Omni-Directional Treadmill System

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Abstract

Our problem definition for a locomotion haptic treadmill is a device that allows a user to walk normally in place in any direction by insuring that the reaction force that is felt remains consistent in all planar directions. A novel Omni-Directional Treadmill is presented in this paper which focuses on modulating the compliance in the plane. Powered offset casters are used as the transmission system to adjust the compliance between the user and the treadmill. The control system is developed using a rapid embedded programming method. A large cloth material or board can be used as the walking surface for the treadmill. A prototype system has been constructed.

1. Introduction

A simple Omni-Directional Treadmill (ODT) has been described as the Holy Grail for virtual reality systems. ODTs or walking simulators can be used in virtual reality environments for gaming, military simulations, or evacuation simulations. They can be used in human motion studies, in perceptual studies for psychology experiments, as indoor exercise equipment, and as language immersion systems. In the past few years, some companies have developed ODTs for locomotion in virtual environments. Such devices allow a user to walk in any direction of travel.

The company Virtual Space Devices, Inc. has an existing commercial product that allows a user to move in two directions [1]. This omni-directional treadmill uses a belt with 3400 rollers in the lateral direction to generate planar motion in the virtual world. The rollers can either spin or translate. However, this treadmill is very complicated, noisy, and does not allow for natural movements. The sideways motion feels very icy, and the user has to wear a harness in case they slip.

In 1999, the Virtual Reality Laboratory at University of Tsukuba developed a Torus treadmill [2]. They use twelve one-dimensional treadmill systems to build the omni-directional locomotion system creating an infinite surface. These belts are connected side by side and mounted on two parallel torus rails. The belt can rotate by itself or be moved around the rail generating omni-directional motion. This ODT has an insensitive area around the center of the walking surface to eliminate chattering when the user walks in the vicinity of the center. This design requires many motors to power the belts, and the surface may not have consistent velocity because of the open loop control.

The Omni-directional Ball-Disc Platform is a passive locomotion device from Tamkang University, Taiwan [3]. There are no motors in the system to drive the surface. Many ball-bearing sensors are mounted on a concave surface. These spherical balls can rotate in three directions. The concave design allows the user to automatically slip back to the center. A passive platform has its advantages. It doesn't require motors and is very easy to control. The disadvantage is that the movement feels like stepping and then sliding.

The US Army funded the development of a locomotion simulator, OmniTrek™, which will allow motion in all directions as well as stair climbing. It is a complex device involving two servo controlled robot arms that will catch the user's feet [4].

The Sarcos Treadport™ was developed in 1995 and is based on a standard treadmill with the user being monitored and constrained by a mechanical tether attached to the user's waist [5, 6, 7]. It has the advantage that the user can walk, jog, and kneel, and the incline of the treadmill can be adjusted to simulate hills, but the physical movement is constrained to one linear direction. By adding a force to the waist with a mechanical tether, realistic hills have been demonstrated

Other inventions include: a giant sphere to walk inside [8], an air-walker [9], a treadmill that rotates [10], an electronic floor to touch [11], different types of bicycles [12], and walking slippers [13].

The problems associated with some of the current systems include: restrictive motion, limited to upright motion, noisy, complicated, a requirement of a tracking system, and acceleration transitions in the plane can cause the user to slip or fall.

In our design, the powered offset caster transmission system is a novel idea to realize the omni-directional motion and compliance control. A powered offset caster can be controlled to either orient a wheel or rotate it. Its

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rotating axis does not intersect with the orientation axis. The offset between the two axes is the key point in developing omni-directional motion because it eliminates the singularity in the Jacobian matrix. Casters are placed on the top of a large piece of cloth material and move the cloth in a planar motion (x, y, and theta).

In section 2, the design of the system is discussed. The powered offset casters and the control system are detailed. Currently we use a rapid embedded programming method to develop our computer control system, hardware, and code [14]. In section 3, the experimental device is discussed.

2. Powered offset casters treadmill system

Muir and Neuman conceptually described the powered caster vehicle in 1986 [15]. Nomadic Technologies, Inc. and the robotics laboratory at Stanford University designed and built this new, wheeled, omni-directional, mobile robot [16].

2.1 Structure Design

The transmission system consists of four powered offset casters. Two motors drive each caster shown in Figure 1. A gearbox connects the two motors together and allows the caster to orient and the wheel to spin. A formal discussion of the kinematics can be found in the following papers [15], [16].

