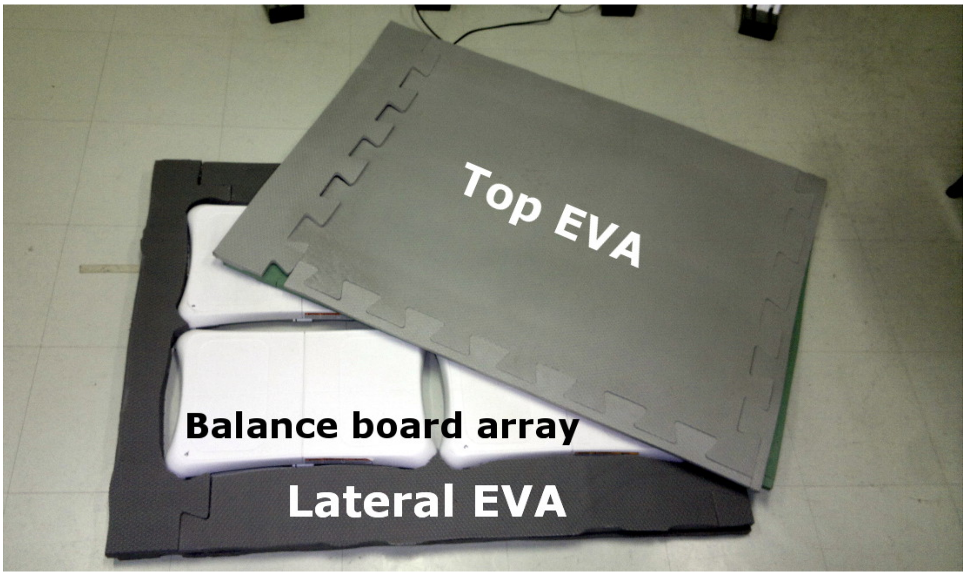
Figure 3.8: Four balances without protective EVA and with gaps.

Source: the author.

The balance boards were surrounded by elevated Ethylene-Vinyl Acetate (EVA) that is a dense foam. They were covered with EVA too, providing an homogeneous surface, with a higher border surface. This subtle surface change, in borders, was enough to be detected by the feet of the users in a simple and natural way, as tests proved. This technique proved to be efficient. Figure 3.9 show the details of surface.

The lateral EVA had approximately a minimum exceeding length of 3 inches around the boards, and was approximately 0.5 inches higher than the height of the Wii balances. The space between the boards was filled with EVA slices.

Figure 3.9: Details view of four balances surrounded by EVA. The lateral EVA is half inch higher than the height of the balances



Source: the author.

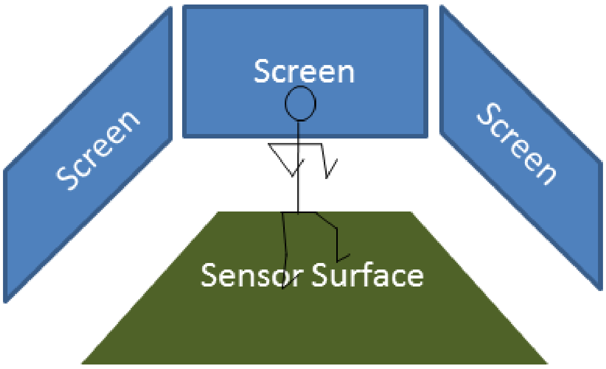
4 EXTENSIONS

The present chapter disposes about the extensions of our Walking in Place (WIP) technique and their uses for specific tasks. We adapted it to be utilized in two side works: inside a *risk assessment simulator* (JORGE et al., 2013) and as part of an *approach for labeling point cloud data* (KRAMMES et al., 2014), for a 3D user interfaces contest. Both works utilized our WIP technique to control the navigation, while the hands were utilized to control other tasks, as selection and manipulation of visual data.

4.1 Risk Assessment Simulator

The risk assessment environment, as presented in (JORGE et al., 2013), was a tool were ordinary users had to identify dangerous situations inside a VE. The physical environment was composed of the WIP platform together with a partial CAVE, a Kinect and optional hand controllers. Complete body simulation was created inside this environment. The CAVE system was composed of three 55 inches screens, with stereo images that surrounded the user field of view. Due to this, the test subjects should preferably always WIP in front of the central screen. Figure 4.1 illustrates the idealized setup.

Figure 4.1: Illustration of the risk assessment environment composed of three screens and additional sensor surface



Source: the author.

The follow process was made to allow the use of our technique with the CAVE in the risk simulator: we made additional processing on the orientation and displacement information, supplied by our technique. The speed information of our technique was handled without further processing by the risk simulator, as displacement speed.

The natural rotational information provided by our technique worked in a one to one ratio: if the user rotates 10 degrees in real world, the same 10 degrees of rotation occur in the virtual environment. However, due the partial CAVE, which cover only near 180 degrees of the field of view, we developed a WIP redirection technique; that allowed that small rotations of the user, in the real world, generates rotational steering, proportional to the angle of turn of the user, while the user keeps stepping on the walking surface.

To accomplish this, in the beginning of the utilization of the device, we save a vector $\vec{O}_{saved}$ containing the orientation of the user on top of the balances when facing the central screen. Given this fixed vector, we compute the rotation speed as the angle between the WIP orientation vector and the $\vec{O}_{saved}$ vector. The result angle is proportional to the displacement information. This allows the rotation to occur only when steps are captured, ceasing the rotation when the user stops walking. Otherwise the rotation speed stays active and causes the camera to rotate continuously. The rotation speed is so utilized to generate a change compute a virtual orientation vector.

We established a dead-zone of 10 degrees around the central position that gaze the front screen. The attenuation is defined as a non-linear curve for angles higher. This avoided that small fluctuations of the orientation information caused rotation and shake on the walk. A clamp in the orientation was also applied to limit the maximum rotation delta. Informal tests with users were executed during the development of the technique, and all users were able to utilize with success.

4.2 Point Walker: a Metaphor to Manipulate Point Clouds

The current proposal was submitted to the IEEE 3DUI contest in 2014. The contest required an alternative technique for manipulation and annotation of point clouds. We introduced the use of a 3D interface combining navigation, manipulation and selections to allow hierarchically label point clouds of different sizes and topographies. Please, refer to the Appendix 7 for the complete article of the proposal.

We proposed a mixed navigation technique for point cloud selection an annotation. As devices, we utilized an HMD for data view, a smartphone screen for volumetric selection, with help of the sensors to allow directional volume deformation and voice to text translation. Together our technique of WIP for orientation and displacement inside the point clouds. To allow easy navigation in the 3D space, the head pitch was utilized to determine the up/down orientation during the walk.

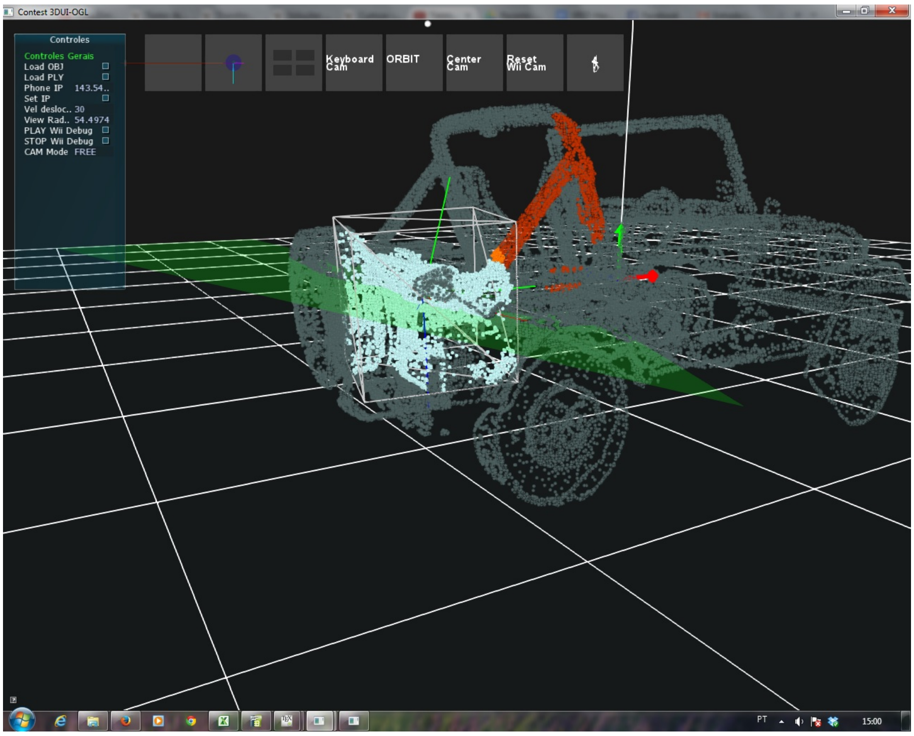
Upon selection, the point sets could be labeled by pointing and selecting labels on a list. New labels could be created using voice. Navigation through hierarchical label levels was possible by leaning forward or backward on the weight platform.

Besides, current smartphones contain enough sensors to work as very precise pointing devices. A combination, of inertial sensors and magnetometer, coupled with multi-finger touch gestures allows using them for 3D selection and manipulation. In our approach, selection of multiple points was achieved by pointing with the device to control a 3D cursor. An infinite ray starting from the user position follows the pointing direction and the intersection of the ray with the data defined the cursor location, similar to the Disambiguation Canvas (DEBARBA et al., 2013).

The IMU sensors of smart-phone plus the screen also provided orientation to manipulate ellipsoidal or cubic selection volumes. It could be deformed in any direction by pinching on the smartphone touch screen while the device is oriented in the direction wanted for the deformation. A square selection tool is visible in the example Figure 4.2.

