Walking About Virtual Environments on an Infinite Floor

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ABSTRACT

This paper presents a new configuration of locomotion interface for walking about virtual space. Traveling on foot is the most intuitive way for locomotion. Infinite surface driven by actuators is an ideal device for creation of sense of walking. We selected a torus-shaped surface to realize the locomotion interface. The locomotion interface employs twelve sets of treadmills. These treadmills are connected side by side and driven to perpendicular direction. Infinite surface is generated by the motion of the treadmills. The walker can go to any direction while his/her position is fixed in the real world. Effectiveness of the device is tested by motion analysis and study on sense of distance.

Keyword : locomotion, walking, navigation, haptic feedback

1. Introduction

Locomotion in virtual environments is one of the major problems in current virtual reality research. The most intuitive way to move about the real world is traveling on foot. People often feel that sense of distance or direction while walking is much better than that while riding on a vehicle. This paper aims at development of a locomotion device which provides sense of walking.

A possible method for locomotion in virtual space is a hand controller. In terms of natural interaction, exertion of walking is essential to locomotion. The primary object of our research is the presentation of a sense of walking while the position of the walker is fixed in the physical world. We have developed several prototypes of interface device for walking. From the results of the research, we found that infinite surface is an ideal device for creation of sense of walking. We selected a torus-shaped surface to realize the locomotion interface. The surface is implemented by twelve sets of treadmills. These treadmills are connected side by side and driven to perpendicular direction. Infinite surface is generated by these treadmills. We call the device "Torus Treadmill."

The motion of the feet is measured by magnetic sensors. The floor moves to opposite direction of the walker corresponding with the result of measurement, so that motion of the step is canceled. Position of the walker is fixed in the real world by this computer controlled motion of the floor. The walker can freely change the direction of walking. An image of the virtual space is displayed in the head-mounted display corresponding with the motion of the walker.

We tested effectiveness of the device. Firstly, forces of the walker's feet against the floor is recorded and compared to those in the real world. Secondary, sense of distance is examined quantitatively in a virtual test course.

2. Previous works on interface devices for locomotion in virtual space

2-1. Treadmill

A simple device for virtual walking is a treadmill, ordinary used for physical fitness. Application of this device to virtual building simulator was developed at UNC[1]. Their treadmill has a steering bar which is similar to that of bicycle. Walkers change direction by controlling the steering bar. Similar treadmill is used at University of Tokyo[2] . The Treadport developed at University of Utah is a treadmill that is combined with a large manipulator connected to a walker[3]. The manipulator provides inertial force to the walker.

2-2. Pedaling device

In the battlefield simulator of NPSNET project, unicycle-like pedaling device is used for locomotion in the virtual battlefield[4]. A Player of the system changes direction by twisting his/her waist.

The OSIRIS, simulator of night-vision battle, utilizes a stair stepper device[5]. A player of the system changes direction by controlling joystick or twisting the waist.

2-3. Gesture recognition of walking

Slaters et al. proposed locomotion in virtual environment by "walks in place." They recognized the gesture of walking using a position sensor and a neural network[6].

2-4. Large manipulators

Two large manipulators driven by hydraulic actuators are developed at University of Utah and applied to a locomotion interface. These manipulators are attached to feet of a walker. The device is named I-Port. The manipulators can present viscosity of virtual ground.

2-5.Omni-directional Treadmill

Omni-directional Treadmill employs two perpendicular treadmills, one inside of the other. Each belt is made from approximately 3400 separate rollers, woven together into mechanical fabric. Motion of the lower belt is transmitted by the rollers to a walker. This mechanism enables omni-directional walking[7].

3. Virtual Perambulator project

We have developed prototypes of locomotion interface for virtual environments since 1989. The primary object of the first stage was changing direction by walker's feet. Controlling steering bar or joysticks is not intuitive in locomotion. We developed the first prototype in 1989[8]. A user of the system wore parachute-like harness and omni-directional roller skate. The trunk of the walker is fixed to the framework of the system by the harness. Omni-directional sliding device is used for changing direction by feet. We developed specialized roller skate equipped with four casters which enables two dimensional motion. The walker could freely move his/her feet to any direction. Motion of the feet was measured by ultrasonic range detector. From the result of measurement, image of the virtual space was displayed in the head-mounted display corresponding with the motion of the walker. Direction of locomotion in virtual space was determined according to the direction of the walker's step. We also tried presentation of virtual staircase by pulling the feet by strings[9].

