Realizing a New Step-in-place Locomotion interface for Virtual Environment with Large Display System

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Abstract

Omni-directional locomotion systems are yet of little advantage in virtual environments (VEs) with limited large display system, where users may experience visual-less situations when they move in a direction that is not covered by the large screen. This paper presents a new omni-directional locomotion interface based on step-in-place movement and a smart-turntable system to impart users with the ability to move freely in any direction within VEs without loosing sight of the displayed images despite their projection on a limited large screen that do not provide surrounding or 360^o visual feedback. A sensor-embedded turntable is used as a walking platform, on top of which users will stand at its center to perform walk in place and turn in place movements to steer their navigation through the virtual environment. However, as a large turn action may put the screen outside user's visual field of view, the turntable will cancel user's turnings by a smooth and passive rotation in the opposite direction so as to keep user oriented toward the center of the screen. The novelty of the interface is that a) it uses a smart-turntable as walking platform that compensate users' rotations rather than their displacements b) no cable attachments are made to the user body c) user can make many full body rotations without loosing sight of the environment, virtually providing a surrounding display despite the use of limited size screen.

1. Introduction

Walking or traveling in general is an important life enhancing activity which is initiated and sustained by the lower part of the human body and it is considered as a necessary daily behavior that human performs to get from place to place. Keeping the same natural mean to move around in VE with large display systems is of great interest for many applications demanding locomotion, such as building evaluation, urban planning, terrain exploration, rehabilitation, and military and vocational training. Though natural locomotion is accomplished in real life almost without conscious thought, it is a very difficult behavior to duplicate within a limited working space of any VE systems without the benefit of a control technique that can mimic human's walking. Therefore, some kind of "virtual locomotion" interface is needed to enable movements over large distances, while remaining within a relatively small physical space.

Despite the increasing use and popularity of VEs with large screen and the development of a variety of omni-directional walking interfaces, virtual locomotion is still a key factor that is missing from most of today's VEs with large screen. Instead, there is still a tendency to use input techniques based on body gestures and hand-held devices as mean of locomotion, such as SpaceMouse™, DataGlove™, and the SpaceBall™ [13][14][15]. These interfaces are basically concerned with passive movements in which users merely exerted control over the driving gear whereas virtual locomotion always involves proprioceptive stimuli generated from within the body by a simple and intuitive stepping movement. The usage of passive interface for locomotion purpose may fail to provide users with some necessary proprioceptive feedback that are of particular importance during mobile navigation. For instance hand-based interface do not stimulates the vestibular system, which could be used as an inertial navigation device for spatial orientation and path integration Worchel [18], Barlow [19] Potegal[20], Wiener and Berthoz [21]. it is widely suggested that the usage of proprioceptive sensing within VE systems enhances considerably user's perceptual ability of spatial orientation. Niels [1][2].

Iwata [9] and Carmen [4] proposed two treadmills based omni-directional locomotion systems that can cancel user displacement and keep them located in the same place while being able to walk into any direction. Both systems are heavy and use a set of sensors and tether attachments for tracking and safety purposes. Iwata stated in [3] that the use of head mounted display (HMD) caused some safety concern and suggested that large display systems are more suitable for hardware similar to their system. Slater [10][11] and Templeman[12] adopted a simpler approach that eliminates the need of moving platform to cancel user displacement, instead they used the step-in-place action to engage user into a walking experience, such action kept a very similar body movement to actual walking behavior but without body propulsion. However, both system were implemented with HMD and used a set of sensors to read user's stepping behavior. VR Systems UK Ltd and VirtuSphere Company have developed a locomotion interface based on a large sphere device inside which the user will be walking on its interior surface. The sphere will rotate about its center as soon as the user starts walking. Different support systems are applied at the bottom and exterior side of the sphere to keep it from rolling away and maintain its rotation about its center. VR system Ltd used a semitransparent sphere so it can project the VE on its surface whereas VirtuSphere provided user with HMD to visualize the simulated environment. Both systems provided a good walking experience but their possible integration into VE with large display is unlikely because of their hardware structure and adopted visual display. Butterfield [22] developed another sphere-based system in 1999 where the user is supposed to walk this time on the exterior surface and the top side of a large sphere. A support mechanism attached to the ceiling was used to keeps users walking on the top of the sphere and holds their center of mass on a vertical axis passing through the sphere. A support mechanism with low friction with the sphere is used as well at the bottom side to keep the sphere from rolling away and rotating about its center in the same time. Although the system would provide a good walking experience, it requires a large amount of vertical space to fit its spherical platform, which obstructs the integration within existing VE with limited large screen. Other linear locomotion systems have been developed to reproduce active walking experience but do not provide user with the ability to use their active and natural body turning to change their walking direction, instead the omni-directional locomotion is achieved by using an extra artificial interface to accomplish a rotation task [6][7]. Noma *et al*.[23] proposed later an improvement for their ATLAS walking interface so as to accommodate turn actions during locomotion. But the system do not support in place. Users are able to change their moving direction only while walking and for angles that are not large enough for a natural move of 45, 60 or 90^o/s.

As mentioned above, a variety of omni-directional locomotion techniques and metaphors have been designed and implemented during the last decade. The various systems would accommodate the dynamic and active walking behavior in an intuitive manner; allowing users to physically walk into all direction and distances without leaving the restricted working space. However, most of the proposed systems, if not all of them, require either a surrounding visual display system, or a HMD device to provide users with the necessary visual feedback at any moving direction. Such requirement hampers considerably the integration of existing locomotion systems into VE with limited large screen such as the case with CAVE or similar large display system.

The major shortcoming of VE with limited large screen, with respect to omni-directional locomotion systems, is the presence of an open area or a "dead angle" where no visual feedback cue can be available. This area is usually located at the opposite side of the center of the display and behind the user, figure 1. The missing visual feedback in some direction puts the traveling experience of little advantage when users make a large physical turn in attempt to explore the rear environment behind them, such move will bring their visual field of view partially or totally outside the display area.

