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Improvements in the Omni-Directional Treadmill: Summary Report and Recommendations for Future Development

by Harrison P. Crowell III, Jim A. Faughn, Phuong K. Tran, and Patrick W. Wiley

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14. ABSTRACT
The omni-directional treadmill (ODT) is a device that converts a user's movements into movements through a virtual environment. Its design allows users to move in any direction, which is important for simulations that require dismounted infantry Soldiers to move and exert themselves in much the same way that they would in the real world. This report provides details of the work done to improve the ODT. This work focused on four areas: (1) improvement of the tracking system's accuracy, (2) reduction in the computational latency, (3) development of a new control scheme, and (4) reduction in the audible noise coming from the ODT. The ODT was improved in each of the focus areas. Items (1) through (3) allowed users to assume more of the postures (e.g., crouching) and motions (e.g., side stepping) that are common to dismounted Soldiers. These improvements also reduced false starts and overshooting of stops by the control system. Construction of an enclosure around the sides of the ODT substantially reduced the audible noise. Recommendations for development of a new ODT include making the area in which the user operates larger and making the device even quieter. In addition, the position-sensing and safety systems should be designed in such a way that the user has even more freedom of movement, and the control algorithm should be refined to allow users to make sharp turns and fine movements more easily.

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1. Introduction

One of the key components of a simulator designed for use by dismounted soldiers is a locomotion interface device (LID). The purpose of this device is to translate the user's movements into movement through the virtual environment of the simulator. By giving users the ability to move through the virtual environment, the LID makes them active participants in the simulation. Movement gives users a sense of distance between points in the virtual environment. Movement allows users to see and hear things from different perspectives in the environment. The LID allows users to interact with objects and other users in the environment. For example, squads can meet to receive orders and then disperse to conduct a mission. Movement enhances a user's experience in a virtual environment, which is why the LID is such an important part of a simulator for dismounted Soldiers.

There are many different devices that can be used as LIDs, ranging from a simple keyboard or mouse to a large complex platform upon which users can crawl, walk, or run. Among the devices, there are two main differences that affect how realistically they can simulate moving through the real environment. The first difference is the degree of equivalence between the user's motions with the device and the way the user would move through the real environment. For example, if the interface device is a joystick, pushing it with one's hand may initiate walking through the virtual environment in a particular direction. Pushing it farther may translate into running through the environment. With regard to equivalence in this example, the question is, how well does pushing a joystick with one's hand equate to walking or running? The second difference among LIDs is the amount of physiological energy the user expends with the device compared to the amount the user would expend in going through the real environment. Thus, equivalence of motion and the amount of energy the user expends on the device compared with that expended in the real world determine how realistically the LID can simulate moving through the real world.

The end use for a particular simulator will determine the degree of equivalence and the difference in energy expenditure that are acceptable. For simulators designed to familiarize users with a particular location, a keyboard may be satisfactory. The keyboard can allow users to move quickly from one location to another and view the environment from different perspectives. However, the end use for the simulator in this project is to investigate issues such as dismounted Soldiers operating equipment while moving or making decisions in a simulated battlefield environment while physically fatigued. Thus, the focus of this project is the development and refinement of a LID that allows dismounted Soldiers to get from one location to another the way they normally do: crawling, walking, or running. It also needs to let them assume the various postures that are common for infantry Soldiers (e.g., lying prone, kneeling, and standing). Finally, it needs to require users to expend the same amount of energy in going through the simulated environment as they would in going through the real environment.

This report provides background information about the development of various LIDs. Then it describes the work done to improve the performance of one device in particular: the omni-directional treadmill (ODT). Evaluations of those improvements are also presented. Finally, the report concludes with recommendations for future development of the ODT.

2. Objective

2.1 Virtual Environment Science and Technology Objective

In 1998, the U.S. Army Research Laboratory's (ARL) Human Research and Engineering Directorate (HRED) began working on an Army science and technology objective (STO) entitled: "Virtual Environments for Dismounted Soldier Simulation, Training and Mission Rehearsal". This STO was a 4-year effort (fiscal years [FYs] 1999 through 2002). Its goal was to develop, integrate, demonstrate, and evaluate technologies, techniques, and strategies for using virtual environments. The focus of the virtual environment system was training, mission rehearsal, concept development, and test and evaluation of tactics and equipment for infantry Soldiers at the squad level (i.e., squad leaders, fire team leaders, and team members). The partners in this STO were the U.S. Army Research Institute (ARI) for the Behavioral and Social Sciences (lead organization), ARL's HRED and Computational and Information Sciences Directorate, and the U.S. Army Simulation, Training, and Instrumentation Command (STRICOM). Under the STO, ARL's HRED was responsible for demonstrating an advanced mobility interface device that provides a realistic perception of movement and an accurate expenditure of energy by the user. For many tasks that an infantry Soldier would perform in a virtual environment, a realistic perception of movement and an expenditure of energy are crucial. This is because movement and expending one's own energy to move are integral parts of combat for dismounted infantry Soldiers. Thus, it is important that Soldiers train (or test and evaluate new tactics or equipment) in conditions that are as close as possible to those encountered in combat.

2.2 Mobility Interface Devices

Before 1998, many mobility interface devices had been built and demonstrated. Some of these devices are shown in figures 1 through 8. These devices provide varying degrees of realism and different energy expenditure requirements.

Sarcos Research Corporation built the Sarcos UniPORT[1] (figure 1) as a proof-of-principle device (Douglass, Marti, & Jacobsen, 1994). It required users to expend energy to move through the virtual environment, and it allowed them to use their hands to hold a weapon or other Soldier equipment while moving through this environment. To move forward or backward through the

[1]UniPORT is a registered trademark of Sarcos Research Corportion.

virtual environment, users pedaled the UniPORT forward or backward, respectively. Resistance on the pedals changed with the slope of the terrain in the virtual environment. Users applied more force to go uphill and less force to go downhill. To turn, users pushed the side of the seat with their thighs in the direction they wanted to go.

The Sarcos TreadPORT[2] (figure 2) is a large, commercially available treadmill that was modified by Sarcos Research Corporation so that the speed of the belt is controlled by the position of the user. The tether attached at the user's waist tracks the user's location and provides force feedback. Christensen, Hollerbach, Xu, and Meek (1998) developed the force feedback controller to compensate for inertial forces that the user would normally feel when changing speeds or going up or down slopes. Users can walk forward or backward on the TreadPORT. They cannot turn in place, but they can turn in the virtual environment while walking. When they walk to the left or right of the center of the treadmill, the scene in the virtual environment rotates in the opposite direction to provide the users with the illusion that they are turning.

Figure 1. The Sarcos UniPORT.

The individual soldier mobility simulator (ISMS), also developed by Sarcos Research Corporation, was intended to be a research device for examining human factors issues related to locomotion interface devices (see figure 3). It consisted of a rigid framework that supported two arms. At the end of each arm, there was a footpad. The user placed his or her feet in bindings on the footpads.

[2]Tread PORT is a registered trademark of Sarcos Research Corportion.

Each of the arms had three degrees of freedom. The arms could rotate about the vertical axes at the joints that connected them to the frame. They could also translate so that the footpads moved horizontally and vertically. The ISMS was linked to a virtual environment and display system. The signals from the ISMS were used to move the user through the virtual environment. Although the ISMS did this in response to users' movements on the footpads, the users' gait was not smooth and natural as it would be if they were walking on level ground.

Figure 2. Sarcos TreadPORT, operating inside a walk-in synthetic environment. (Photo courtesy of Sarcos Investments.)

The ODT (U.S. Patent 5,562,572) is a prototype mobility interface device that allows the user to walk or run in any direction on its active surface. This unique device (see figure 4) was developed by Virtual Space Devices, Inc. It has an outer belt and an inner belt. Each belt includes rollers, and the rollers of the outer belt are at right angles to the rollers of the inner belt. A mechanical linkage is used to sense the user's position. The position information is sent to a control computer that drives the belts of the ODT and returns the user to the center of the active surface.

The Institute for Simulation and Training in Orlando, Florida, built the fully immersive team training (FITT) research system (see figure 5) for ARI. It was designed as a research tool to help examine team training in virtual environments (Lampton & Parsons, 2001). FITT provides the means for subjects to move through the virtual environment by walking in place. Sensors just above the user's ankles are used to determine stride length for the user walking in place, and the amount of time that a sensor is above a defined height determines the stride length. To walk backwards through the virtual environment, the user lifts one foot at a time, swinging it behind his or her body and then placing it down next to the other foot. The direction of travel is determined by the orientation of the user's torso.

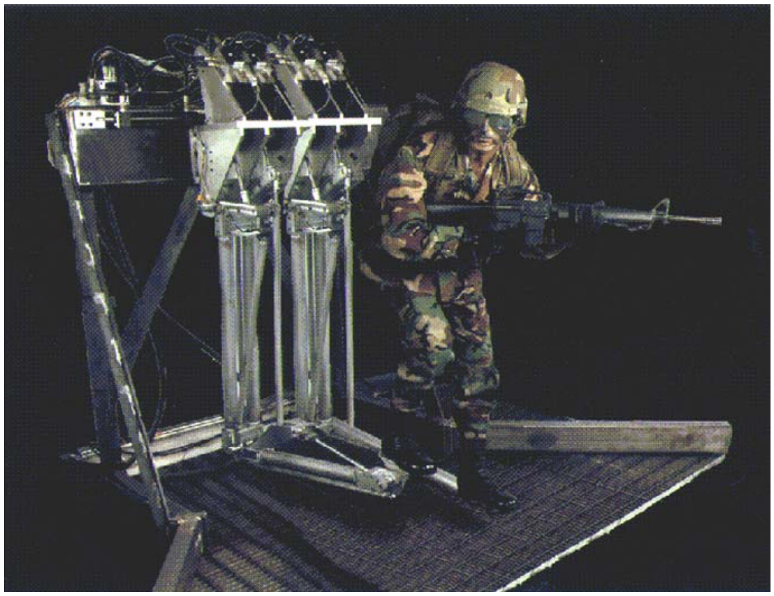


Figure 3. ISMS.

Figure 4. ODT.

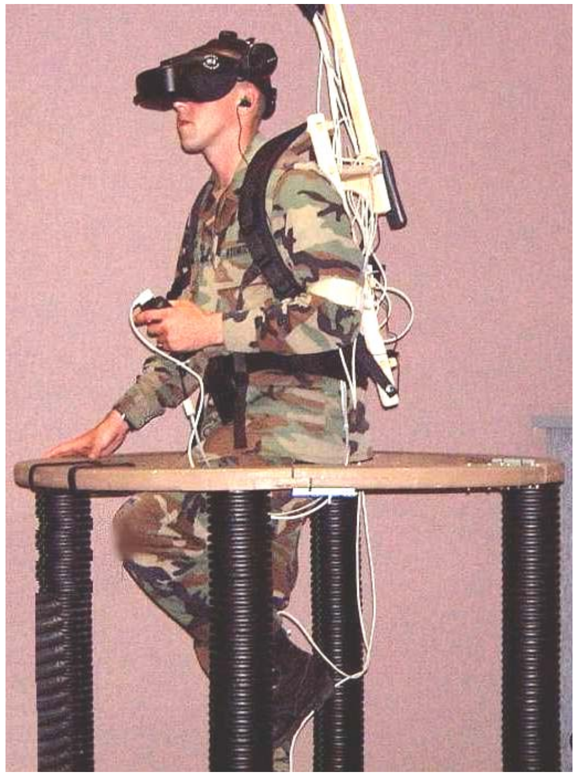


Figure 5. FITT.

Two other devices that were nearing the end of their development in 1998 were the CyberSphere and the CyberStrider. The CyberSphere is a translucent, hollow sphere that is supported on a base by a low-pressure cushion of air. The user moves through the virtual environment by crawling, walking, or running inside the sphere. The motion of the sphere is tracked so that the scene projected onto the sphere changes according to the user's movements (Higgins & Kouchy, 2001). The CyberSphere was developed in the United Kingdom by Virtual Reality Systems UK, Ltd. Diagrams of the CyberSphere are available at the web site, http://www.vr-systems.ndtilda.co.uk/ sphere1.htm#Description. Figure 6 shows the CyberStrider, which was built by Cybernet Systems Corporation (Jacobus, Veronka, & Cussen, 1998). The operator is supported by two footpads. The prototype CyberStrider was completed, but it was not integrated with a virtual environment or demonstrated with a user controlling the device via the footpads.

Another interesting system, which was available in 1998 and developed by Veda, Inc., uses optical tracking to locate the user within a defined volume (Lockheed Martin, 1997). The Veda System is shown in figure 7. Video cameras mounted on poles at the corners of a 6-m by 6-m (20-ft by 20-ft) capture area track reflective markers placed on the user. There is a 0.9-m-(3-ft)-diameter circle in the center of the capture area. When the user is inside the circle, movement through the virtual environment begins automatically. Direction is determined by the orientation of the user's body.

Outside the 0.9-m (3-ft) circle but still within the capture area, the user can move freely, and those movements translate into equivalent movements in the virtual environment.

Figure 6. CyberStrider (Jacobus et al., 1998, page 17), contract number M67004-96-C-0027. Used with permission.)

Figure 7. Veda system.

In 1993, the Naval Air Warfare Center's Training Systems Division developed the team tactical engagement simulator (TTES) for the U.S. Marine Corps. In the TTES, the user stands in front of a large screen. Movement through the virtual environment is via a foot pedal on the floor (Goodman, Porter, & Standridge, 1977) (see figure 8). Pressing down on the front half of the foot pedal makes the user go forward, and pressing down on the back half of the foot pedal makes the user go backward.

Figure 8. TTES.

Other mobility interface devices that were available in 1998 included unidirectional treadmills with handles (Brooks et al., 1992) or buttons (Singer, Allen, McDonald, & Gilda, 1997) for the users to push in order to steer through the virtual environment. Like the FITT, there were other devices that allowed the users to move through virtual environments by walking in place (Slater, Usoh, & Steed, 1995; Grant & Magee, 1998). Development of one such device, "Gaiter," began in 1997 at the Naval Research Laboratory (Templeman, Denbrook, & Sibert, 1999). Gaiter uses the direction, extent, and timing of the user's leg motions to control movement in the virtual environment. Another mobility interface device available in 1998 was the virtual perambulator (Iwata & Fujii, 1996). In this device, users wearing special sandals pushed on a waist-high railing while sliding their feet across low-friction material placed on the floor. The sliding motion detected by sensors on each foot was translated into movement through the virtual environment. Researchers in ARL's Information Science and Technology Directorate (now the Computational and Information Sciences Directorate) developed an additional interface device that was available at that time. This device was based on a commercially available stair stepper exercise machine. Movement on the stair stepper was translated into forward movement through the virtual environment, and a joystick was used for turning. The main drawback of this device was that it required much physical effort to move through the virtual environment. Finally, there were, of course, desktop workstations that allowed users to move through virtual environments via joysticks, keyboards, or mice. However, they are not natural ways for most Soldiers to move through the environment, and they require only a minimal expenditure of energy by the user.

2.3 Simulator Evaluations

In 1997, a series of engineering experiments and user experiments was sponsored by STRICOM. These experiments were conducted to evaluate simulators that could be networked and used as a tool for research and analysis of issues affecting dismounted infantry (Lockheed Martin, 1997). Four simulators were used in each of the experiments. Each of the simulators provided a different locomotion interface, display system, and weapon tracker to be evaluated. The simulators that were chosen for these experiments were selected on the basis of diverse features they provided, the expected cost versus benefit of the simulator, and the availability of the simulator.

2.3.1 Engineering Experiments

The engineering experiments took place 21 April 1997 through 9 May 1997. They were held in the Advanced Distributed Simulation Technology II, Operational Support Facility in Orlando. Lockheed Martin Information Systems provided this facility under a contract with STRICOM (Lockheed Martin, 1997).

The engineering experiments were conducted to examine key features of various systems and technologies and to assess their usefulness in simulators for dismounted Soldiers. The simulators were evaluated for their ability to allow the user to move, see, and shoot. Because the focus of this report is locomotion interfaces, only the movement tasks are discussed. Each simulator used a different mobility interface device. The four mobility interface devices were the Veda System, the ODT, a desktop workstation with a joystick, and TTES.

The movement task involved walking a specified course in the virtual environment. The Soldiers who participated in this experiment were told to go as quickly as possible and to avoid colliding with walls, doorways, or other objects. The Soldiers started in open terrain and then entered and passed through several buildings. The time required to complete the course and the number of collisions were measured for each Soldier on each device. To get additional information about the systems, the Soldiers also completed a questionnaire.

2.3.1.1 Results

For the movement task, it took Soldiers approximately three times longer to complete the course on the ODT compared to the TTES, but the number of collisions was 2.5 times greater on the TTES than the ODT or the Veda System (see table 1). The questionnaire results indicate that the Soldiers found the TTES least difficult to use and most realistic. In contrast, the ODT was found to be the most difficult to use even though it provided a natural way to move through the virtual environment.

Table 1. Completion times and collisions for the mobility interface devices used in the engineering experiments.

	Mobility Interface Device			
	ODT	TTES	Veda System	Workstation
Course Completion Time (sec)	560	188	321	296
Number of Collisions	135	335	132	182

2.3.2 User Experiments

Two weeks after the engineering experiments, the user experiments were conducted in the Land Warrior Test Bed at Fort Benning, Georgia. The experiments were conducted over a period of three weeks. Unlike the engineering experiments, which examined features of the simulators, the purpose of the user experiments was to examine the ability of the simulators to allow Soldiers to perform dismounted infantry tasks in virtual environments. Three squad-level missions were performed. Two missions were in open terrain: assault an enemy position and defend an enemy assault. One mission was in an urban environment: clear a sniper from a building. Three of the four LIDs used in the engineering experiments (the Veda System, the ODT, and the TTES) were used in this experiment. The desktop workstation used in the engineering experiments was replaced by a desktop workstation developed by the Training and Doctrine Command Analysis Center, White Sands Missile Range, New Mexico. (The only substantial difference between the workstations used in each experiment was the visualization software.) Qualitative data about the user's experiences with the simulators were collected via questionnaires.

2.3.2.1 Results

Overall, the Soldiers' responses on the questionnaires indicated that the simulator that used the ODT was ranked best for tasks involving movement, orientation, visual recognition, and weapon usage. An examination of the questionnaire responses for each simulator reveals the strengths and weaknesses of each system. The simulator that used the ODT was ranked best for system flexibility, ease of task performance, ability to perform in a tactically sound manner, and ability to perform in a realistic manner. The Soldiers liked the ODT as a LID because they actually used their legs to move through the virtual environment. However, they felt unstable on the ODT, and they felt that their movement through the virtual environment was too slow.

The TTES was also rated highly for many tasks. Soldiers were able to move very quickly using the foot pedal, and the system allowed them to walk up to the display screen and look around corners. Some of the difficulties encountered included controlling speed, crawling by using the foot pedal, and movement within buildings (i.e., collisions).