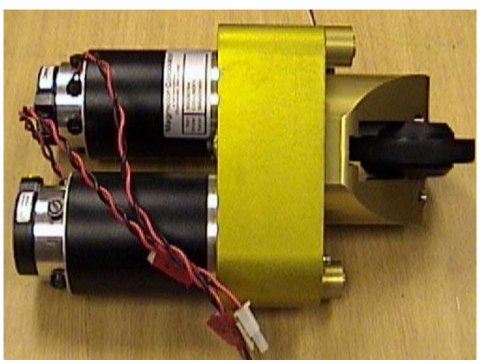
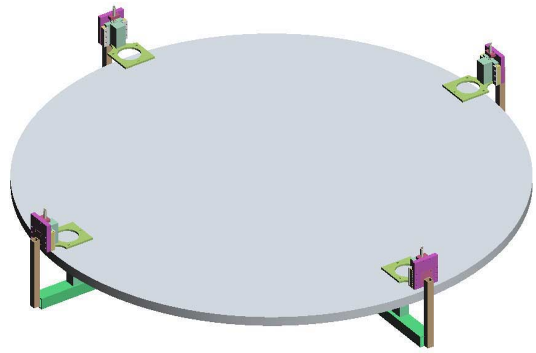


Figure 1. A Powered Offset Caster

In the current research, we built a circular platform shown in Figure 2 with a diameter of 1 meter. The platform is made of wood and it is laminated on top to reduce the friction between the treadmill cloth and the wood surface. Four steel holders are fixed around the table to mount the casters. An 8ft by 10ft Neoprene-Coated Nylon Tarp is used as a substitute for common treadmill cloth. When the treadmill translates, the extra cloth is wrinkled underneath the platform. An infinite surface is discussed in Section 4.

The cloth is translated by the frictional force between the caster and itself. This friction force has to overcome the friction between the cloth and the wood surface. When a heavy object is placed on the top of the cloth, more pressure is added to the casters. A screw on each holder can adjust the pressure. The outer part of the caster is made of rubber and can deform with increased pressure.



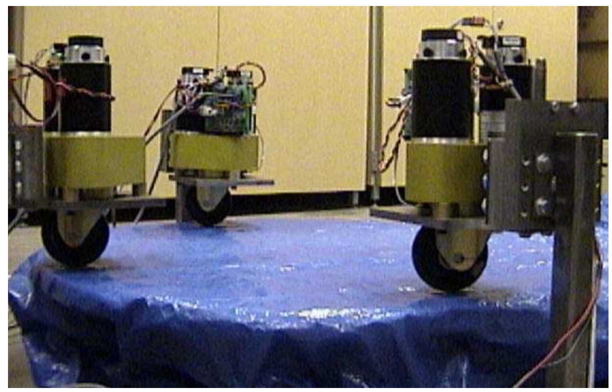


Figure 2. In the upper figure, a diagram of the wood structure for the floor is shown. In the lower figure, the experimental platform is shown with the cloth on top of the floor.

In order to make a safe walking surface for the user, the platform approximately needs to be 2.8m in diameter which allows the user to walk inside a circular area with a diameter of 2 meters.

We also considered safety equipment for the user to prevent falling. The LiteGait walking system from Mobility Research, Inc. has a harness which fixes the person from top.

2.2 Control system

We use a rapid embedded programming method to develop our computer control system, hardware, and code [14]. The primary components of the system include MATLAB's Real Time Workshop™, xPC Target™ Toolbox, a motion control processor (LM629N-8), and a digital I/O board (CIO-DIO192).

A real time system is needed to control the treadmill to make sure that it reaches the desired position or desired

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velocity. The flow diagram of the system is shown in Figure 3.

The standard Jacobian is used to calculate the wheel and caster angular velocities given the desired Cartesian velocity, the wheel radius, *r*, and the offset, *b*. The inverse of the Jacobian always exists because of the offset value, *b*.

$$\begin{pmatrix} \dot{\Theta}_{wheel} \\ \dot{\Theta}_{caster} \end{pmatrix} = \begin{pmatrix} -\frac{1}{r}\cos(\Theta_{caster}) & -\frac{1}{r}\sin(\Theta_{caster}) \\ -\frac{1}{b}\sin(\Theta_{caster}) & \frac{1}{b}\cos(\Theta_{caster}) \end{pmatrix} \begin{pmatrix} \dot{X} \\ \dot{Y} \end{pmatrix}$$

The desired motor positions are then obtained by integration and are sent to the motor via the digital input/output board. The servo control loop is performed in the motion control processor.