The walkers of the first prototype, however, felt uncomfortable by pressure of the parachute-like harness. We therefor replaced the harness with a belt around the waist[10]. We put brake pad at the tow of the roller skate, by which stability of the walker was increased. While the walker steps forward, the break pad generals friction force at the backward foot.

Our former system has two major problems: (1)waist belt restricted up-down and turn around motion of the walker's body, and (2)weight and height of the roller skate spoilt natural motion. In order to over come those problems, we developed a new frame and sliding device[11]. A hoop was set around the walker's waist in which he/she can physically walk and turn about. Diameter of the hoop was 60 cm. The walker can freely change the direction of walking. Novice users of the system can hold the hoop so that they can easily keep the balance of their bodies. Trained users of the system can push their waists against the hoop and they can walk fast or can even run. Since we don't use any harness, walker's body has no restriction. We developed a new sliding device using rubber sandal in stead of steel roller skate. Low friction film is put at the middle of the sole. Rubber sole at the toe played a roll of brake pad. Material of the floor sheet was selected in accordance with the low friction film and brake pad. Figure 1 illustrates final version of the Virtual Perambulator. We demonstrated it at the Interactive Communities venue in SIGGRAPH'95. During five-days conference, 235 people experienced the device. We observed behavior of the walkers and 94% of them succeeded in rhythmical walking.

The Virtual Perambulator with a hoop and sliding sandals achieved the first objective; the walker can change direction freely. However, one problem was left. Walkers had to slide the feet by themselves. In other words, the device was passive. Walkers had to get use to the sliding action. We therefor aim to develop an active device which moves corresponding with motion of the walker.

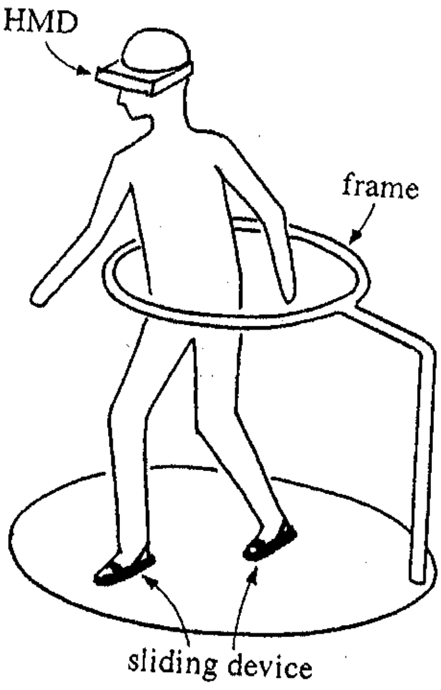

Figure1. Virtual Perambulator

4. Locomotion interface using infinite surface

A key principle of active locomotion interface is to make the floor move in a direction opposite to the direction of the walker. The motion of the floor cancels displacement of the walker in the real world. Such an active floor needs infinite area. We must decide geometrical configuration of an active floor in order to realize an infinite walking area. A closed surface driven by actuators has an ability to create an unlimited floor. We must consider following requirements for implementation of the closed surface:

1) A walker and actuators must be put outside of the surface.
2) walking area must be a plain surface.
3) Material of the surface must not be stretchable.

Shape of closed surface, in general, is a doughnut with holes(Figure 2). If the number of holes is zero, the surface is a sphere. The sphere is the simplest infinite surface. However, the walking area of the sphere is not a plain surface. A very large diameter is required to make plain surface on a sphere, which restricts implementation of the locomotion interface.

A closed surface with one hole is called torus. A torus can be implemented by a group of belts(Figure 3). These belts makes plain area for walking. A closed surface with more than two holes cannot make plain walking area. Thus, the torus is the only shape which is suitable for a locomotion interface.