Soldiers rated the desktop workstation highly for its ability to let them engage targets. However, Soldiers felt that sitting at a workstation and moving via a joystick was an unrealistic way to interface with a virtual environment. Their preference was to stand and hold a weapon.

The Veda System was the lowest rated simulator. Although some Soldiers liked the head-mounted display (HMD) that was used to present the virtual environment, they had difficulty moving in open terrain and moving through a building.

2.4 Selection of the ODT

After surveying the LIDs available at the time and evaluating the results of the engineering experiments and the user experiments, the ARL team decided to work to improve the ODT. This decision was based on three facts. First, the ODT was the only device available that allowed users to walk and run in any direction. These are natural means for moving through the real world. Second, users do expend physiological energy to move through the virtual environment using the ODT. Third, the Soldiers who participated in the user experiments ranked the simulator that used the ODT as best for tasks involving movement (Lockheed Martin, 1997). Thus, in September 1998, the ODT was moved from Fort Benning to ARL at Aberdeen Proving Ground (APG), Maryland.

3. The Project to Improve the ODT

3.1 Detailed System Description

The ODT is composed of five subsystems that form a unique mobility interface device: (a) belts that form the active surface, (b) a position-sensing system, (c) a control computer, (d) a drive system, and (e) a safety system (see figure 9). The treadmill belts that form the active surface contain more than 6,000 rollers. One belt is nested inside the other and the rollers meet at right angles (see figure 10). As the outer belt rotates, it provides motion in the x direction. When the inner belt rotates, it provides motion in the y direction by engaging the rollers of the upper belt and causing them to roll. The vector sum of motion in the x direction and the y direction produces motion in any direction on the active surface. Unlike most treadmills, which run at set speeds, the ODT automatically adjusts to the speed of the user. A belt around the user’s waist connects the user to a mechanical linkage that contains sensors that continuously monitor the position and direction of the user. The sensors provide these data to a control computer. The control computer then performs the calculations necessary to drive the servomotors that move the inner and outer belts. Thus, the belts are automatically and simultaneously controlled to keep the user centered on the ODT. The control computer also sends data about the user’s speed and direction to the computer that controls the virtual environment through which the Soldier is moving. The user views the virtual environment on an HMD or on large screens set up around the ODT. For safety, the system operator continuously monitors the user, and the ODT can be stopped several different ways. The system operator can push an emergency stop button to interrupt power to the servo system. The system operator can also trigger a software interruption from the control computer to stop the system. In addition to these methods, the user wears a harness that is tethered to the mechanical linkage. If the user should fall, the safety strap that tethers the harness to the mechanical linkage pulls a pin on a safety switch that opens a circuit that stops the servo system. This automatically stops the treadmill belts and suspends the user from the gantry that supports the mechanical linkage.

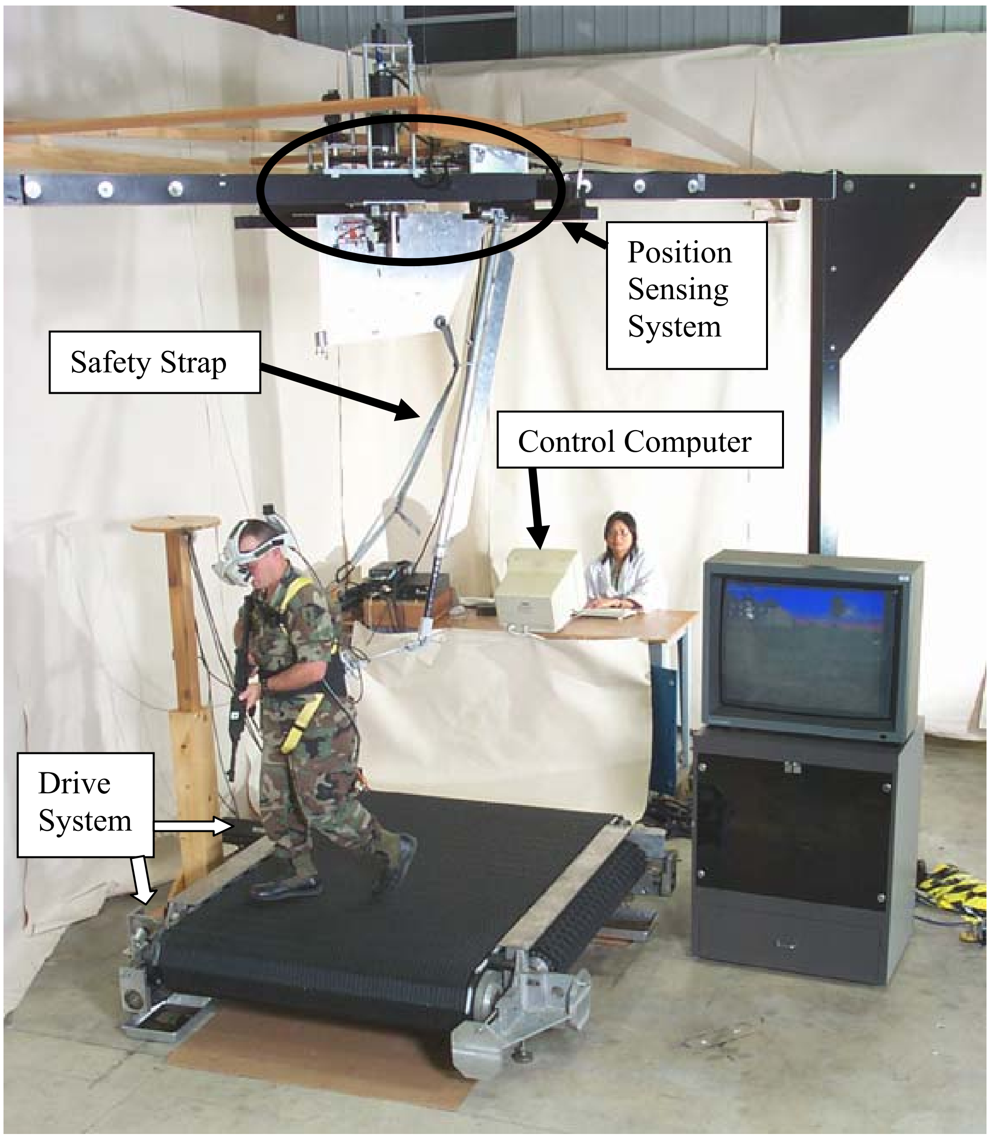


Figure 9. The ODT and its subsystems.

A force feedback system developed for the ODT was designed to act through the mechanical linkage to apply forces to the user. These forces would simulate the inertial forces that users would feel when changing velocity or going up or down hills. The force feedback system was not operational at the time the ODT was moved to ARL.

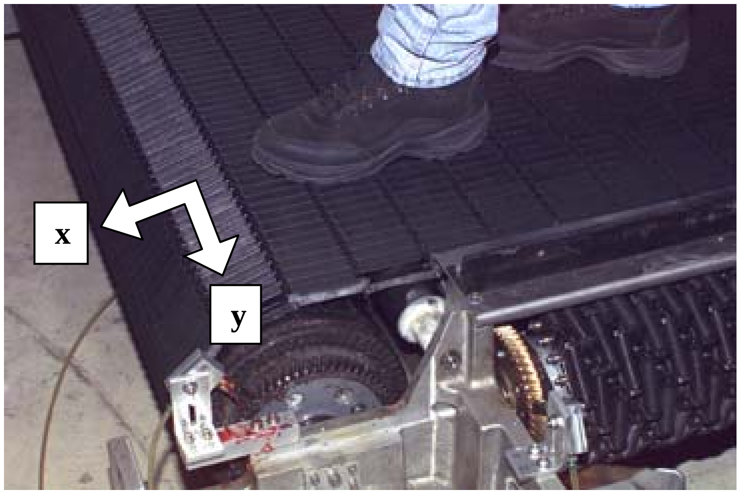


Figure 10. The rollers that comprise the active surface of the ODT.

Some of the physical characteristics of the ODT described by Darken, Cockayne, and Carmein, (1997) are given in table 2.

Table 2. Physical characteristics of the ODT.

Overall Dimensions	
Length	2.21 m (87 inches)
Width	2.01 m (79 inches)
Height	0.46 m (18 inches)
Weight (approximate)	1089 kg (2400 lbs)
Size of Active Surface	1.3 m x 1.3 m (50 inches x 50 inches)
Materials (frame and structural components)	Aluminum and Stainless Steel
Rollers	
Quantity (approximate)	3400 per belt
Material	Molded Nylon
Servo Amplifiers	
Manufacturer	MTS Systems Corporation, Eden Prairie, MN
Model	MPA-25
Operating Voltage	80 V DC to 260 V DC, 45 Hz to 65 Hz, single phase at 30 amps or three phase at 18 amps continuous maximum operation
Motors	
Manufacturer	Custom Servo Motors, Inc., New Ulm, MN
Part Number	MPM1143FRME-947
Type	Brushless DC
Maximum Input Voltage	±10 V DC
Maximum Output	3.12 kW (4.18 hp)
Maximum Operating Speed	3400 RPM
Belt Speed (Range)	
Original Limit	±2 m/s (4.5 mph)
Current Limit	±3 m/s (6.7 mph)
Maximum Possible	±4 m/s (8.9 mph)

As mentioned earlier, the mechanical linkage used to track the user's position (see figure 11) is attached to a gantry made of structural aluminum members bolted together. There are two rotary potentiometers and a rotary encoder that sense the joint angles of the mechanical linkage. The two potentiometers are situated at the upper joint of the mechanical linkage. The rotary encoder is situated where the linkage attaches to the gantry. See table 3 for specifications of the encoder and potentiometers. The adjustable link can be lengthened or shortened to accommodate users of various heights. The lower link is connected to the adjustable link at a biaxial joint. However, this joint does not have any sensors. At the end of the lower link, there is a belt that wraps around the user's waist.

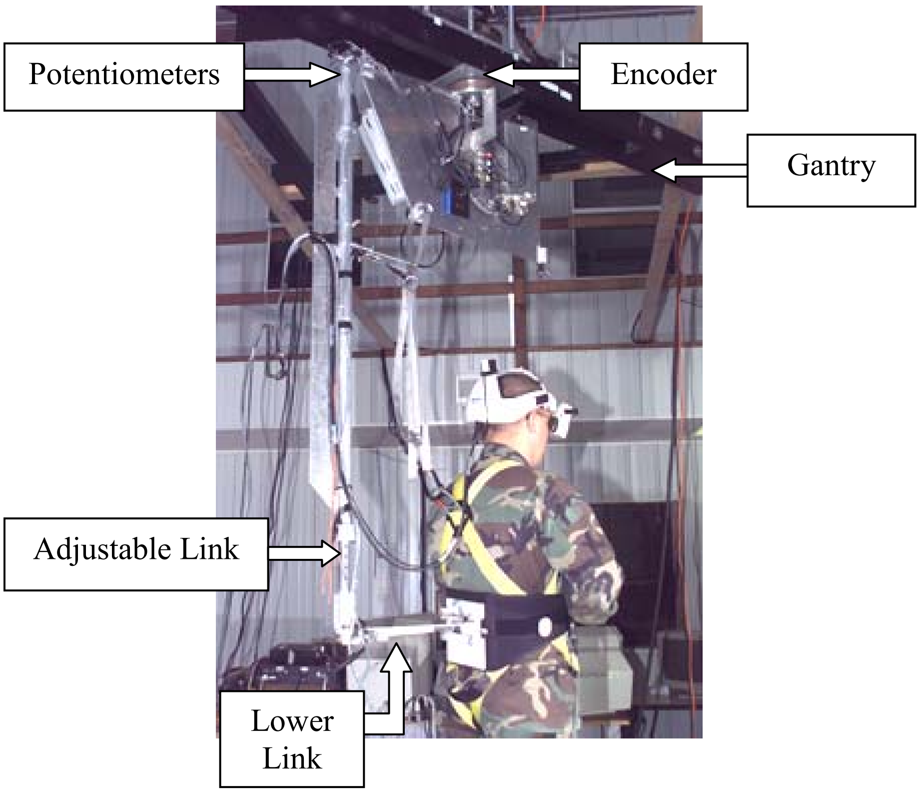


Figure 11. The mechanical linkage.

Table 3. Encoder and potentiometer specifications.

Encoder	
Manufacturer	Hathaway Motion Control, Computer Optical Products, Inc.
Model and Serial Number	4796R, CP-850-12AN-360
Rotation	360 degrees
Resolution	12 bits
Input Voltage	12.6 V DC to 16.6 V DC
Output Voltage	0 V DC to 10 V DC
Potentiometers	
Manufacturer	Unknown
Model and Serial Number	9627, 550T232R5C3B1150K
Rotation	270 degrees

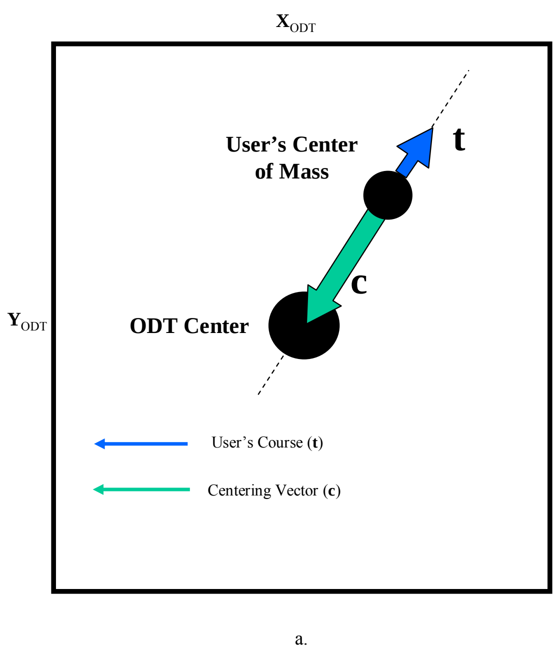
The signals from the encoder and the potentiometers on the mechanical linkage go through an analog-to-digital (A/D) input-output (I/O) board and then into the control computer. The specifications for the A/D board and the control computer are shown in table 4. The control computer uses the signals from the encoder and the potentiometers to move the inner and outer belts so that the user stays centered on the ODT. The control computer also sends the user's speed and direction to the computer that controls the virtual environment. Thus, when the user views the virtual environment, it looks as if s/he were moving through that environment.

Table 4. A/D board and control computer specifications.

A/D Board	
Manufacturer	Versalogic Corporation
Model	M12CT97
Analog Input	16 single ended or 8 differential (16-bit)
Analog Output	2 (12-bit)
Digital I/O Lines	16
Control Computer	
Manufacturer	Ziatech Corporation
Model	ZT89LT02
Microprocessor	single board, 33MHz, 486DX

3.2 Shortcomings of the ODT

Although the ODT is an ingeniously designed device, and it has been operated safely for more than 7 years, it has its shortcomings. In 1997, Darken, Cockayne, and Carmein documented some of the shortcomings noticed during the development of the ODT and at the engineering and user experiments. They noted that the ODT was "extremely loud". At top speeds, the audible noise from the ODT was approximately 85 dB. (The safety release for the ODT requires everyone within 4 m (13 ft) of the ODT to wear hearing protection.) Also, users were limited to upright postures because of the mechanical linkage, and because of limits placed on the servomotors, users were limited to walking or jogging speeds. The most serious problems noted were related to users having difficulty maintaining their balance. When the user turned in place or leaned forward, the control system interpreted that as a signal that the user wanted to begin walking. Thus, the system was prone to false starts. Also, when the user stopped walking, the ODT was supposed to slowly return the user to the center of the ODT's active surface. However, the ODT tended to overshoot this point. Then the ODT quickly reversed direction and again overshot the center. Often, this caused users to become imbalanced until the ODT finally stopped overshooting the center of the active surface. Another serious problem with the ODT involved turning. The ODT's control system was designed to return the user to the center of the active surface along the line through the center of the ODT and the user's center of mass. In the plane of the ODT's active surface, the vector from the user's center of mass to the center of the ODT is called the centering vector, **c** (see figure 12a). If the user made a turn when s/he was not at the center of the ODT, the user's course vector, **t**, (i.e., the direction that the user's center of mass translates) and the centering vector became misaligned (see figure 12b). This misalignment could cause users to become imbalanced because their feet were being returned to the center of the ODT along a vector that was different from their course vector. In order for the user to feel that s/he is moving in the direction of the course vector **t**, s/he must also move laterally (vector **l**) to compensate for the fact that the control system returns the user to the center of the ODT along the centering vector **c**. This has been termed the "skating effect" because, to create the lateral motion, users must push off the sides of their feet much like one does when skating. When side-stepping, users encountered all the problems of false starts, overshooting stops, and misalignment of the course and centering vectors. In fact, Darken, Cockayne, and Carmein (1997) note that the side-stepping task was the only task in their study that caused enough of a stumble to trigger the safety switch to stop the ODT. In summary, Darken, Cockayne, and Carmein (1997) identified audible noise, limitations to the user's postures and movements, and especially instabilities in the control system that tended to cause the users to become imbalanced as the main problems with the ODT.



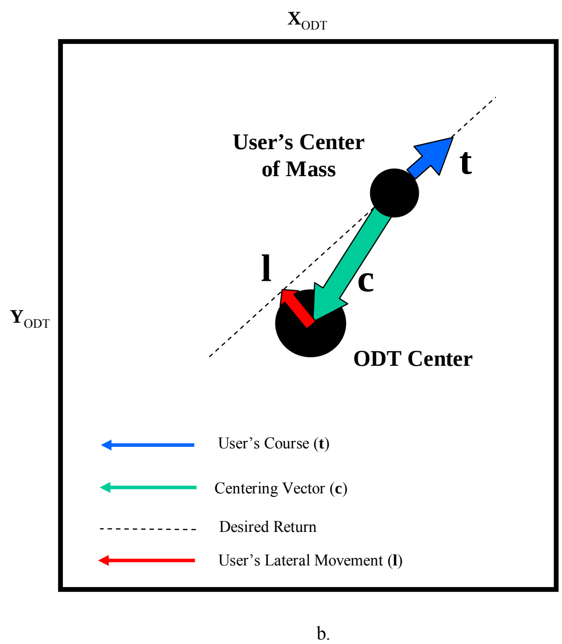


Figure 12. Course and centering vector (a) aligned and (b) misaligned.

After the ODT was brought to ARL, additional problems were discovered:

1. The small size of the active surface limited the step length of users with long legs.

2. Electrical noise in the signals from the encoder and the potentiometers provided false signals to the control system.

3. The processor in the control system computer was slow.

4. Unexpected interruptions from the operating system affected the computational latency and reliability of the control system.

5. In addition to problems with audible noise, the ODT also produced ultrasonic noise that interfered with ultrasonic position sensors.

