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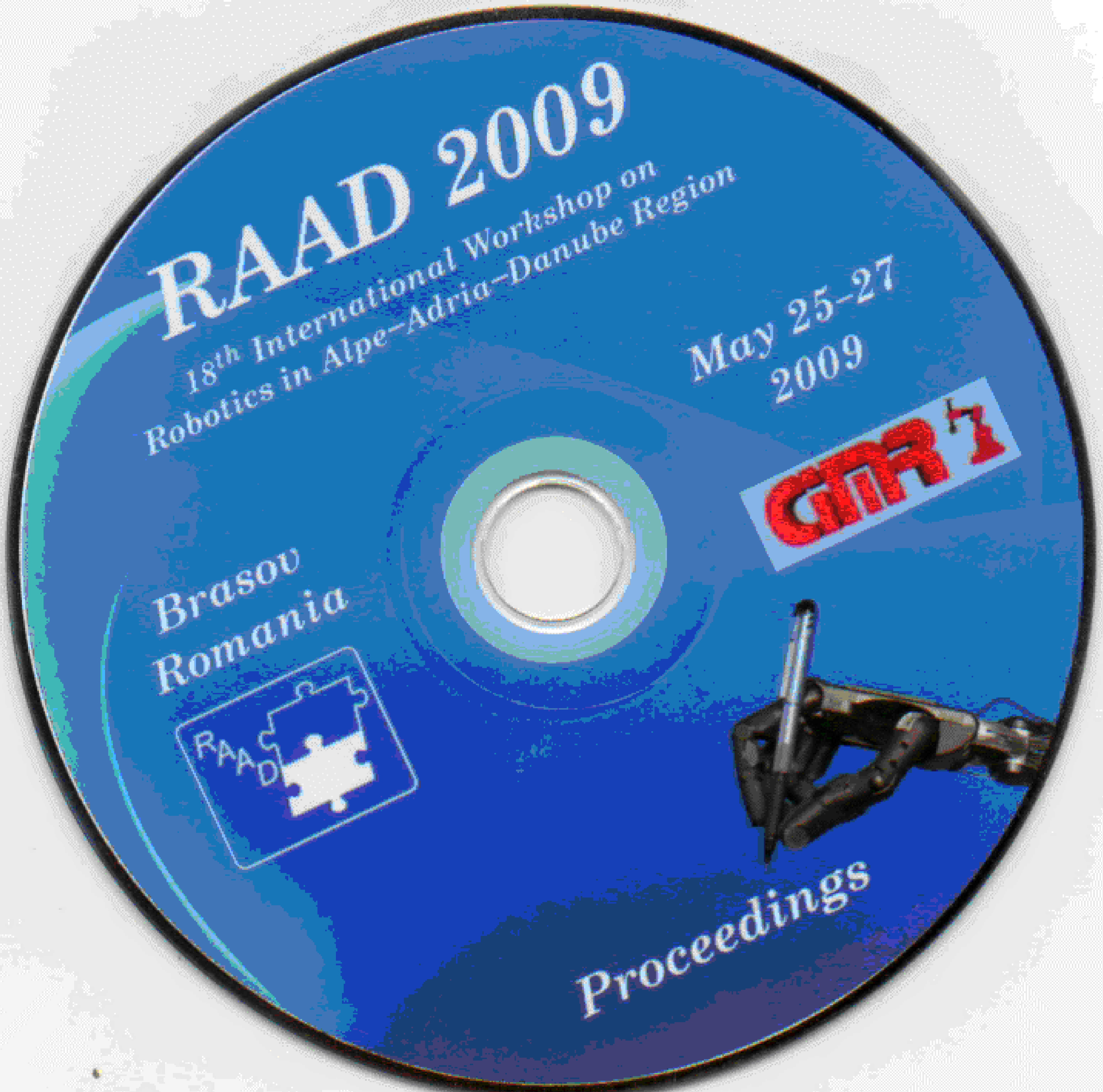