The translation of the selection volume could be achieved with a one finger drag on phone screen. As the selection volume is deformed, additional cloud points are covered by the volume and are then flagged for selection. When the user is satisfied with the selection. Multiple selections were possible to define a main selection area, that could be added or removed from the current selection. On end of selection process, the user could point to a finish icon and use voice to assign a label to the set of points.

Figure 4.2: Square selection example used. WIP was utilized for positioning



Load OBJ ☐
Load PLY ☐
Phone IP 143.54..
Set IP ☐
Vel desloc.. 30
View Rad.. 54.4974
PLAY Wii Debug ☐
STOP Wii Debug ☐
CAM Mode FREE

Source: the author.

To avoid errors between head orientation obtained from the HMD and feet orientation obtained with the boards, we had to solve the orientation drift caused by the HMD sensors. We applied the comfort pose algorithm (REUS et al., 2013). This solution not required any additional tracking sensor or infrastructure. The algorithm relies on the assumption that people tend to align body and head comfortably a few seconds after looking to either side. Position drift does not occur in our setup. Figure 4.3 illustrates a typical use of the device for this work.

Figure 4.3: Demonstration of the use of the composing operation mode. Hands are free for pointing task

Source: the author.

5 EXPERIMENTS AND RESULTS

We elaborated a set of experiments in order to validate our technique of walking in place and the proposed safety device. The experiments conducted during formal validation were:

- **Experiment A - Precision experiment**: A small standardization experiment, where we compared our technique against inertial sensors (magnetometer + gyroscope);
- **Experiment B - User preference**: An experiment to detect the walking in place freedom: the user preference between a vehicle mode metaphor versus and human mode metaphor for walking in place;
- **Experiment C - Lateral walking**: A test to evaluate the ability of the technique to infer users orientation and strafe movements;
- **Immersion Study**: A simple immersion test made in addition to Experiment B in which a surprise event was triggered during the end of the test to check the response of the subjects.

The standardization experiment, defined as **Experiment A**, we would like to determine that our technique is able supply correct orientation for a person, as the same as a standard device such as a gyroscope provide orientation. For this experiment we utilize an Inertial Measurement Unit (IMU) attached to users waist as reference to get user orientation. During the same test, users walk and rotate over our platform, following a path.

For Experiment A, we will run one test per user. It will be compared the orientation data (yaw) captured with the IMU from the user under test, against the orientation provided by our technique of walking in place. We expect that our technique to be as good as a IMU system, inferring that the correct orientation is generated by our technique.

The second experiment, **Experiment B**, we would like to infer the users preference between two walking in place metaphors which we will call vehicle mode of walking in place (henceforth called only of vehicle mode) and humans mode of walking in place (henceforth called only of human mode of walking in place).

The two metaphors, vehicle mode and human mode were conceived during pretests done with our device of walking in place. During previous tests, users conceived that during walking in place, the avatar in the Virtual Environment which they were inserted always displace in the Virtual Environment, while doing rotations over the walking in place platform. It was not possible to do sharp turns inside the Virtual Environment with our technique in that point.

Based on this fact, we elaborate a additional version of our technique that allowed the avatar inside the Virtual Environment to stop displacing while the user in the real world do rotated over the walking in place platform. This technique was composed of an inhibitor module for displacement as presented in previous chapters. In resume, the two metaphors:

- With the human mode, users could made sharp turn while using our technique or,
- With vehicle mode the walking control was more similar to a vehicle control than the human way of walking.

Giving a mode detailed understanding of the topic, in vehicle mode, physical rotations of user caused the virtual avatar inside the Virtual Environment to have a displacement in position (walk) while proceeding a rotating inside the VE. The inhibit module, presented in the technique description, inhibited walking while rotation occurs. For this experiment we utilized the same path created for Experiment A. Subjects using a HMD and on top of the walking in place platform proceeded 2 tasks of following a path, were the walking in place was either as human mode or vehicle mode.

We start requesting the users to answer a questionnaire for user characterization (see Appendix B). Each user executed two techniques, with a interval for answering questions about the feeling using our platform of walking in place to control their navigation inside the Virtual Environment. We help users with the use of the HMD and explain the basics about how to move with our device, explaining also the task: to follow a path defined by arrows and arcs inside the Virtual Environment, as precise and as faster as they could.

We measure the path taken by each user as well as the time and the length to finish the trajectory, both for vehicle and for human modes. We alternate between subjects the first tests applied, sometimes being human mode, sometimes being vehicle mode. The questions in Appendix C were applied in the end of both tests.

With this test we would like to know if subjects were able to control more easily the movement inside the Virtual Environment either with the human mode or with the vehicle mode. We also would like to known with of the techniques modes will allow better control of the avatar (camera) inside the Virtual Environment, staying close to the optimal path.

Experiment C was done to identify the ability of our technique in detecting lateral walking of subjects. It was taken in the end of Experiment B. We asked the users to do a set of predefined movements on top of our platform. Users do not utilized HMD during this tests. Only data from the sensors was recorded to be utilized in the validation of our technique. With Experiment C, we expect to be able to detect the discrimination ability of our technique for three types of movement detection: walking, rotation or lateral walk.

We also evaluate of the safety device proposed in this work, the tactile floor. The utilize the final questionnaire (Appendix D), and also visually evaluate use of the device by users.

In the following subsections we present details about the physical and virtual environments that were utilized during the experiments and the tests results.

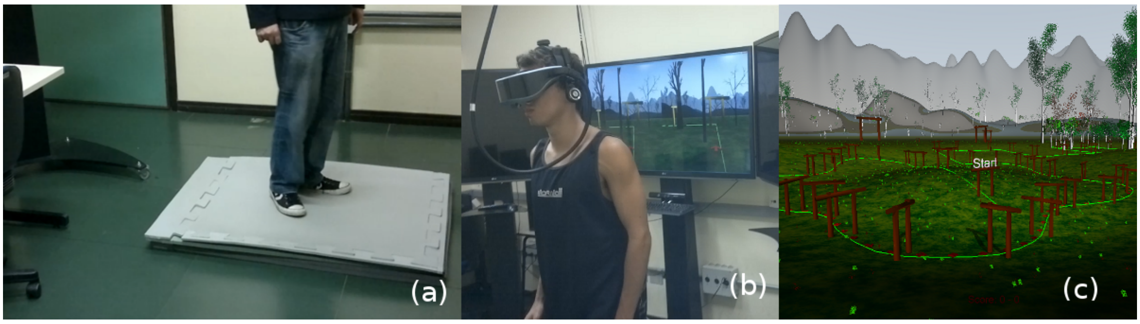
5.1 General Experimental Setup

5.1.1 Physical experiment environment

The physical test environment for all Experiments consisted of the surface containing four Wii Balance Boards underneath, disposed to form a near square layout, with the safety EVA covering them, as previously presented in our proposal description. This guaranteed an easy mountable device. Empty spaces between balances were filled with EVA and do not caused problems in the detection of user weight. It guaranteed some support from user feet, as presented previously.

No guard-rails were utilized for user's protection and only the slightly elevated surface borders provided tactile feedback for user feet about the limits of the walking area. Figure 3.9 present the surface, with the cover removed. Other surface layouts are possible; however they were not tested, as this configuration provides a simple setup and wide surface area. The set of images in Figure 5.1 present the setup and environment for a typical user.

Figure 5.1: WIP surface in use: (a) our platform; (b) User wearing an Sensics HMD; (c) VE detail



Source: the author.

5.1.2 Virtual experiment environment

The virtual test environment consisted of a wide open field, surrounded by mountains, with a fixed well-market path with arrows and arcs. The users were ask to follow the path and try to pass through the arcs in some Experiments A and B. Figure 5.2 presents some illustrations of the environment. The environment was open for walking. For experiment A and B, users utilized a Sensics HMD which was utilized to present the Virtual Environment of the test, with field of view set in 120 degrees.

5.1.3 Virtual camera

For all tests, the users had the freedom of walking in place in any direction, on top of balances. Only the pitch of the user head was translated to the virtual camera. We chose this because during informal validation of the tests, the yaw drifting caused misalignment between head and body and caused loss of body balance for most of users.

The final freedom of the user inside the Virtual Environment (to control the camera) had four degrees of freedom. Two degrees of linear motion in the (x, y) plane, allowing displacement through the field, one degree for orientation, allowing change the direction of the displacement and a degree for the pitch, allowing the user to lock up and down.

The composition of the final user position was defined by orientation the body, who gave the direction of walk, with in some tests was supplied by our technique (that is, by the movement of the feet of the user over the platform) or by a gyroscope in some tests. The virtual camera inside the Virtual Environment was attached to this body frame, looking to the same direction of the body, but with ability to change the pitch as said before. The follow relation was applied to calculate such camera configuration:

Figure 5.2: Virtual space presented as a challenge to the users

Source: the author.

$$Cam = Wip_Position, Wip_Orientation, Head_Pitch$$

No limbs or other body parts were simulated during any of the tests.