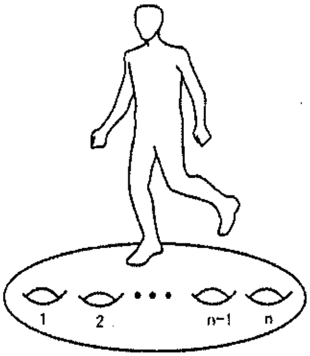

Figure 2. closed surface

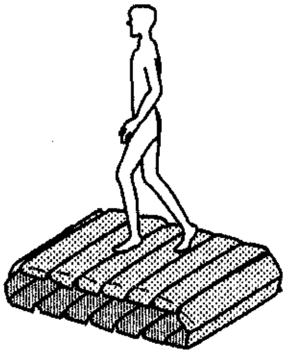

Figure 3. torus composed by a group of belts

5. Torus Treadmill

A locomotion device using torus is implemented by a group of belts connected to each other. The Torus Treadmill is realized by these belts. Figure 4 and 5 illustrates mechanical configuration of the Torus Treadmill. Figure 6 shows overall view of the apparatus. The Torus Treadmill employs twelve treadmills and each treadmill is driven by an AC motor. Those treadmills move the walker along the X direction. Power of each motor is 80W and controlled by an inverter. The maximum speed of each treadmill is 1.2m/s.

Twelve treadmills are mounted on two endless rails and actuated by four chains. The rails and chains move the walker along the Y direction. An AC motor is employed to drive the chains. Power of the motor is 200W and the maximum speed is 1.2m/s. Width of each belt is 250mm and overall walkable area is 1m x 1m.

A problem of this mechanical configuration is the gap between the belts at the walking area. In order to minimize the gap , we put a driver unit of each treadmill alternatively. The gap is only 2mm by this mechanism. Figure 7 shows the driver unit of treadmills.

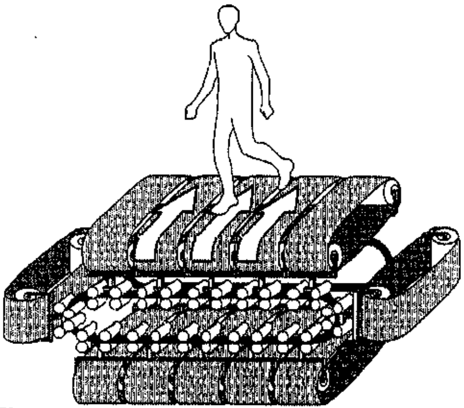

Figure 4. Torus Treadmill (X motion)

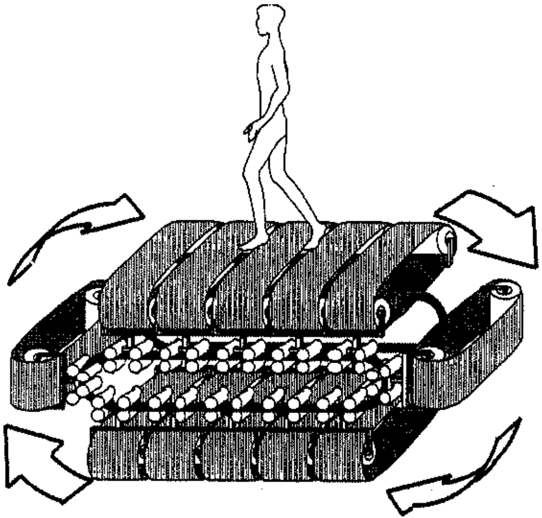

Figure 5. Torus Treadmill (Y motion)