3.3 Approach to Solving the Problems

After identifying problems associated with the ODT, the ARL team focused on four areas in which to improve the ODT. The first area was improving the accuracy of the tracking system. The second area was reducing the latency in computing the user's position and orientation. The third and most challenging area was developing a control scheme that allowed the user to move more naturally on the ODT. The fourth focus area for the team was reducing the audible noise from the ODT.

3.3.1 Improving the Accuracy of the Tracking System

As previously mentioned, the mechanical linkage, with its encoder and two potentiometers, tracks the user's position on the ODT. Figure 13 shows the locations of the encoder and the two potentiometers. Diagnostic data obtained with software developed for this project indicated very high noise in the signals coming from the encoder and the potentiometers. Figure 14 shows the voltage from the encoder and the potentiometers measured at the point where they entered the data acquisition board. These measurements were made when the mechanical linkage was hanging freely. The voltages should be constant values because there was no movement at the encoder or potentiometers. Obviously, a great deal of noise was entering the system. The main cause for the high noise was the wiring between the sensors (i.e., encoder and potentiometers) and the data acquisition board on the control computer. The wiring from the encoder and the potentiometers to the data acquisition board was done with 6-m-(20-ft)-long, unshielded, parallel cables that were terminated in a single-ended signal mode. This type of wiring is susceptible to interference from all the noise sources in the surrounding environment (i.e., everything from 60-Hz signals in the electric power within the building to radio frequency transmissions).

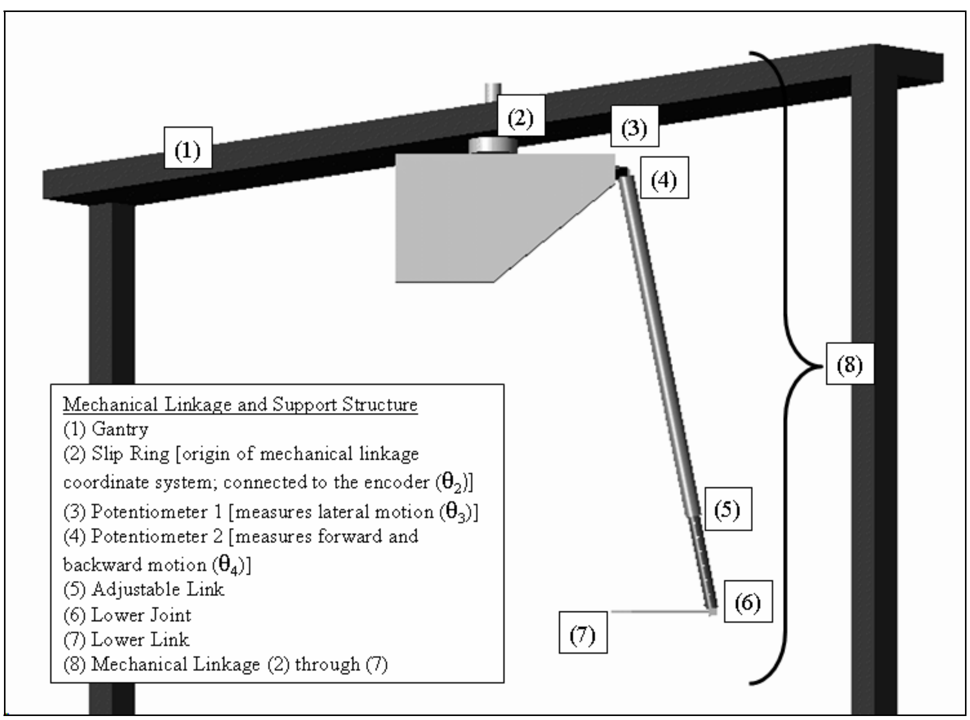


Figure 13. Mechanical linkage and support structure.

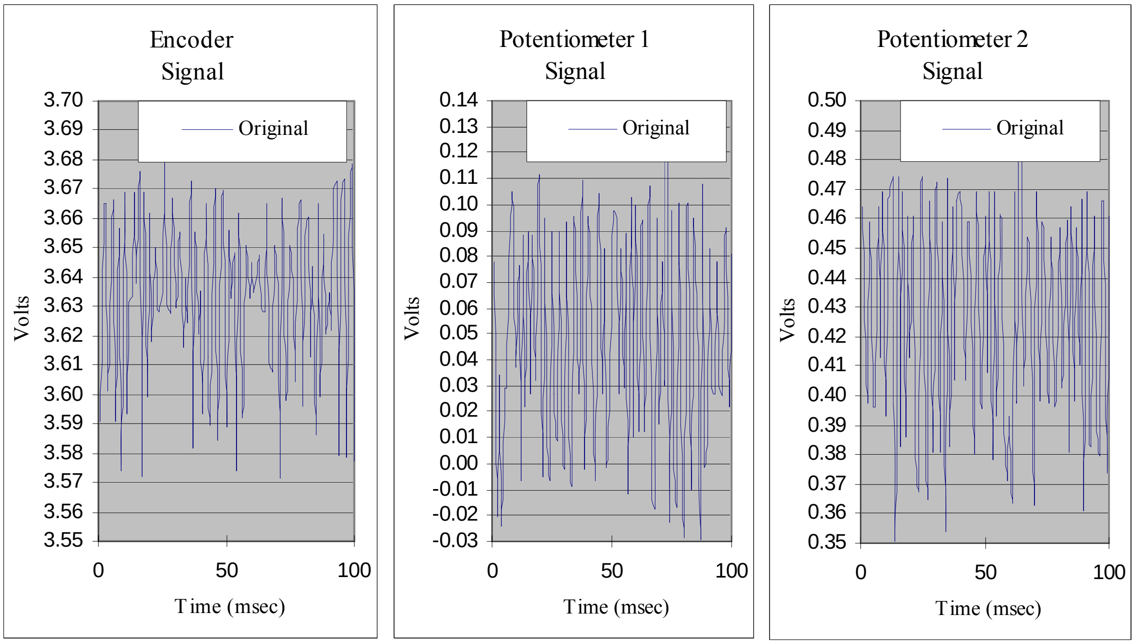


Figure 14. Measurements of voltage entering the data acquisition board when the mechanical linkage hung freely (original wiring).

In order to reduce the noise and increase the signal levels from the encoder and the potentiometers, the ARL team made several hardware modifications. These modifications included changes in the wiring, changes in the power supply for the potentiometers, and reconfiguration of the data acquisition board. The unshielded, parallel cables from the encoder and potentiometers to the data acquisition board were replaced with coaxial cables. The new cables were also separated from the high voltage alternating current (AC) power cables that supplied a force feedback system, which is no longer in use. Both of these actions were taken to reduce the interference from electrical noise in the environment. Next, low-pass filters were added to the sensor signal circuitry just before the connection with the data acquisition board. The low-pass filters block unwanted high-frequency signals. The sensor system circuitry was also re-grounded to eliminate the noise inadvertently contributed by the original grounding scheme. Then the direct current (DC) voltage supplied to the potentiometers was increased from 5 volts (V) to 48 V. In order to keep the input voltage to the data acquisition board within its range of ±10 V DC, another potentiometer was connected to each potentiometer at the upper joint. Figure 15 is a wiring diagram for the potentiometers. These modifications increased the range of the voltage input to the data acquisition board from less than ±2 V DC to approximately ±5 V DC over the range of motion for each potentiometer. Finally, the data acquisition board was reconfigured. The board was changed from 12-bit input to 16-bit input in order to increase signal resolution and reduce quantitization noise, and then the coaxial cables were attached to the board in differential signal mode to eliminate common noise detected along the transmission path.

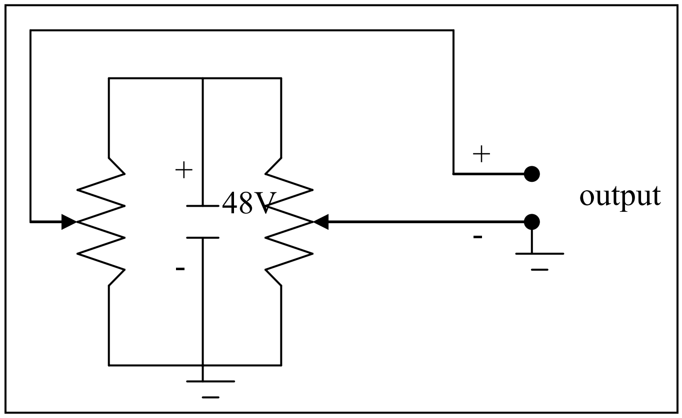


Figure 15. Potentiometer circuit.

All these modifications resulted in substantial reductions in the noise entering the data acquisition board. Figure 16 is a comparison of the original tracking system and the improved tracking system. This figure shows the voltage from the encoder and the potentiometers of the improved tracking system superimposed on the voltages from the original tracking system. These measurements were made when the mechanical linkage was hanging freely. For the improved tracking system, the voltages from the encoder and the potentiometers are closer to being constant values as expected when the mechanical linkage is hanging freely. Figure 17 shows the standard deviations of the same voltages shown in figure 16. The standard deviations for the improved tracking system are more than 80% lower than the standard deviations for the original tracking system. Thus, the modifications of the tracking system provide position data that are much more accurate and more stable than the original tracking system.

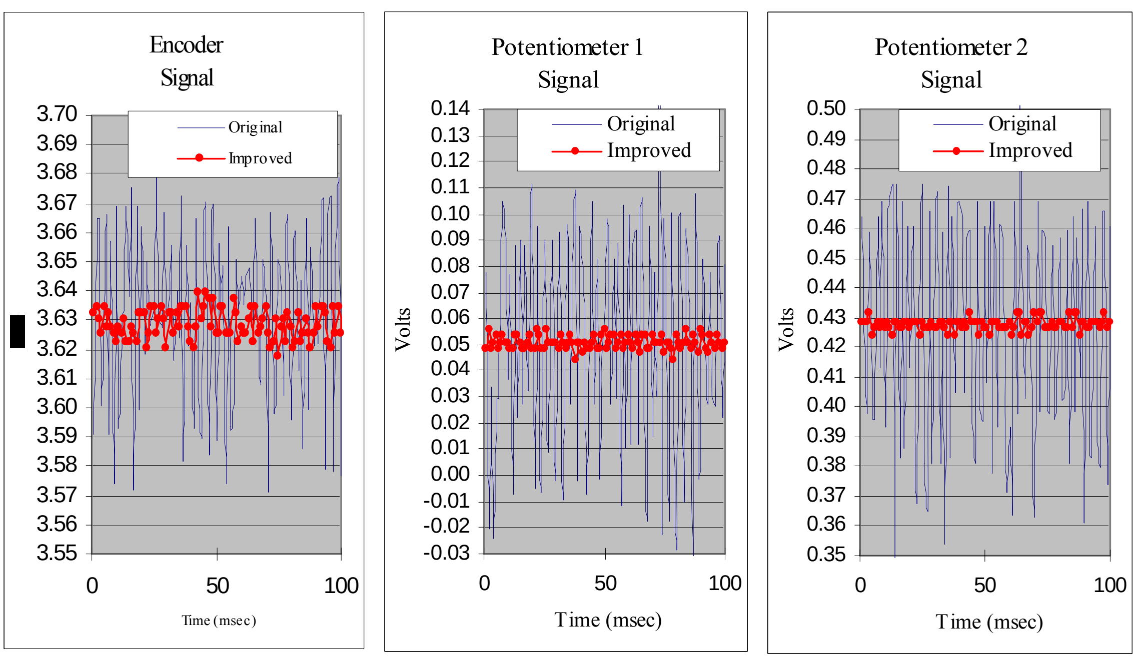


Figure 16. Measurement of voltage entering the data acquisition board when the mechanical linkage hung freely (original and improved wiring).

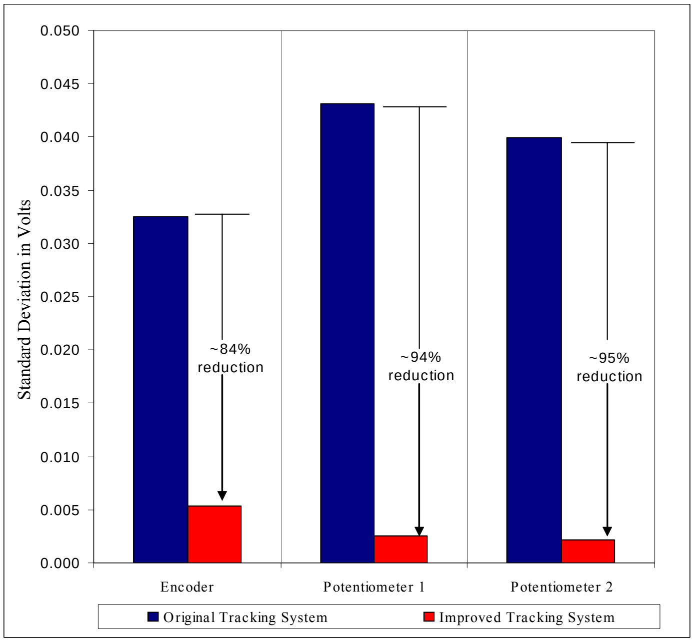


Figure 17. Comparison of standard deviations in the voltages after the improvements in the wiring.

Another improvement in the accuracy of the tracking system was the development of calibration procedures.

3.3.2 ODT Calibration

There are two parts to calibrating the ODT. Part I involves calibrating the rotary potentiometers. This is done to reduce their inherent nonlinear effects. Part II involves locating the origin of the ODT relative to the mechanical linkage coordinate system in order to develop a transformation matrix. This transformation matrix is used to relate user position tracked by the mechanical linkage to the ODT coordinate system.

3.3.2.1 Part I: Potentiometer Calibration

In addition to accounting for the nonlinearities inherent in the potentiometers, the calibration procedure also produces a "look-up" table. This table provides the user's position directly from the voltages output by the encoder and the potentiometers. The table saves time that would otherwise be taken to calculate the user's position from the angles of the mechanical linkage's joints.

Both of the ODT's potentiometers are situated at the top of the mechanical linkage (see figures 11 and 13). The potentiometers were installed on the mechanical linkage in such a way that the voltage across each potentiometer is supposed to be zero when the adjustable link hangs freely. However, it is difficult to mount potentiometers in such a way that the voltage can be adjusted to exactly zero. Therefore, a small error value (also called the zero offset) is recorded for each potentiometer at the beginning of the calibration process.

To calibrate the potentiometers, a template such as the one shown in figure 18 was created. It was printed on a large piece of paper and mounted on a wooden panel. The radius of the arc on the template is equal to the length of the adjustable link of the mechanical linkage (188.8 cm [74-5/16 inches]). The radial lines are spaced 5 degrees apart, and the grid is composed of 2.54-cm (1-inch) squares. A program was written to collect the output voltage from the potentiometers at 5-degree increments. First, the template was aligned with the x axis of the ODT. For movement in the x direction, measurements were made from -15 to 25 degrees. This covered the range of movements that a user could make in the x direction. Then the template was aligned with the y axis of the ODT. In the y direction, the calibration measurements were also made from –15 to 25 degrees. Although users on the ODT stay within the range –15 to 15 degrees in the y direction, calibration measurements were taken as far as 25 degrees because it was easier to measure two additional points during calibration than to modify the calibration program to accommodate a different range for the y direction.

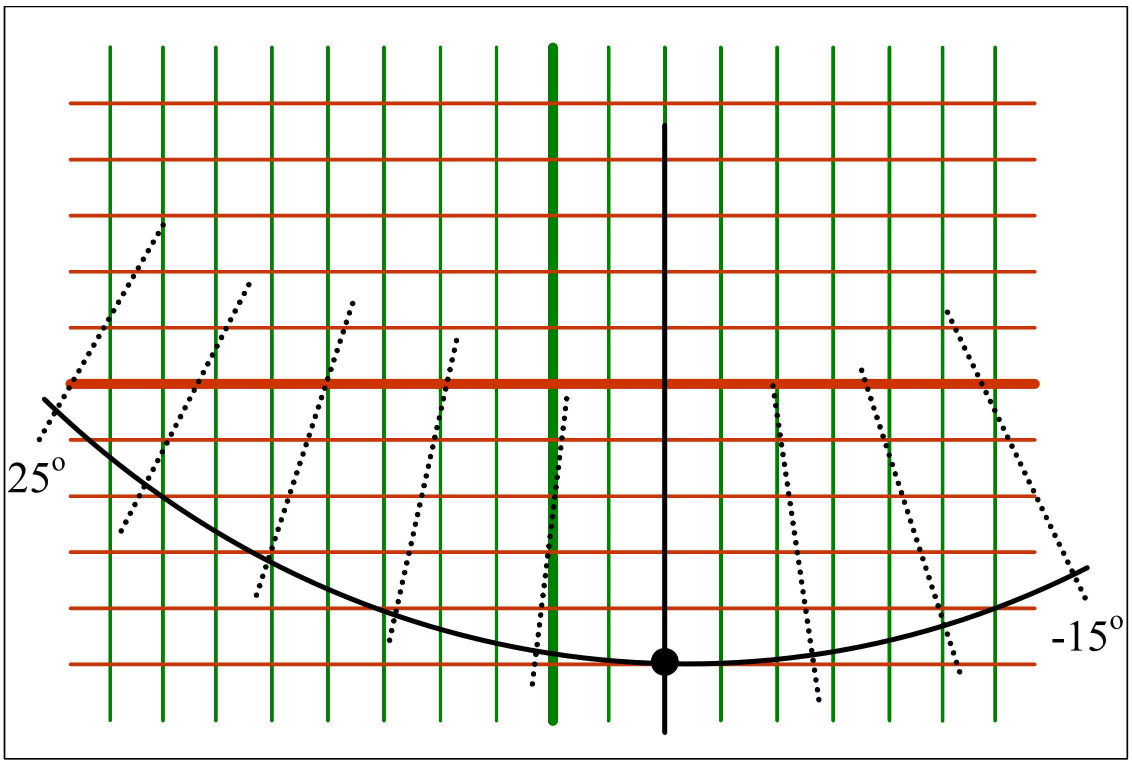


Figure 18. Potentiometer calibration template.

The measurement process always starts at -15 degrees and then proceeds in the positive direction. The first value calculated is the Index_Offset:

$$\text{Index\_Offset} = (v(-15°) - v_o) * 1000 + 0.5$$

in which v(–15°) is the voltage measured when the arm is positioned at –15 degrees and v_o is the zero offset (i.e., the voltage recorded when the mechanical linkage hangs freely). The units for v(–15°) and v_o are volts (V). The difference between v(–15°) and v_o is multiplied by 1000 to convert it to millivolts (mV) and 0.5 mV are added to round the value upward. Thus, Index_ Offset is the potentiometer voltage (in millivolts and corrected for the zero offset) when the adjustable link is at -15 degrees.