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Proceedings of the RAAD 2009
18th International Workshop on Robotics in Alpe-Adria-Danube Region
May 25-27, 2009, Brasov, Romania

A Treadmill Approach for the Human Walking Simulation in a Virtual Environment

Adrian Stavăr[a], Marius Carp[b], Mădălina Dascălu[a] and Doru Talabă[a]

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Abstract. The present paper presents an approach for virtual walking system in immersive environments based on an innovative treadmill solution. A survey of the virtual walking systems for immersive environments followed by the formulation of our research goals is also presented. Different methods and systems for walking in virtual environments are discussed and the main principles of virtual walking systems are identified and classified. Advantages and disadvantages for the various principles identified are presented and then comparatively our approach is presented, as well as future ways of development.

Keywords. Virtual Environment, Treadmill, Omni-directional, Holonomic, Immersion Sensation

1. Introduction

The purpose of this paper is to present a novel approach for walking-like-navigation in virtual environments based on a robotic system with two DOF's. First we summarize the existing projects in the virtual walking in immersive environments domain, to observe and to analyze different characteristics of the applications developed so far and then our system and approach is presented in this respect.

The paper is organized into five parts. The introduction part shortly describes the article content. In the second part which is a state of the art in virtual locomotion devices, we summarize the solutions of the most important existing devices. We divided this chapter into two parts depending on the period of time in which the projects were developed and presented to the scientific and public environment. The chapter is concluded with a short analyze of the present devices drawbacks. In the third chapter we described our system's goal indicating the main features that a product must have for Virtual reality Applications. In the second and third part of the chapter we presented our actual work and we sketched future progress and development directions. Short conclusions about the research in this domain, our work and references are presented at the end.

2. State of the Art

In the recent years various Virtual Reality techniques have been developed with implications in different areas of interest. One of the most important issues with technical solutions currently just in their early stages is that of a device capable to permit a user to walk unrestricted into a virtual environment. If this shall be achieved there shall be many domains of applications known or undeveloped yet that will imply using this technique of navigation. Some of the actual domains that would benefit from such technology are computer games, computer graphics, environment simulators, military simulators and others.

2.1. Previous work

From a literature survey that we performed, we identified three technical solutions of interest for virtual walking purpose, shortly introduced here below.

The first device is called *Omni-direction Ball-bearing Disc Platform* (OBDP) (Huang et al., 2000), Fig. 1.

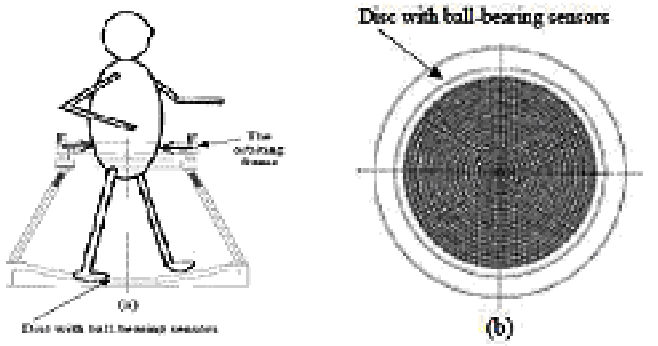

Fig. 1. The OBDP device
(a) side view; (b) the surface of the OBDP

The OBDP device is unique compared with other devices because no motor is used and practically it is a passive design. It has significant features like two-dimensional walking, absence of tracking devices and a safety support element. The main element of the platform is represented by the ball-bearing disc locomotion device which has a double role: to support omni-directional walking as well as to detect user's movement. The concave shape of the disc including nineteen concentric circles provided with 975 steel balls and position sensors, permit's user to walk in any direction and to slip back in the centre of the disc after every step is made. An orbiting frame around user's waist has the role to support and equilibrate user when walking by applying a constrain force to keep him in centre of the disc. A suggestive image is presented in Fig. 1 (a).