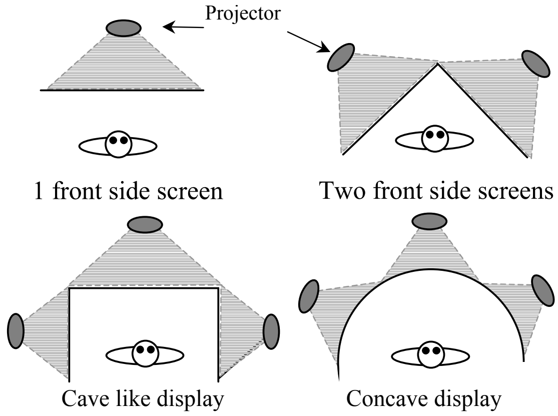

Figure 1: *Top view of some common large-display* systems

The challenging part in integrating omni-directional locomotion interfaces and VE with limited large screen has been always how to let users perform comfortable and effective life-like navigation without being physically displaced outside the limited area of the interface and without loosing sight of the projected images of the VE?

The present paper presents a new omni-directional locomotion interface that can be integrated to a wide variety of VEs that use a limited large screen. The interface employs the step-in-place technique with a smart-turntable mechanism to impart users with the ability to freely engage in a life-like walking or traveling experience into any direction without loosing sight of the displayed environment despite the limitation of screen size area.

Taking into consideration the shortcomings of other omni-directional locomotion systems, the proposed interface is designed to promote the following main points:

- Body centered: the locomotive actions controlling the travel within the VE are initiated and sustained by the lower part of the body as in real life. This approach will preserve user's natural reflexes and navigational control skills.
- Omni-directional: users can guide their traveling in any direction.
- Attachments free: no cable or bulky devices attachments are made to users' body. Such as HMD or wired sensors.
- Simplicity: the walking interface is easy to use and easy to learn.
- Compact: the hardware system is relatively compact and fit most of the VE with large screen.

2. System overview

The developed system as illustrated in figure 2, is composed of three main parts: a walking platform, sensing system, and large display system. The interface employs a turntable as walking platform on top of which users will stand and interact with the virtual environment that being projected on the large screen. Initially users will stand at the center of the turntable and face the center of the large screen. Users can engage into a virtual walking experience by stepping in place without propelling their body. Step-in-place movement will be detected by the sensing system and treated as a gesture of moving forward in the VE. To change the moving direction or to explore the surrounding environment in general, users are required to turning their body about its vertical axis while remaining at the same position, the same natural turning action they perform in real life. The turn-in-place action is treated as a gesture changing the direction of the viewpoint. However, as the large screen provides a limited projection area, a large turning action will put the displayed image outside users' visual field of view. To overcome such limitation and keep users continuously oriented toward the screen and provided with enough visual display, the turntable platform will smoothly and passively rotate in the opposite direction of users turning. The passive compensation of users' active turning will continue until users regain their initial orientation.

At the front side of the system a large display is provided for graphical projection of the VE. For the experimental prototype the screen was 2.5 m wide and 2.5 m high.

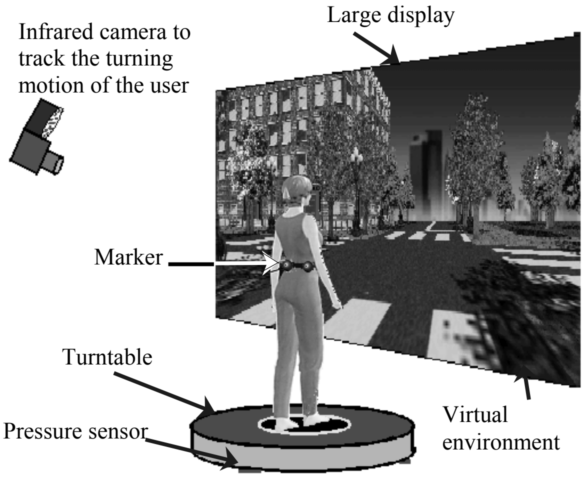

Figure 2: *An overview of the proposed system.*

2.1. Walking platform

The usage of a turntable as walking platform is intended to compensate users turning movement by passive and smooth rotations, hence keeping users oriented toward the screen and avoid them a visual less situation even when they perform large turns. However, turntable rotations should not in any case disturb user's walking behavior or threaten their stable posture. It is suggested that passive rotation and acceleration should be kept under some threshold values to ensure its transparency to the user. Otherwise users attention may be shifted time to time from the VE to safety or body's balance concerns.

To provide a smooth and well-controlled passive rotation we designed and developed, in collaboration with Cyverse Company - Japan, a new kind of high performance turntable platform based on linear motor technology. Actually, at first we used a turntable driven by a servomotor via a set of gears. After some usage we realized that the noise generated by the gears is little bit noisy and might be perceived by the users, who may realize then that they are being rotated. To hide, as much as possible, the passive rotation from being perceived at least in its early stage is necessary for the transparency of turntable system. It is essential that the turntable is able to deliver quite and stable rotation and fine acceleration to guarantied a smooth compensation of users' turning.

The developed turntable, shown in figure 3, is 70 cm wide and 10 cm high and has the following features and technical characteristics:

a) Noise less: No hearable noise is delivered during turntable rotation. The presence of such auditory cues may help users to perceive their passive rotation or its direction.
b) Jolt less: the surface of the turntable remains stable during stepping and turning movements or other physical actions. It does not deliver any perceptible vibrations, jolt, or tilting that may increase user's awareness of the passive rotation
c) The turntable controller is capable of fast updating and precise rotation control. Acceleration and deceleration can be performed very smoothly and finny.
d) The turntable is directly controlled from a remote personnel computer interface.

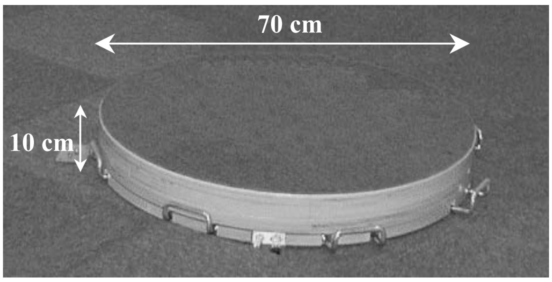

Figure 3 : *Top view of the developped turntable*

However, during stepping-in-place movements users may unintentionally step away from the center of the turntable [16], leading them to step close to the edge or totally outside of the platform. To prevent users from stepping outside the platform and maintain their position at its center, we delimited the walking area where users are required to step and turn by a cylindrical ring with 37 centimeters in diameter and 1cm thick, which can be haptically sensed by feet, figure 4. User will be required to adjust their standing or stepping position whenever their feet fall on the ring.