Next, the Angle_Index is calculated. Angle_Index is the potentiometer voltage (in millivolts) at each of the measurement points minus the potentiometer voltage when the adjustable link is at -15 degrees.

$$\text{Angle\_Index} = (v(i) - v_o)^* \, 1000 + 0.5 - \text{Index\_Offset}$$

in which v(i) is the voltage for angles: -15, -10, -5, 0, 5, 10, 15, 20, and 25 degrees.

Then the change in angle per millivolt (δa) for each 5-degree increment of the calibration is calculated.

$$\delta a = 5° / ((v(i + 5°) - v(i))^* \, 1000 + 0.5 - \text{Index\_Offset})$$

These formulas were used to generate a look-up table to provide angles corresponding to every 1-mV change referenced by the Angle_Index. The entries in the look-up tables are Angle_Index and Angle. The first entries in the table are Angle_Index = 0 and Angle = -15 degrees. Then in a loop, the Angle_Index and Angle are calculated:

$$\text{Angle\_Index} = \text{Angle\_Index} + 1$$

$$\text{Angle} = \text{Angle} + \delta a$$

Initially, δa is the change in angle per millivolt for the increment from -15 to -10 degrees. The values of Angle_Index and Angle are calculated and entered into the look-up table until Angle_ Index = Angle_Index for –10 degrees. Then the procedure is repeated for each of the 5-degree increments in the x and y directions in order to complete the look-up tables.

3.3.2.2 Part II: ODT Coordinate System Calibration

The main purpose of the ODT coordinate system calibration is to calculate a transformation matrix that will allow points measured in the mechanical linkage coordinate system to be transformed into points in the ODT coordinate system (see figure 19).

The ODT transformation matrix is given by [ODT transform] = [ODT origin translation][ODT rotation around X-axis][ODT rotation around Y-axis][ODT rotation around Z-axis]:

$$ODT_{trans} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ X_o & Y_o & Z_o & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C\theta_x & S\theta_x & 0 \\ 0 & -S\theta_x & C\theta_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\theta_y & 0 & -S\theta_y & 0 \\ 0 & 1 & 0 & 0 \\ S\theta_y & 0 & C\theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\theta_z & S\theta_z & 0 & 0 \\ -S\theta_z & C\theta_z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

in which X_o, Y_o, and Z_o are the coordinates of the ODT origin, and θ_x, θ_y, and θ_z are the rotation angles of the ODT coordinate system relative to the mechanical linkage coordinate system.

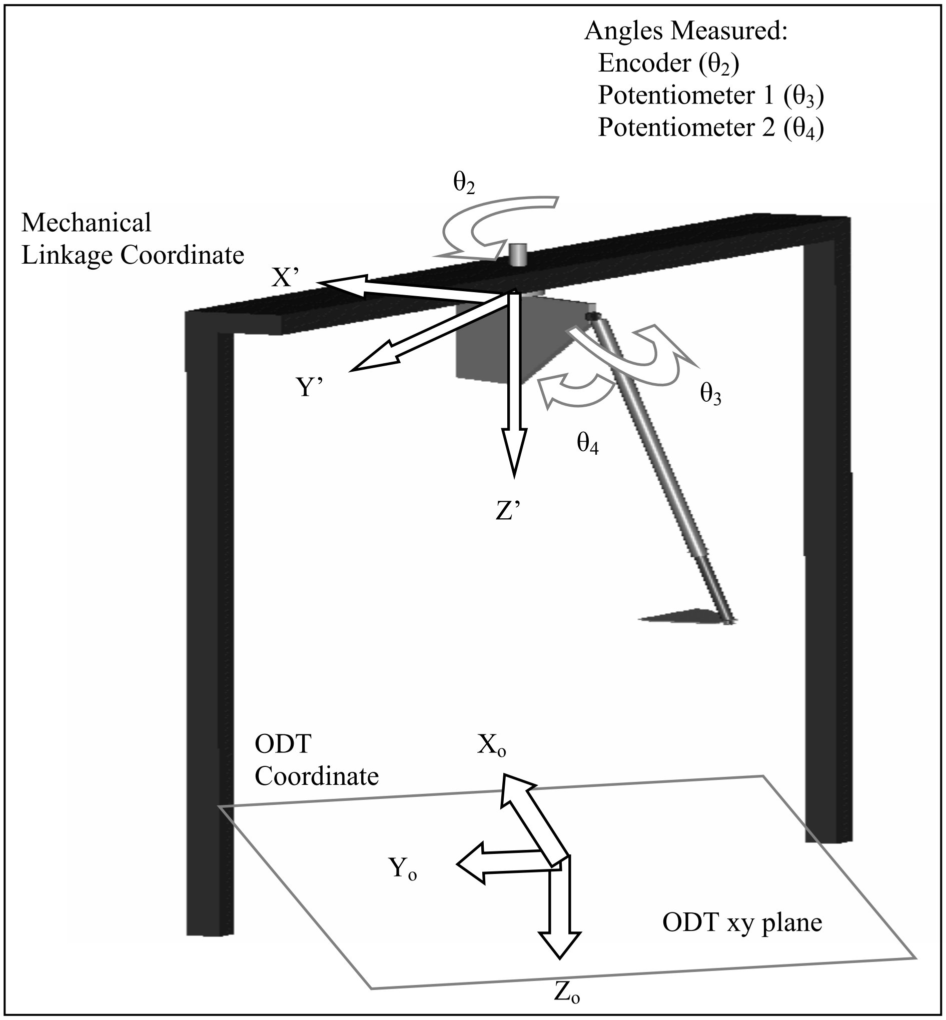


Figure 19. Coordinate systems and angles measured.

In order to locate the origin of the ODT in the mechanical linkage coordinate system and to identify the rotation angles that relate the mechanical linkage coordinate system and the ODT coordinate system to each other, the template shown in figure 18 is placed flat on the ODT. The axes of the template are aligned with the axes of the ODT coordinate system. (As mentioned before, the origin of the ODT coordinate system is located at the center of the ODT, the x axis is parallel to the outer belt movement and the y axis is parallel to the inner belt movement.) The adjustable link is extended so that a pointer at the end of the link can touch the template. The objective is to measure three points on the ODT (the origin of the ODT, one point on the x axis, and one point on the y axis) in order to define the xy plane of the ODT coordinate system relative to the mechanical linkage coordinate system. The formula to calculate the position of the pointer on the template surface is

[End point] = [Zero point][translate to potentiometers'joint X'-direction][translate to end point Z'-direction][rotate around X'-axis][rotate around Y'-axis][rotate around Z'-axis]

$$[x\ y\ z\ 1]_{pointer} = [0\ 0\ 0\ 1]\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\P&0&0&1\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&AL&1\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&C\theta_3&S\theta_3&0\\0&-S\theta_3&C\theta_3&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}C\theta_4&0&-S\theta_4&0\\0&1&0&0\\S\theta_4&0&C\theta_4&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}C\theta_2&S\theta_2&0&0\\-S\theta_2&C\theta_2&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

Here, P is the fixed distance from the center of the slip-ring (origin of the mechanical linkage coordinate system) to the center of potentiometers, and AL is the length of the adjustable link. (P and AL are measured with a tape measure.) The angles θ_2, θ_3, and θ_4 are measured by the encoder, potentiometer 1, and potentiometer 2, respectively, and $C\theta_2$, $S\theta_2$, $C\theta_3$, $S\theta_3$, $C\theta_4$, and $S\theta_4$ are shorthand for the cosines and sines of the angles. Then by positioning the pointer on the template at the origin of the ODT and using the formula, we calculate the location of the ODT origin in the mechanical linkage coordinate system. In these procedures, the most important parts are calibration of the x and y coordinates; the z coordinate is ignored.

The next step is to determine the rotation angles around the x, y, and z axes of the ODT coordinate system. The ODT coordinate system is formed by two vectors on the ODT plane (the x axis and y axis) and their normal vector at the center of the ODT. The procedures just used to locate the origin of the ODT in the mechanical linkage coordinate system are repeated to locate a point on the x axis and a point on the y axis. These three points form two vectors: OX and OY on the ODT surface. The cross product of these two vectors gives the vector OZ, which is perpendicular to the surface of the ODT. The vector OZ is then normalized to obtain a unit vector normal to the ODT plane in the mechanical linkage coordinate system.

In order to calculate the rotation of the ODT coordinate system relative to the mechanical linkage coordinate system, the normal vector is projected onto each plane. If the normal vector is projected onto the yz plane, the x component will be zero and its coordinate on the yz plane will be

$$n_{yz} = (0, y_n, z_n)$$

The z axis unit vector (u_z) in the mechanical linkage coordinate system is

$$u_z = (0,0,1)$$

The angular rotation around the x axis, θx, can be calculated as the arccosine of the dot product of the normal vector n_{yz} in the xy plane and unit vector u_z as follows:

$$\theta_x = \mathrm{acos}[(n_{yz}.\ u_z)/|n_{yz}|]$$

Similarly, if the normal vector is projected onto the xz plane, the y component will be zero and the vector will be

$$n_{xz} = (x_n, 0, z_n)$$

Then the angular rotation around the y axis, θ_y, will be

$$\theta_y = \text{acos}[(n_{xz} \cdot u_z)/|n_{xz}|]$$

To determine rotation about the z axis, θ_z, the vector OY is multiplied by the following transform:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ X_o & Y_o & Z_o & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C\theta_x & S\theta_x & 0 \\ 0 & -S\theta_x & C\theta_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\theta_y & 0 & -S\theta_y & 0 \\ 0 & 1 & 0 & 0 \\ S\theta_y & 0 & C\theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

To give OY'.

Then θ_z is calculated as follows:

$$\theta_z = \text{acos}((OY' \cdot u_y)/|OY'|)$$

in which u_y is the unit vector along the y axis:

$$u_y = (0,1,0)$$

Finally, the values calculated for θ_x, θ_y, and θ_z are substituted into the equation given previously for the ODT transform. Then with the following formula, the ODT transform is multiplied by the vector that locates any point in the mechanical linkage coordinate system in order to locate that point in the ODT coordinate system.

$$[x\ y\ z\ 1]_{ODT} = [x\ y\ z\ 1]_{\text{mechanical linkage}} \times [\text{ODT transform}]$$

3.3.3 Reducing Computational Latency and Increasing Reliability

Although the computer and data acquisition board that were delivered with the ODT were adequate to operate the ODT, look-up tables were added to the control code, and the operating system was changed in order to reduce the computational latency and increase reliability. In addition to the look-up table generated in Part I of the calibration, look-up tables were generated for routine mathematical computations such as sines and cosines. These look-up tables reduced the number of real-time calculations that needed to be made. Also, the operating system for the control computer was changed from Windows[3] 95 to Microsoft-Disk Operating System (MS-DOS) to eliminate the periodic interruptions and increase reliability.

3.3.4 Development of a New Control Scheme

After improving the accuracy of the tracking system, developing calibration procedures, and changing the operating system for the ODT, the next step was to develop a new control scheme. This involved three steps: (a) identification of dynamic system characteristics of the ODT,

[3]Windows and MS-DOS are trademarks of Microsoft Corporation.

(b) development of a system model, and (c) development and implementation of a new control algorithm. In a series of experiments, we identified characteristics of the ODT that allowed us to define it mathematically. This mathematical representation of the ODT's characteristics was used to develop a system model to represent the ODT. With this system model, we simulated various conditions that are important to effective control of the ODT. Finally, the system model provided the basis of the control algorithm that was implemented to improve the performance of the ODT. The details of each of these steps are presented in the next three sections.

3.3.4.1 System Identification Experiment

The first step in designing a new controller for the ODT was to identify the system dynamics. An experiment was conducted to characterize the system and define a transfer function for the ODT. The experiment was conducted in three phases. The first phase focused on identifying a transfer function for the outer belt and its drive train in response to a unit step change in voltage under various loads. The second phase focused on identifying a transfer function for the inner belt and its drive train in response to a unit step change in voltage under various loads. The third phase focused on identifying transfer functions for the belts and drive trains in response to voltage changes in excess of a unit step. The transfer functions that were identified in each of the three phases of this experiment were used to define one transfer function that characterizes the ODT. This transfer function was used as the baseline model for the system. Then a new control algorithm for the ODT was developed from this baseline model.

The methods and materials used in each phase of the system identification experiment were similar. To provide discrete voltage changes for the motors, the belts were activated and controlled with commands entered via the ODT control computer's keyboard. Sandbags were added to a wooden box placed on the active surface of the ODT to incrementally vary the load. Each sandbag weighed approximately 18.2 kg (40 lb). An optical position-measuring system from Motion Analysis Corporation (Santa Rosa, California) was used to provide an independent measure of the belt position and velocity for each trial.

The first phase of the experiment focused on the outer belt's response to load changes, given a unit voltage input. Data were collected with the Motion Analysis system and analyzed by MATLAB[4]. Figure 20 displays the response to a unit voltage input with no sandbags in the box on the belt. The blue curve represents actual data and the red curve represents a fitted dynamic model for the outer belt (i.e., motion in the x direction).

[4]MATLAB is a registered trademark of The MathWorks, Natick, Massachusetts.

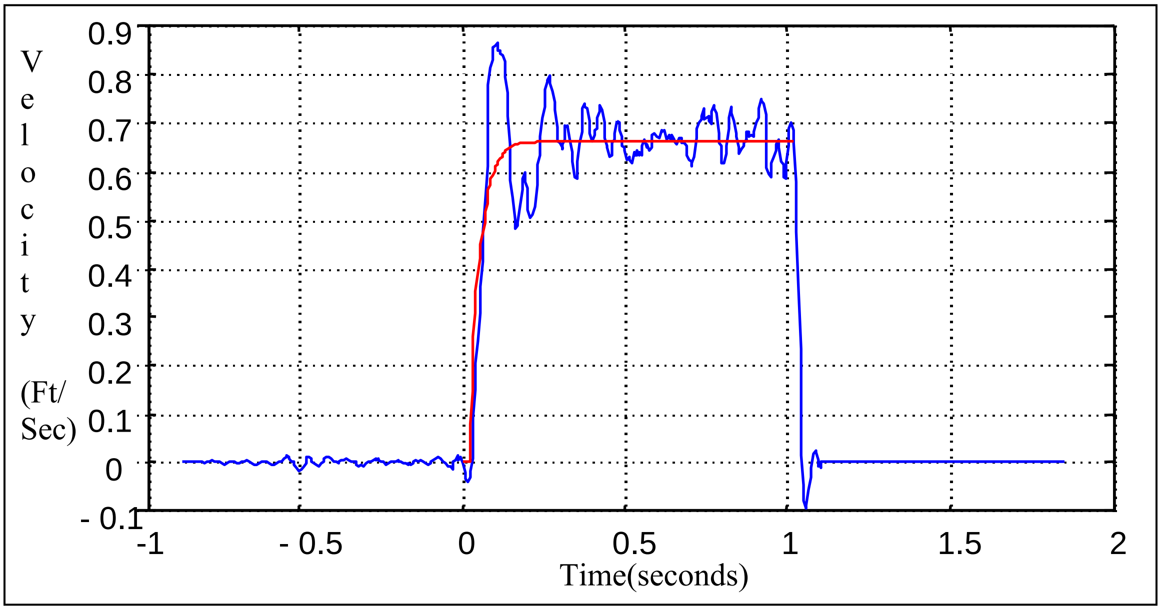


Figure 20. Velocity response of the outer belt to a unit voltage step input.

Regardless of the load in the box, the response for each condition produced a similar curve, yielding the following transfer function:

$$TF_x = (.66*e^{-0.06s})/(0.035s+1)$$

In the second phase of the experiment, the response of the inner belt and its drive train to a unit voltage input under various load conditions was measured. Figure 21 displays the response to a unit voltage input with no sandbags in the box on the belt. The blue curve represents actual data and the red curve represents a fitted dynamic model for the inner belt (i.e., motion in the y direction). Note that the curve for the y-belt response is inverted because the data were captured in the negative y direction.

Again, regardless of the load in the box, the response for each condition produced a similar curve. The transfer function for the inner belt is as follows:

$$TF_y = (.67*e^{-0.1s})/(0.04s+1)$$

The third phase of the experiment was performed to examine the response to increasing step changes greater than 1 V. For each trial, the belt was loaded with four sandbags. Three trials were run for each belt, in which a 2-, 3-, and 4-V step input was applied to the motors. Both the inner and outer belts behaved the same and produced curves similar to those of figures 20 and 21. The transfer functions for the three step changes in voltage are

$$TF_{2v} = (.68*e^{-0.06s})/(0.05s+1)$$

$$TF_{3v} = (.67*e^{-0.06s})/(0.05s+1)$$

$$TF_{4v} = (.66*e^{-0.03s})/(0.08s+1)$$

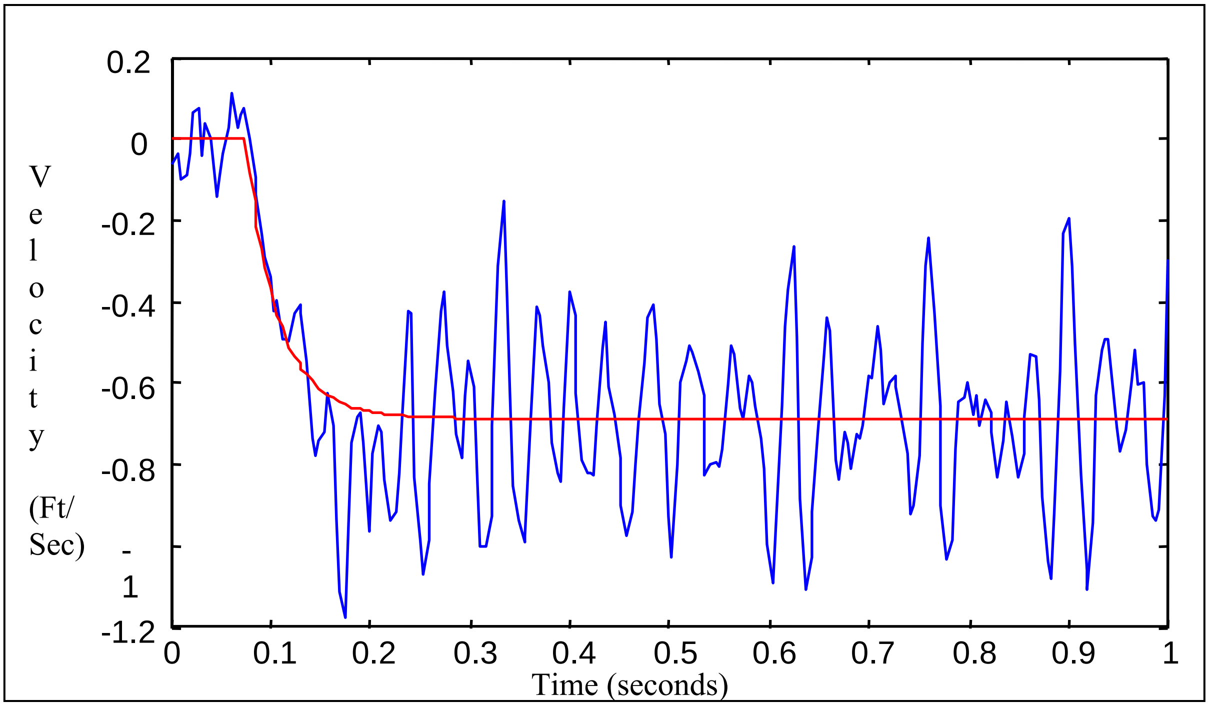


Figure 21. Velocity response of the inner belt to a unit voltage step input.

