Super-Feet: A Wireless Hand-Free Navigation System for Virtual Environments

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Abstract. Navigation is a fundamental task in virtual environments. Some of the metaphors that are used to determine where users want to be placed at each moment are based on physical locomotion. Usually, these techniques require the use of several sensors and complex algorithms. In this paper, we present Super-Feet, a wireless navigation system controlled by natural movements without requiring invasive methods or devices. It uses a low-cost infra-red system to detect the instantaneous position of both feet and this information is translated into a walking and rotation velocity in the environment. Preliminary results show that Super-Feet navigation is more accurate but slower than joypad based navigation systems.

Keywords: User Interface Events, Navigation in Virtual Environments, Virtual Reality Ergonomics.

1 Introduction

Navigation is a fundamental task in real and virtual environments. Users of virtual environments need methods to change their instantaneous position. In order to define a navigation system, there are two components of locomotion that have to be controlled: the direction and the velocity of motion. Different travel techniques have been developed to control these parameters based on several assumptions, and different classifications have been proposed to describe these travel techniques.

One of these classifications is based on the interaction metaphors that are used to control the navigation. Bowman [1] organizes travel techniques by six common metaphors: physical locomotion, steering, route-planning, target-based, manual manipulation and scaling. All of these techniques have different advantages and disadvantages that can make them more or less suitable depending on the application. However, the most natural techniques for the user are based on physical locomotion.

In this paper, we present Super-Feet, a system based on the physical locomotion metaphor. In the following points, we will describe more in detail other developments that have been made in navigation systems based on this kind of metaphor, so we can analyze the advantages and disadvantages of our proposal compared with these systems.

1.1 Physical Locomotion Navigation Systems

The first approximation that can be thought as a way to move inside virtual environments is to use exactly the same movements as in the real world, that is, to physically walk. This technique is natural, provides vestibular cues and promotes spatial understanding [1]. Real walking navigation systems have to be based in a wide-area tracking system that detects the instantaneous position of users while they walk. An example of this kind of tracking systems is the HiBall Tracker [2, 3, 4]. A HiBall (infrared sensing system) is fixed to each object that has to be tracked, pointing towards the ceiling, where a system of fixed infrared beacons is placed. This optical tracking system provides six degrees of freedom. Real walking is also used in other kind of applications, such as augmented reality outdoor systems, allowing users to move in a wide area in the real world. An example is the mobile augmented reality system (MARS) [5] which uses GPS and inertial/magnetometer orientation sensors to detect the position and rotation of the user.

An approach that can take the benefits of the naturalness of the movements without requiring the use of a wide-area tracking system is walking in place. This technique allows movements along big distances in the virtual environment while remaining in a small area in the real world.

One of these systems is the Virtual Treadmill [6], a system which tracked head motion of users and detected steps using a neural network. It requires that participants reproduce the physical head motions generated during actual walking but without physically locomoting. The pattern analyzer determines if users are walking in place, and if this is the case, makes them move forward in the direction of gaze.

As Templeman describes [7], the U.S. Army Research Institute in conjunction with the University of Central Florida's Institute for Simulation and Training also proposed a system for walking in place based in vertical motion of the feet. The movement starts when the foot is moved above a vertical threshold. The rotation is controlled by an electromagnetical tracker placed between the shoulders.

A system based on a similar approach is the one developed by Grant and Magee [8]. In this case, the movement of the user was controlled by moving the foot forward or backward over the floor. The rotation is calculated as the average direction between both feet. An electromagnetic tracker is also used in this case.

Gaiter system [7] is also based on stepping movements. Different movements of the legs are used to control the velocity and direction of motion. In order to track these movements, electromagnetic trackers are attached to the knees to control translation and rotation of the lower leg. Besides, the system also uses force sensors on shoe insoles to follow the different forces that are apply to the ground. A step occurs when a foot looses the contact with the floor.