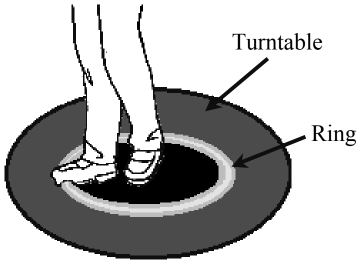

Figure 4: *A special ring is used to delimit the stepping area.*

2.2. Sensing system

In respond to user stepping and turning movements the system have to move and orient users in the VE according to their expressed locomotive behavior. A proper updating of the viewpoint and visual feedback will create the sense of linear and circular vection that impart users of the feeling of being really moving through the virtual world. A mismatch between user's movement and its expected visual feedback may weaken user's ability of spatial orientation. Therefore, a reliable stepping and turning sensing system is necessary to keep the integrity between proprioceptive action and their visual effect.

Magnetic sensors are widely used in tracking body movement. Slater and templeman used such sensors, but differently, for their step-in-place locomotion system. Slater attached the sensor on the head to track its oscillation caused by the stepping motion. Templeman attached few sensors on the waist, knees, and pressure sensor on the feet. Although both sensing systems do succeed to get enough information about the stepping motion, their wired attachment restrict however user's movement and may disturb their walking experience. for instance a continuous turning may wand the wire around their bodies. Moreover, putting sensors on their designate position on the body may take time or need a assistance from a second person. Beside these shortcomings, all step-in-place locomotion interfaces uses HMD to display visual feedback, which is not suitable for large display systems.

In this research, we propose a new approach for tracking user stepping by embedding load sensors under the walking platform. These load sensors are used to monitor the different ground reaction forces (GRF) between users' stepping and the walking platform. To reliably gather GRFs generated by the different stepping actions, we have embedded four sensitive FlexiForce load cells on the bottom side of the turntable. The load cells are integrated into a force-to-voltage circuit that converts the sensed pressures into analog signals. The FlexiForce cells are sensitive to the pressure being applied to their contact surface. The signals gathered from the four-load cells are then converted from analog to digital by a National Instruments data acquisitions board plugged into a standard PC. By filtering and analyzing the received data the system is able to recognize different signal patterns referring to different stepping actions. Thought the algorithm is capable of ignoring unclassified stepping patterns, users are asked usually to maintain certain standard stepping or leg movements to optimize and to not confuse the algorithm. Figure 5 shows the placement of the four pressure sensors (*P1, P2, P3, P4*).

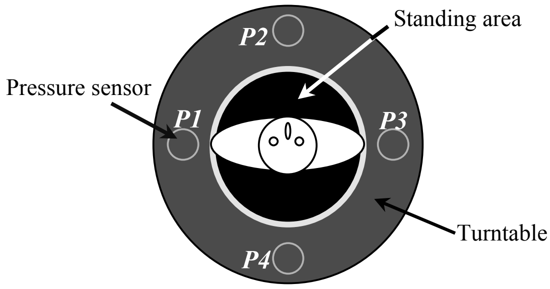

Figure 5: *Four load cells are embedded within the turntable to register pressures caused by the stepping action.*

To track user-turning actions, we used a computer vision interface, which is composed of an infrared camera and two colored markers. The two markers have a spherical shape with light reflecting surface. Each marker has a sticky side that can easily stick to clothes. The markers will be attached next to each other in the horizontal plane. Both markers will be attached to the backside of the body facing the infrared camera. The attachment position can be shoulders, waist or head depending on the application. The infrared camera is placed behind the user and fixed at higher position from which will capture the overall scene of the system including the markers. By using image-processing technique, we can extract from the captured images markers' position. And by a simple tracking algorithm we can calculate the angle variation of the user body. More detail will be provided later in the paper.

3. Locomotion Control

Navigation through the VE is directed by a set of control actions that mimic natural walking movements, which can be either displacement or turning. For instance, stepping in place is treated as a gesture indicating the user intends to move forward. Rotation about the body's vertical axis is treated as a gesture changing the walking path direction. In the following two section we will discuss in detail how our system implements and controls the virtual locomotion

3.1. Virtual displacement

Virtual displacement allows users to translate their position in the virtual environment without changing their spatial orientation. Virtual displacement is the result of active stepping action that controls linear body translation in the virtual world creating the sense of linear vection or walkthrough feeling. It can be forward displacement, backward displacement, sideward displacement or a combination of them. Each displacement has its own movement pattern that the system can recognize and according which update the visual display.

3.1.1. Forward displacement

Forward displacement can be achieved by a simple step-in-place movement that reproduces the same physical leg actions generated during actual walk but without physically locomoting, which is walking without body propulsion, see figure. Stepping in place action will swing laterally user's body like a pendulum, shifting the body's mass from left to right and vise versa. Such mass movement will generate rhythmic changes to GRF in accordance with the stepping actions, figure 6. Data received from pressure sensors during a stepping action is illustrated in figure 7. For the clarity of the graph we show the data registered from sensor P3, referred in figure 5. The periodic pattern of stepping actions is clear and can be easily detect by using simple statistical analysis. For the current prototype system we used just the simple standard deviation algorithm to decide about the nature of the stepping action.