5.2 Experiment A - Precision Test

5.2.1 Experimental Protocol

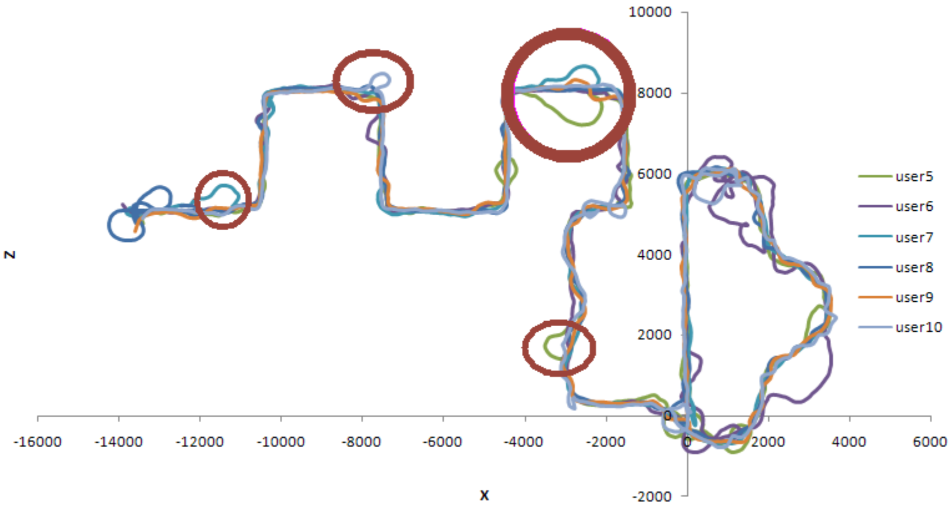
We elaborate this test to analyze the precision of our device and technique in detecting the correct orientation, as a standardization experiment. The users utilized HMD and an Inertial Measurement Unit (IMU) developed by our group, attached to their chest.

The test population was six users, five man and one women, all students. In the begin of the test, we ask to users to fill a basic form. We explained how to utilize the HMD and how to utilize our devices and technique. The users were allowed for some time of adaptation, were they were free to walk in virtual environment using our technique.

After the adaptation, we present to the users with a virtual path. They were asked to walk in place on top of our WIP Surface, and to follow the path as precise as they could. The path presented is illustrated in Figure 5.3. It was composed of straight and curved areas, to try to challenge the users during the test.

We only present a basic consent form to the execution of this test for users, which gave to us permission to use the captured data.

Figure 5.3: Typical data for comparison between gyroscope and magnetometer versus our WIP proposal



Source: the author.

5.2.2 Results of Experiment A

During the execution walking we measured the walking trajectory and the IMU orientation information of the users. The test was applied to 6 individuals, from the laboratories at UFRGS during 2013. The data captured during the tests indicated that the technique was able to detect the correct orientation of the users in 95% of time. Figure 5.3 illustrates the visual path generated by our WIP for the six subjects.

The data comparison for one user, between IMU and WIP is presented in Figure 5.4. The changes from 180 to -180 in the graph were expected during the rotations in the graph. A single failure is seen in this graph, around 2001 and 3001 samples. The star shape of the path could be seen in the image as a descended sinusoidal between 2001 and 9001 samples. The path with *sharp turns* is visible between 9001 and 18001 samples.

We detected that noise or step behavior caused our technique to misinterpret the real user orientation sometimes, making an incorrect 180 degree change in virtual orientation. This happens usually when natural user balance bypass the threshold levels of orientation detection. This behavior is visible in the Figure 5.4, marked by the red circles. To fix the situation, users had to rotate to circumvent the wrong direction. In order to fix this situation, we experiment with finer adjusts on our technique filtering process, which improved the orientation detection in reduce the generation of wrong orientations. We did not do further research regarding this issue.

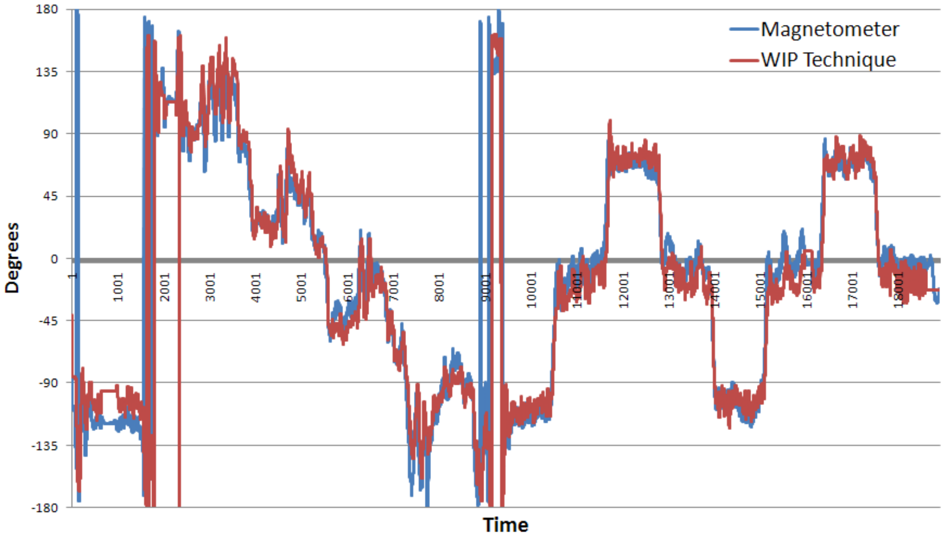
5.3 Experiment B - Vehicle versus human mode of WIP

5.3.1 Experimental Protocol

The Experiment B was composed of two main tests, to analyses the human or vehicle preference modes that our technique could provide. In human mode, when the user largely rotates over the platform, the displacement speed inside the virtual environment is ceased, utilizing the inhibit technique proposed earlier. In vehicle mode, sharp turns do not change the displacement speed, so all the walk process happen in curves.

The first task when a subject executed the Experiment B was the fulfilling of an ini-

Figure 5.4: Typical data for comparison between gyroscope and magnetometer versus our WIP proposal



Source: the author.

tial questionnaire by which the users was characterized. We tried to identify if previous experience with games or balance board could had some influence in the tests results. Appendix B, C and D present the questions applied to the subjects.

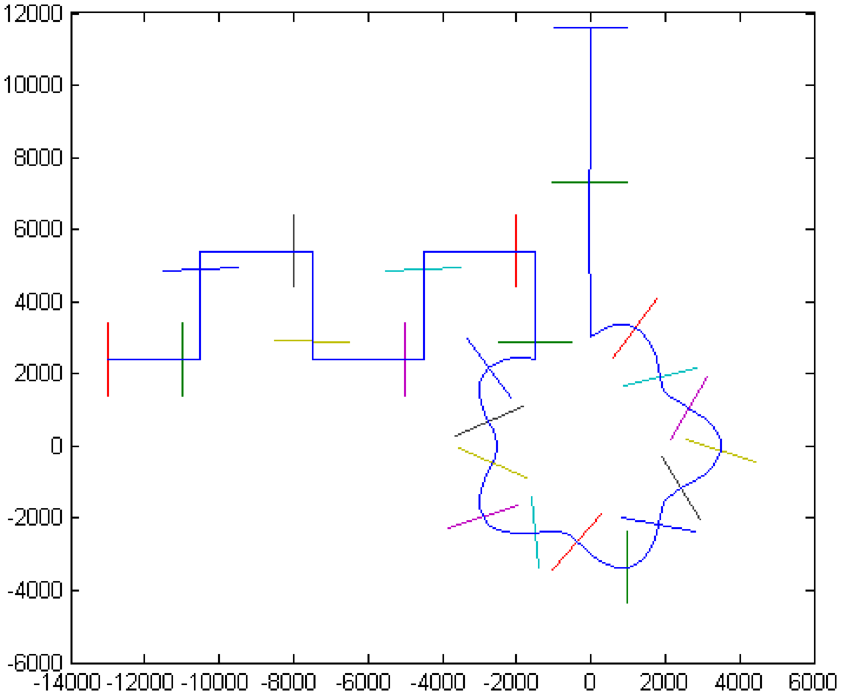
The execution of the tests was the following:

- Fill of basic characterization questionnaire (Appendix B)
- The execution of lateral walking test, which consisted of basic movement execution, without any visual feedback (for further analysis) and capture of data for further analysis.
- Explanation about the HMD usage
- Explanation about the tactile border of the walking surface as safety measurement
- Adaptation phase: users could adapt to the HMD and were free to walk in the virtual environment, without limitation, as long as they wanted, until they felt comfortable (pre test)
- Explanation about what to do during the test: follow the path defined by the arrows
- Execution of Test one
- Solicitation to the fulfillment of a form with questions about the impressions of the technique (Appendix C)
- Execution of Test two
- Solicitation to the fulfillment of the form containing questions for the test (Appendix C, the same set of questions was applied)
- A final questionnaire about the overall feeling with the technique. (Appendix D)

The same set of questions was applied for tests, one and two, representing human or vehicle modes. The users were explained, about the test they were going to do, and asked to follow the path as near as possible, trying to pass the arcs in the environment. Information about the vehicle or human mode was given to the user.

Orientation was given that lost arcs should be ignored and users should continue the path in front, avoiding turns to get back the last position. After each tests, they were asked to answer a questionnaire (questionnaire in append B). The path for all the tests was identical and is presented in Figure 5.5.

Figure 5.5: Path for all tests. Cross lines represent the arc in the path



Source: the author.

5.3.1.1 *The path*

The shape of the path was defined as 4 main areas, for analysis, as follow:

- a start area surrounded by a fence
- a straight path
- a curved path
- a sharp curved path
- a last surprise straight path with a surprise obstacle

The entire path contained arcs. They are visible in the figure 5.5 as colored transverse lines in the path. The beginning and the end of the path were marked in the VR by arcs with a text. The user had to pass through arcs, to start and finish the test. However we do not count the success rate in pass arcs.

The straight part of the path was the easy one to be followed, and we believe that should not have significant differences between techniques, considering time to complete and distance to walking the path.

The curved path could help to us identify the accuracy of control of the walk using the technique, as an analysis of the time and distance taken to conclude could had differences between techniques.

The third path, alternated one, should test the ability to do sharp curves, and we will try analyzing the continuity of the walking of the users in this part.

5.3.1.2 About the test metrics

The metrics considered during the execution of the tests, were time and length to complete the path by subjects, and the time and length to complete individual paths (from the previous subsection).

5.3.1.3 About the tests and data analysis

The raw data from the balances was recorded with temporal information, which allows reprocessing with new signal processing approaches. The temporal position information was also saved and was utilized to extract information about the path followed by users from the original tests.