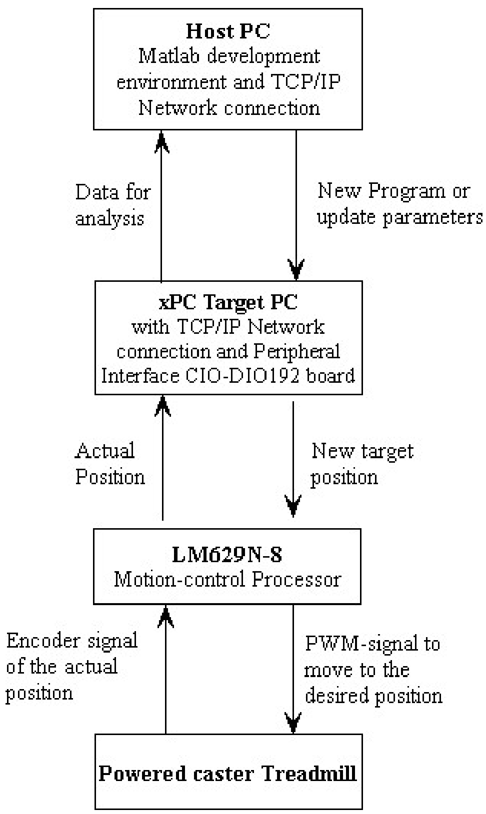

Figure 3. Flow diagram of the system. All development work is completed on a host PC running MATLAB under the Windows environment. The executable code is transferred to the target PC using standard Ethernet, and it runs the model in real-time to control the treadmill system.

3. Experimental Work

The experimental work to construct the active treadmill has progressed in several stages. Planar motion was achieved by orienting and controlling the casters based on the Jacobian matrix. A prototype was built which can move a board in small planar motions shown in Figure 4. In this experiment, the board was automatically moved in a square and the user was forced to follow the treadmill's movement. The surface felt consistent and solid in all planar directions. We also tried to walk on a passive treadmill to find out how the force affects the orientation of the casters. The last stage, building a revolving, continuous floor, will be completed in the future.

Figure 4. Active controlled treadmill with initial concept. The moving surface was translated in a square pattern and the user walked freely in a planar motion. The friction between the casters and the moving surface was enhanced by the weight of the user.

3.1 Motion control in the X and Y directions

A control system for the base was developed using MATLAB xPC. The motors of the manipulator are controlled using the LM629N-8 motion-control processors from the National Semiconductor. Figure 5 shows the compiled Simulink model. The desired Cartesian velocities are the input signals. The "Kinematic" block converts the desired Cartesian velocities to the joint (motor) positions based on the following equations,

$$\theta_{TM} = \frac{1}{2\pi r}\int\left[-\dot{X}\cos(2\pi\theta_{SM}) - \dot{Y}\sin(2\pi\theta_{SM})\right]dt$$

$$\theta_{SM} = \frac{1}{2\pi b}\int\left[-\dot{X}\sin(2\pi\theta_{SM}) + \dot{Y}\cos(2\pi\theta_{SM})\right]dt$$

θ_{TM} is the angular position of translation motor; θ_{SM} is the angular position of steering motor. $\dot{X}$ and $\dot{Y}$ are the desired Cartesian velocities, and r is the radius of the wheel and b represents the caster offset.

The compensation blocks cancel the coupling between the steering motor and the translational motor. Lastly eight motor signals are sent to the "motorout" block that sends the desired positions to the motor processors. The eight "Target Scopes" allow the motor signals to be displayed on the target PC.