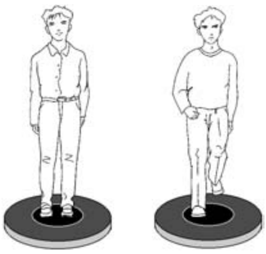

Figure 6-a: Step in place movement

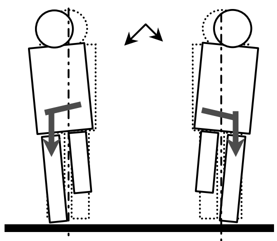

Figure 6-b: Changes in the GRF

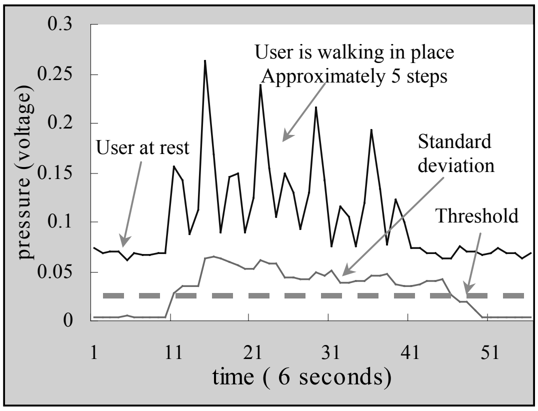

Figure 7: *At rest the pressure variation is negligible. However during step-in-place the sensor change remarkably its status.*

3.1.2. Sideward displacement

Sideward displacement is a very important stepping action that is used to fine the forward displacement, avoid obstacles, or to adjust standing position. In our system, sideward displacement is mimicked by a simple sidestep action as in real life. Being at the center of the walking platform, the user moves laterally one of the feet to its respective left or right side and stand on that foot by putting most of the body weight on the same side, figure 8. However, due to the limitation of our walking platform, only one sidestep can be performed otherwise user will step outside the turntable platform. If successive sidestep are to be generated, user hold the side step for a longer time so the system will tread the action as multiple sidestepping which will be ended when the user bring back his foot to the center of the walking platform.

During sidestepping action, the data received from the different pressure sensors are presented in figure 10. It is clear from the graph that the sidestepping action has a specific pattern that distinguishes it from other stepping patterns.

Figure 8: *Sideward*

Figure 9: *Backward*

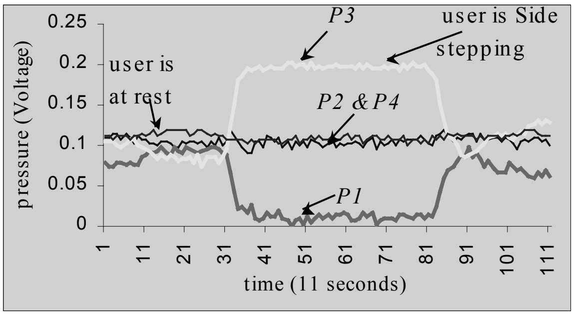

Figure 10: *Pressure registered during sidesteps*

3.1.3. Backward displacement

Backward displacement action is very similar to the sideward displacement action except that the user will make one step backward instead of sidestep, figure 9. Pressure sensors react differently than the sidestepping but have similar pattern.

3.2. Virtual Turning

Turning action is a fundamental move that users should be able to perform in order to discover area outside their visual feedback. Despite displacement, turning action does not translate body's position, but it can be performed while being relatively at the same spot. Turning actions are used to orient users toward their intended moving and viewing direction. The proposed system kept this action natural where users are able to change their walking and viewing direction by actively turning about their body's vertical axis. That is pivoting while staying at the same spot. The turning action is tracked by analyzing the sequence of captured images taken with the infrared camera. Whenever a new walking direction is computed, users' viewpoint is updated to match the real turned angle. However, in VE with limited large display system, a large turning action may put the displayed image partially or totally outside users' visual field of view, figure 11. To avoid a possible sightless situation we used the turntable platform to compensate for any active turning with a passive rotation of the turntable but in opposite direction. For example, if the user turns to the left side the turntable has to move smoothly to the opposite direction, to the right, until the user face again the center of screen. In the next section we discuss in more details the mechanism of passive cancellation of user turning.

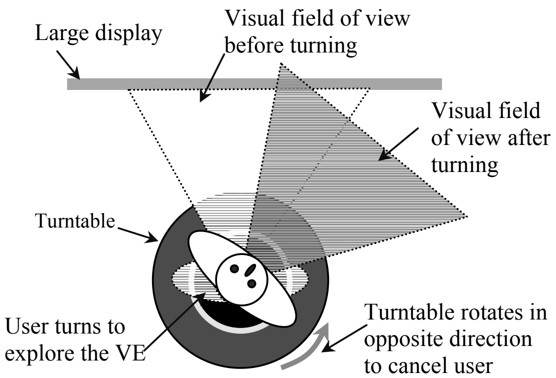

Figure 11: *User's turning can be canceled by rotating the turntable in the opposite direction.*

4. Turntable Control

Ideally, if the system can rotate the turntable at a speed equal to the user turnings without a time delay and without misbalancing, all turning actions would be immediately canceled and users could be kept facing the screen all the time. However, it is difficult to achieve such synchronization because a sudden rotation of the turntable with some speed may disturb users' standing and stepping actions, hence shifting temporarily their interest from the virtual experience to their balance and posture stability. Therefore, the passive rotation of the turntable must be kept smooth and within a limited speed that the user can withstand with no safety fears, and more importantly and preferably a speed that can hide as much as possible the passive rotation from users. Although as human, our vestibular system, in particular the semicircular canal, is sensitive to body rotation, we believe that a smooth and well calibrated control of the passive rotation speed might be hided or ignored during virtual interaction without much notice from the users. Hence an optimum cancellation would try to satisfy the following two conditions:

a- Cancel users turnings as soon as possible. Real-time cancellation would be the optimum.

b- Minimize as much as possible user awareness about the passive rotation. Zero awareness would be the optimum.

It is nearly impossible to satisfy both conditions with their optimum during the cancellation of natural turnings, which are usually carried at a speed ranging between 45^{o}/s and 90^{o}/s, though smaller turnings are quite possible. At such turning speeds, *a* condition would require immediate and fast rotation, whereas *b* condition would require slow and smooth rotation. To maintain a balanced tradeoff between the two conditions while canceling user turnings, few parameters regarding turntable rotation and its perceptual effect were studied and determined. For this aim, we carried out two psychophysical experiments that investigate users ability to detect passive self-rotation and their ability to withstand fast rotation. The goals of these experiments were to determine 1) approximately the passive rotation speed from which users start feeling the self-rotation. 2) To determine the maximum velocity that can be applied to users without affecting their movement and postural stability. During the trials we manipulated few parameters related to rotation speed, speed acceleration, user posture (standstill, stepping), and visual feedback (with and without cue).