The path length of the Virtual Environment was compared against each subject results when they follow the path, as individuals that finish the path faster could have take shortcuts during the path following.

The first test in Test B, human or vehicle modes were alternated between subjects. Always after the last test, after passing the last arc, a message was displayed to user, suggesting them to get faster as they could to a target arc.

During this trajectory, a giant box fall from in the pathway to this last arc, blocking the passage. This required that the users to deviate from it. This was done to check the users reaction during an unexpected event using the technique.

The vehicle and human tests were compared one against another, in time and length to complete the path to search for evidences that some of the techniques could provide better control.

5.3.2 Results of Experiment B

The execution of this test was proposed to evaluate the ability of control walking in VR either as a vehicle or a human modes. The overall resume of the users performing the Test B: the test was executed with 52 subjects; from these, 47 were men and 5 were women, with ages between 20 to 41 years; the test population where students from the 2014 Interactive Human Computer (IHC) class from *Universidade Federal do Rio Grande do Sul* (UFRGS), and some other class colleagues, all which had not used the technique previously.

From the test population or 52 users, 44 user (84%) were able to finish all tests. The 8 left users were unable to finish the tests because cyber-sickness, difficulty in use HMD or to see the stereo image in adequate way. Most of the 52 users report some level of cyber-sickness or dizziness, reported in the text box left for opinions in end of test.

After each test, the same set of questions was made to users: Experience with the technique, difficulty to walk passing the arcs, immersion feeling, comfort and overall difficulty. We chose this questions as their appear in other works of the area. We use the Likert scale (between 1 and 5), with 1 representing very bad or very few (negative response) and 5 representing very good or very often (the positive response).

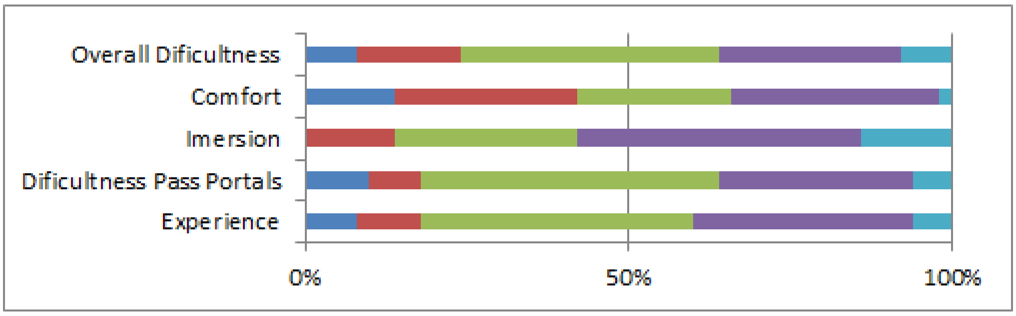
In respect to the graphs colors in 5.6 and 5.7: dark blue means very bad, red means bad, green means neutral, purple means good and cyan means very good.

The characterization of the answers applied after test was analyzed to try figure out if there was some level of correlation between previous characteristics of users, difficulty in using the technique, the performance using the technique and if previous training with games had some influence.

We could identify that users that had better experience with the techniques also report having better comfort, but also tend to have said to have had bigger difficulty with the techniques.

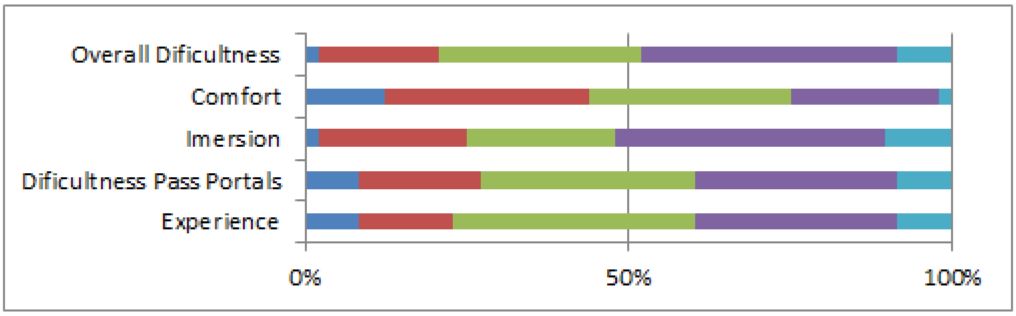
The immersion feeling between the two techniques was similar between users, with correlation of 0.61. Similar correlation in the comfort between the two techniques was of 0.58. This tendency may mean that tests may have been very similar from the user perspective. The overall form results, for vehicle and for human mode are in Figure 5.6 and 5.7.

Figure 5.6: Overall responses for test in vehicle mode. The rotation and walk were not separated to each other in this mode



Source: the author.

Figure 5.7: Overall responses for test in human mode. The rotation and walk were separated to each other in this mode



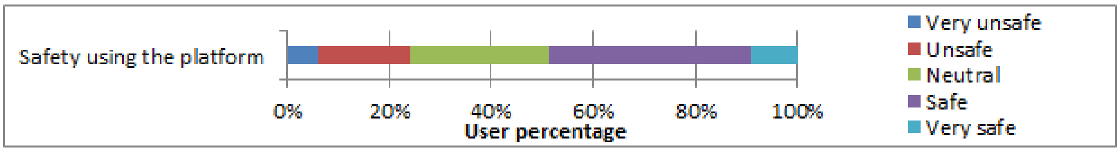
Source: the author.

The responses for both the questionnaires presented similar results for human and vehicle mode. We could point that most of users experience easy to use the technique, with some comfort, that had good immersions feeling, and had an overall good experience using the technique. However the good experience conflicts with the reported feelings of cyber-sicknesses reported in opinion described by subjects. In Vehicle mode users had a better feel. This method allowed faster and more free walk.

We ask for the users in the end of the second test about their overall feeling of safety during the use of the technique, in the top of the walking surface of balances. The results are presented in Figure 5.8. Near 75% of users felt very safe, safe or neutral in the end of tests and less than 30% felt unsafe on top of the surface. From the population who did the test, only two users had difficulties in detecting the tactile border of the walking surface and steeped out it, which correspond to 4.5%.

This illustrates that the use of tactile surface may be a good option for a WIP.

Figure 5.8: Safety using the WIP surface (or platform)



Source: the author.

In respect to the path done by the users: given the total of 44 tests, we removed five users from the set for data analysis due taking very long times to finish the tasks. Regarding the removal of the five users, we were able to identify visually during the test their difficulty to end the task and the test.

The main problem resides in the frequent orientation change without real user orientation change happen. Some possibilities are that these users have a different center of mass control, and our technique was unable to work properly. These represent special cases not studied deeply in this study. The remaining of analysis were done with the remaining 39 valid tests.

We analyze: the time and length to complete path; the time and length of walk for each segment for each test and for each user. We grouped the analysis in the follow hypotheses sets:

- Look for possible better timing (less is better) when the user utilize vehicle or human like control mode

  for complete path

  for individual path

- path distance near ideal, to end the test, when the user utilize vehicle or human like control mode.

  for complete path

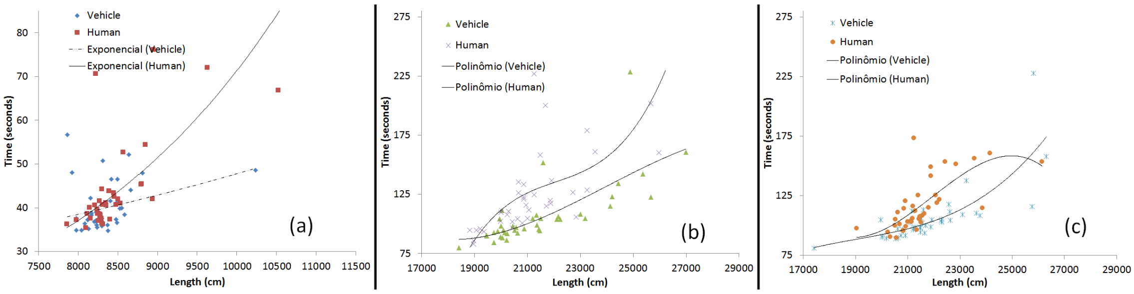
  for individual path

- Look for possible better timing due the learning effect between techniques, when the user pass from test one to test two, whatever it was.

The time and length for each test are given in the dispersion graphs in Figure 5.9 (a,b,c) for each type of path, for the 44 valid users. The speed displacement inside the Virtual Environment increased up to a top speed of 2.5 m/s during walk, when steps are identified.

Time and length to complete each path had strong correlation, and confirm that longer walkers take more time to end the task. In the graph, a tendency line was plotted together with each data sequence to help identify tendencies.

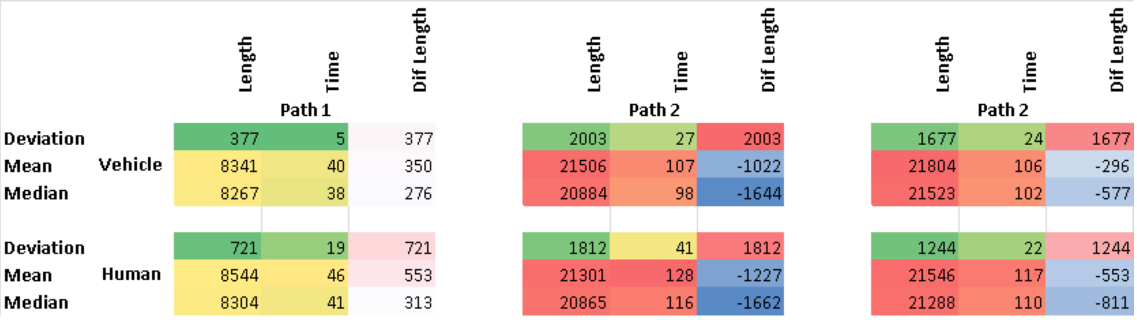
Figure 5.9: Graph visualization with the *time* for each user that conclude the experiment of walking as a vehicle and human mode. Split in sub-paths (a), (b) and (c). Each dot represent an test subject



Source: the author.