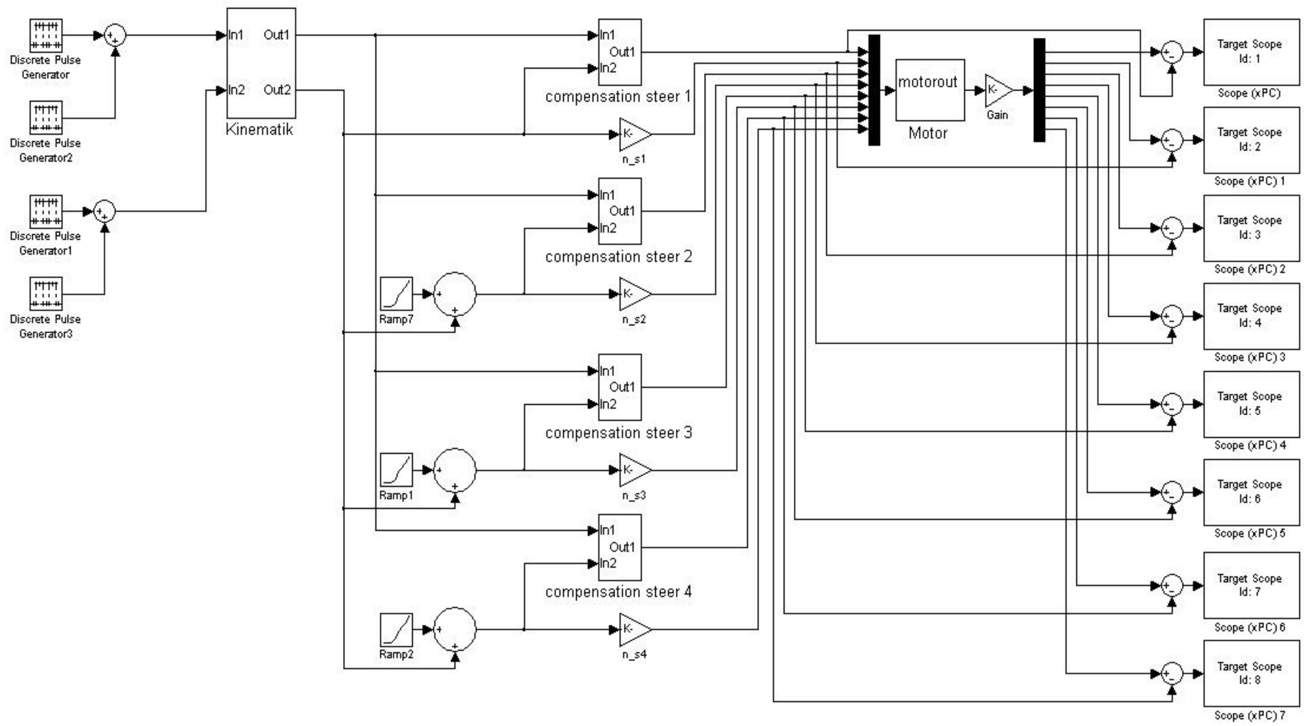

Figure 5. MATLAB Simulink model for motion control

3.2 *Damping and stiffness control*

A control system for the base was developed to adjust the desired damping and stiffness coefficients. To control the desired damping and stiffness of the system, we developed a damping and stiffness equation based on the motor torque and the gear transmission ratio.

The damping in the plane should feel consistent in any planar direction. A diagonal matrix with equal stiffness values in the X and Y directions is chosen. The Jacobian is used to calculate the needed torque on the wheels. If the wheels are current controlled, the desired torque values can be sent directly to the controller taking into account the gear ratios. If the wheels are position controlled, then the desired torque commands are converted into desired position commands using a simple stiffness law.

$$J = \begin{pmatrix} -r\cos(\Theta_{caster}) & -b\sin(\Theta_{caster}) \\ -r\sin(\Theta_{caster}) & b\cos(\Theta_{caster}) \end{pmatrix}$$

$$\begin{pmatrix} \tau_{wheel} \\ \tau_{caster} \end{pmatrix} = J^T \begin{pmatrix} a & 0 \\ 0 & a \end{pmatrix} J \begin{pmatrix} \dot{\Theta}_{wheel} \\ \dot{\Theta}_{caster} \end{pmatrix}$$

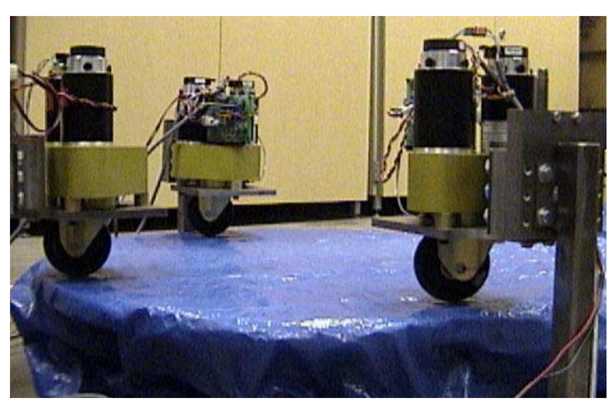

Figure 6. Prototype of the Powered caster treadmill

Here, a defines the stiffness value; θ_{caster} defines the orientation angle of the caster, and θ_{wheel} defines the rotation of the wheel.