Based on the different results collected during the above psychophysical experiments, we concluded by assuming the following six points:

1. Turntable rotation is composed of two phases. A acceleration phase during which the rotation speed will continue to increase gradually. And a deceleration phase during which the rotation speed will continue to decrease gradually.
2. During the acceleration phase, rotation speed of the turntable continues to increase gradually. It is determined by a linear equation as a function of time of the form $V_a=a*t_a$. Where V_a represents the speed, *a* its constant acceleration and t_a is the time variable.
3. Acceleration is a constant and equal to $10^{o}/s^2$
4. Maximum speed that can be generated by the turntable is 50^{o}/s
5. During the deceleration phase, rotation speed of the turntable continues to decrease gradually but at rate twice faster than the acceleration phase. That is mainly to compensate the slower start of speed rotation. Deceleration speed is also determined by a linear equation as a function of time of the form $V_d = d * t_d + c$. Where V_d represents the speed, *d* its constant acceleration, t_d the time variable, and *c* the rotation speed at $t_d=0$, the start of speed deceleration
6. The turntable can reach the maximum speed of 50^{o}/s within five seconds.

Based on these 6 assumptions, the system would be able to cancel users turning action with a passive rotation of the turntable while maintaining a fair tradeoff between the above mentioned *a* and *b* conditions. A typical run of the acceleration and deceleration algorithm is shown in figure 12.

In the following section we will discuss how the rotation speed of the turntable is controlled so as to keep user facing the screen and provided appropriate visual feedback. The cancellation phase has to be well matched with the visual cue otherwise a perceptual conflict between the provided information cues will be displayed to the user.

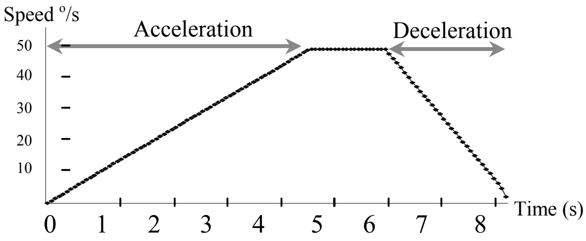

Figure 12: *Typical run of the turntable acceleration and deceleration*

4.1. Rotation speed control

Initially the turntable is at rest and its rotation speed is set to zero. It starts rotating whenever the user turns for an angle greater than the dead-angle. The dead-angle is the threshold angle within which the system does not consider user's action as a gesture of turning, figure 1. The rotation speed starts from zero and continue to rise gradually and in proportional to time as shown in the following equation, which was determined in the previous section.

$$v_a = 10.0 * t$$

$$v_a = v_{\max} \qquad if\ v_a > v_{\max}$$

$$v_{\max} = 50^o / s$$

Where v_a denotes the rotation speed of the turntable, v_{max} the maximum rotation speed. At the beginning t is equal to 0, the turntable is at rest with no velocity. Once the acceleration starts, v_a continue to rise until the system decides an otherwise action.

The decision to increase, holds, or decrease the rotation speed of the turntable is based on two parameters: the current user angular orientation and the current rotation speed of the turntable.

4.2. How the turntable cancel user turning?

The system continuously track user's action and adjust accordingly the rotation speed of the turntable. In general, As long as the turntable is rotating the system updates its speed and makes sure that it provides the optimal reaction to users' turning. To maintain an appropriate control the system continuously resolves a set of equations to respond mainly to the following question. "Based on the current user orientation and the current rotation speed of the turntable, what direction the user will be heading to if the turntable begin-immediately to decelerate?" The decision making process is generally as follow:

Assume that the current user orientation is α, and taking into consideration the current rotation speed of the turntable, the system can estimate the final user orientation β if the turntable is immediately decelerated. Upon the β value the system can take an immediate decision, which can be one of the following.

[1] If ($-\Delta 0 < \beta < +\Delta 0$) then the system will maintain the current rotation speed, which is good enough to bring user back to her/his initial position exactly when the deceleration phase

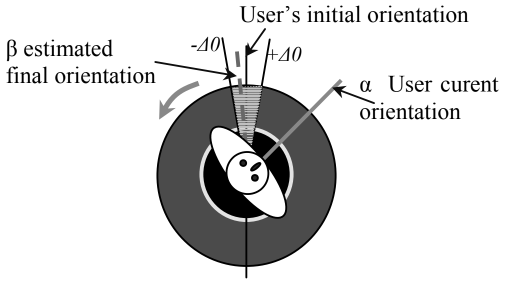

Figure 13-a: rotation speed should be maintained

[2] If ($\beta < -\Delta 0$) then the system has to start immediately the deceleration phase with some adjustment so as to stop the turntable within the range of dead-angle

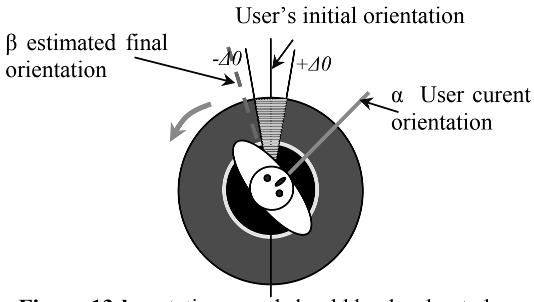

Figure 13-b: rotation speed should be decelerated

[3] If ($+\Delta 0 < \beta$) then the system have increase immediately the rotation speed. Until β fall within the dead-angle.

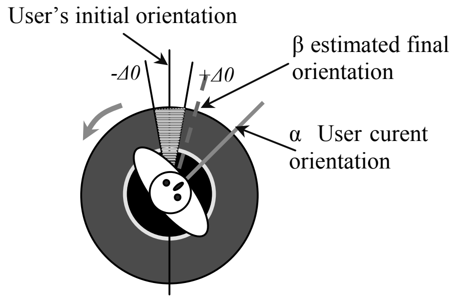

Figure 3-c: rotation speed should be increased

Even in case of a sudden or fast change of user's turning, the system can decide whether to re-accelerate again to compensate the new changes or to continue the current deceleration. The estimation of final user orientation is computed in the following way. As we mentioned earlier, the deceleration is defined by a linear equation as function of time.