The mean times and length to end each segment of the path are presented in the table 5.10 for walking as a vehicle and human mode. In both data it is possible to identify that the Human mode cause the walking to be slower.

Figure 5.10: Mean time and length to end of the path for each kind of test and each path



		Path 1			Path 2			Path 2		
		Length	**Time**	**Dif Length**	**Length**	**Time**	**Dif Length**	**Length**	**Time**	**Dif Length**
Deviation		377	5	377	2003	27	2003	1677	24	1677
Mean	**Vehicle**	8341	40	350	21506	107	-1022	21804	106	-296
Median		8267	38	276	20884	98	-1644	21523	102	-577
Deviation		721	19	721	1812	41	1812	1244	22	1244
Mean	**Human**	8544	46	553	21301	128	-1227	21546	117	-553
Median		8304	41	313	20865	116	-1662	21288	110	-811

Source: the author.

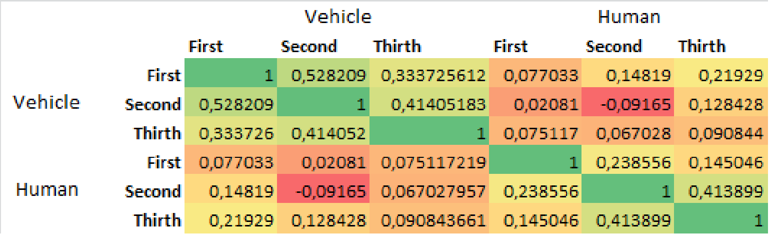
We try to find some correlation in length differences between real path length and length take to end each path, test and user (6 type of data on total), and could only identify *small correlation* between *walk in vehicle mode between first and second path* (0.52 correlation) and *second and third paths* (0.41 correlation).

With this, we can hypothesize that users tend to have similar walking pattern between paths, with similar difficulty to walk. Figure 5.11 presents the correlation table for all possible variations.

We also look statistically with ANOVA at the results of time and length between tests done by users in vehicle and human walking mode, with the isolated parcel of paths, to see if there were any significant changes. The noticeable differences with statistical significance that were found are:

- In path 1 (straight line) users using vehicle mode were significantly faster (mean 40 second) than using human like mode (mean 46 second) with 0.05 of significance.

Figure 5.11: Correlation table between time differences from the optimal path



		Vehicle			Human		
		First	Second	Thirth	First	Second	Thirth
Vehicle	First	1	0,528209	0,333725612	0,077033	0,14819	0,21929
	Second	0,528209	1	0,41405183	0,02081	-0,09165	0,128428
	Thirth	0,333726	0,414052	1	0,075117	0,067028	0,090844
Human	First	0,077033	0,02081	0,075117219	1	0,238556	0,145046
	Second	0,14819	-0,09165	0,067027957	0,238556	1	0,413899
	Thirth	0,21929	0,128428	0,090843661	0,145046	0,413899	1

Source: the author.

- In the path 2 (sinusoidal path), also users were faster in the vehicle mode than in human mode (107 seconds versus 128 seconds).

- In the third path, again the time to finish the path as vehicle was inferior compared against human mode (106 versus 116 seconds) with 0.04 of significance.

The statistical analysis does not revealed any differences in the length taken by users to end the tests. We believe that walking in place like human was slower, due the inhibition in walking during the displacement when users rotate.

Analysis the path walked by the user and taking out the order of the tests, we identify that *users tend to like more the vehicle mode of walk when this was applied first*. This may be due the tiredness of using the technique for a second time, that make users under-evaluate the second time technique, which in human mode was slow.

We do not find any significant correlation with users that had game abilities or joystick usage and their performances during the test. There was found some degree of correlation between the test order and the performance in the test, pointing that *the second test applied to subjects, human or vehicle, tent to have better timing or take little distance to end the path*. This is based on the statistically significance of p=0.0007 in the path 2 for vehicle mode, where the mean of users walked 225 meters in the first test and 204 meters to conclude the same trajectory in the second test.

Reduction in length to end the task also happen for users using human walking mode after had trained with vehicle in first: *221 meters when made as first test versus 205 meters when made as second test*. Taking the time into account, users tended to take less time to conclude the path 2 in the second execution:

- for vehicle mode: *with 117 seconds in this was the first test against 95 seconds when it was the second test*, with 0.009 of statistically significance.

- for human mode: *with 144 seconds versus 113 seconds with 0.01 of significance.*

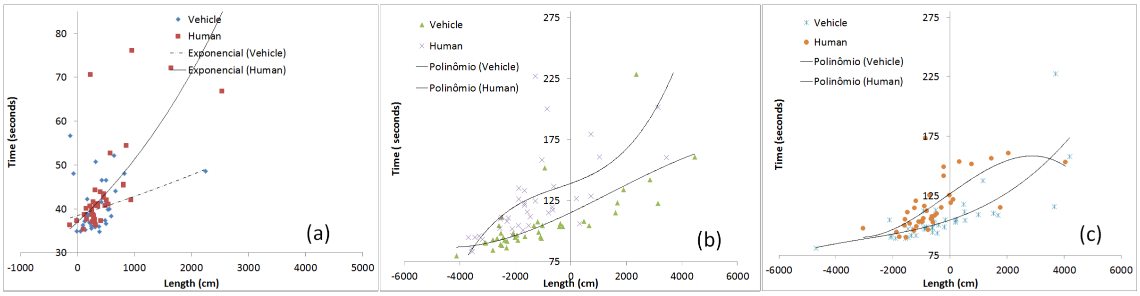
For the path 3, in human mode, there was a mean difference to end the path, with 124 second against 109 when this was take as second test (p=0.03). There were no significant differences to conclude this path taking length and time values for vehicle. Though this analysis inflicts in some way the blind test splitting of population, from this set of results, we can pinpoint that some level of learning happen during the use of technique, as users tend to go better in the second execution of the test.

The graph in Figure 5.12 presents dispersion with the differences between real path length and taken length, for each path for each user and test. The origin of the system, (X, Y), represent the best distance.

Is possible to identify that in path 1 some users walk less than the length of the path. This was due the cuts done in the data, and it represents less than 1 meter.

In the path 2, most of users walk a path little than the ideal path, up to 20 meters less. This happen again in path 3, indicating that users take shortcuts in the path.

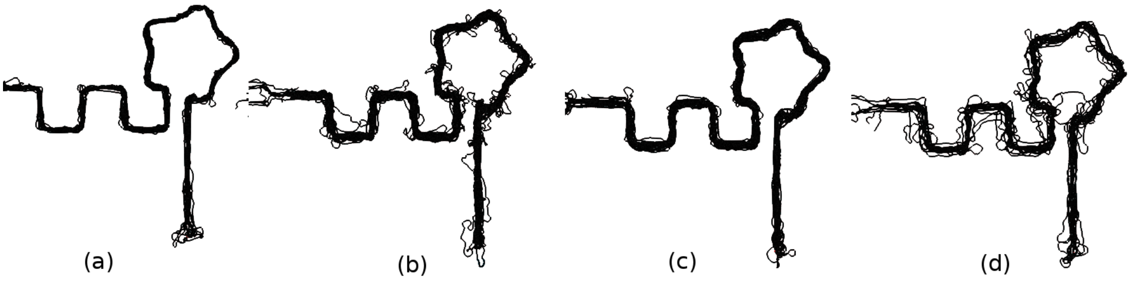
Figure 5.12: Dispersion graph for all users. Length is the difference between optimal path and real path. (a) straight path (b) sinusoidal path (c) sharp corner path



Source: the author.

The over-imposed path for all the 44 users, for both tests is presented in Figure 5.13 for appreciation. The previous identified shortcuts in the dispersion graphs are visible in this graph. The worst walkers are separated in this graph. The splitting between good and bad walkers was visual.

Figure 5.13: Path taken by users as vehicle and human. (a) human mode good followers (b) human mode bad followers (c) vehicle mode good followers (d) vehicle mode bad followers



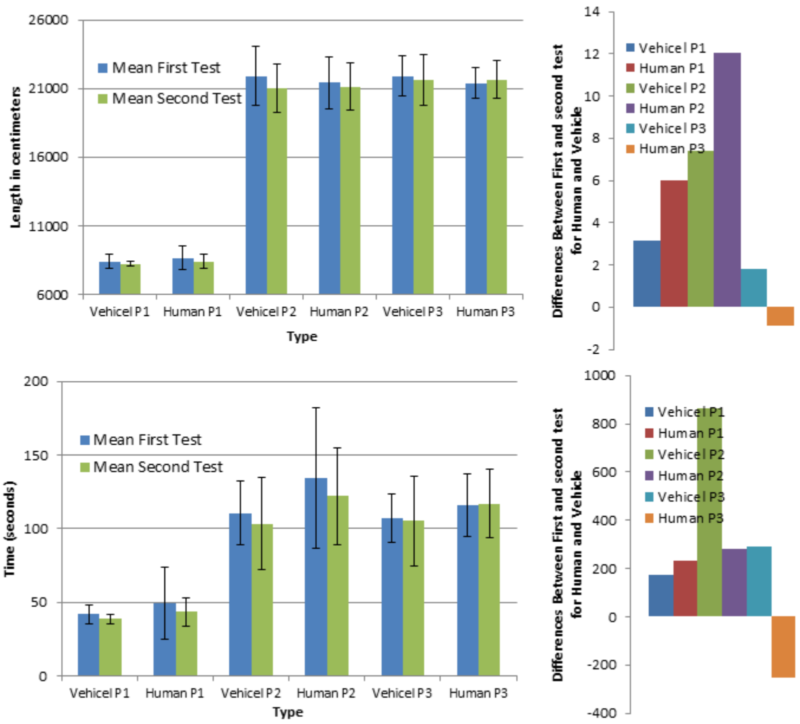
Source: the author.