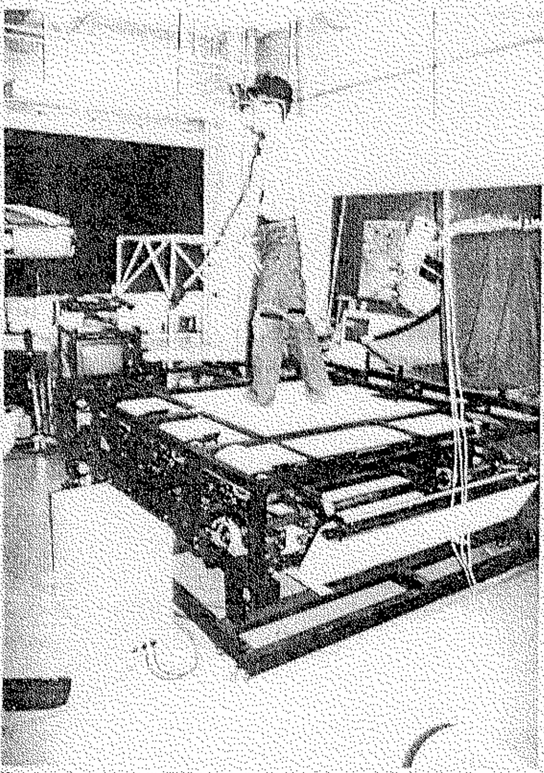

Figure 6. overall view of the Torus Treadmill

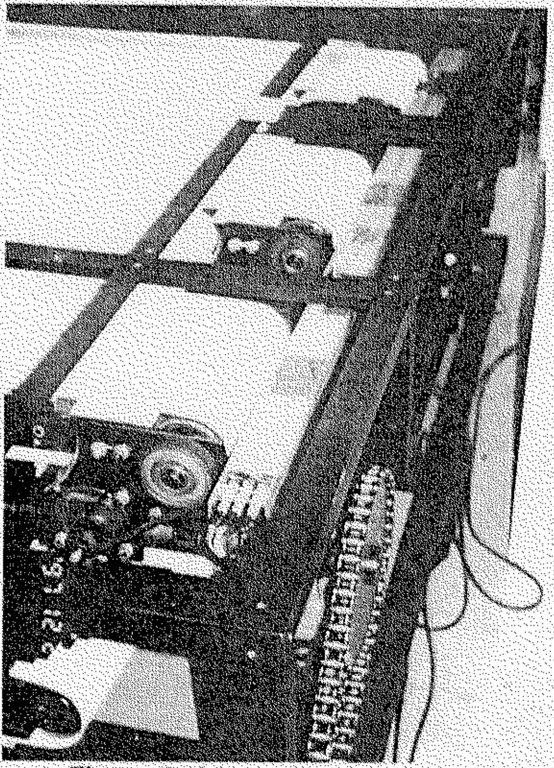

Figure 7. driver unit of treadmill

6. System configuration

The overall system of the Torus Treadmill employs two computers: a graphics computer for a real-time image of virtual space and an I/O computer which supervises motors and sensors. These computers are connected by serial (RS-232C) communication line.

6-1. Graphic computer and display

Real-time image of the virtual space is generated by a Silicon Graphics workstation. We use SGI Indigo2 with MAXIMPACT graphics engine. The CPU of the workstation is R4400, which manages model of virtual space. The image on the CRT of the workstation is converted to NTSC standard video signal, and sent to the HMD. We set two windows on the CRT and each image is taken by a video camera. We currently use a Glasstron (made by SONY) HMD. The liquid crystal display has 180,000 pixels. The horizontal field of view is 30 degrees.

6-2. I/O computer and sensors

The I/O computer supervises the Polhemus sensors and motor drivers for the Torus Treadmill. The I/O computer is a PC with Pentium II 300MHz. We use magnetic sensor(Polhemus FASTRAK) for body tracker for the walker. Polhemus sensor is connected to RS232C port of the PC. The motor driver unit is also connected to RS232C port of the PC.

6-3. Motion tracker

A scene of the virtual space is generated corresponding with the results of motion tracking of the feet and head. The motion of the feet and head is measured by Polhemus FASTRACK. The device measures 6 degree-of-freedom motion. Sampling rate of each point is 20Hz. Two receivers are set at the knees. We cannot put the sensors near the motion floor because a steel frame distorts magnetic field. The length and direction of a step is calculated by the data from those sensors. View point in virtual space moves corresponding with the length and direction of the steps. Overall update rate of the system is 15Hz. Major duration is caused by data transmission from Polhemus sensors to host workstation.