It takes the general form $v_d = c_d * t_d + C_d$. Where v_d is the velocity during deceleration. c_d, C_d are unknown variables to be computed so as to smoothly stop the turntable when the user is brought back to the initial orientation. At the beginning of the deceleration we know that

$v_d = v$ *where v* is the current rotation
$t_d = 0$

Applying these values to $v_d = c_d * t_d + C_d$ we get

$C_d = v$

As well, at the end of the deceleration the turntable should be at rest and that the deceleration time is half the used time for acceleration. That means:

$v_d = 0$
$t_d = t_a/2$

Again, applying these value to $v_d = c_d * t_d + C_d$, gives us the following values

$0 = c_d * t_d + c$
$\Rightarrow c_d = -c/ t_d$

Finally, replacing C_d and td by their respective values we get

$\Rightarrow c_d = - 2v_a / t_a$

As shown, the two parameters needed for the deceleration phase can be computed at any time. Now we need to find the final angular position at which the turntable finish the deceleration phase and stop.

Since the angular velocity of turntable is known, as a function of time, then it can be integrated to get the angular position at any time td. In particular when $t_d=t_a/2$, (deceleration is twice faster than the acceleration) which gives

$$w(t_d) = \int v(t_d)\ dt_d + C_1$$

Or,

$$w(t_d) = \frac{c_d}{2} t_d^2 + C_d t_d + C_1$$

The constant of integration C1 is determined from knowing the user's angular position at the time td=0, which is the current orientation.

Once the final angular position is estimated, it will be compared to the three conditional statements made earlier, and upon the matched case the system will control the turntable. During turntable rotation the angular changes of the viewpoint within the virtual environment correspond to user's turning actions. The displayed image is kept synchronized with user movement while taking into consideration the effect of rotating turntable.

5. Visual feedback

Each time the system recognizes a user movement as a control action, the displayed image will be updated according to the expected action's effect. The displacement in the virtual environment is achieved by a linear translation of the viewpoint in the walking direction. In the current version the size of the displacement is fixed for all stepping action. For forward movement the user is displaced about 60 cm in the VE, which correspond approximately to the natural traveled distance during one step in the natural life. Fixing the virtual displacement for stepping actions may not correspond to user's desired walking paste, which is in contrast with real stepping in real life where users can control step size as well its frequency. Having such locomotive features give users a high level of adaptability to the terrain and to the nature of experience. For example, users could hurry in case of emergency, but walk slowly during shopping or promenade. The current version of the system does not for the present step size control and walking speed controls. Nonetheless the issue is being under study and will implement in the near future.

Despite the displacement actions, turning movement and its virtual effect were kept natural. Speed and accuracy of their turns in the VE corresponds to their real body turning. When a user makes a turn, the projected image will be scrolled by the same angle as the user turning. The angular change and velocity of the virtual turn is the same as the physical movement of the user, active turning and passive rotation combined. Adjusting the synchronization between users turning, passive turntable rotation, and the images scrolling provided a stable visual feedback without affecting users visual ability.

6. System Evaluation

To demonstrate the system ability to cancel users' turning, five graduate students tested a "Follow-Target" task in an outdoor virtual environment. Which represents a simple outdoor park with a flying virtual object in the space. The flying object has a spherical shape and continuously moving around a circular path. During the experiments, users were positioned at the center of the circular path and asked to keep their body oriented as much as possible toward the flying target, figure 14.

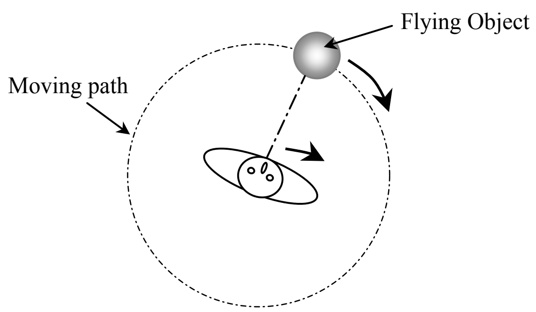

Figure 14: *User's task is to keep looking as much as possible to the rotating object*

To help the tracking task, users were provided with a graphical frame that represents their real orientation in the virtual environment. They were asked to superpose the center of the visual frame on the moving object; a captured image from the simulated environment is illustrated in figure 15.

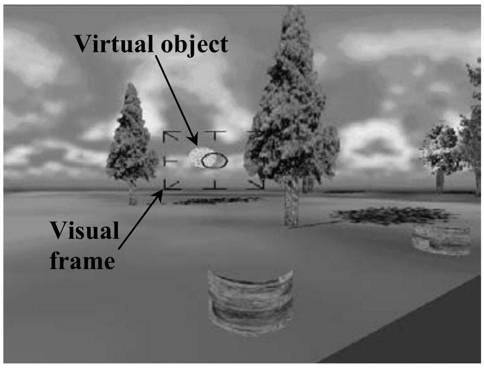

Figure 15: *Screenshot of the simulated environment*

At the beginning of each trial the flying object is at rest and located at the center of the screen. Once the user is ready, the object starts to move along the predefined circular path around the user with a slow speed that increased with time. Users were asked to keep their body oriented toward the flying object by rotating their body around its vertical axis and not moving only the head, because during all this experiment the markers were placed on the waist. For each trial the object was tracked until it reaches a certain speed from which users couldn't follow any more or the object disappears from the screen.

If the assumptions and algorithms presented earlier are correct users will be able to track the flying object for many full rotations without loosing its sight. The result of this experiment will give an idea about how good and how fast users can perform rotation with the system.

Figure 16-a and 16-b represent two data samples collected from the same user at the beginning of the trial and at its end. Both sampling were taken during a time period of 22 seconds each. From our observation to the different results, all five users were able to track accurately, in each trial, the flying object for many full rotations without loosing its sight, see figure 16-a. For many trials, tracking was tilted a bit during the first seconds then it became more stable. This behavior was the same for most users, which suggest a process of accommodation to the tracking task. To follow the moving object and keep it centered within the graphic frame, users continuously adjusted their turning actions in accordance with the flying speed. In return the turntable responded for every change possible. This fact is very clear from the graph representing the user's real orientation, where each deviation from the original orientation zero is followed by a counter-deviation. Since the passive rotation is carried smoothly and has usually a delay over active turning, users' orientation will gradually move a way from the center of the screen if a continuous turning with increasing speed is performed. At a flying speed near to 40o/s, all users were physically oriented toward a range between 15o to 25 o from the center of the screen. See figure 16-a.