We must cite also that a change was made in the test during their execution. The path in the test environment was initially composed of a center line and arrows. It was changed to only to arrows after the 24th user. This gave 24 tests with a center line plus arrows and another 20 users with only arrows. Before this change, 6 users back off the tests with difficulties in following the path. After this change, all users ended the test. We believe that a further study need to be made to analyze better the influence of the path markers or kind of markers to accomplish a task.

The Figure 5.14 present the mean and deviations for time and length, for each path and each type of tests, as well as the differences amplified in the graphs on the right. ANOVA didn't found any significant difference between the groups of users that ended the task.

Based on visual details annotated during the attendance of the pre test phase, we realize that uses, inside the VR tend to walk to far objects distributed in the space (a

Figure 5.14: Mean times and length to finish the test before and after the changes in the path



Source: the author.

sinusoidal sculpture and trees), with relative easiness, deviating from obstacles. During the adaptation phase, most users feel comfortable in walking in place, with their own targets in mind. However was noticeable than users had more difficulty in following a fixed path.

This details pose to us than maybe the kind of task to be done influence the feelings and the performance of users. This may be an interesting factor to further analysis.

5.4 Experiment C - Lateral Walking

5.4.1 Experimental Protocol

The experiment C was done as a sub test in the beginning of Test B and was a *blind* test. We ask to users execute a series of movements on top of our prototype surface, without the use of HMD. The main interest in this test was the ability of detection of lateral walking movements against forward walking and rotational movements, by our technique.

We requested the users to do the following movements:

- aligned their body to one predefined direction
- take five steps in place

- rotate 90 degrees to the right
- take more 5 steps in place
- rotate 180 degrees to the left
- take more 5 steps in place
- execute a lateral walk movement to the right once
- execute a lateral walk movement to the left twice
- execute a lateral walk movement to the right twice
- execute a lateral walk movement to the left once
- end with 5 steps in place

The raw data from the sensors from the balances was recorded during the period that the subjects were doing the above procedure. We made a post processing to try identifying the lateral walk from the recorded data. Due the temporal variations in the time to execute this task, we chose to perform a visual inspection and classification of results. Several users had problem identifying right and left, which make lateral movements to be in opposite directions for some tests.

5.4.2 Results of Experiment C

We were able to proceed with the test with 51 subjects. From these, 4 had difficulties in ending the test or not ending at all, and were eliminated as we could not identify correct data, leaving 47 tests to be analyzed.

The proposed technique in such tests was able to detect lateral walking and rotational movements from 21 users (41%) accurately. Other 35 individuals had only lateral walk movements detected with accuracy, giving this a total of 60% of success for lateral walking success. The partial recognition of rotations was 27%, totalizing approximately 68% of success for rotation. Table 5.1 present the resume of such data. The sets of information in this table eventually overlap.

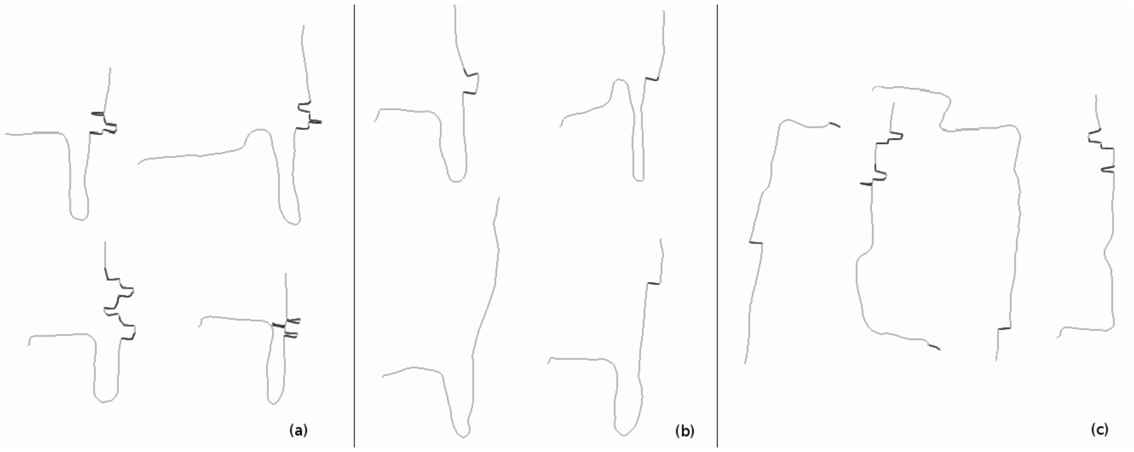
Table 5.1: Success rate in detection of movements

	Number of tests	Percentage
Total of tests	51	100
All correct	21	41,17
Rotation good	31	60,78
Rotation parcial	14	27,45
Rotation bad	2	3,92
Strafe Good	35	68,62
Strafe Partial	4	7,84
Strafe Bad	8	15,68

Figure 5.15 present some examples of path generated by the use of technique after the processing. Note in the figure (a), correct identification of orientation and lateral walk

movements. In (b), four examples of failure in the identification of lateral walking movements. In (c), four examples of complete errors in the identification of lateral walking and rotation.

Figure 5.15: (a) correct detection of orientation and strafe movements; (b) only detection of strafe movements; (c) only detection of rotation and strafe movements. All these are based on real data from users



Source: the author.

We believe that, the accurate identification of rotational movements was due the small amount of steps taken by the subjects during the procedure. Possible more steps during the rotational movement could help in the identification of orientation change, such as in the 180 rotations.

5.4.3 Weight Influence

A possible assumption during the test was that the subject's weight could interfere in the final results. However, we were unable to identify the weight interference factor in the ability of the technique in identify the walking in place.

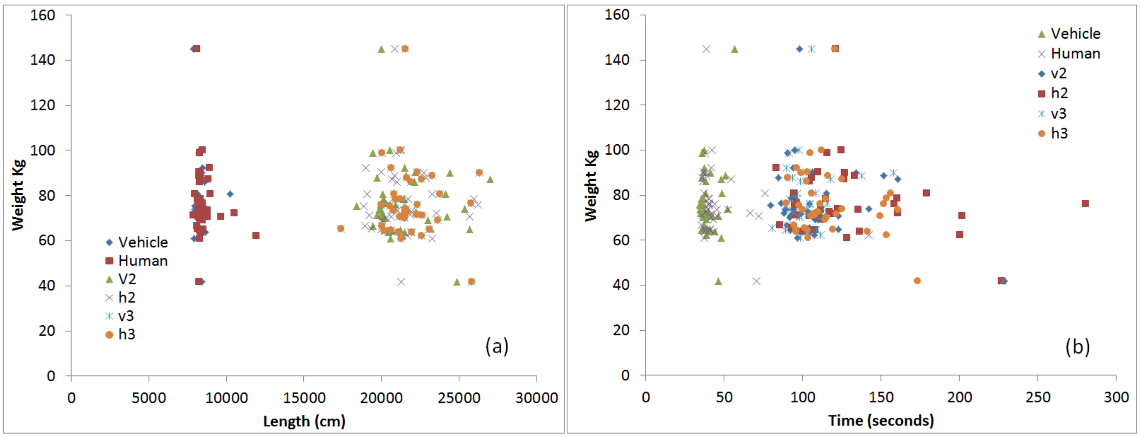
We do not found any correlation between user's weight and performance in the tests, either in time to end the task or speed to end the test. Figure 5.16 presents the dispersion plot between weight versus length to end the test and weight versus time for all users. The marker format represents the path section.

5.5 Immersion Study

We elaborate a simple test in the end of the study B to try to identifying the immersion of users in the environment. When the user had passed the last arc in the environment, a message was displayed, asking them to get, fast as possible to a new blue arc, 50 meters ahead. As users move, a surprise giant box falls from the sky, right in between the end and the user path. About 7 seconds were given to the users read the message and the box fall.

Users could choose to try get through the box or deviate from it. We register in paper all the users' reactions. From the 44 valid users, 93% deviated from the obstacle. We register the user's verbal frustration in have to deviate box. Few users try to pass through the box, and as collision happen, they tend to rotate and get in course of deviation.

Figure 5.16: User weight distribution versus length to end path (a) and weight (b)



Source: the author.

All 44 users were able to get right in the direction of the new finish line. Many of the subjects expressed frustration with the new target. However, subjects had much easiness in follow to a target, when compared to follow a path. The deviation of the box appeared to be much easier, as it blocked a substantial area in the way, that following a path in the environment.

6 CONCLUSIONS AND FUTURE WORK

This study presented an expandable walking in place interface. It was composed of a hardware part, the set of Wii balance boards and a developed tactile surface used as a safety device. In the software side, we developed an algorithm that processes the raw data from the balance boards and was able to detect orientation and displacement of a user on top of it. This detected information is available to be utilized to control locomotion in virtual environments. The work started with a survey of walking interfaces, their types, costs, and limitations.

We have elected a set of points to guide our development. By the end of our study, we were able to achieve all of these points. The development of the interface started with the use of pressure boards, and signal analysis. We were able to detect, with our hardware and software approaches, the orientation of a person using our device, and infer the displacement and lateral walking effectively from the sampled data from the balances. However, the detection of a person doing the lateral walking over our device still needs more research, which could be done in the future with the saved data of our tests with users.