Martin Schwaiger's (Schwaiger et al., 2006), *A foot following locomotion device with force feedback capabilities* is a seven DOF device that allows free movement of the user in any direction without restrictions. The system differs from the existing 2D foot followers by added new rotational degrees of freedom. It can provide uncommon movement situations including 90 degree turns and sidesteps because of its seven DOF capabilities. There are three DOF on each step and one rotational DOF on device, as presented in Fig. 2.

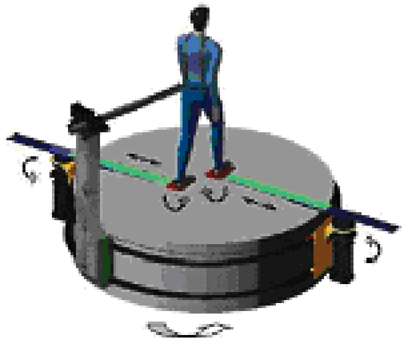

Fig. 2. The foot locomotion device

The system includes the following components: two telescopic arms provided with footpads, a carriage mounting system and a rotational system. Together these systems assure a complex walking pattern as shown in Fig. 3. diagram.

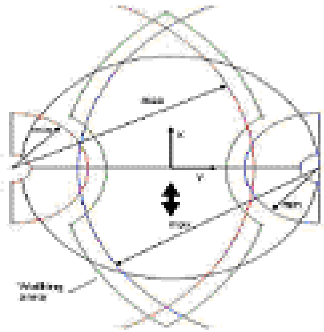

Fig. 3. Rhomboid shaped walking diagram

The figure presents the movement pattern of left (red) and right (blue) arms which describes two circular ranges of operation. A linear walking implies the use of telescopic arms (green), footpads (red) and the carriage mounting system (blue) represented in Fig. 2. Rotational walking (90 degrees turns and side movement) adds movement of the rotational system (yellow).

The *Walk simulation apparatus for exercise and virtual reality* invented by Julian David Williams (Williams et al., 2008), Fig. 4, is a concave platform on which the user steps using special footwear designed to assure minimum friction. Like the OBDP device this is a passive system too, using no motor powered elements. Movement is permitted in any direction, at any speed, including even jumping. Changing direction is done by letting the front foot slide in the new direction while the back foot follows. The platform can be made out of special material offering extra grip. Another way to enable locomotion is by using special footwear like roller-skates which decrease friction. Tracking is made by use of special VR glasses and sensors mounted either on the user or inside the platform.

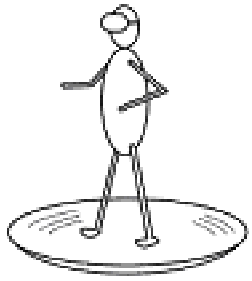

Fig.4. Walk and run simulation device

2.2. Recent inventions

The String Walker project (Iwata et al., 2007) (http://intron.kz.tsukuba.ac.jp/stringwalker/stringwalker.html) involves a pair of shoes actuated by motor-pulley mechanisms, Fig.5. These actions take place on a motor controlled, 1800mm in diameter, turntable that involves omni-directional locomotion.

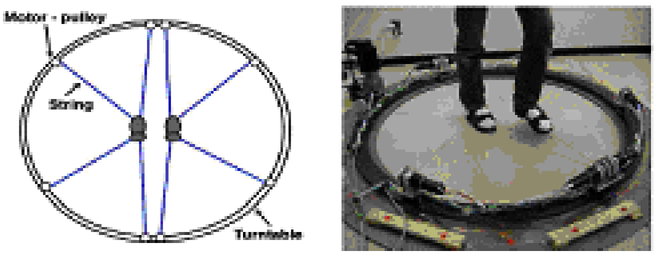

Fig. 5. The String Walker device
(a) basic structure; (b) overall view

Each shoe is connected to the motor mechanisms using four independent strings. The motor-pulley mechanism has a double role: to actuate the strings and to measure position and orientation of the shoe. There are also touch sensors in every shoe that detect the stance and swing phase of walking. This device provides six plus one DOF including three independent DOF's for each foot given by the motor pulled strings, and the turntable – the seventh DOF. Fig. 5. (a).