3.3 Translating the Surface

The prototype of the powered caster treadmill has been constructed and is shown in Figure 6.

Theoretically, two casters are able to move the cloth in a planar motion. As a starting point, we used three casters for the experiment and they are placed around the platform. The motion control program described in section 3.1 was implemented to move a big piece of cloth.

Figure 7 shows the actual velocity and position versus the desired velocity and position when the wheels are moved in a square motion. In this case, the casters are not touching the surface. The maximum translational speed was 0.75m/s and the desired path was followed very well.

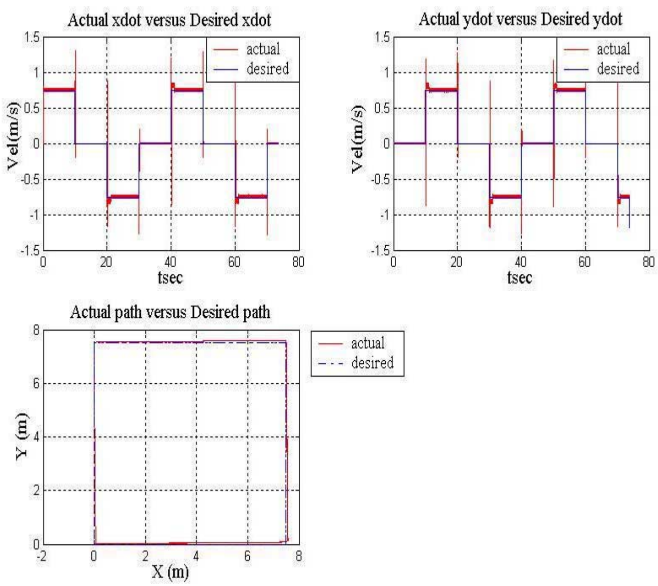

Figure 7. Velocity and position data for a desired square motion

Figure 8 shows experimental results when moving the cloth with a 15 lb load on it. The desired path is shown by a thin blue line and the actual path determined from the powered wheels and casters is shown by a solid red line. When moving, the cloth is collected and stored in the gap between the platform and the supporting brackets for each caster unit. The user can control the speed and the direction with a joystick.

Since the cloth material is not stiff, wrinkles can occur when the friction force and wheel velocities are not controlled precisely. Currently, we drive the lead wheel with a 1% overspeed to stretch the cloth and reduce the wrinkles.

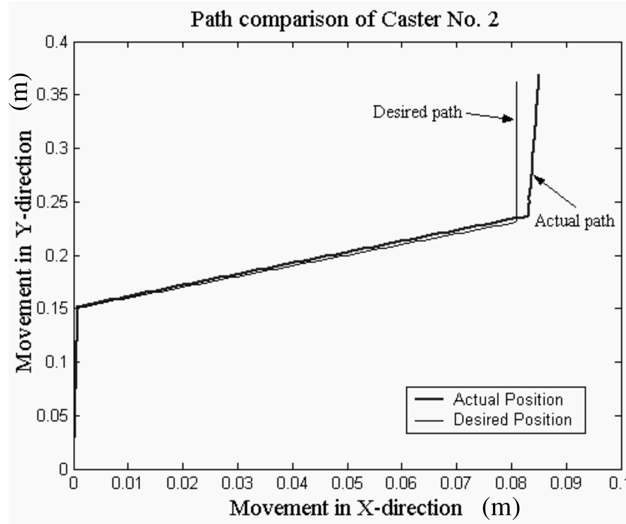

Figure 8. Driving the cloth through a desired path

3.4 Modeling Forces on the Treadmill

The forces acting on the belt are primarily due to the belt friction against the floor surface and the impact of the user's foot against the belt surface. It is estimated that the maximum impact is 3 times the body weight equaling 2646 N and the maximum braking force from the impact is 316 N [17]. The coefficient of friction for our surface is estimated to be 0.2. Therefore, the braking force against the belt is approximately 600 N during peak impacts. The continuous force on the belt is caused by the friction from the user's normal force, and is estimated to be 170 N.