Notice that the time constant was approximately 0.04 second for the 1-V step input. For the 2-V and 3-V step input, the time constant was 0.05 second, and for the 4-V step input, the time constant was 0.08 second. This indicates nonlinearity in the system's response to large voltage increases, which is undesirable. However, for incremental increases in input voltage, the ODT's response was linear. Fortunately, the ODT will not be required to accept large input voltage steps. Time delays in human movement are such that the voltage changes will not be large step changes. Rather, the changes will occur incrementally. Thus, one transfer function can be used to describe the behavior of the ODT.

The transfer function that best describes the behavior of the ODT is

$$TF_{ODT} = (0.67*e^{-0.035s})/(0.035s+1)$$

This baseline transfer function has a DC gain of 0.67 foot per second, a time delay of 0.035 second, and a time constant of 0.035 second. The time constant is smaller than might have been indicated by the experiment, but 0.035 second was chosen so that the controller would be more conservative (i.e., not overshoot the steady state velocity goal) and be more robust to system changes over time (i.e., less prone to deviate from steady state as a result of signal changes that may occur over time).

3.3.4.2 System Model

The baseline ODT system transfer function that was developed as a result of the system identification experiments provides control based on velocity. However, we want to control the ODT based on the position of the user. Thus, the baseline ODT system transfer function was multiplied by the unit integrator 1/s to yield

$$TF_{ODT} = (0.67*e^{-0.035s})/ (s*(0.035s+1))$$

Now a change in voltage signals a change in the user's position. Note that the baseline model is now a second order system having an additional pole with the root equal to zero in the denominator. This enhances stability and makes the system ideal for a proportional-integral-derivative (PID) controller. For systems that are second order, a PID controller is optimal because any closed loop behavior can be achieved, provided that there is no time delay. The time delay for the ODT's motors, while not zero, is small enough that a PID controller was chosen to provide control for the ODT. The system model is shown in figure 22.

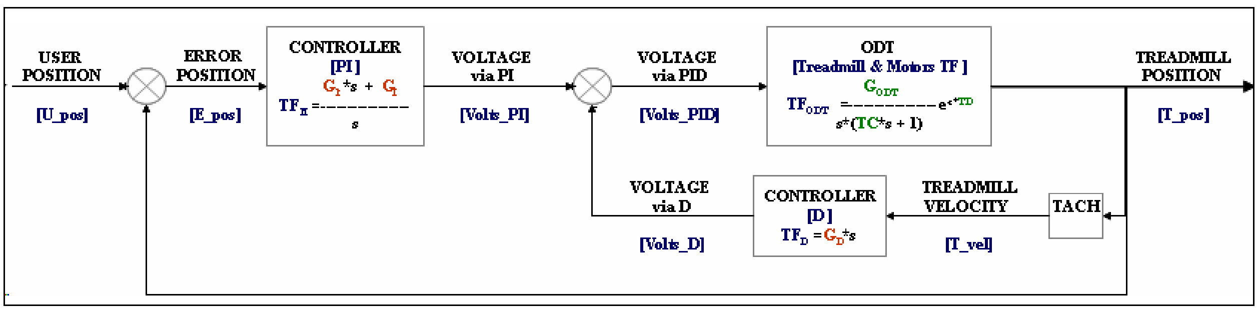


Figure 22. System model.

Reduction of the system model yields a closed loop transfer function as follows:

$$TF_{sys} = \frac{T\_pos}{U\_pos} = \frac{Se^{-s*TD} * G_P * G_{ODT} + e^{-s*TD} * G_I * G_{ODT}}{S^3 TC + S^2\left(1 + G_D e^{-s*TD} G_{ODT}\right) + Se^{-s*TD} * G_P * G_{ODT} + e^{-sTD} * G_I * G_{ODT}}$$

Once again, MATLAB was used to perform a cycle of modeling, simulation, and analysis to yield the final values for the PID controller in order to provide a stable and robust control system. Figure 23 shows the final system model, which was created and evaluated with Simulink[5].

Analysis of the response to a unit step input for the closed loop system, as shown in figure 24, indicates the desired results. Note that the system settles in about 1 second for a unit step change in voltage input to the motor.

Also, note that there is no overshoot in the response, which means that the system will not return the user past the starting point on the ODT. This eliminates the unsteadiness that users experienced with the original control system as a result of oscillations by the system as it returned the user to the starting point.

[5]Simulink is a registered trademark of The MathWorks.

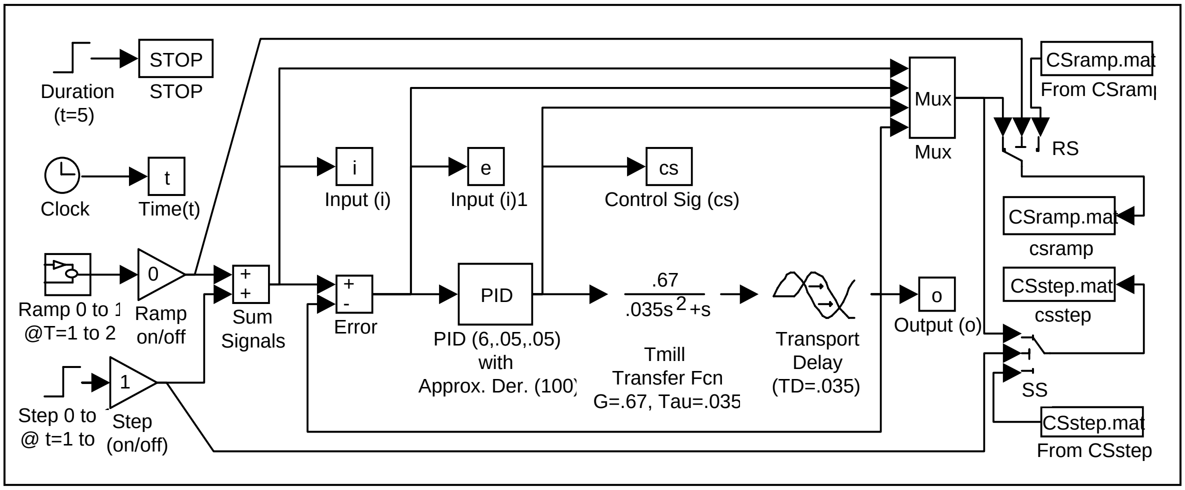


Figure 23. Final system model.

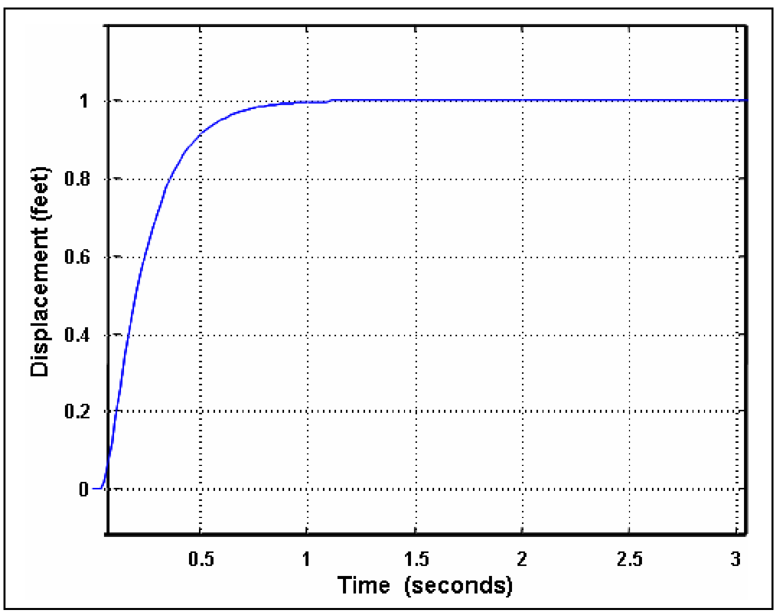


Figure 24. Response of the ODT system model to a unit voltage step input.

3.3.4.3 Control Algorithm and Software

The system model that was created as a result of the system identification experiments was used as the basis of the improved control algorithm for the ODT. The new control algorithm overcomes many of the shortcomings of the original control algorithm. The new algorithm was created so that the ODT would not have false starts or overshoot stops. It was also designed so that initiating and terminating gait would be smooth and natural for the user. Most importantly, the new control algorithm was created to handle the mismatch between the centering vector and the user's course in a way that allows the user to turn more naturally and to side step.

To eliminate false starts and to smooth the initiation and termination of gait, the active surface was divided into two control zones. The first control zone is the space inside a small circle around the user's initial position. This circle has a 15.24-cm (6-inch) radius. The second control zone is the space outside that circle. Each zone has a different control model with different gain, integration time, and derivative time. The transition between these two zones is smoothed, based on the speed of the user when s/he reaches the border of the circle.

In order to handle the mismatch between the user's course and the centering vector, a floating coordinate system was developed. In essence, this system moves with the user. It has its origin at the user's center of mass (COM). The x axis is the direction that the user is facing, and the y axis and z axis are defined by a left-handed coordinate system in which the z axis points downward. The user is returned to the center of the ODT along the x and y axes of the floating coordinate system (see figure 25). The speed with which the user is returned along the x axis of the floating coordinate system is the speed at which the user is moving in the x direction of the floating coordinate system. The speed with which the user is returned along the y axis of the floating coordinate system is below the threshold of the user's perception of movement. This reduces the "skating effect" associated with the original control algorithm.

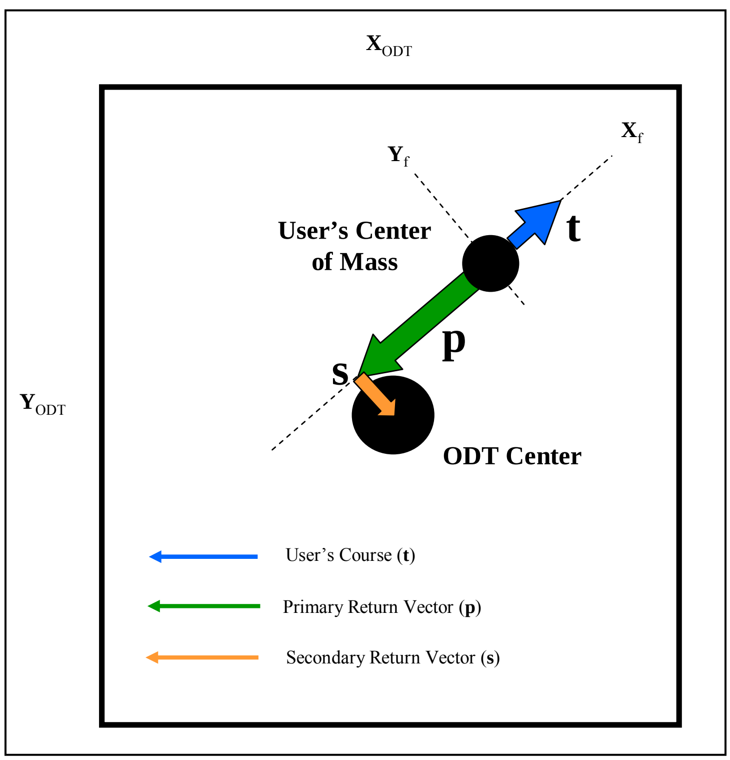


Figure 25. Floating coordinate system.

In order for the tracking system to give the user's position and direction in terms of the floating coordinate system, several coordinate transformations must be made. In fact, three coordinate systems are used in order to calculate the user's position for control purposes. These coordinate systems are the mechanical linkage coordinate system, the ODT coordinate system, and the floating coordinate system.

The mechanical linkage coordinate system is designated as O', X', Y', Z' (see figure 26). The origin of this coordinate system is located along the axis of the encoder where it intersects with the bottom of the slip ring. The Z' axis points down with the gravity line. The X' axis is determined by the direction of the encoder when it gives a reading of zero volts. The Y' axis is perpendicular to the X' axis and the Z' axis so that it forms a left-handed coordinate system.

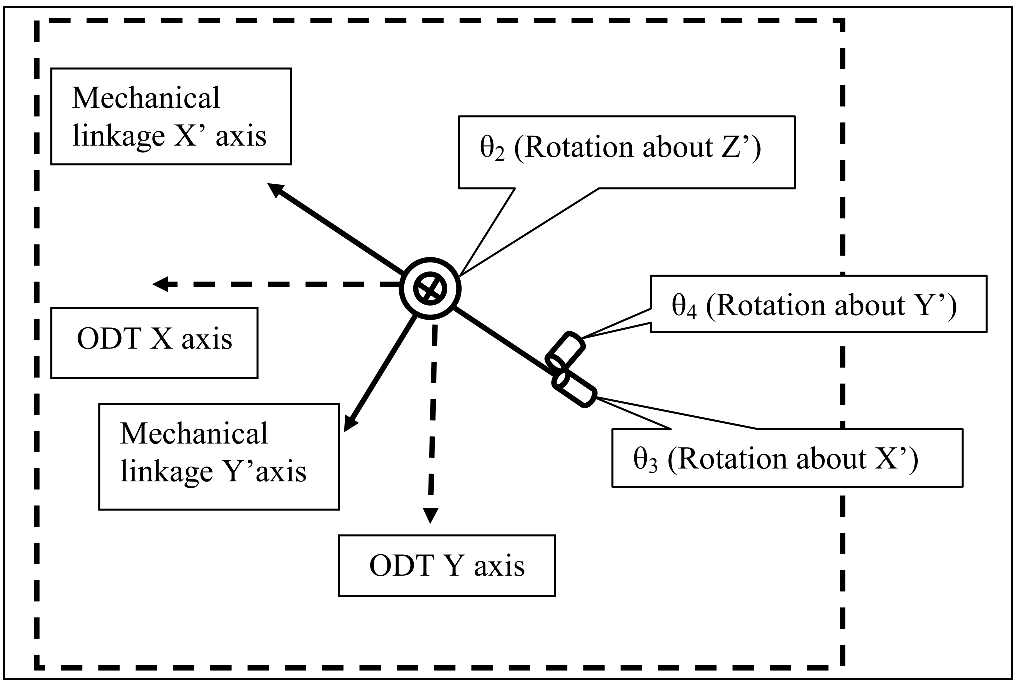


Figure 26. Top-down view of the mechanical linkage coordinate system (X', Y', Z') and the ODT coordinate system (X, Y, Z). (The Z' and Z axes point downward.)

The ODT coordinate system designated O, X, Y, Z, is a coordinate system in which the origin is located at the center of the active surface. The positive X axis is the direction that the user is moving when a positive voltage is applied to the servomotor that drives the outer belt. This rule is also applied to determine the positive Y axis. If the user moves along the positive y axis, a positive voltage will be applied to bring the user back to the center. The Z axis is downward, forming another left-handed coordinate system, as shown in figure 26.

The user's position in the mechanical linkage coordinate system and the ODT coordinate system are used to determine his or her position in the floating coordinate system. When the user moves, the angles θ_4, θ_3, and θ_2, which rotate around Y', X', and Z' axes, respectively, in the mechanical linkage coordinate system are calculated from the potentiometer and encoder signals. Assuming that the distance from the origin of the mechanical linkage coordinate system to the center of the potentiometers is the same as the distance from the user's center of mass to the end point of the adjustable link, the mathematical formula used to calculate the coordinate (x, y, z) of the user's center mass in the mechanical linkage coordinate system is

[Center of mass point in the mechanical linkage coordinate system] = [point at zero] x [translation of arm length] x [rotation around X'-axis] x [rotation around Y'-axis] x [rotation around Z'-axis]

$$[x\ y\ z\ 1]_{User'sCOM} = [0\ 0\ 0\ 1]\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&AL&1\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&C\theta_4&S\theta_4&0\\0&-S\theta_4&C\theta_4&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}C\theta_3&0&-S\theta_3&0\\0&1&0&0\\S\theta_3&0&C\theta_3&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}C\theta_2&S\theta_2&0&0\\-S\theta_2&C\theta_2&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

in which AL is the length of the adjustable link, Sθ and Cθ are shorthand for sine and cosine of the angle θ, respectively. Then this point in the mechanical linkage coordinate system is transformed into the ODT coordinate system as follows:

[ODT point] = [mechanical linkage point] x [ODT translation] x [ODT rotation around X'] x [ODT rotation around Y'] x [ODT rotation around Z']

$$[x\ y\ z\ 1]_{ODT} = [x\ y\ z\ 1]_{mechanical\,linkage}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\x_o&y_o&z_o&1\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&C\alpha_1&S\alpha_1&0\\0&-S\alpha_1&C\alpha_1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}C\alpha_2&0&-S\alpha_2&0\\0&1&0&0\\S\alpha_2&0&C\alpha_2&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}C\alpha_3&S\alpha_3&0&0\\-S\alpha_3&C\alpha_3&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

in which x_o, y_o, z_o is the coordinate of the ODT center in the mechanical linkage coordinate system and α_1, α_2 , and α_3 are the rotations of the ODT coordinate system relative to the mechanical linkage coordinate system. The rotations of the ODT coordinate system relative to the mechanical linkage coordinate system are determined in the calibration process, which was described in section 3.3.2.2.

Finally, the user's COM position is transformed into the floating coordinate system for control purposes:

[course point] = [ODT point] x [course translation] x [course rotation around Z]

$$[x\ y\ z\ 1]_{course} = [x\ y\ z\ 1]_{ODT}\begin{bmatrix}1&0&0&0\\1&0&0&0\\1&0&0&0\\x_g&y_g&z_g&1\end{bmatrix}\begin{bmatrix}C\theta_2&S\theta_2&0&0\\-S\theta_2&C\theta_2&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

in which x_g, y_g, z_g are the coordinates of the user's initial position (or goal position) in ODT coordinate system. Note, only rotation about the Z' axis (θ_2) is used to determined the user's course.

The control algorithm is implemented through a closed loop PID controller. Figure 27 is a block diagram of the ODT controller. In this control scheme, $e_n(t)$ = Error at time t = Goal position – User position; $U_n = e_n * PI$, and it is derived as follows: The Laplace transformation of the proportional – integral (PI) controller has the form: $PI = K(1 + 1/T_i s)$, in which K is the gain of the PI controller and T_i is the integral time. Next, the continuous Laplace transformation is converted into a digital z transformation for implementation by replacing s with

$$S = 2/T\ (1 - z^{-1}/1 + z^{-1}),$$

in which T is sampling time.