7. Control algorithm

In order to keep the position of the walker at the center of the walking area, the Torus Treadmill must be driven corresponding with the walker. The control algorithm is required to achieve safe and natural walking. From our experience in the Virtual Perambulator project, the walker must not be connected to harness or mechanical linkages. Those devices restrict motion of the walker and spoilt natural walking. Control algorithm of the Torus Treadmill must be safe enough to remove the harness from the walker. At the final stage of the Virtual Perambulator Project, we succeeded in removing the harness using a hoop frame. The walker can freely walk and turn about in the hoop. The hoop supports the walker's body while he/she slides the feet. We introduced the function of the hoop into control algorithm of the Torus Treadmill. We put circular insensitive area at the center of the walking area. If the walker goes out from the area, the floor moves in the opposite direction so that the walker is carried back into the insensitive area.

Figure 8 illustrates basic idea of the control algorithm. Position of the walker is measured by two Polhemus sensors put on the knees. The middle point of these sensors can be assumed to be a central point of the body. Point G represents central position of the walker. We put insensitive area at the center of the walking area. The floor does not move while point G is inside the insensitive area. If point G goes out form the insensitive area , the floor moves so that point G goes back to this area. The insensitive area is a circle whose diameter is 20cm. Distance between point G and the circle determines motor power. Motor power increases in proportion to the displacement of point G from the insensitive area. The active floor performs as a virtual spring which pulls the walker back to the center of the walking area. This control algorithm enables the walker to smooth acceleration and deceleration.

The insensitive area removes chattering of the Torus Treadmill. The floor does not move while the walker is turning about at the center of the walking area.

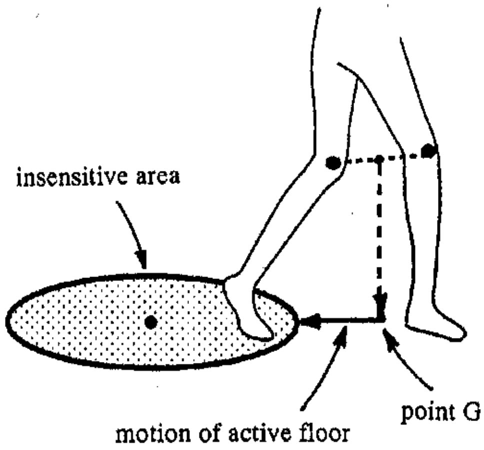

Figure 8. method of floor motion

8. Performance evaluation

8-1 Behavior of first-time users

Active area of the current prototype of the Torus Treadmill is 1m X 1m, by which width of the step of the walker is limited to 30cm. Actual speed of treadmills is 1.2m/s. Those mechanical limitations oblige the walker to walk slower than natural walking. First-time users of the system are told about this limitation before they experience it.

We accepted 58 visitors in my laboratory. None of them wore safety harness. They didn't suffer from unstableness while walking or changing direction. Nine people tried sidestep and backward walking spontaneously. The control algorithm supports arbitrary orientation of the body so that the walker is carried back to the insensitive area while he/she is sidestepping or backward walking.

8-2. Motion analysis

We recorded motion of the walker to examine effectiveness of the Torus Treadmill. Three Polhemus sensors are put on the walker: one at the waist and two at the knees. We observed motion of the knees while walking. The best position of the sensor is a foot. However, we cannot put the sensor at that position because of distortion of the magnetic field caused by the steel frame of the Torus Treadmill.

We compared trajectories of the knee position of the walker on the Torus Treadmill and on the real ground. The subjects are tolled to walk on the Torus Treadmill same speed as on the real ground. Figure 9 shows the result of the experiment. Vertical axis of Figure 9 indicates horizontal displacement of the knee position from the waist position. The result indicates that trajectory of the Torus Treadmill is close to that of the real ground. The control algorithm as mentioned in previous section is successful in creating natural walking.