The working principle is quite simple. User's position in virtual space is permanently adjusted by the feet tracking system. There is a circular area placed in the centre of the turntable called dead zone in which the G point of the person must be kept. Every adjustment of the user's walking direction is made accordingly with this zone by pulling the user's feet back in this area.

Another interesting approach regarding walking into virtual environment is *CyberWalk* project (Robuffo Giordano et al., 2008) (http://www.cyberwalk-project.org/), Fig. 6. It is an EU project that involves locomotion using an omni-directional treadmill along with a marker less tracking, optimised control and some other techniques that allow a user to walk in VR in a free fashion. The platform is made out of several belts which form an infinite plane along XY axes, Fig. 6 (a).

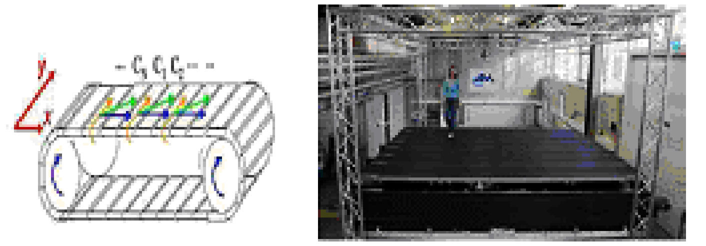

Fig. 6. The CyberWalk device

In fact there are 25 conventional treadmills pulled on the X axis. The whole system is driven on the Y axis, by a drive chain. This allows a walking area of 4.5m by 4.5m and permits the user to walk at a rate of about 2m per second. The key of this system is that each treadmill moves independently from the other ones and from the drive chain. This allows the user to move freely in any direction indefinitely.

The Italian research group (members of Universita di Roma "La Sapienza") from the project team who created CyberWalk, desgined also another interesting virtual walking system called CyberCarpet (De Luca et al., 2006, 2007). CyberCarpet is a virtual walking nonholonomic platform that permits user to have unconstrained omni-directional locomotion, Fig. 7 (a).

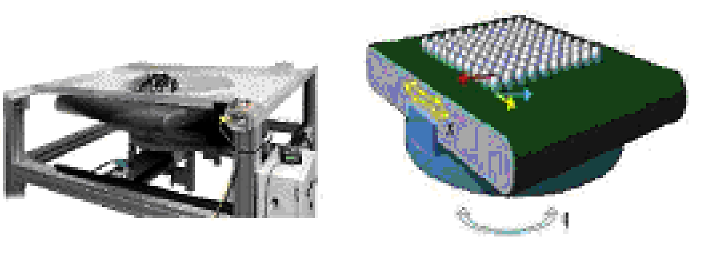

Fig. 7. The CyberCarpet device
(a) structure; (b) ball-bearing platform

The platform consists of two actuating mechanisms, one linear (includes a ball-array belt) and one angular, Fig. 7 (b), a vision and tracking system and two processing and control systems, one for image and one for platform's control. Mechanical structure and systems architecture is presented in Fig. 8.

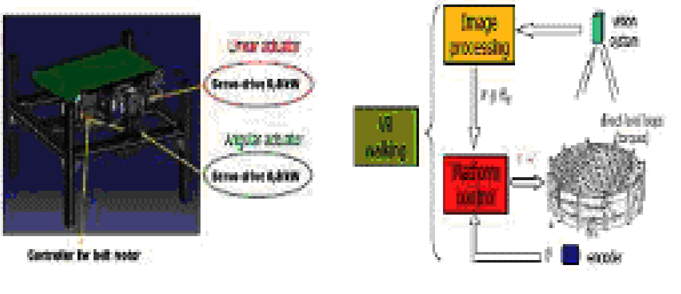

Fig. 8. The CyberCarpet device
(a) mechanical structure; (b) system architecture

Captured images are used to control platform movement that is processed and then correlated to user's movement in order to force keeping user's body position to the centre of the platform. Two vectors provide information for controlling platform's movement: users pose (position and orientation) and angular position of the turntable. Ball-bearing platform's role is to capture and transmit forces both from user's feet and underlying platform.