Then $U_n(z) = e_n(z) * PI = K[(1 + (1 + z^{-1})T)/(2Ti(1-z^{-1}))] * e_n(z)$.

With some simple rearrangement,

$$U_n(z) = u_n(z)z^{-1} + K[(1 + T/2Ti)e_n(z) - (1 - T/2Ti)z^{-1}e_n(z)].$$

Converting back to time domain

$$U_n(t) = u_n(t\text{-}1) + K[((1 + T/2T_i)e_n(t) - (1 - T/2T_i)e_n(t\text{-}1), \text{ and } U_m(t) = u_n(t) - T_d * \text{belt speed}.$$

In this implementation, the belt speed is obtained directly from the servomotors and fed back to the A/D converter for control calculations. Thus, this control scheme is designed to return the user to the starting point by moving him or her along the x and y axes of the floating coordinate system. This control scheme was implemented in the C programming language. It is run on the control computer via MS-DOS.

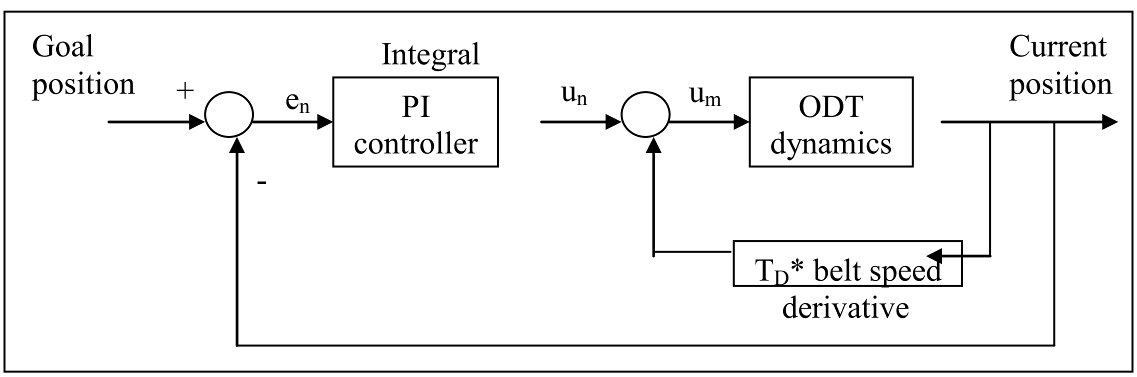


Figure 27. Block diagram of the ODT control.

3.3.5 Reducing Audible Noise

The focus of this task was to build an enclosure that would reduce the noise emitted by the ODT. The noise-reduction enclosure is shown in figure 28. It surrounds the sides of the ODT, and it has an opening so that the user can move on the active surface. The noise-reduction enclosure was constructed of 5-cm by 10-cm (2-in. by 4-in.) wood framing, 1.3-cm (0.5-in.) and 1.9-cm (0.75-in.)

plywood, and was lined with 5-cm-(2-in.)-thick sound absorption foam. The foam is Soundmat[6] plastic barrier, with a 0.0015-inch-thick Tedlar[7] coating manufactured by the Soundcoat Company (Deer Park, New York). Soundmat is a flexible, open cell, polyester foam that has a plastic barrier sand-wiched between two layers of foam. The pressure-sensitive adhesive backing on the foam was used to attach it to the interior surfaces of the noise reduction enclosure. The foam was installed with overlapping joints or compression seams to prevent sound leaks, and each joint or seam was then sealed with duct tape to provide a smooth, continuous surface on the interior of the enclosure.

Figure 28. Noise-reduction enclosure.

To evaluate the effectiveness of the noise-reduction enclosure, three sets of noise measurements were made. The first series of noise measurements was made to determine if there were differences in the noise generated by the X belt, the Y belt, or both belts run simultaneously. These measurements were made with a Nortronics model 830B real-time analyzer. The microphone was a Bruel & Kjaer 4136 condenser microphone calibrated with a 4220 piston phone at a sound pressure level of 124 dB. All the sound measurements were taken in Building 518 at APG where the ODT was situated. The perimeter around the ODT was cleared of all ancillary equipment and furniture when the measurements were taken. This was done to minimize any sound reflections.

Readings were taken at several locations approximately 5 cm (2 in.) above the active surface of the ODT (see figure 29; locations marked with black circles). Because the readings were consistent at each location, only one measurement was recorded for each belt and velocity combination.

We controlled belt speeds by setting the voltage supplied to the drive motors. This was done through the ODT control computer. The voltages selected were 0.5, 1, 2, 5, and 7 V. This range of voltages covered the range of speeds that a user might travel on the ODT (i.e., crawling [0.15 m/s] to jogging [2.1 m/s]).

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[6]Soundmat and Soundcoat are registered trademarks of the Soundcoat Company.
[7]Tedlar is a registered trademark of DuPont.

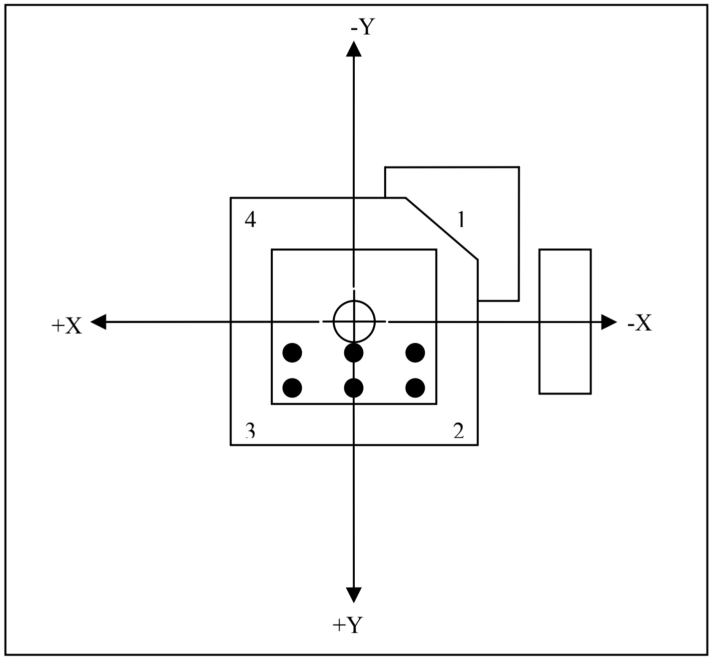

Figure 29. Locations of belt noise measurements.

The data collected (see table 5) indicate that the sound levels when the X and Y belts were run together were essentially the same as when the Y belt was run by itself. Therefore, subsequent sound measurements were taken for the Y belt running in the positive direction.

Table 5. Noise levels.

	Noise Level (dBA)				
	Belt and Direction of Movement				
Input Voltage	**+x**	**-x**	**+y**	**-y**	**+x & +y**
0.5	72	74	84	84	84
1	83	84	94	95	94
2	94	94	104	104	105
5	108	108	114	114	114
7	112	112	118	116	116

Next, a series of measurements was made to determine if there were differences in noise as a function of location around the ODT (see figure 30). Locations A through E represent places where visitors might stand and watch a demonstration of the ODT. These points are approximately 1.8 m (6 ft) from the noise-reduction enclosure. Location F is the position for the ODT operator. The operator stands behind a tall table that holds two monitors, keyboards, and other equipment needed to run the ODT. The measurements at locations A through F were taken at 157 cm (62 in.) above the ground. This is the average between the ear height of a 90th percentile male and a 5th percentile female. This average was selected to simplify data collection because the sound levels did not change between the heights of 137 cm (54 in.) and 178 cm (70 in.). The user measurements (locations G, H, and I) were taken at the center of the belt area at heights of 61 cm (24 in.), 137 cm (54 in.), and 178 cm (70 in.) above the belt surface. These locations represent the approximate ear height for users crawling (hands and knees), ear height of a 5th percentile female, and ear height of a 90th percentile male, respectively. A measurement was taken diagonally 6.7 m (22 ft) from one corner in order to examine the sound level as a function of distance from the ODT. Two input voltages were selected for this series of measurements: 2 V and 5 V. These represent slow walking and jogging speeds, respectively.

The data in table 6 show that the highest noise levels occurred in the center of the ODT where the user would be located (positions G, H, and I). The noise levels at the locations for the operator and visitors are essentially the same.

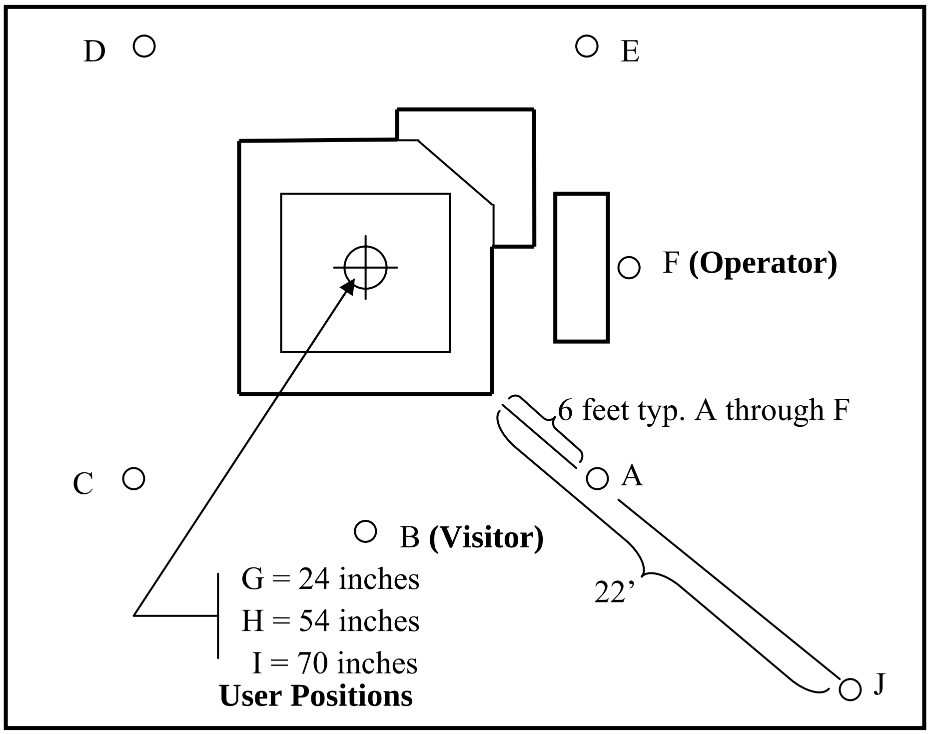

Figure 30. User, visitor, and operator locations.

Table 6. Noise levels at user, visitor, and operator locations.

	Noise Level (dBA)	
	Input Voltage	
Position	2v	5v
A	85	95
B	86	96
C	86	95
D	86	96
E	86	95
F	85	95
G	97	107
H	92	102
I	89	98
J	-	90

In the final series of measurements, the objective was to compare the noise emitted by the ODT for three conditions: (a) without the noise reduction enclosure, (b) with the noise reduction enclosure in place, and (c) with the noise-reduction enclosure in place and Soundmat PB foam on the floor underneath the ODT. Data were collected at the locations occupied by the visitor (B), operator (F) and user (G, H, and I). The input voltages to the motor were 2 V and 5 V.

Table 7 shows the results of these measurements. For the user's location at the 61 cm (24 in.) and 137 cm (54 in.) heights, the highest noise levels occurred when the noise-reduction enclosure was in place. This may be because noise was reflected off the floor, and its only means of escape from the noise-reduction enclosure was through the opening for the active surface of the ODT. When the sound-absorbing foam was placed on the floor under the ODT and the noise-reduction enclosure was in place, the noise reductions ranged from 0.5 dB(A) to 2.1 dB(A) for a 2-V input and 1.1 dB(A) to 1.5 dB(A) for a 5-V input. The foam on the floor probably reduced the noise that was reflected off the floor and out through the opening in the noise-reduction enclosure.

Table 7. Final series of noise measurements.

Noise Level (dBA)					
Volts	**Position**	**Height**	**Without Noise Reduction Enclosure**	**Noise Reduction Enclosure**	**Noise Reduction Enclosure with Foam on the Floor**
2	Operator	65	83.1	81.8	82.3
2	User	24	94.9	95.6	94
2	User	54	90.3	92.1	90
2	User	70	88.9	88.7	88.4
2	Visitor	65	85	83.4	83.2
5	Operator	65	92.9	90.4	91.1
5	User	24	103.6	104.2	102.7
5	User	54	99.4	100	98.7
5	User	70	98.3	97.4	97.2
5	Visitor	65	95.3	92	92.1

For the operator, the highest noise levels occurred when the noise-reduction enclosure was not present. With the noise-reduction enclosure in place, the noise levels were reduced 1.3 dB(A) and 2.5 dB(A) for input voltages of 2 V and 5 V, respectively. The 2.5-dB(A) reduction shows that the enclosure reduces the sound pressure level at the operator's location by nearly one half. For the visitor, the highest noise levels also occurred when the noise-reduction enclosure was not present. With the noise-reduction enclosure in place and foam on the floor beneath the ODT, the reduction in the noise was 1.8 dB(A) for a 2-V input. For a 5-V input and with the noise-reduction enclosure in place, the noise was reduced 3.3 dB(A). This corresponds to reducing the sound pressure level at the visitor's location by more than one half.

The purpose of the noise-reduction enclosure was to help reduce the noise emitted from the ODT. Although it did not reduce the noise for the operator, user, or visitor enough for us to request a change in the requirement for hearing protection to be worn within 4 m (13 ft) of the ODT, it did produce reductions in the sound pressure level. The noise-reduction enclosure provides several other benefits as well. It surrounds the entire ODT except for the active surface. This greatly enhances safety by eliminating any possibility of bodily injury from exposed parts of the ODT's drive system. As mentioned previously, the active surface of the ODT is approximately 46 cm (18 in.) above the floor. Some users reported concern about "running off the ODT and falling onto the ground". The enclosure extends the plane around the perimeter of the active surface. The noise-reduction enclosure provides a platform approximately 61 cm (2 ft) wide around the active surface. This reduces users' perceptions that they might run off the edge of the ODT. Finally, operators and maintainers can stand on the noise-reduction enclosure and work on the mechanical linkage or help users with clothing, equipment, or test instrumentation.

4. Energy Expenditure Experiment

4.1 Objective

The objective of this experiment was to compare the physiological demands of walking on the ODT with the demands of walking in the real world. The real-world path upon which subjects walked was a 10-m-(32-ft)-diameter circle around the ODT in building 518 at APG. When subjects walked on the ODT, they wore an HMD in order to view a representation of the real-world path. We created the representation by texturing a computer model of building 518 with digital photographs of the building's interior. The hypotheses of this experiment were

1. There would be no difference in physiological demand for walking on the ODT through the virtual environment versus walking through the real environment.

2. Physiological demand would increase as a function of walking speed and load carried.

4.2 Methods

Six male Soldiers (a sample of convenience) gave their informed consent and participated in this experiment. Demographic and anthropometric characteristics of the subjects are shown in table 8. The investigators have adhered to the policies for protection of human subjects prescribed in AR 70-25.

Table 8. Demographic and anthropometric characteristics.

Number of Subjects	Gender	Age (years)	Height (cm)	Weight (kg)
6	Male	28 (18 to 43)	180 (168 to 191)	76.3 (62.1 to 90.2)

We determined physiological demand by measuring the following dependent variables: oxygen uptake, heart rate, and rating of perceived exertion (RPE). Oxygen uptake was determined by an

Oxylog2[8]. Heart rate was measured by a Polar[9] Heart Watch. A 15-point psychophysical scale was used to measure the Soldier's RPE (Borg, 1973).

The independent variables in this experiment were course, speed, and load. There were two conditions for course, real world and ODT, and two conditions for speed, 0.67 m/s (1.5 mph) and 1.1 m/s (2.5 mph). There were also two conditions for load, 4.0 kg (8.8 lb) and 15.6 kg (34.3 lb). The 4.0-kg (8.8-lb) load was the minimal load. It consisted of the Soldier's boots, battle dress uniform (BDU), and the Oxylog2 and heart watch. The 15.6-kg (34.3-lb) load represented the weight of an assault load. It consisted of everything in the minimal load plus an armored vest, load-carrying equipment, two inert grenades, six mock rifle magazines, and two 1-quart canteens filled with water.

Soldiers received training in how to walk on the ODT. After a brief rest period, they began the data collection trials. These trials involved walking on the assigned course at the assigned speed and carrying the assigned load for approximately 10 minutes. On the real-world course, subjects followed one of the experimenters. The experimenter walked around the course with a pacing wheel to ensure that subjects walked at the correct speed. When subjects were on the ODT, they followed a virtual target that moved at the assigned speed around the path in the representation of building 518. Each data collection trial began with a 5-minute warm-up period to allow subjects to get a steady state for oxygen consumption and heart rate. Then readings were taken from the Oxylog2 and Polar heart watch at minutes 6, 7, 8, and 9. Immediately after the Oxylog2 and Polar heart watch reading were recorded at minute 9 and before they stopped walking, subjects were asked for their RPE. Then there was a 5-minute break. This process continued until each Soldier completed a collection trial in each of the conditions. The order of the conditions was randomized.

The data processing and analysis involved calculating the mean oxygen consumption and the mean heart rate for each trial based on the readings taken at 6, 7, 8, and 9 minutes. Then an analysis of variance (ANOVA) was performed on the oxygen consumption, heart rate, and RPE data. The level of significance was set at $\alpha = 0.05$.

4.3 Results

The results of the ANOVA for each of the independent variables (oxygen uptake, heart rate, and RPE) are given in table 9. All three of the dependent variables were affected by course, speed, and load, and there were no interactions. The mean oxygen uptake, heart rate, and RPE values for each course, speed, and load are shown in figures 31, 32, and 33, respectively. Oxygen uptake, heart rate, and RPE all are significantly higher for the ODT versus real-world course, higher speed versus lower speed, and heavy load versus light load. The percentage differences are shown in table 10.

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[8]Oxylog2 is a registered trademark of P. K. Morgan Limited, England.
[9]Polar is a registered trademark of Polar Electro.