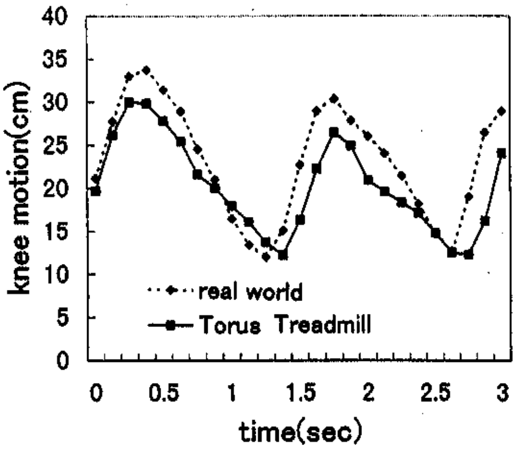

Figure 9. trajectory of knee motion

8-3. Pressure of the sole

We also measured pressure of the sole of the walker for evaluation of naturalness of walking. Two force sensors are put underneath the sole of the walker: one is at the toe and the other is at the heel. Each sensor is composed of straingauge and diaphragm. Sensing range of the sensor is 0 ~ 20 Kg/cm2 and Inearlity is 1%. Figure 10 shows result of measurement on the real ground. Peek of each curve indicates the time when the walker lays the weight on the foot. Figure 11 shows result of measurement on the Torus Treadmill. Those results shows that transition of the weight on the Torus Treadmill is close to that on the real ground.

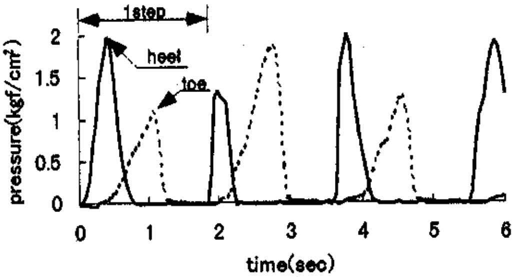

Figure 10. pressure of the sole (real ground)

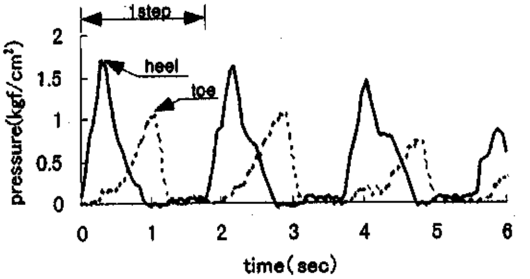

Figure 11. pressure of the sole (Torus Treadmill)

9. Application of the Torus Treadmill to distance estimation

A psychological experiment was conducted to investigate human sense of distance. Quantitative study on human spatial recognition performance in the real word is very difficult because scene of the real world contains various information. Computer-generated virtual space is indispensable to create a controlled experimental environment. Witmer and Kline used a conventional treadmill for traversed distance estimation in virtual spaces[12]. In 1992, we utilized our early version of Virtual Perambulator to study sense of distance[10]. In order to examine effectiveness of exertion of walking in virtual spaces, we set similar virtual test space using the Torus Treadmill.

(1) Method

The test course of the experiment is a straight path as shown in Figure 12A. The scene of the test space provided to the subjects are plain wall and floor as well as a flag. Subjects are asked to walk along the path from the starting area to the flag watching the CG image by HMD. The width of the path and the height of the walls are 3m. The starting area is 5m deep and the depth of this area is tolled to the subjects. As subjects moved along the course, they memorize distance between the starting line and the flag. After they finished walking, they are asked to plot the position of the flag on a data sheet on which the walls and starting area are marked. Figure 12B shows an example of a data sheet. We prepared seven estimated distances: 10,15,20,25,30,35 and 40m. These distances are randomly displayed to the subjects. The subjects of the experiments are 7 university students(6 males, 1 female). They voluntary participated in the experiment.

In order to examine the effect of exertion of walking, following two conditions are set for the experiments:

1) Traveling by walking
2) Traveling by joystick

Direction of flight is determined by the left/right input, and speed is determined by back/forward input.