At the level of 2007 CyberCarpet was the fastest and largest implementation of any ball-bearing platforms, having capabilities of 2m/s on linear and 2rad/s on rotational movement and an area of 0.8m.

At a conceptual level CyberWalk is one of the most similar projects regarding our idea about a VR walking device. The main difference is that we are using a treadmill instead of a ball-bearing belt for linear movement. Another difference refers to our mechanical design of the angular motion platform, because we intend to use a circular platform provided with one or two motor actuated wheel under the linear treadmill.

VirtuSphere (Medina et al., 2008) (http://www.virtusphere.com/), developed by VirtuSphere Inc. Fig. 9, is a unique device offering a more realistic immersion feeling, also giving full freedom of movement, while assuring natural posture. It has a sphere shape made out of latticed ABS plastic, tall enough to hold a person, resting on a stable platform that has wheels attached to it, allowing movement in any direction.

The device has a platform composed of 25 wheels that support the sphere which assure that knocking off is made impossible.

As the user walks or runs, the sphere rolls on the wheels, accommodating the motion. The wheels are equipped with sensors that describe direction, information then passed through a CPU to the user's HMD, changing the virtual view.

Fig. 9. The VirtuSpehere Device

The VirtuSphere is designed to help in military training, but can also be a tool for use in entertainment or real-time simulations of events.

One of the most interesting and most recent inventions in this domain is the *CirculaFloor* (Iwata et. al., 2005) (http://intron.kz.tsukuba.ac.jp/CirculaFloor/CirculaFloor_j.htm).

CirculaFloor, Fig. 10, was developed by a team lead by professor Iwata from Tsukuba University, Japan. It is a locomotion interface that is using a group of tiles involving a holonomic mechanism that permits omni-directional motion.

Fig. 10. The CirculaFloor device

System's basic locomotion element is a mechanical tile called *Vmax Carrier*, capable to develop an omni-directional movement. The infinite surface is practically given be the tiles' movement, giving the user the possibility to walk into a virtual environment but standing still in reality. This is achieved by a complex system that uses position sensors put on each tile, to track movement of the feet, a laser range finder that measures the walker's position and a PC that controls the tiles' locomotion through wireless RS232c modules. Each movable tile has a 586mm (W) x 586mm (D) x 92mm (H), a weight of 16.2 kg and can carry a load of 80 kg in 1200mm/s.

Functional principles are almost the same as in the StringWalker device. A circular 200 mm diameter dead zone is placed in the centre of the walking area, a G point or projection of the central position of the walker is calculated and a locomotion algorithm permanently updates the tiles' position to force the G point of the walker to be in the dead zone all the time. Pulling back direction and velocity of the tiles are calculated using the direction and the distance between the G point and the dead zone's circle. This algorithm cancels the walker's movement in any arbitrary direction.

2.3. Discussion on the existing inventions

Observing the solutions presented above, the problem of virtual walking could be formulated as the development of a system to cancel the user's real motion while walking in a Virtual Environment. Two main principles could be identified as being used so far to solve this problem. The first principle we called it "kinetic compensation" since it is based on applying forces *on the user* in order to compensate the forces applied by the ground and the second principle is called "kinematic compensation" since it involves a system that compensates the motion of the user by moving the walking ground in opposite direction with respect to the user motion – thus the two motions cancelling one each other.