Table 9. ANOVA results

Dependent Variable	Oxygen Uptake		Heart Rate		RPE	
Source	**F**	**p-value**	**F**	**p-value**	**F**	**p-value**
Course	32.98	**0.002**	19.17	**0.007**	13.24	**0.01**
Speed	82.88	**0.000**	145.82	**0.000**	7.68	**0.03**
Load	14.91	**0.012**	10.13	**0.024**	8.34	**0.03**
Load x Course	3.43	0.12	0.99	.036	0.25	0.63
Load x Speed	0.76	0.42	2.28	0.191	1.62	0.25
Speed x Course	0.003	0.96	1.41	0.29	3.28	0.12
Load x Speed x Course	0.39	0.56	0.07	0.80	0.42	0.54

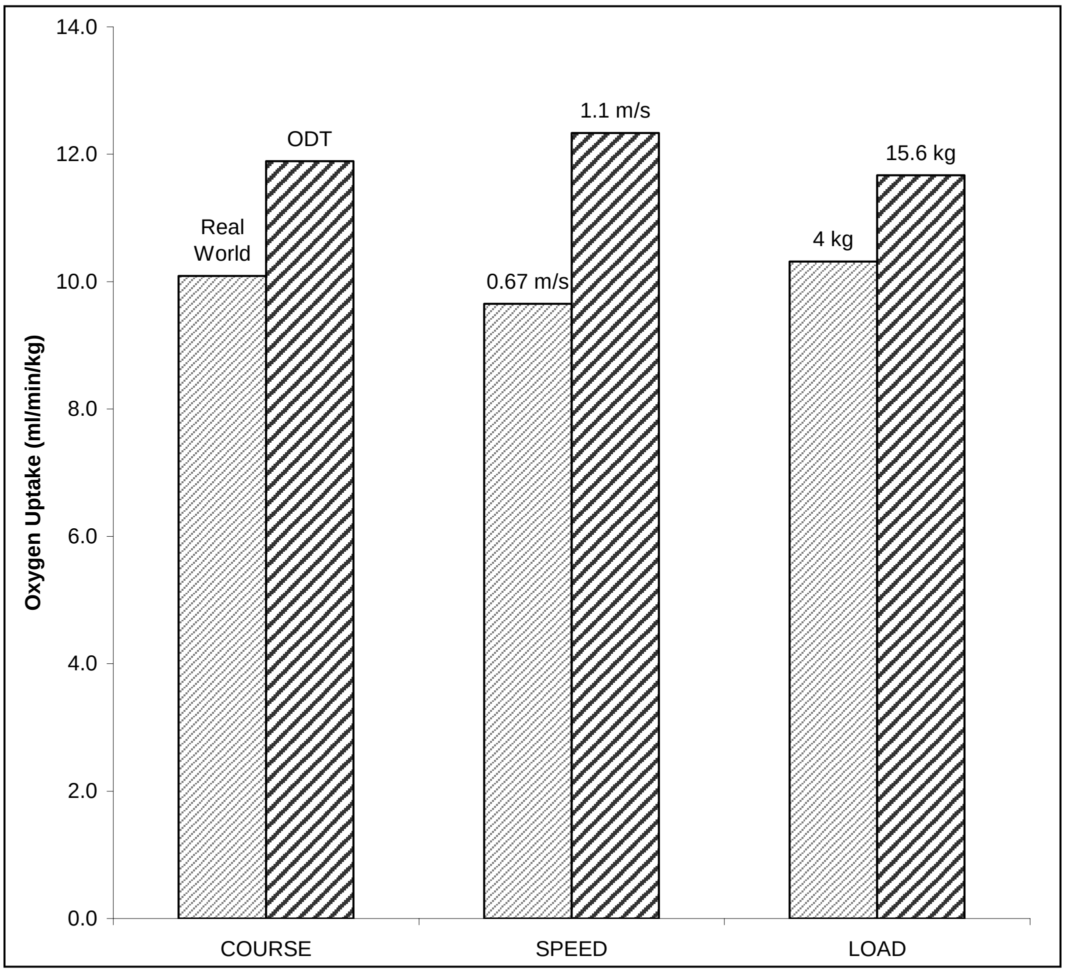

Figure 31. Oxygen uptake for each course, speed, and load.

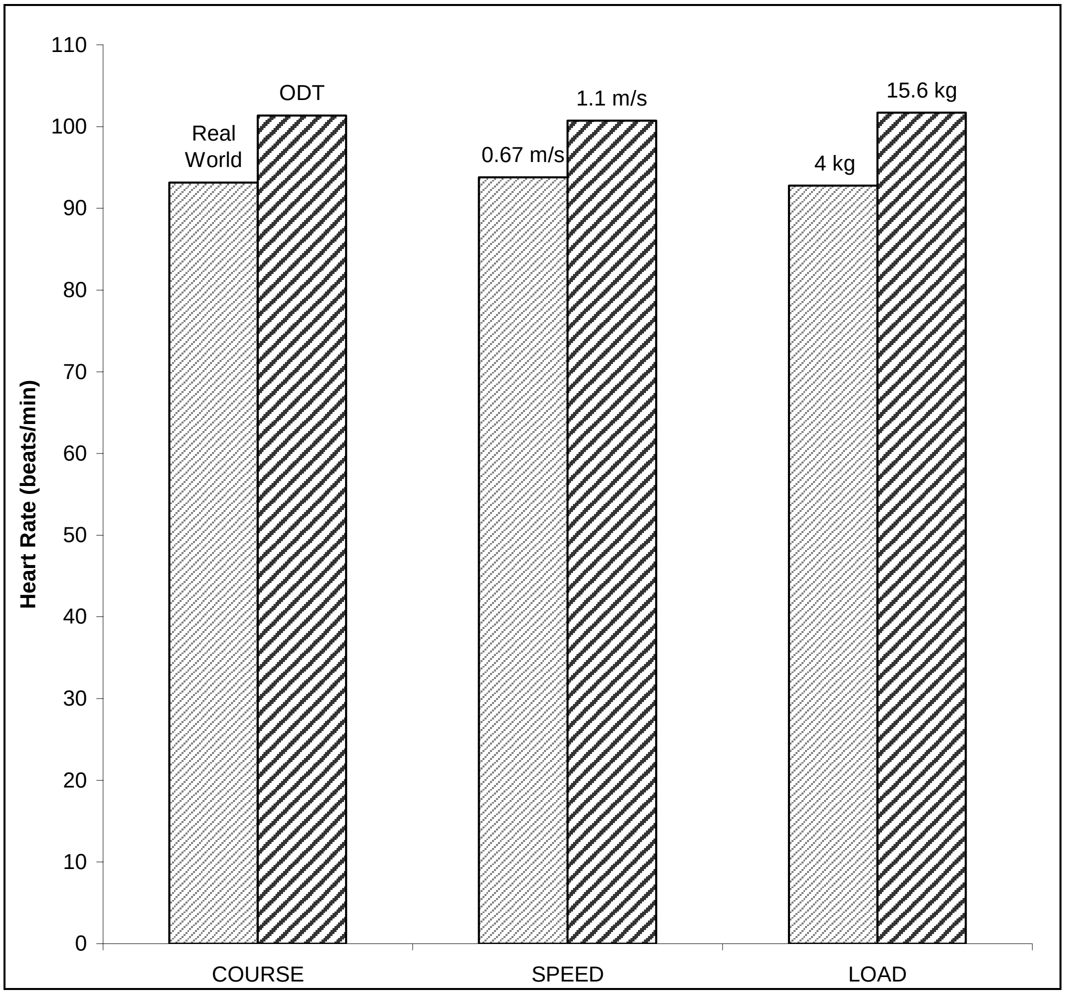

Figure 32. Heart rate for each course, speed, and load.

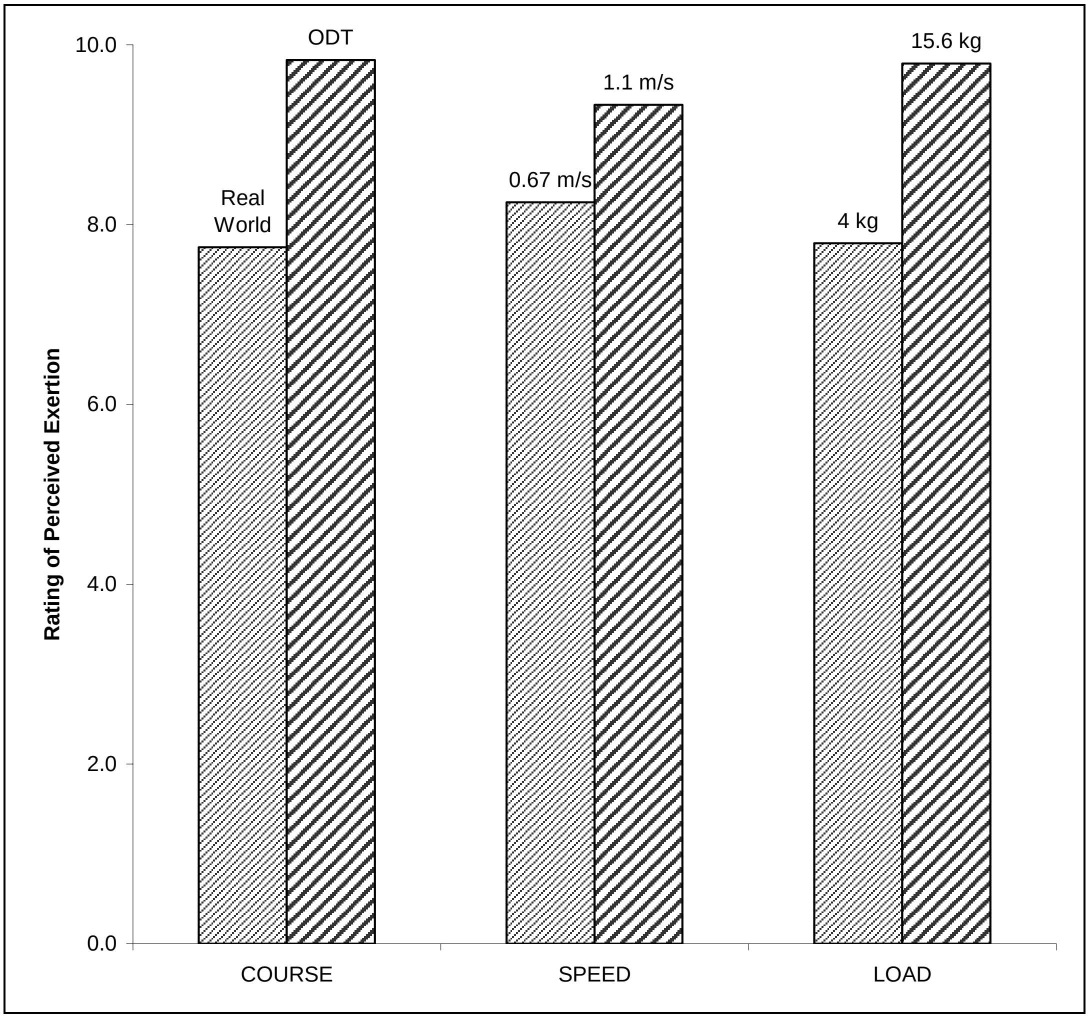

Figure 33. RPE for each course, speed, and load.

Table 10. Percentage increase in the dependent variables for each of the courses, speeds, and loads.

	ODT Versus Real World	1.1 m/s Versus 0.67 m/s	15.6 kg Versus 4 kg
Oxygen Uptake	17.8	26.8	13.6
Heart Rate	8.6	9.7	7.4
RPE	25.6	12.0	25.6

4.4 Discussion

The physiological demand required to walk on the ODT and the real-world course (as measured by oxygen uptake, heart rate, and RPE) increased as a function of speed and as a function of load. This is consistent with results of other studies (Gupta, 1955; Malhotra, Ramaswamy, & Ray, 1962; Soule & Goldman, 1972; Pandolf, Givoni, & Goldman, 1977). Contrary to expectations, the physiological demand required to walk on the ODT was greater than that required to walk on the real-world course. This greater physiological demand required to walk on the ODT may be the result of the user's interaction with the ODT and the display system used to view the virtual environment. Perhaps users are not or do not feel as stable on the ODT as they do on the ground. If users are unstable on the ODT or if they think they may lose their balance, they will activate more muscles in order to maintain stability. This would, of course, increase their physiological demand. Another explanation may be related to the field of view (FOV) of the HMD. HMDs do not give users the same FOV that they have in the real world. This smaller FOV could have allowed subjects in this experiment to frequently stray off the path in the virtual environment. Then they would have had to walk faster to catch up with the virtual target each time they strayed off the path. If so, this would have increased their physiological demand.

4.5 Conclusions and Recommendations

For the path traversed in this experiment and with the equipment used to display the virtual environment, the physiological demand was greater for subjects on the ODT. This was in contrast to the hypothesis that there would be no difference in physiological demand for walking on the ODT through the virtual environment versus walking through the real environment. The other hypothesis of this experiment (that physiological demand would increase as a function of walking speed and as a function of load) was supported by the results of this experiment.

Even though the physiological demand is greater when subjects are on the ODT, it may be possible to improve the ODT to reduce the difference in the physiological demand to make it more like walking in the real world. If stability and FOV are causes for the increased physiological demand, perhaps more training and better displays could help. If users are provided with more training, they may feel more relaxed and more stable on the ODT. This will allow their gait to be more efficient and thus reduce their physiological demand. More training and better displays could also allow users to become more familiar with the way an environment appears, and thus they would be less likely to stray from a designated path.

5. FYs 2000 and 2001 Culminating Events for the STO

As mentioned previously, the project to improve the ODT's control system was part of an Army STO. The goal of the STO was to develop the capabilities that will enable infantry Soldiers to participate in simulations of dismounted combat. To assess progress toward this goal, the STO partners (ARI, ARL, and STRICOM) held annual demonstrations and evaluations called "culminating events". A culminating event was held in each of the four years of the STO; however, the ODT was part of the culminating events in 2000 and 2001 only. In 1999, the improvements in the ODT were not sufficiently advanced for it to be demonstrated at the culminating event. In 2002, the ODT was not available for the culminating event because it was being integrated into a new simulation facility at ARL.

5.1 FY 2000 Culminating Event

The plan for the FY 2000 culminating event was to network several simulators: ODT, FITT, Real Guy Immersive and Real Guy Desktop from Veridian Engineering, Inc. (Orlando), and soldier visualization station (SVS[10]) and conduct a distributed interactive exercise. The ODT was at ARL at APG. The FITT was at the Institute for Simulation and Training in Orlando, and the Real Guy Immersive, Real Guy Desktop, and SVS Desktop were at STRICOM's Technology Development Center, also in Orlando. Unfortunately, a strike by workers at the telephone company that services APG prevented the installation of the T-1 line needed to connect the ODT with the simulators in Orlando. Nevertheless, the teams at APG and Orlando conducted a modified version of the culminating event from 26 to 28 September. The team in Orlando was able to network their simulators to examine advances in dismounted infantry (DI) semi-automated forces (SAF) (i.e., computer-generated forces), voice and gesture recognition for control of DI SAF, simulation of looking through night vision devices, movement through complex urban terrain (sewers and multi-story buildings), use of the dynamic terrain algorithms, and the capability of after-action review (AAR) software.

Like the evaluation in Orlando, the evaluation at APG examined movement through complex urban terrain and the use of dynamic terrain algorithms. However, the focus was on the ODT. The primary goals were to demonstrate the improvements in the ODT control system, integrate the ODT with the dismounted infantry simulation (DISim) software developed by our ARL partner (Thomas, 2002), and demonstrate that a user on the ODT and a user of another simulator could interact in a networked simulation. During the culminating event at APG, the goals for the ODT were met and areas that needed improvement were noted.

The culminating event at APG began with a familiarization session that allowed the participants (two male Soldiers from the Aberdeen Test Center) to familiarize themselves with the ODT and the virtual environment. First, the Soldiers were trained to use the ODT. Each Soldier became accommodated to moving on the ODT in about 10 minutes. They were able to initiate and terminate gait naturally. They did not experience false starts or overshoot stops during the training, and they were able to make gradual turns smoothly. Then each Soldier, in turn, donned an HMD so that he could see the virtual environment he was traveling through when he walked on the ODT.

In the HMD, the Soldiers saw a virtual environment that was presented to them by the DISim software. The virtual environment was urban terrain that included multi-story buildings and sewers. The Soldiers were able to move around and through the buildings easily. They could drop into and move through the sewers; however, they could not leave the sewers because the ODT does not have any means for climbing ladders. To get the Soldiers out of the sewers, an operator at a keyboard changed the Soldiers' elevation.

[10]SVS is a trademark of Reality By Design, now Advanced Intractive Solutions, Monterey, California.

Next, the Soldiers each interacted with a user on another simulator (a workstation with a joystick) that was situated in building 321 at APG and networked with the ODT which was in building 518 (APG). In the networked simulation, the Soldier and the other user were each able to fire weapons. The effects of these weapons were displayed in DISim as holes and rubble generated by the dynamic terrain algorithm. The Soldier on the ODT and the user at the workstation were able to follow each other through the virtual environment. Walking speed for the user with the joystick appeared to be faster than walking speed for the user on the ODT. They also worked together as a two-person team and conducted a room-clearing task.

Then one Soldier on the ODT had the opportunity to interact with DI SAF in the virtual environment and use cover and concealment to move from building to building. This Soldier said that at times he "forgot" that he was connected to the ODT's mechanical linkage. He was so immersed in the simulation that he did not remember the limitations of the ODT. A few times he moved very slowly to the edge of the zone of reduced gain. Then he leaned forward to look around a corner. When he did that, the ODT gave him a false start because he was right at the edge of the zone of reduced gain. Other times, the Soldier made sharp turns rather than gradual turns to go around obstacles. These sharp turns caused a momentary unsteadiness because the course vector became misaligned with the centering vector.

In summary, despite the fact that the ODT could not be networked with the simulators in Orlando, the culminating event was successful and several good lessons were learned. The ODT's improved control system performed as expected. Training time on the ODT for these Soldiers was brief (approximately 10 minutes). The ODT was integrated with the DISim software. The Soldiers on the ODT were able to move through complex urban terrain and interact with someone on another simulator in a networked simulation exercise. Observations and feedback from the Soldiers also revealed that some Soldiers became so immersed in the simulation that they forgot that they were on the ODT. As a result of this culminating event, it was apparent that further refinements needed to be made in the control system in order to allow users to make sharp turns. Also, the speed at which users travel through the virtual environment should match the speed at which they feel they are traveling on the ODT.

5.2 FY 2001 Culminating Event

The FY 2001 culminating event was held at Fort Benning from 24 to 27 September. The demonstration and evaluation consisted of a series of squad-level exercises conducted in the Simulation Laboratory at the Dismounted Battlespace Battle Lab (DBBL). The objectives were to demonstrate the virtual environment simulation and training capabilities developed under the STO and to obtain feedback about those capabilities from the Soldiers who participated in the exercise. The capabilities that were demonstrated and evaluated included the utility of the AAR software, new behavior and control mechanisms for the DI SAF, improved representation of the virtual environment, improvements in the ODT, realism of the holes and rubble provided by the dynamic terrain (DT) server, and the value of the mission planning and training tool (MPTT).