In other cases, physical locomotion techniques are used with complex mechanical devices, such as treadmills, bicycles and wheelchairs. Templeman [7] classifies mechanical locomotion systems in unidirectional and multidirectional ones. Unidirectional systems limit movement to one direction, and a special action is necessary for rotating in the virtual environment. One of the first systems to be used was the treadmill proposed by Brooks [9]. This system has a handle to control the rotation. On the other hand, multidirectional systems allow users to move in any direction. One example of this kind of systems is the omni-directional treadmill [10]. This system is composed of two perpendicular treadmills, one inside of the other, which allow users to walk in any direction. Iwata [11] proposed a torus-shaped surface as a locomotion interface. This system uses twelve sets of treadmills which are connected side by side and driven to perpendicular direction. The effect of infinite surface is generated by the movement of these treadmills. The Sarcos Treadport is a locomotion interface consisting of a large tilting treadmill, an active mechanical tether, and a CAVE like visual display. The treadmill employs orthogonal overlapping bands to create a totally walkable two-dimensional surface. The tether's linear axis is motorized to push or pull on the user, thereby simulating unilateral constraints, slope, and inertial forces that intensify the walker's physical effort [12]. The main problem of these kinds of systems is that their complexity generates limitations and constraints on the natural movements of users.

Some studies have compared different physical locomotion navigation techniques. Slater [13] compared their virtual treadmill with walking in place and concluded that users without previous navigation experience reported a higher subjective presence when they walk in place using the virtual treadmill than when they fly along the environment (hand-pointing navigation method). Usoh [14] added real walking as a third condition, and found that the simplicity, straightforwardness and naturalness of real walking was significantly better in the real walking system. Besides, both kinds of walkers had higher subjective presence than flyers.

Some approximations combine different navigation metaphors. An example is the Step WIM [15]. In order to move in large areas, this system presents a world in miniature (WIM) that appears below the users' feet so their real position in the virtual environment coincide with their position in the WIM. A special interface has been designed for the feet, so that users can tap their toes or heels to decide when they want to be translated to other places in the virtual environment. This interface (Interaction Slippers) [16] is made embedding a wireless trackball device into a pair of slippers.

2 Technical Aspects

The main objective of this work has been to develop a hand-free navigation system that leaves a greater freedom for other interactions with the system using the hands. The system has to be applied in settings of reduced dimensions and without requiring complex devices that can be invasive for the user.

A physical locomotion approach was selected. The use of real walking systems [4, 5] was discarded, as the use of this kind of systems in a small area is not suitable to control movement in big virtual environments. On the other hand, as one of our goals is simplicity, we also decided to avoid systems based on mechanical devices, such as treadmills [9, 10, 11]

Super-Feet can be included in the category of walking-in-place devices. Similarly to other approaches [6, 7, 8], our system has to be based on some kind of tracking device in order to know the position and movement of the parts of the body that control the advance velocity and rotation inside the virtual environment. All these systems are based on electromagnetic tracking devices, used with force sensors in the case of *Gaiter*. In our case, we have decided to use optical tracking, because this technology is less sensitive to noise, and our hardware configuration does not require an excessive workload for the computer. Besides, it is not a problem to have a direct line-of-sight between the camera and the tracked objects.

Super-Feet has to detect instantaneous movements of the feet and associate them to velocities in the virtual world. According to previous studies [13, 14], the naturalness of movements seems to be related with higher presence in the virtual environment, so we have decided to use an approach based on natural feet movements as similar as possible to real walking.

2.1 Hardware Configuration

Super-Feet detects the movements of the users' feet in a non-invasive way using a low cost infra-red commercial tracking system: Optitrack [17]. This commercial system includes an infra-red camera which is connected to the computer via USB interface. Optitrack includes an application programming interface that is used to communicate and obtain information from the camera. The object tracking that can be made using this technology is very precise and reliable. Reflective markers have to be placed on objects to be tracked and inside the field of view of the camera. Once the camera has been connected, LEDs emit infra-red light which is reflected when it comes in contact with the markers. The camera can then receive the reflected light and determine the position of the markers.

This commercial system has been used to prepare the physical configuration associated to Super-Feet, as can be observed in Figure 1.

Fig. 1. In the left image, the relative position of the user and the infra-red camera can be observed. The right image shows a view of the reflective markers from the camera perspective.

Users will be seated on a chair during the exposition to the virtual environment and move their toe tips up and down, and laterally, to control the different movements in the virtual world. The Optitrack camera will be placed on a tripod in front of the user. The user has to wear two flexible plastic covers (similar to sockets) that can be adapted for different feet sizes. Each of these covers has a circular reflective marker on it.

2.2 Software Tools

The functionality of the system has been implemented in a software library that can be used from external applications. The library has been developed using the Visual C++ programming environment and makes use of the functions provided by the Optitrack API. The library has been adapted for its use from Brainstorm eStudio software [18], which has been used to program the environments used during the ergonomic evaluation.

2.3 System Description

While both feet are still and placed at equal distances to the symmetry axis, walking and rotation velocity are zero.