However, it was observed in most trials that from a speed of 50 o/s, users' orientation tends faster to the limit of the screen. Theoretically, moving at any speed above 50o/s will result in an unrecoverable gap between the object's angular position and users' orientation. This fact is caused by the limitation of the turntable's speed, which is fixed at a maximum of 50o/s. A clear delay is shown in figure 12-b between user's orientation and object's angular position which will be placed out side the screen and disappear from a speed near to 70o/s. The flying speed of the object is manifested in the two graphs by the number of full rotation made during the same 22 seconds period of time. In figure 16-a the object made about 2.5 rotations whereas in figure 16-b it was twice faster, about 5 rotations.

Although the system was tested on an extreme situation where the user is continuously turning with an increasing speed. We think that the interface could keep user fairly oriented toward the screen under natural or normal circumstances where turns are generally short and limited in time. However, based on the limitations shown in this experiment, users are adviced beforehand about the effect of fast speed and required to perform moderate actions.

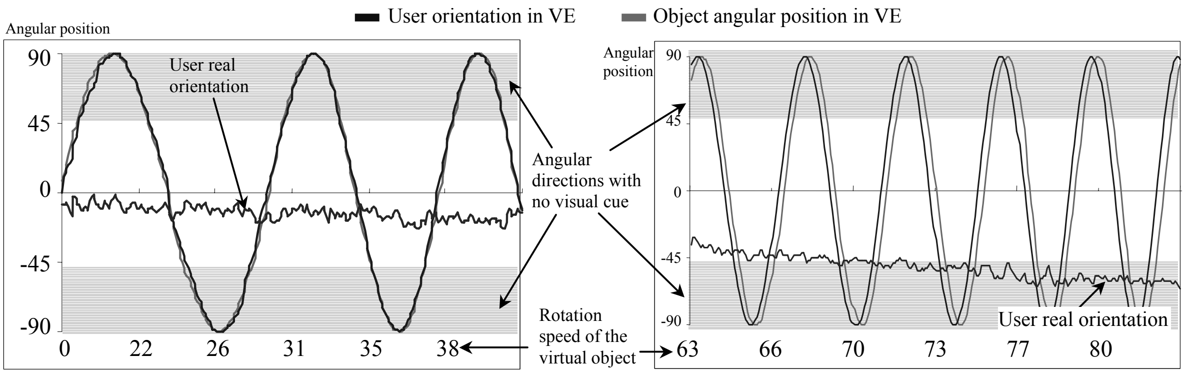

Figure 16-a: User's orientation in the VE is similar to object's angular position. Despite full rotations in VE user's real orientation is kept toward the display

Figure 16-b: the rotation speed of the object become too fast for the system to keep user oriented toward the screen. At a speed of 70^{o}/s the object is out of sight.

Nonetheless, we believe that the performance of the system could be better if a larger visual field of view is provided. In the experimental set up, users were provided with 2.3m x 2.5m screen allowing about 96o of horizontal field of view. It was shown that a rotation of about 45o/s was effectively canceled.

7. Applications and Comparisons

The turntable interface was integrated and tested in an environment that demands active locomotion system and which requires a life-like turning actions to control the moving direction. The experimental setup is shown in figure 17, and the simulated environment is shown in figure 18. It is a simple road that has two wide corners that needs large turning actions. To keep the walking path within the road, users were instructed beforehand to maintain as much as possible their traveling at the center. To compare the navigational performance of the turntable system with other usual and common interfaces, we provided users with a joystick interface to execute the same task. The result will be used to compare both step-in-place and joystick navigational control abilities. The joystick interface was chosen because of its popularity and also it has an accurate control over position. It is widely used in remote control manipulations, robot arm control and other operations that need accurate positioning. Its advantage in comparison to other navigational interfaces is that it has a very stable response and performance (exact and immediate) to user's commands.

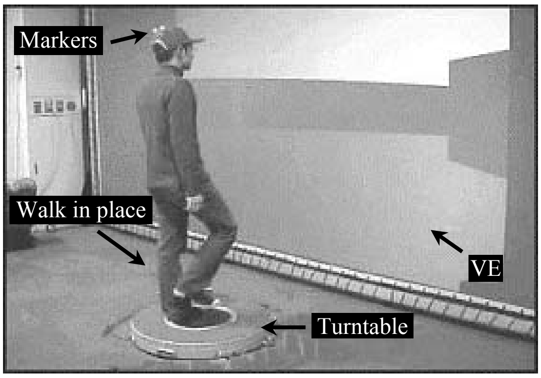

Figure 17: *Overview of the experimental set up*

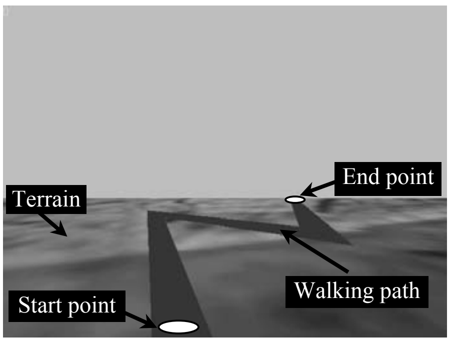

Figure 18: *experimental walkthrough environment*

Before the experimental trials five graduate students were allowed to walk along the road by means of the Joystick and the step-in-place interfaces to get accustomed to both modes. During the experiment each user repeated the walking experience twice, once with the step-in-place interface and once with the joystick interface.

Data collected from both interfaces are presented in figure 19. It shows the traced paths for three trials only performed by different users. One used the joystick and two others used the step-in-place interface. The other trials are omitted for better clarity of the graph. As the figure shows, it seems that the walked paths during the step-in-place mode and the Joystick mode didn't differ too much in term of navigation and reaching the goal. All users were able to maintain a close position to the center of the road with both interfaces. With Joystick mode, the average deviation from the center of the path was about zero during straight walk and about 30cm during turns. Note that the start point for each trial was placed at the center of the road. Whereas with the step-in-place mode the deviation from the center was greater with an average of 40cm during straight walk and an average of 80cm during turns. Actually, it was expected for the straight walk that the joystick would perform perfectly in comparison to the step-place mode.