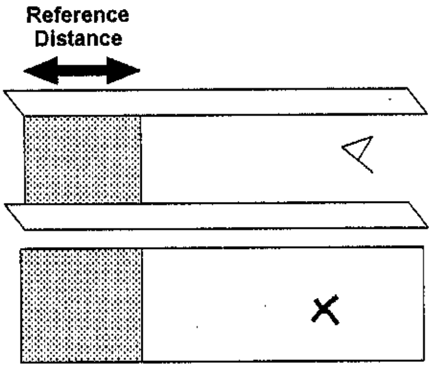

Figure 12. test course and data sheet

(2) Results

The relationship between physical distance and estimated distance is shown in Figure 13. In this case, physical distance is a distance between the starting line and the flag in the virtual test course. Estimated distance is evaluated from the data sheet. Error bars on the curves indicate standard deviation of estimated distance. The result shows that the subjects underestimate distances. Comparing two conditions, estimated distances by joystick are lower than those by walking. Ratio of estimated distance and physical distance of walking is 0.821, on the other hand, that of joystick is 0.751. Difference of these values is significant by T-test($t=3.16 > 2.00$; $p<0.05$). The result indicates that exertion of walking improves sense of distance.

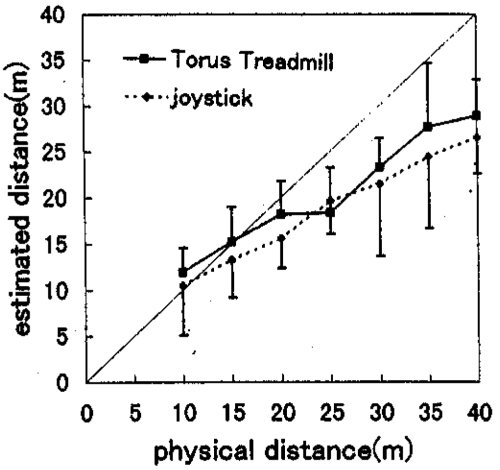

Figure 13. result of distance estimation

10. Discussion

Limitation of the current system is caused by the size of walking area. Walkers of the system must be careful of the edge of active floor and cannot step widely. In case the walker moves faster, the active floor must cover wider step. Overall size of the device is 2m x 1.8m, which is determined by the width of the entrance of our laboratory. Walking area can be easily extended by using a longer belt and more treadmill units.

If the Torus Treadmill allows the user to run fast, we will have to treat with a new control problem. In case the walker changes direction while he/she is running fast or accelerating, misaligning of forward and centering vectors will occur[7]. Figure 14A illustrates misaligning angle of forward and centering vectors. The misaligning causes unstableness of the walker. We can treat this problem with washback technique which is typically used in flight/driving simulators. The motion platform of a simulator presents initial acceleration, then slowly returns to the original position at an imperceptible speed. Figure 14B illustrates the washback technique applied to the Torus Treadmill. At the moment the walker changes direction, centering vector is set at the same direction as forward vector. The centering vector makes offset from the center of the walking area. After the walker finished changing direction, the offset is slowly recovered at an imperceptible speed.

In case the walker's acceleration is large, the walker should feel inertial force caused by the acceleration. The inertial force caused is also presented by similar technique as used in flight/driving simulators. Inertial force can be generated inclination of the floor. A part of gravitational force is applied to the walker's body as inertial force while the floor is inclined. Inclination of the floor can be realized by combining motion platform under the Torus Treadmill.