Looking to the solution presented it appears that *Omni-direction Ball-bearing Disc Platform* (OBDP) (Huang et al., 2000), *A foot following locomotion device with force feedback capabilities* (Schwaiger et al., 2006) and *The String Walker* (Iwata et al., 2007) are of kinetic compensation type while *The CyberWalk* (Robuffo Giordano et al., 2008), *The CyberCarpet* (De Luca et al., 2006, 2007) and *CirculaFloor* (Iwata et. al., 2005) belong to the kinematic compensation type. Comparing the two principles, it can be said that the kinetic compensation based systems often involve force flows that close through the user, aspect that is normally felt as uncomfortable and artificial, reducing thus the degree of realism, so important in Virtual Reality applications. In contrast with this, the kinematic compensation systems are superior both from comfort point of view and natural interaction and user navigation. In turn, these systems need very complex tracking systems able to identify and even to anticipate the user intention of motion such as to be able to generate the compensation motion in real time.

Various prototypes of interface devices for walking into VR environments have been developed in the recent years. Most of them show interesting features and ideas that will allow researchers to finally find a way in the near future to develop a fully omni-directional, immersing device capable to simulate real human walking in virtual environment. In this section some drawback elements and functions on the most important existing prototype categories are identified.

Early treadmills were capable of moving only in back and forward direction. Most recent developments allow omni-directional walking but encounter different problems. They are very large, bulky and complex mechanisms, some of them weighting several tones, occupying large areas and being impractical. A common characteristic is that they allow walking only on flat surfaces thus limiting simulation of the real surface. In some possible applications there could be a need of walking on up or downhill surfaces. Other limitations are given by the control mechanisms of a treadmill device and of the treadmills' acceleration causing inertia forces on the walker, forces not present in real locomotion. Speed and consistency are also unresolved issues.

The CirculaFloor was developed to overcome drawbacks of treadmills like weight and area which made them difficult to install and properly implement in other places as laboratories. In this sense CirculaFloor is a more compact hardware system. Another treadmill disadvantage resolved by the CirculaFloor is scalability. The system can be extended and upgraded easily by adding more mechanical tiles which allow an extension of the surface space. System limitation is given by its complex actuation mechanism of the tiles which does not permit sufficient walking speed. Another problem is given by the accurate control of the tiles.

Devices like the ones of Schwaiger et al., 2006, and Huang et al., 2003, have the disadvantage of high cost of the components given by sensitivity of the sensors and tracking algorithms which do not support side stepping. In fact OBDP's main disadvantage is that the user motion is not exactly compensated kinetically but by a force applied at waist level of the user, which could cause unstable gait. The same problem appears at Williams (2008) *Walk simulation apparatus for exercise and virtual reality,* given by unstable gait.

Systems such as Power Shoes or String Walker have problems in allowing the user to have a correct posture and gait. Generally they use a number of motors for actuating the strings or the flexible shafts that drive the shoes. Another major limitation of these methods is the need of a high degree of accuracy required for tracing user's foot-pad.

VirtuSphere has the advantage of a greater immersion sensation compared to other devices (treadmills or carpets) and also giving virtual full freedom of movement. It presents disadvantages of dimension and complexity. While the Cyberwalk system is a very large system and therefore suitable only with HMD based VR systems, the Cybercarpet seems to pose problems at high speed at the level of the ball bearings that the user is walking on.

3. The proposed System

3.1. Goal

Our goal is to design a virtual walking system that is perfectly adapted to the way the humans are moving. For this purpose, the first observation is that the human gait is composed basically of a linear motion plus a turning capability, while lateral walking is not commonly used because of the feet interference. This is the reason, the technical solution we propose materialise these two DOF's, leading us to the idea of a translational carpet having rotational capability. The type of the system proposed is of "kinematic compensation" and is a very similar approach with Cybercarpet except the ball bearings system that supports the human in the Cybercarpet case. The main difference is that the carpet motion is directly transmitted to the walker, which probably will need some specific control input in order to avoid inertial shocks to be transmitted to the feet during the walking process.