Taking into consideration the accuracy of joystick manipulation we judge the results as quite acceptable. Users were able to maintain accurate turns and did not have trouble of controlling their locomotion, which if happened could result in a wide deviation from the center. It is also remarkable to note that most of the users appreciated the active locomotion saying that they had a better feeling of navigation and did not thought as manipulating a device while stepping.

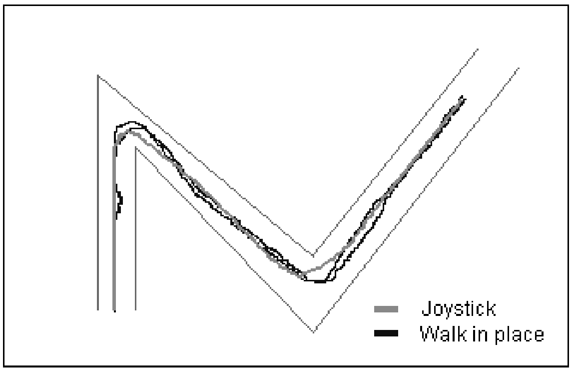

Figure 19: *Joystick and locomotion walkthrough path*

8. Conclusion

The proposed locomotion interface provided a consistent means of taking virtual steps in any direction within VEs and is compatible with wide range of natural actions. The Locomotion is initiated and sustained by the lower part of the body as in real life. Virtual displacement is achieved by stepping-in-place, whereas a natural turning about the vertical axis of the body controls virtual turning. Such physical based and life-like actions allow users to keep their natural reflexes and navigational skills to move around VE. The novelty of the present work is the use of a smart-turntable with embedded sensor as a walking platform, which is able to passively cancel user's turning action. The three distinguishing advantages of such technique are: 1) the use of turntable technique as walking platform to cancel turning rather than displacement 2) allow virtual surrounding projection with a single large screen. Users can make full turns in the VE without loosing sight of the projected image. 3) Finally, The system demands no wired attachment to the user's body.

The developed system is shown to be easy to use, intuitive and compact in compare to other omni-direction platforms. However, the current system do not allow user to control their displacement speed, and step size. A current version under development will solve these problems and evaluate in the same time the level of perception regarding distance and spatial positioning.

References

1. Chance S.S., Gaunet F., Beall A.C., & Loomis J.M. (1998) Locomotion mode affects the updating of objects encountered during travel: the contribution of vestibular and proprioceptive inputs to path integration. Presence: teleoperators and virtual environments, 7 (2), 168-178.
2. Witmer B.G., Bailey J. H., Knerr B.W., & Parsons K.C. (1996) Virtual spaces and real world places: transfer of route knowledge. Int. J. of Human-computer studies, 45, 413-428.
3. Iwata H., & Yoshida Y. (1999) Path reproduction tests using a torus treadmill. Presence, Vol. 8, No 6, December 1999. pp:587-597
4. Darken R., Cockayne W., & Carmein D. (1997) The Omni-Directional treadmill: a locomotion device for virtual worlds. Proc. of UIST'97. pp:213-222
5. VR Sphere: http://www.ndirect.co.uk/~vr-systems/sphere1.htm
6. Noma H., & Miyasato T. (1998) Design for locomotion interface in a large-scale virtual environment. ATLAS: ATR Locomotion Interface for Active Self-Motion. DSC-vol.64, Proc. of the ASME Dynamic Systems and control division. Pp:111-118
7. Christensen R. R., Hollerbach J.M., Xu Y., & Meek S.G. (1998) Inertial force feedback for a locomotion interface. DSC-vol.64, Proc. of the ASME Dynamic Systems and control division. pp: 119-125
8. R.W. Soutas-Little, J.C. Otten, & A.J. Hull (1987) Use of computer aided design and analysis in gait and athletic footwear evaluation. ASME AMD, vol84, pp: 349-352
9. Iwata H., & Fuji T. (1996) Virtual perambulator: a novel interface device for locomotion in virtual environment. Proc. of IEEE VRAIS'96, pp: 60-65
10. Slater M., Usoh M., & Steed A. (1995) Taking steps: the influence of a walking technique on presence in virtual reality. ACM Trans. On conputer-Human Interaction, 2(3), pp: 201-219
11. Usoh M., Arthur K., Whitton M.C., Bastos R., Steed A, Slater M. and Brooks F.J. (1999) Walking>Walking-in-place>Flying, in virtual environments. SIGGRAPH'99 computer graphics proc., pp:359-364
12. Templeman J.N., Denbrook P.S., & Sibert L. E. (1999) Virtual Locomotion: walking in place through Virtual Environments. Presence: Vol. 8, No. 6, pp:598-617
13. Bowman D.A., Koller D., & Hodge L.F. (1997) Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques. Proc. of VRAIS'97, Albuquerque, New Mexico, 45-52.
14. Ware C., & Osborne S. (1990) Exploration and virtual camera control in virtual three-dimensional environments. Computer graphics 24(2), 175-125
15. Zhai S., & Milgram P. (1993) Human performance evaluation of isometric and elastic rate controllers in 6-DOF tracking task. Proc. of SPIE, technical conf. Of Telemanipulator and space telerobotics, 2057, 130-141.
16. Fukuda T. (1984) "The stepping test: two phases of the labyrinthine reflex". In: Statokinitic reflexes in equilibrium and movement. University of Tokyo press; Chap. 8, 110-12.
17. http://www.virtusphere.com/
18. Worshel P (1952) "the role of vestibular organs in spatial orientation" J. Esp Psychology. V44:: 4-10
19. Barlow JS (1964) "Inertial navigation as a basis for animal navigation" Theor Biol vol 6: 76-117
20. Portegal M (1982) " Vestibular and neostriatal contribution to spatial orientation: Portegal M edition Spatial abilities. Academic press, London, pp 361-387
21. Wiener S., Berthoz A)(1993) "Forbrain structures mediating the vestibular contribution during navigation" Berthoz A. Edition Mltisensory control of movement. Oxford University Press, Oxford, pp 427 – 455
22. Butterfield A. United States Patent 6,135,928. October 24th 2000
23. Noma H., Sugihara T., Miyasato T (2000) Development of ground simulator for Tel-E-Merge system. Virtual Reality 2000 conference. New Brunnswick, NJ, USA. pp: 217-224.