Based on the test of a vehicle versus human mode, executed for validation and the user responses, we concluded that *users preferred the vehicle mode of walk* from the qualitative responses. The results pointed out that users tend to conclude the test in vehicle mode faster when compared to human mode. However, to fix their position in the Virtual Environment of the test, more walk had to be done in this mode, making users walk longer spaces for the three sub-paths tested in the experiments.

Both vehicle and human tests presented similar qualitative responses. We identify that previous experience with game controllers of any kind do not provide enhancements in the use of the technique. The analysis of the last sub-path showed that most of the users tended to walk smaller lengths (twenty meters) than the original path size. This suggests that users become tired of the test and take shortcuts, or become smarter using WIP for long, fixed path. Was possible to detect that slower walkers were those who tried to keep in the center of the path, and achieve better results.

We proceed with visual inspection of signals from step-in-place from some users who had performed good walking pattern and bad walking patterns. We identified that walk is a very individual process, as users distribute the foot pressure in several different ways, even for walking in place movement. Further research can be done in the attempt to classify the user's way of step. The weight of subjects and the performance using or device and techniques revealed not to be an issue for our technique of detection. Our device and software proved to be immune to this variable with the test population, however further analysis should be made.

Eight users had difficulty in keeping the path during experiment B, thus they were removed from the analysis. This led us to a change in the Virtual Environment of the test, removing the center line for the path. We know that this is not a good practice. We could not find statistical evidence other than reduction of the level of abandonment of the test. However, the kind of task to be done by the users, as path or target follow can be an interesting research for alternative walking interfaces. We believe that a deeper analysis of the kind of target could be done, as users during the adaptation phase explore the virtual environment with relative easiness using the technique.

We attempt to study other ways to detect lateral walking. Digital filter functions and neural network for discrimination between walking and lateral walking were made, without success in discriminating correctly between the two. Further research is needed to refine the set of input data for training and comparison with neural networks. We conclude that the present technique for lateral walking detection with our device is still inefficient, generating displacement when lateral walking happens or lateral walking during the displacement.

The surface for WIP proved to be safe for long-term use. The set of 51 users, 8 users (15%) had problems of lack of balance during tests and give up on the use of balance platform. One possibility is that users had an intense dependency on visual clues for body balance due the restricted feedback of the HMD in providing visual yaw and roll feedback information. Another possibility is the fear of miss-steeping the tactile surface. However, only one user pointed out that fear. The users reported that the tactile surface to be good in helping their identification of the walking limit border.

Is important to mention that a high number of users reported in the commentary session of the forms about experiencing cyber-sicknesses during the tests. This is reported in the literature of the field extensively, and we could not improve on this problem with our technique. Some works have addressed this issue with precise head tracking, with supposed success in reducing this problem.

The technique identified with success the orientation of users, with minor problems of detecting orientation changes. This represented less than 10%, and need further research for enhancements. Students during UFRGS *Portas Abertas* in 2013 and 2014 public openings and during IEEE 3DUI in 2014 contest participation compose more than 200 people which informally used the technique for navigation in Virtual Environments.

We developed two main pieces of our technique in different setups: for use in a redirection technique, which was utilized with a CAVE display for a risk assessment simulator; and for use with an alternative technique to manipulate objects in the IEEE 3DUI 2014 contest, were users utilized our technique to easily navigate in a Virtual Environment and mark points. Both techniques need further investigations, as to know if our technique allows better precision for precision tasks as point tagging, or navigation in complex scenes.

Further research of interest could be allowing multiple users on top of large surfaces and detecting their mimic of walking individually, which minimum interface between them. This can allow the use of the technique in open areas with multiple users. A better lateral walking detection, definition of back walking approach and the kind of target task in tests are also very interesting points for further research. We could conclude that we achieve the goals for our walking in place device, proposing a cheap device, easy to utilize and setup. We were able to expand the WIP technique for large surfaces, in ways no previously done, achieving a improved WIP alternative for human computer interaction.

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7 APPENDIX A

The Point Walker Multi-label Approach

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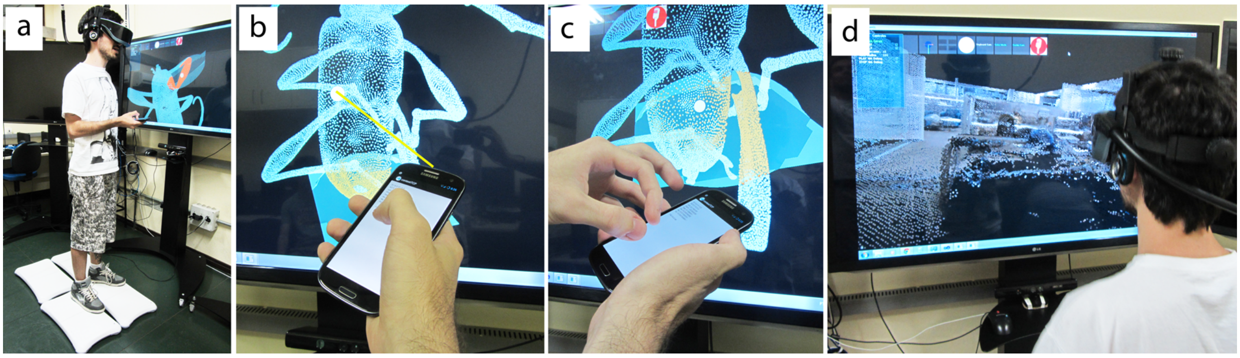

Figure 1: From left to right: the user on the platform wearing an HMD and holding the pointing device; a ray cast for coarse selection; a highlight of the fine selection by pinching on the handheld screen; a resulting labelled model.

ABSTRACT

This paper presents a 3D user interface to select and label point sets in a point cloud. A walk-in-place strategy based on a weight platform is used for navigation. Selection is made in two levels of precision. First, a pointing technique is used relying on a smartphone and built-in sensors. Then, an ellipsoidal selection volume is deformed by pinching on the smartphone touchscreen in different orientations. Labels are finally selected by pointing icons and a hierarchy of labels is automatically defined by multiple labelling. Voice is used to create new icons/labels. The paper describes the concepts in our approach and the system implementation.

Index Terms: H.5.2 User Interfaces [Input devices and strategies]: 3D Interaction—

1 INTRODUCTION

In times of big data, sensor devices such as laser scanners can provide huge amounts of geometrical information in the form of point clouds. To be useful for a number of applications in many areas, these data must be visualized, manipulated and classified by effective usable interaction techniques.

In this work we introduce the use of a 3D interface combining navigation, manipulation and multiple selection to hierarchically label point clouds of different sizes and topographies. The interface relies on a weight platform to track user steps for navigation within the environment and around objects. It also explores the sensor capability of smartphones to provide a pointing device for coarse selection and to manipulate an ellipsoidal selection volume. Upon selection, the point sets can be labelled by pointing and selecting labels on a list. New labels can be created using voice. Navigation through hierarchical label levels is possible by leaning forward or backward on the weight platform. The interface has been built to be used with an immersive display system. We tested with a conventional HMD, as depicted in Fig. 1a.

In the remaining of the paper we describe our interaction approach, the system implementation and a few results.

2 APPROACH OVERVIEW

Three-dimensional point clouds can vary from the surface of a small object that we explore by moving around, to large city environments that we explore by flying over or walking inside. Thus, we wanted to conceive a system which allowed great mobility for easily turning and visually inspecting all portions of the data. Our system consists of a navigation model similar to the real world walking and rotating. To avoid heavy installed infrastructure, we use a portable weight platform to track velocity and direction of a user walking in place on top of it.

For about a decade, smartphones evolved and are now ubiquitous. They contain enough sensors to work as very precise pointing devices. A combination of inertial sensors and magnetometer coupled with multi-finger touch gestures allows to use them for 3D selection and manipulation. In our approach, selection of multiple points is achieved by pointing with the device to control a 3D cursor. The pointing direction defines a ray and the intersection of the ray with the data defines the cursor position, similar to the Disambiguation Canvas [1]. The cursor is an ellipsoidal volume that selects all the points inside it. It can be deformed in any direction by pinching on the smartphone screen while the device is oriented in the direction wanted for the deformation. As the selection volume is deformed, additional cloud points are covered by the volume and are then flagged for selection. When the user is satisfied with the selection, they can assign a label to the set of points.

A voice recognition framework in the smartphone can be activated when a new label is to be created. As our design expects an

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immersive user display, using voice for typing helps keeping the immersion. Notice that nothing is displayed on the smartphone's screen. It is used merely as an input device. Points can receive many labels. For example, a point in an eye is also part of a head that is part of a body. Assignment of multiple labels gives rise to a hierarchy of labels. With our approach, the user navigates through label levels by zooming in and out, similarly to a map where country, state, major city and small town labels appear as we zoom in. The user action to zoom into the hierarchy is to lean forward or backward, a movement quickly understood by the weight platform.

Next section details the implementation of these principles.

3 IMPLEMENTATION

The system has been implemented in C++ with OpenGL and using the following hardware: a PC, an Android based smartphone; a Sensics HMD; 4 Wiimote balance boards.

3.1 Navigation

An array of balance boards compose the walking platform. The system also works with a single board, but due to the user immersion, 4 boards provide a safer and more comfortable surface. The boards communicate with the PC through a bluetooth protocol. We implemented an algorithm that merges the readings of 4 balance boards to compute the user's body center of mass projected on the walking surface ($\vec{C}$). This is a generalization of Wang [3]. The center of mass is calculated as $\vec{C}(t) = \sum_{i=1}^{M} \vec{u}_i a_i(t)$, where $\vec{u}_i$ is the position of a sensor in the array of boards, $a_i(t)$ is raw sensor i data over time and M the total number of sensors. Fig. 2 shows the matrix configuration tested with two boards (eight sensors).