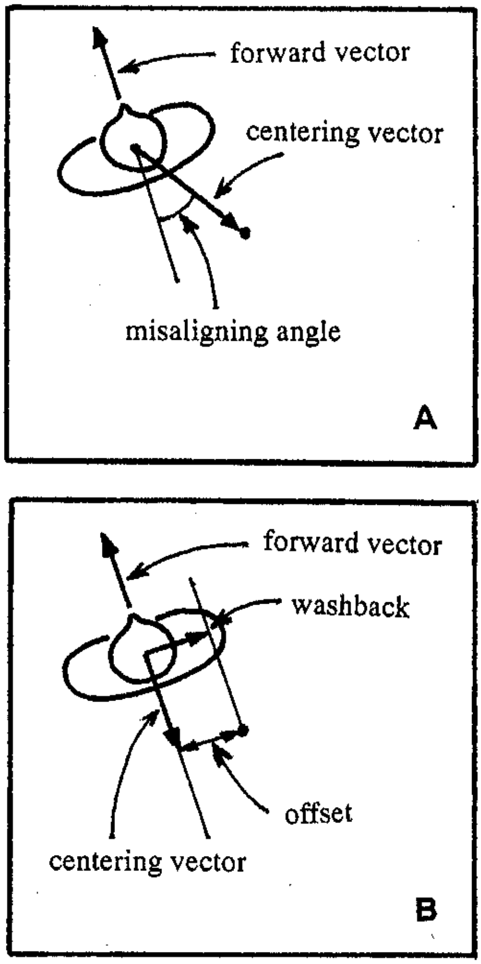

Figure 14. misaligning angle and washback technique

Compared to other locomotion devices, the T Treadmill has advantages. Omni-directional Treac provides similar function as the Torus Tread However, small cylinders woven is the belts gene severe noise and bite the body of the walker when he crawls on the surface. The Torus Treadmill is free these troubles.

Further more, mechanical configuration of T Treadmill has potential to present uneven surface suc staircase. Uneven surface can be generated by repla belts of treadmills to array of linear actuators. Figur illustrates modified Torus Treadmill which is equip with linear actuator array driven by a treadmill. In 1 we tried presentation of virtual staircase by pulling roller skates by strings. It was not successful becaus lack of stability. The actuator array as shown in Figur will be free from such stability problem.

Large manipulators which carry a walker can pre uneven surface. However, the device restricts the b of the walker, especially he/she cannot turn about.

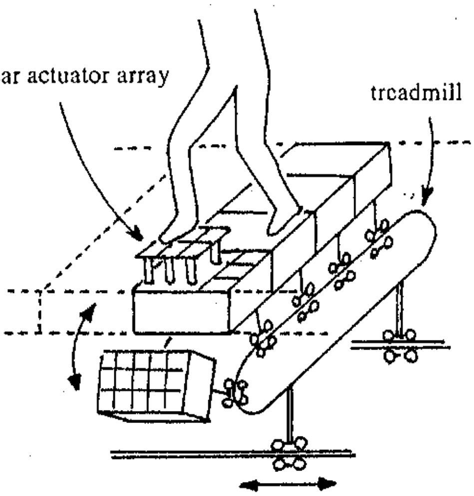

Figure 15. presentation of uneven surface

11. Practical application of the Torus Treadmill

The Torus Treadmill provides natural locomotion and it will be applied to various walkthrough simulation. As a serious application of our locomotion interface, we are working with the Ship Research Laboratory to develop an "evacuation simulator[12]." The Ship Research Laboratory is a national research institute which belongs to the ministry of transportation of Japan. Analysis of evacuation of passengers during maritime accidents is very important for ship safety. However, it id impossible to carry out experiments with human subjects during actual disaster. Therefor they introduced virtual reality tools for simulation of disaster in order to analyze evacuation of passengers. They b built a virtual ship that includes smoke generator and inclination of the vessel. Currently, Virtual Perambulator is applied to the virtual ship. A motion platform is combined to the Virtual Perambulator so that inclination of the floor is presented. Experiments of evacuation are carried out for construction of mathematical model of passenger's behavior in disaster. The Torus Treadmill will be effective in such experiments.

12. Conclusion

This paper has shown our current works on an interface device for locomotion in virtual spaces. A Torus-shaped treadmill is developed and a control algorithm is implemented. Stability of the device succeeded in removing safety harness from walkers. Usability tests proves that the device enables natural walking. Quantitative experiment showed that exertion of walking enhances human sense of distance. Although the current system needs improvement in its performance, the Torus Treadmill is an ideal configuration for a locomotion interface.

Locomotion by walking motion is intuitive and is inevitable in study on human behavior in virtual environments. We are applying the system to research on human model of evacuation in maritime accidents. Future work will involve finding more application of the Torus Treadmill in which exertion of walking is indispensable.

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