In order to start moving, the user has to move alternatively up and down toe tips from each foot. The markers are placed in the toe tips, so the rest of the leg and the heel can remain fixed. The system calculates the individual vertical velocity of each foot. A filtering is applied to the calculated velocities in order to achieve smoother variations and movements. The walking velocity that is obtained is proportional to the minimum of these two vertical velocities. If users move feet quickly, they will achieve greater velocities in the virtual environment.

If the user moves a foot away from the symmetry axis of the image, the camera acquires a rotation velocity in the direction of the displacement. The modulus of this rotation velocity is proportional to the distance to the symmetry axis of the image which is calculated at the beginning of the session as the mean point between the two markers. In order to calculate this position, an initial calibration process is required which takes only a few seconds during which the user has to remain still in the repose position.

3 Usability Test: Method and Results.

We performed an ergonomic evaluation of Super-Feet in order to understand the usability of the device in performing some basic movements in a digital environment. We decided to adopt as a criterion for this evaluation the performance of a device that is commonly used in similar tasks, namely a joypad, and performed what is called a 'comparative evaluation' [19]. The movements selected for the tests were the following: a pre-defined path within a labyrinth-like environment; a double curve corridor; a rectilinear path along a corridor; a free walk in a two-floors indoor space in search of three specific items.

The labyrinth tested the usability of the devices in terms of accuracy and speed. Participants did not have to choose directions and were instructed to complete the route as fast as possible and without colliding with the walls. We measured the overall time spent, the overall length of the route covered, the number of impacts on the wall and the number of changes in directions.

In the double curve route corridors, participants were instructed to complete the route in the shortest possible path in order to check the accuracy of the device. We measured the overall length of the route covered, the number of impacts on the wall, the time to complete the task and the number of changes in direction.

In the rectilinear path, participants were asked to walk as fast and as straight as possible. The two devices were calibrated in order to have the same peak velocity, so that we could compare the time spent to accomplish the task. We also measured the number of changes in directions in order to assess the ease of maintaining a straight direction.

The final task was designed to examine longer and more variegated courses of action with a video-analysis, which will not be discussed here. For the purposes of this evaluation we only considered performance in terms of number of items found and time taken to find each one of them.

All data were collected by a special software within a User-Interface Events (UIE) paradigm, based on the automatic gathering of the user's operations on the interface together with their time of occurrence [20].

3.1 Design and Procedure

Three different devices were compared:

1. Super-Feet: Participants used Super-Feet to move around the environment and, simultaneously, to explore it visually.
2. Super-Feet and HeadTracker: Participants used Super-Feet to move around the environment. To explore it visually they could either move with Super-Feet as in he previous condition, or rotate their head without changing their position in the environment, thanks to a Head-Tracking System (HTS) (Intersense Intertrax2). In this way they could choose to decouple movement and visual exploration.
3. Joypad: Participants used a two-stick joypad. The stick on the left was used to move on the horizontal plane as in Super-Feet, while the right stick allowed visual exploration.

The participants were divided in three groups of 12 people (6 men and 6 women), and assigned to one condition each. All participants executed the four tasks in the same order. Before the task series, participants signed an informed consent and had a training session of at least 5 minutes in a special digital environment to practice with their own experimental device until they declared to have understood its functioning.

The experimental setting was the same for all of them: they were positioned at a 2.83 meters distance from the screen, sitting, and the OptiTrack camera was at 65cm distance from the heels. The dimensions of the screen were 3.20×2,40 meters (see figure 2). Participants were not familiar with any of the device employed in the experiment.

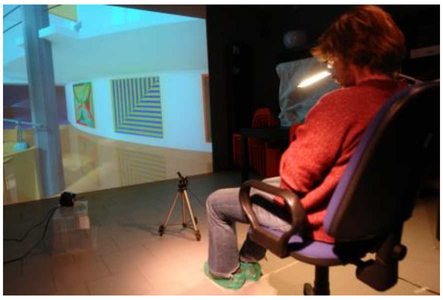

Fig. 2. The experimental setting.

4 Results

A one-way, between-subjects ANOVA was used to compare different measures in the three conditions. In the *first task*, the end of the labyrinth is reached more fastly with the joypad [$F_{(2,35)}$ =8,774, p < 0,002], even though with a longer route than with the Super-Feet ($F_{(2,35)}$=3,338, p<.05; Tukey HSD Test, p<.05) (figure 3). This could mean that Super-Feet allows to draw more precise trajectories, but with a higher expenditure of time. There was no significant difference in the amount of collisions, but they were rare events, since the environment was large enough to avoid them. Similarly, there was no significant difference in the amount of direction changes.