The continuous torque from the MagMotor C33-I-300 motor is 0.92 Nm and the peak stall torque is 8.5 Nm. The gear ratio for the translating motor is 4.72 and the radius of the wheel is 0.055m. With 4 motors, the continuous supplied force is 320 N and the peak supplied force is 2900 N.

A simulation was performed using the motor and caster characteristics to determine if the impact loading would significantly decrease the belt velocity. A PI controller similar to the Treadport was simulated [17]. In Figure 9, the actual belt velocity was very close to the desired belt velocity.

3.5 Design of a Passive controlled treadmill

A passive controlled treadmill allows the force of the user on the surface to change the casters' velocity and steering angle. Many researchers have discussed the problems of determining exactly the "intended" path of the user. The sensor data can be noisy and slow, and if inaccurate can cause the ODT to move in the opposite direction as the user, causing him to fall. By allowing the user to move the surface, a sensor is not needed to determine the user's "intended motion".

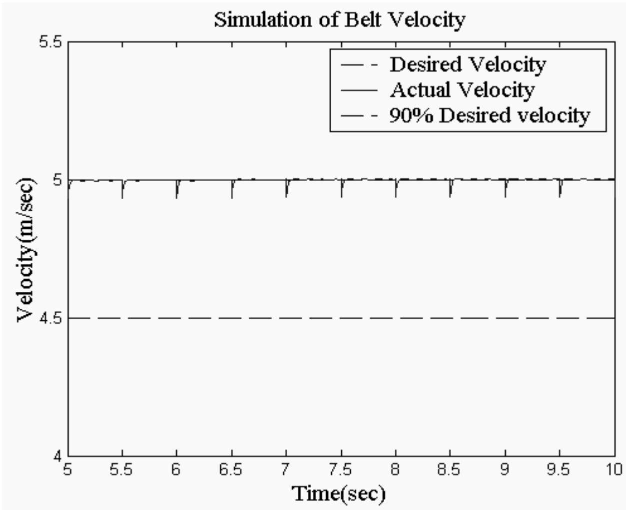

Figure 9 Simulated belt velocity with impact loading from the user

To give the user a natural feeling, the movement needs to be damped by controlling the stiffness of the rolling wheel and allowing the steering axis to move freely. This unique observation simplifies the control system and the translating wheel is damped, not the caster.

We tried walking on a non-motorized surface with passive casters shown in Figure 10. The resistance of the translational wheel can be varied giving the user the feeling that he can normally walk, not the feeling of ice. It verifies the theory that the force from the user can be used to change the orientation of the wheel. Passive treadmills do have problems such as the difficulty of keeping a constant velocity or increasing/decreasing the rolling inertia of the system.

Figure 10. Test with non-motorized casters

4. Future Work

We have completed building and controlling the casters and verified that they can move the cloth surface in a planar motion. A polyethylene surface has been added to reduce friction between the walking surface and the cloth. In the future, the powered ODT must be able to orient, accelerate and decelerate in the plane based on the user's motion. A control system must adapt to the person's desired motion. The control will require a safe, fast and accurate response to re-center the user. We propose to use a mechanical tether to determine the walking direction. Different sensors such as a camera system or a passive caster could be used as well.

Lastly, the cloth must be a closed surface to create an infinite floor. The design of the closed surface has been filed in the full patent. It consists of a ball of cloth supported around the circumference by spherical rollers common in the conveyor industry.

5. Conclusions

A new omni-directional treadmill is designed to control the planar stiffness. Powered casters are used as the transmission system for the ODT allowing the direction of the walking surface such as a belt to be changed easily and smoothly.

Our prototype is very simple and quiet using a powered system of one, two, or four casters. A flat or curved surface is moved in any planar direction and can be rotated as well. The resistance felt by the user can be modulated by the motors powering the casters, or brakes modulating the torque. This simple ODT system will allow users to turn and walk freely in a virtual world.

Acknowledgements

A provisional patent was filed by the co-authors at ASU in November 2001 and a full patent was filed in November 2002. We would also like to acknowledge the support of researchers at Nomadic Technologies, Inc.

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