Thus, the system is designed to have a very simple two DOF architecture, Fig. 15. First degree of freedom is given by the linear axis of direction necessary for back and forward movement (1) and the second degree of freedom is represented by the angular movement of the platform necessary for side and turn motion (2) practically creating infinite virtual space. System's limits given by walking space, linear and angular velocities, acceleration and inertial forces and moments (felt by the user in different cases), weights and the limits of payload that give system stability, have to be experimented and simulated. A very structured and profound modelling of these processes needs to be done in order to have proper answers to all these questions. This paper will present the hardware development performed by the authors in researching this new walking simulator. There are quite a few applications known in this domain, capable to capture and represent human walking in virtual reality in an appropriate fashion.

A problem yet unresolved is creating a human locomotion model which is a key point for interpreting data into virtual reality. In this sense we will design a proper model approach in order to capture, represent and simulate human walking in virtual environment.

Our system is designed to work in different VR applications which include locomotion like environment simulators, especially building architectural simulators.

3.2. Up to date

To design our system we developed a classic treadmill using a *Energetics Power Run 3000 HRC treadmill*, Fig. 11, having the following characteristics: 150cm (L) x 50cm (W) band, with incline capabilities between 0 to 15 degrees, capable of moving a person of 135 kg and providing a stop band key in case of emergency.

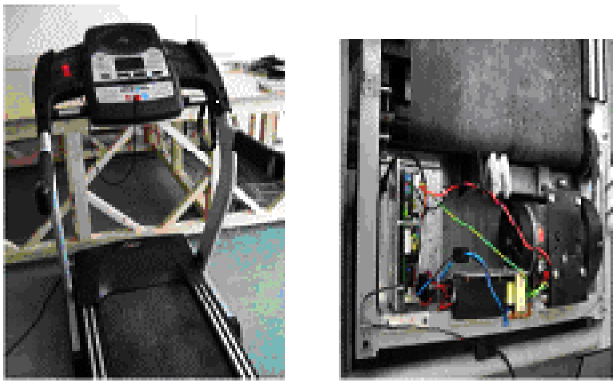

Fig. 11. Energetics Power Run 3000 HRC treadmill
(a) basic structure; (b) DC motor, control and Hall sensor

The system is powered by two DC motors of 180V, 7.5A, one for moving and the other one for inclining the band's degree.

Initially the treadmill was designed to work with its own predefined programs: 19 for running, 2 for pulse and 2 user-defined.

To command and control the band's movement and speed we designed a control device, Fig. 12, which includes:

- Laptop
- Command and Control program
- Ethernet link
- Lantronix XPort
- Serial link
- ATmega8 with UART controller
- Galvanic isolation modules with opto-couples

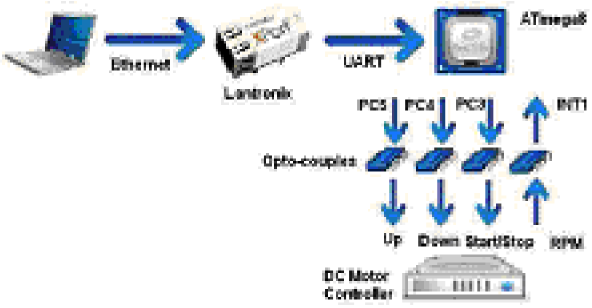

Fig. 12. Speed Control Flow

For controlling motor's speed and thus band velocity we used a very simple technical solution based on the treadmill's Hall sensor. The Hall sensor is used for numbering rotational cycles of the DC motor wheel and determines velocity value of the band. This offers us a method to control the system's speed.

In this sense we designed a user friendly command and control interface, Fig. 13, for controlling DC motor speed.

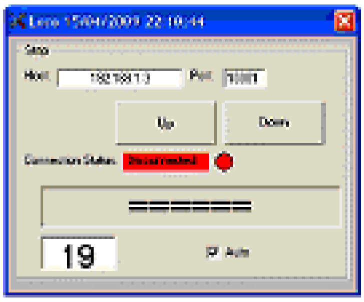

Fig. 13. Command - control interface

Two working modes were implemented:

- A up/down speed mode with specific role of increment/decrement motor's velocity, manually by using fine incremental unit value
- An auto adaptive mode using a predefined reference velocity value that enables DC motor to adapt it's speed to this point in a gross incremental unit manner

The auto adaptive mode induces an oscillating phase in motor's functionality. For this reason, in present, we are working on a better algorithm and program for increasing stability. In parallel we are studying a proportional-integrative-derivative (PID) method using Ziegler-Nichols theory for reducing system's oscillation.