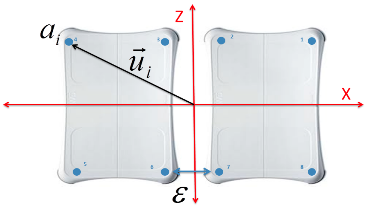

Figure 2: Balance board array and parametrization.

The pattern of change in the center of mass $\vec{C}$ while walking allows us to estimate pace and body direction. The center of mass is derived over time to generate a directional impulse response when the user steps in some direction ($G(t) = d\vec{C}/dt$). Such operations occur on the plane. Direction is obtained as follows: a perpendicular vector is first calculated from $\vec{N}(t) = perpendicular(\vec{G}(t))$ and then the walking direction angle over time, α(t), is computed.

Moreover, to avoid drifting between head orientation obtained by the HMD and feet orientation obtained by the boards, we applied the comfort pose algorithm [2]. This solution does not require any additional tracking sensor or infrastructure. The algorithm relies on the assumption that people tend to align body and head comfortably a few seconds after looking to either side.

3.2 Selection

A Samsung Galaxy SIII Android phone is the mobile device used for selection. An app has been implemented that works as a server reading sensor data and sending them through the network. The data is grouped in a string sent through TCP over wifi. The string is read by the PC client that parse it and use the sensor data to construct a pointing vector.

The vector is then used to cast a ray. Each point of the point cloud is set with a radius defining a small sphere. Intersection between the ray and the spheres define a selection region. The closest sphere to the user is computed and an ellipsoidal cursor is displayed at that sphere's position (Fig. 1b). Cursor position is updated in real time as the user points towards the cloud. When the user finds some points they want to select, they tap on the handheld device, causing the cursor to stop follow. From this moment, a pinch movement on the device's touchscreen scales the ellipsoid one the direction of the plane corresponding to the device's orientation (Fig. 1c). The user can then reorient the device and keep deforming the ellipsoid until he/she is satisfied with the points being covered. Another tap brings back the ray cast allowing to select one among a set of icons corresponding to labels. This action will assign the label to the selected set of points.

3.3 Labels and Hierarchy

As soon as a set of points is selected, the same pointing device is used to select a label from a list of icons. The respective label is then assigned to those points. To create a new label, the user selects 'new', activating the voice recognition system based on the Google API in the smartphone. The user then speaks a name for the label, which will be promptly converted to a string and sent together with the sensor information in the TCP package. The name is used to create a new label ready to be used.

As the user adds more labels to points, a hierarchical data structure is automatically created, placing smaller point sets in lower levels of the hierarchy. For example, if points of an eye have been previously labeled 'EYE', when the whole head is labeled 'HEAD', the head will assume a higher level in the hierarchy.

For hierarchy visualization, the user action is to lean forward/backward. This causes a weight displacement on the weight platform that triggers changes in the label hierarchy level being displayed. This is a natural interface as in the real world people lean forward to see more details and backward to grab more context.

4 RESULTS AND FINAL COMMENTS

We performed the labeling task on a couple of models provided by the contest organization for demonstration. Fig. 1d brings an example.

We presented an involving and usable approach for multiple 3D point selection an labeling. Our solution proposes a full body user experience where hand-pointing and pinching is used to specify an ellipsoidal selection volume. Navigation, in turn, uses an improved walk in place technique that includes walking direction in a natural way. Hierarchical visualization of labels uses the well known zoom-into-map approach. As future work, we are planning user studies to confirm the usability and effectiveness of the approach. We also plan tests with an annotation application in medicine.

We believe that the technique can be implemented with even simpler hardware, e.g. the Oculus Rift, being mobile and accessible for a huge number of applications that combine navigation selection and manipulation.

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8 APPENDIX B

8.1 Portuguese

Editar este formulário

Caracterização do usuário

Este formulário tem como objetivo caracterizar os sujeitos voluntários para os testes. Os dados aqui utilizados serão usados única e exclusivamente para fins de pesquisa cientifica. As informações aqui presentes, bem como àquelas coletadas durante os testes ou depois deles serão mantidas anônimas.

*Obrigatório

ID *

Este campo reserva-se a uso interno.

Nome completo *

Idade *

Sexo *

○ Feminino
○ Masculino

Escolaridade *

▼

Nos últimos seis meses, com que frequência você tem jogado games? *

Ex: Nintendo Wii, Xbox, PlayStation, PC, tablet, etc.

○ Nunca
○ Raramente
○ Ocasionalmente
○ Frequentemente
○ Sempre

Quando joga, com que frequência usa joypad ao invés de teclado? *

○ Nunca
○ Raramente
○ Ocasionalmente
○ Frequentemente
○ Sempre

Possui algum problema de visão? *

Ex: Baixa visão, miopia, hipermetropia, astigmatismo, discromatopsia, etc.

○ Sim

○ Não

Se a resposta à pergunta anterior foi positiva, qual seu problema visual?

Possui alguma experiência prévia com a balance board do Wii? *

○ Sim

○ Não

Já utilizou algum dispositivo de interação alternativa? *

Head Mouted Display, CAVE, Joysticks especiais

○ Sim

○ Não

Se a resposta à pergunta anterior foi positiva, quais os dispositivos?

Já jogou games ou assistiu a filmes em 3D estéreo? *

○ Sim

○ Não

Se a resposta à pergunta anterior foi positiva, classifique sua experiência com o recurso 3D estéreo.

	1	2	3	4	5	
Muito ruim	○	○	○	○	○	Muito boa

Se você considera ter tido uma má experiência ao usar o recurso 3D estéreo, descreva o que lhe desagradou.

Enviar

Nunca envie palavras-passe através dos Formulários do Google.

Com tecnologia

8.2 English

User characterization

This form aims to characterize the subjects volunteers for the tests. The data used here will be used solely for the purpose of scientific research. Information presented here, as well as information collected during or after the tests will be kept anonymous.

*Obrigatório

ID *

This field is reserved for internal use.

A sua resposta

Full name *

A sua resposta

Age *

A sua resposta

Sex *

○ Female

○ Male

Education *

Selecionar ▾

9 APPENDIX C

This questionarie was applied to both modes of walking: as human and as vehicle.

9.1 Portuguese

Editar este formulário

Questionário Final - sem limitação caminhada

Este questionário tem como objetivo obter informações subjetivas que reflitam a sua opinião pessoal a respeito do teste do qual você está participando. Sua sinceridade nas respostas é muito importante para nós. Lembramos ainda que as informações aqui coletadas serão utilizadas apenas para fins científicos e serão mantidas anônimas.

*Obrigatório

ID *

Este campo reserva-se para controle interno.

Classifique como foi sua experiencia ao utilizar a técnica de caminhar no mesmo lugar? *

	1	2	3	4	5	
Muito ruim	○	○	○	○	○	Muito boa

Quão difícil foi chegar até o destino atravessando os arcos? *

	1	2	3	4	5	
Muito difícil	○	○	○	○	○	Muito fácil

Ignorando o fato do ambiente não ser muito realista, o quanto você se sentiu imerso no ambiente, como se estivesse caminhado realmente? *

	1	2	3	4	5	
Não me senti imerso	○	○	○	○	○	Me senti muito imerso

Como você classificaria a técnica quanto ao conforto? *

	1	2	3	4	5	
Muito desconfortável	○	○	○	○	○	Muito confortável

Como você classificaria a dificuldade em usar a técnica?

	1	2	3	4	5	
Muito difícil	○	○	○	○	○	Muito fácil

Caso tenha sentido algum desconforto ao realizar o experimento, descreva-o abaixo.

Enjôo, tontura, claustrofobia, angústia, etc.

Comentários gerais

Todo e qualquer comentário sobre a sua experiência durante o teste é muito bem-vindo.

Enviar

Nunca envie palavras-passe através dos Formulários do Google.

Com tecnologia

9.2 English

Final Questionnaire - no walking limitation

This questionnaire aims to provide you with the information you have about your personal opinion regarding the test you are participating in. Your sincerity in the answers is very important to us. We also remind you that the information collected here will be used only for scientific purposes and will be kept anonymous.

*Obrigatório

ID *

This field is reserved for internal control.

A sua resposta

How was your experience using the same technique? *

	1	2	3	4	5	
Very bad	○	○	○	○	○	Very good

How difficult was it to reach the destination through the arches? *

	1	2	3	4	5	
Very difficult	○	○	○	○	○	Very easy

10 APPENDIX D

10.1 Portuguese

Editar este formulário

Formulário Escolha Final

Este questionário tem como objetivo obter informações subjetivas que reflitam a sua opinião pessoal a respeito do teste do qual você está participando. Sua sinceridade nas respostas é muito importante para nós. Lembramos ainda que as informações aqui coletadas serão utilizadas apenas para fins científicos e serão mantidas anônimas.

*Obrigatório

ID *

* Este campo reserva-se para controle interno.

Dentre as duas técnicas, qual você achou mais natural? *

Inercial ou Walking in Place

▼

Dentre as duas técnicas, qual você mais gostou? *

▼

O quão seguro voce se sentiu sobre a plataforma de WIP? *

	1	2	3	4	5	
Muito Inseguro	○	○	○	○	○	Muito Seguro

Enviar

Nunca envie palavras-passe através dos Formulários do Google.

Com tecnologia

10.2 English

Final Choice Form

This questionnaire aims to obtain subjective information that reflects your personal opinion regarding the test you are participating in. Your sincerity in the answers is very important to us. We also remind you that the information collected here will be used only for scientific purposes and will be kept anonymous.

*Obrigatório

ID *

* This field is reserved for internal control.

A sua resposta

Which of the two techniques did you find most natural? *

Inertial or Walking in Place

Selecionar

Which of the two techniques did you like the most? *

Selecionar

How secure did you feel about the WIP platform? *

	1	2	3	4	5	
Very Unsafe	○	○	○	○	○	Very safe

SUBMETER