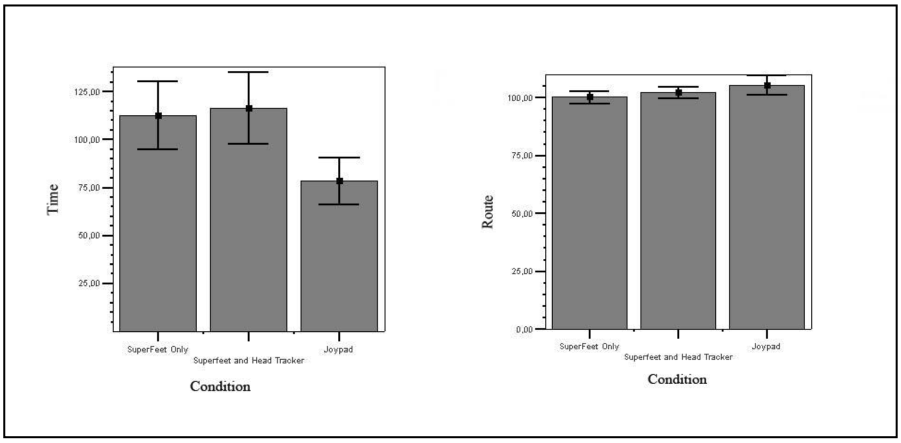

Fig. 3. Time to accomplish the first task (left), route length (right) in the three conditions.

In the *double curve task*, where speed did not count, no significant difference was found among the three conditions in any measure. This could be related to the fact the devices differ only in the trade-off between accuracy and time.

Therefore, the result of the *third task*, where participants had to cover a straight corridor in the shortest time, is of great interest. In fact, we found a better performance in the condition with the Joypad [$F_{(2,35)}$=4,002, P<.03] (figure 4).

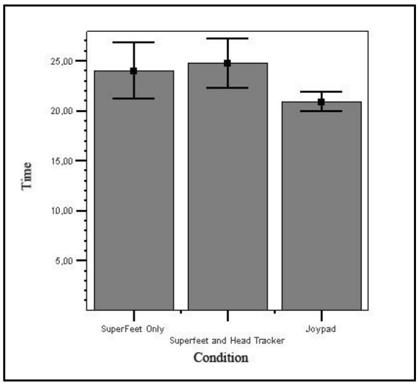

Fig. 4. Differences in time necessary to complete the task in the three conditions.

Since the peak speed of Super-Feet and Joypad is almost the same, the difference between the two devices may suggest that it is more difficult do keep a peak speed for a long while by moving the feet fast instead of just by keeping a stick pressed. Super-Feet engages the body more directly with physical effort, and in fact in these two conditions the variance is greater, probably due to different physical endurance. No comparison was made on the directional changes since they only occur once.

We did not find any significant difference in the performance indexes in the *fourth task* (number of items found, time taken to find each item) even though the task required visual exploration, which could have favoured the conditions with Headtracker and Joypad. Super-Feet was able to produce the same performance as the other conditions even though it did not allow an independent visual exploration.

5 Conclusions

The results of the usability test show that there were no significant differences in performance indexes between Super-Feet and the Joypad. This allows us to conclude that Super-Feet can be used as a navigation system with similar results to the ones achieved with a commonly accepted navigation device as the joypad.

As we have told in the introduction, the use of one navigation device or another for a particular virtual environment will depend on the specific purpose of this environment. Super-Feet was designed to achieve two basic goals, which are simplicity and the possibility of leaving user's hands free. The main advantages that have been obtained with this system when compared with other physical locomotion systems are:

1. It does not require the complexity of mechanical devices such as treadmills. That makes it more portable and less invasive for the user.
2. It is based on feet movements, so hands are left free for other interactions inside the virtual environment.
3. It is not based on electromagnetical tracking devices, so it is less sensitive to noise and interferences.

In synthesis, Super-Feet seems more physically engaging and a more accurate device than the Joypad, which may be useful or not according to the task. When speed is required at the expenses of accuracy and for a long time, then a joypad may perform better.

In any case, more research will have to be done in specific applications of Super-Feet to analyze how it contributes to the specific objectives of these applications and which are its advantages and disadvantages when compared with other navigation systems.

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