Another step that we've made was to redefine the DC motor controller, and controlling application for reverse walking. Fig.14 presents a block diagram of a very simple and effective solution, using a relay as a switch for changing DC motor's current polarity, a diode for protection of super voltage spikes and a MOSFET transistor for command.

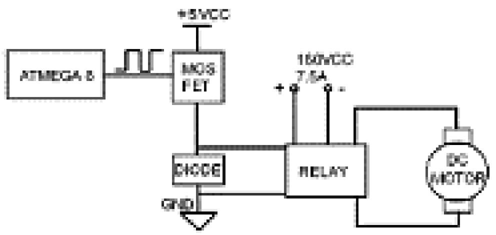

Fig. 14. Block diagram for controlling motor movement

Thus, a full control of the treadmill speed is developed in order to have a good response at different weights and masses. The aim is to create an *omni-directional* treadmill, capable to rotate 360 degrees payload (about 200kg) consisting of the treadmill and the user, Fig. 15.

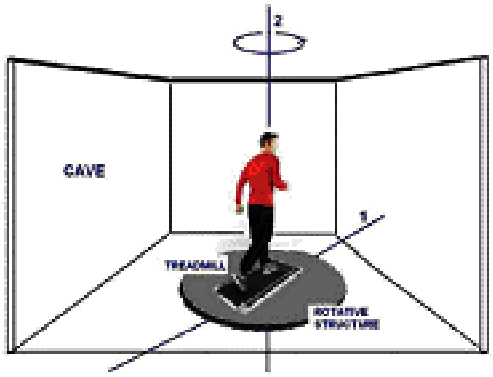

Fig. 15. The proposed two DOF, omni-directional treadmill: 1- linear motion, 2 - rotative motion

For this purpose one or several *Maxon EC 60 motors* are necessary for rotating the structure. This is a brushless motor, 48V nominal, 400W, 7000 RPM maximum speed. Control of the motor position is done using an *EPOS 70/10 controller*. Both motor and controller are shown in Fig.16.

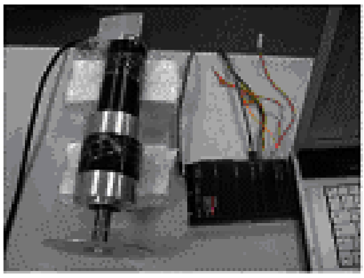

Fig. 16. Maxon EC60 (left), EPOS70/10 Positioning Controller (right)

3.3. Future work and direction of development

An important aspect, next to be done, is creating an application necessary for inclining the band during locomotion on uneven surfaces. This along with an application will give a high degree of *immersion sensation* in virtual environment.

The final stage of our project will include a series of computer simulations and a mathematical model of human walking that will validate our work.

4. Conclusions

As the literature synthesis presented in this paper reveals, current research and current applications are still far from the moment when there will be a close identity between natural walking and walking in virtual reality. Even though a number of interesting and innovative ideas were put into practice, as we've seen, none of them really resolved this issue totally.

The first functional test performed with the technical solution proposed in this paper validated the functionality as it was conceived and brings in new ideas on how to develop such a system and we anticipate an effective result from the navigation viewpoint. Parallel research is being currently conducted on the cognition of walking in order to derive the necessary rules and algorithms for identifying the user walking intention in real time in order to be able to command and control the treadmill such as to compensate kinematically the user motion in real time. Large scale experimental tests are planned to be conducted in the next stage in order to assess the user's comfort, stability, maximum speed allowed for walking and many other performance parameters.

Nevertheless, answers to the existing problems regarding walking in virtual environments will need a systematic and profound study, both at theoretical and experimental level.

5. Acknowledgements

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