The scenarios used in each of the exercises were designed to be approximately 20 minutes long. They were intended to force the Soldiers to use the various new virtual environment technologies or capabilities. There were eight scenarios:

1. Support Operations Checkpoint
2. Hostage Rescue
3. Support by Fire
4. Assault and Clear a Building
5. Roving Patrol
6. Downed Helicopter
7. Crowd Control
8. Air Assault and Clear a Building

Seven of the scenarios took place in the fictional town of "Dlubak". The eighth scenario took place in a high-rise building in "Goldburg", a fictional town adjacent to Dlubak. In the exercises, the Soldiers were part of a United Nations Protection Force sent to monitor conditions in Dlubak. The virtual environment used to represent Dlubak was the Shugart-Gordon military operations in urban terrain (MOUT) facility at Fort Polk, Louisiana.

The scenarios used in the culminating event involved one squad, their platoon leader, opposing forces, and civilians. Some of these participants were real people in simulators or at workstations; others were DI SAF. They interacted over the network shown in figure 34. The squad was composed of two fire teams (Alpha and Bravo). One member of the Alpha Fire Team was on the ODT. The squad leader, the other members of the Alpha Fire Team, and the Team Leader for the Bravo Fire Team were in SVSs. The other four members of the Bravo Fire Team were DI SAF. The Bravo Team Leader controlled them with the voice recognition system. The platoon leader communicated with the squad members over a radio network. The platoon leader, who was also the exercise controller, viewed the events on the workstation used by the DI SAF operator. The DI SAF operator controlled the opposing forces. He could also help the Bravo Team Leader control his DI SAF team members if needed. One member of the opposing force was a person using an SVS desktop simulator. This person provided creativity and flexibility to the opposing force. The other elements of the network were the DT server and the AAR software.

Using the equipment just described, 12 Soldiers participated in the demonstrations and evaluations of the culminating event. One group of six Soldiers participated on 24 and 25 September, and a group of six different Soldiers participated on 26 and 27 September. On the first day for each group, they received a briefing that covered (a) the purpose of the exercises, (b) the nature of the performance and questionnaire data to be collected and the procedures that would be followed to ensure the privacy of information collected, (c) safety procedures, and (d) administrative information. After they completed two questionnaires, the Soldiers were assigned a duty position (squad leader, fire team leader, or fire team member), based on their rank. Then all the Soldiers received approximately 1 hour of instruction and practice in the use of the SVS.

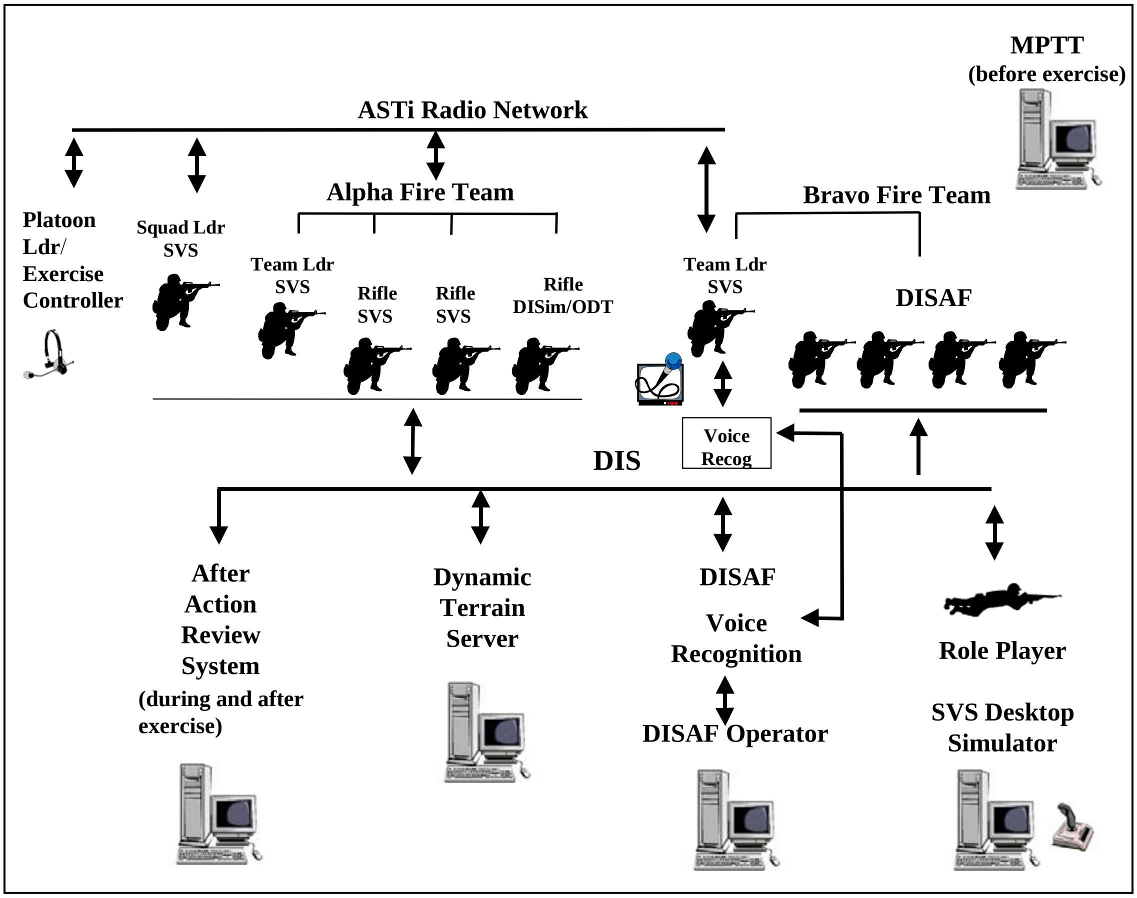

Figure 34. Culminating event network at DBBL.

After the SVS training, the Soldiers received additional training that was appropriate for their duty position. The squad leader received background information about the general situation for the imminent exercises and reviewed MOUT tactics and procedures. The team leaders received training in how to use the voice recognition system to control the DI SAF, and the fire team members received training on the ODT. During the ODT training sessions, each Soldier had approximately 20 minutes to use the ODT and become familiar with it. Two of the Soldiers used the ODT during the exercises. The third Soldier was trained as a backup. This completed the morning session for the first day.

In the afternoon, the Soldiers completed three exercises, one familiarization exercise and two training exercises. Each exercise started with a briefing about the mission. Then Soldiers moved to their simulators (SVS or ODT) and calibrated their weapons. After the exercise, Soldiers participated in the AAR. Then after a short break, they began the next exercise. After the AAR for the third exercise, the Soldiers were finished for the day.

On the second day for each group of Soldiers, they completed the remaining five scenarios. After they finished the AAR for the last scenario, they completed a series of questionnaires. The Soldiers who used the ODT also participated in a debriefing session.

5.3 Results

The results of the culminating event that are relevant to the ODT are summarized in this section. All the results from the 2001 culminating event as well as a detailed description of the event are available in the report by Knerr et al. (2002). Because only four Soldiers used the ODT and completed locomotion system questionnaires, the results only indicate trends for the ODT.

The questionnaire results for the ODT are shown in table 11. Overall, the ODT received a "good" rating for its ability to allow Soldiers to move across open terrain. Its ability to allow the user to move naturally, maintain balance, maneuver around obstacles, and maintain position relative to team members was rated "fair". It received somewhat low ratings for its ability to allow the Soldiers to maneuver close to other people in the virtual environment, look around corners, move through doors, and move tactically. It received low ratings for its ability to allow the users to maneuver around corners, move around inside buildings, and move quickly.

In general, the Soldiers felt that their movement through the virtual environment using the ODT was too slow. Although it did happen sometimes for one of the Soldiers, most of the Soldiers hardly ever got so immersed in the virtual environment or so comfortable on the ODT that they forgot that they were on it during the scenarios. Because the ODT sometimes caused the Soldiers to move when they were not ready and because some Soldiers seemed to be more comfortable on the ODT than others, their ratings on the question: "Did you feel safe on the ODT?" covered the range from *Never* to *Usually*.

During the debriefing, the Soldiers made very positive comments about their ability to observe 360 degrees around themselves when on the ODT. The HMD combined with the ability to turn their bodies on the ODT allowed them to observe their environment much more easily than they could in the SVS. In fact, during one scenario, the Soldier on the ODT spotted and engaged an enemy Soldier on the floor inside a doorway, whom two Soldiers in the SVSs moved past without seeing. The Soldiers also liked the ability to side step on the ODT. The Soldiers said that simulators that include systems such as the ODT or the SVS could be useful to the Army for training or mission rehearsal. They felt that such systems would be useful for learning the layouts of buildings and practicing moving through those buildings. They also felt that these systems would be useful for MOUT training, specifically room clearing. However, the Soldiers also described several problems and weaknesses with the ODT. They felt that the active surface of the ODT was too small. It limited their ability to move. The mechanical linkage restricted them to upright movement, so they could not kneel, go prone or crawl. These Soldiers also needed more time than the Soldiers in the 2000 culminating event to become comfortable with moving on the ODT. Occasionally, the cables going to the HMD and the radio that was used to communicate with other squad members became wrapped around their bodies.

Table 11. ODT ratings.

Task	Rating Frequency					
	Very Poor	Poor	Fair	Good	Very Good	Mean
Move Across Open Terrain	0	0	1	2	1	3.00
Move Naturally	0	1	3	0	0	1.75
Maintain Balance	0	1	3	0	0	1.75
Maneuver Around Obstacles	0	2	1	1	0	1.75
Maintain Position Relative to Team Members	1	1	0	2	0	1.75
Maneuver Close to Other People in the Virtual Environment	1	0	3	0	0	1.50
Look Around Corners	0	3	0	1	0	1.50
Move Through Doors	0	2	2	0	0	1.50
Move Tactically	1	1	1	1	0	1.50
Maneuver Around Corners	1	2	0	1	0	1.25
Move Around Inside Buildings	1	0	2	0	0	1.00
Move Quickly	1	3	0	0	0	0.75
Question	**Never**	**Hardly Ever**	**Some-times**	**Usually**	**Always**	**Mean**
Did your speed of movement through the virtual environment feel correct?	1	1	2	0	0	1.25
Did you forget that you were on the ODT during the scenario?	2	1	1	0	0	0.75
Did you feel safe on the ODT?	1	1	1	1	0	1.50
Did the ODT cause you to move when you were not ready?	0	0	4	0	0	2.00
Was your speed	**Too Slow**	**About Right**	**Too Fast**			
	4	0	0			

Notes: N = 4; Point values for responses: Very Poor = 0, Poor = 1, Fair = 2, Good = 3, and Very Good = 4; Never = 0, Hardly Ever = 1, Sometimes = 2, Usually = 3, and Always = 4.

In summary, the 2001 culminating event was successful, and it confirmed several of the lessons learned in the 2000 culminating event. The ODT's improved control system performed again as expected. Some Soldiers can become so immersed in the simulation that they forget they are on the ODT. The Soldiers on the ODT were able to move through complex urban terrain and interact with others in a networked simulation exercise. However, more training time, perhaps two 20-minute sessions, should be given to the Soldiers who will use the ODT. Also, the speed at which users travel through the virtual environment should match the speed at which they feel they are traveling on the ODT and the speed at which users on other simulators are traveling. As in the 2000 culminating event, it is apparent that further refinements need to be made in the control system in order to allow users to make sharp turns. The active surface of the ODT needs to be larger. The mechanical linkage that locates the user on the active surface needs to be replaced with a sensor that does not restrict the user to being upright. The cables that go to the HMD and the radio need to be run differently so that they do not interfere with the user's movements. These modifications will allow ODT users to take longer, more natural strides, crouch, kneel, go prone, and crawl.

6. Control of the ODT With a Non-Contact Sensor System

The mechanical linkage that senses the user's position and direction of the ODT was identified as a problem early in the use of the ODT. The physical configuration of the linkage restricts user's movements. Users are required to maintain an upright posture (no crouching, kneeling, or lying prone). The linkage also rotates back and forth out of phase with users when they walk and jog on the ODT. This places noticeable but not uncomfortable forces on the user at the points where the mechanical linkage attaches to the belt around the user's waist. The rotation of the linkage may also contribute to error in the course data. To overcome these problems, experiments were conducted with a non-contact sensor system to track the user's position and direction.

After surveying the market for non-contact sensors that would work in an environment that contains metal, we chose the IS-600 Mark 2 from InterSense, Inc. (Burlington, Massachusetts). In April 2000, InterSense loaned ARL an IS-600 Mark 2 for a 30-day trial. The IS-600 Mark 2 is a hybrid inertial and ultrasonic sensing system that provides 6-degree-of-freedom motion tracking. It also uses infrared (IR) transmitters and receivers to trigger the ultrasonic transmitters.

The ODT's control code was modified to accept position and direction information from the IS-600 Mark 2. It provided all the data necessary for the user to start, stop, walk, jog, side step, and turn on the ODT, and it was much less restrictive than the mechanical linkage. However, a problem was noticed. Occasionally, the ultrasonic signals were not transmitted. Two potential causes were identified: (a) IR energy from lights near the ODT interfering with the IR trigger for the ultrasonic transmitters, and (b) ultrasonic noise from the ODT interfering with the ultrasonic receivers.

Troubleshooting to determine the cause of the problem began immediately. First, the nearby lights were turned off. When this was done, the ultrasonic transmitters began to work properly. This confirmed that IR sources in the room were a problem for the IS-600 Mark 2. At that time, a sound meter that could record noise in the ultrasonic range was not available so it was not possible to determine if the ODT generated ultrasonic noise that would interfere with the IS-600 Mark 2. Also, after the nearby lights were turned off, the problem could not be reproduced. Therefore, it seemed that the cause of the problem was IR sources in the room.

The IS-600 Mark 2 was returned to InterSense at the end of the trial period. Purchase of an IS-600 Mark 2 was not pursued because of preparations for the imminent culminating event. However, there was still interest in replacing the mechanical linkage with non-contact sensors.

7. Integration of the ODT With the Tactical Environment Simulation Facility (TESF)

At the end of FY 2001, ARL contracted for the development of the TESF. Part of the TESF is the immersive environment simulator (IES), which is a state-of-the-art virtual reality display environment that can be used for conducting human factors experiments (see figure 35). To create the look, sound, and feel of moving through the virtual environment, a display system, a virtual environment generator, a sound system, and the ODT were integrated. The display system is a RAVE[11] II from FakeSpace Systems, Inc. (Kitchener, Ontario, Canada) It consists of three screens that are each 3.81 m (12.5 ft) wide and 3.05 m (10 ft) high. The bottom of each screen is approximately 0.457 m (1.5 ft) above the floor. Images of the virtual environment are projected onto the back of each screen. The middle screen is stationary, and the side screens can be positioned to create an 11.4-m (37.5-ft) flat wall or they can be rotated 90 degrees with respect to the middle screen to form three sides of a box. An Onyx[12] 3400 computer from Silicon Graphics, Inc. (Mountain View, California) is used as the virtual environment generator. The sound system consists of 44 speakers that will be placed on the walls, ceiling, display screens, and floor to create at three-dimensional audio environment. The ODT is used as the means for traversing virtual environments via natural locomotion. The integration of these components will enhance the user's sense of being immersed in the virtual environment.

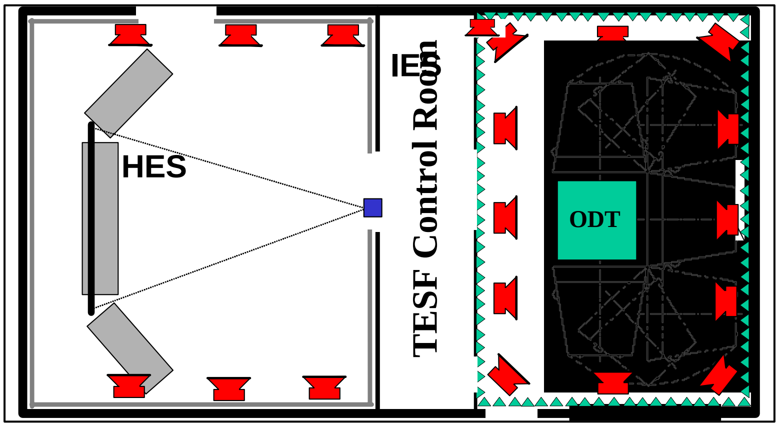

Figure 35. Overhead view of the TESF. (The IES is seen on the right side of this figure. In the IES, the ODT is in the middle of the FakeSpace RAVE II and it is surrounded by speakers. The walls are lined with anechoic foam to create a free-field sound environment.)

[11]RAVE, which is not an acronym, is a registered trademark of FakeSpace Systems, Inc.
[12]Onyx is a registered trademark of Silicon Graphics, Inc.

As part of the TESF contract, an IS-900 sensor system was purchased from InterSense, Inc. The IS-900 is more accurate than the IS-600 Mark 2, and it does not use IR transmitters to trigger the ultrasonic transmitters. The IS-900 system that was purchased contained four sensing stations. Each sensing station can be used to track a different point. The sensing stations detect signals from ultrasonic transmitters that are in known locations. Software within the IS-900 system analyzes the ultrasonic signals detected by the sensing stations to calculate the position and orientation of each sensing station.

In September 2002, the first step of integrating the ODT with the IS-900 began. The sensor data from the IS-900 were sent directly to the ODT control computer. This arrangement worked as expected. Position and direction data from the IS-900 were used successfully to control the ODT. The next step was to link the ODT and the Onyx 3400 computer so that as the user moved on the ODT, the scene on the RAVE II changed appropriately. To accomplish this, the sensor data from the IS-900 were sent to the Onyx 3400. Then, with a program called trackd[13], the position and direction of the user were sent to the ODT control computer. Using those data, the ODT control computer drove the servomotors to return the user to the center of the ODT. The ODT control computer also sent the user's speed and direction to the Onyx 3400 computer so that the virtual environment would be correctly displayed on the RAVE II. By the end of December 2002, this integration was complete.

In January 2003, a problem became apparent. When users jogged on the ODT at relatively high speeds for 30 to 60 seconds, the ODT no longer responded to changes in the user's speed. The ODT maintained a constant speed even when the user tried to slow down.

An effort to determine the cause of the problem was initiated. Ultrasonic noise from the ODT was suspected of interfering with the IS-900. A sound analyzer that records noise in the ultrasonic range was obtained. Measurements showed that the ODT generates approximately 65 dB of 40-kHz noise at waist height above its center. This is where the IS-900 sensing station was situated.

The ultrasonic transmitters for the IS-900 are on a grid approximately 10 feet above the ODT and on rails around the ODT at the height of the noise enclosure box. The signals from the IS-900's ultrasonic transmitters are at 40 kHz ±5 kHz, and when they are measured waist height above the ODT, they are approximately 65 dB. Obviously, ultrasonic noise from the ODT was interfering with the signals from the IS-900 transmitters.

To overcome the problem with interference, two solutions were attempted. First, we tried to reduce the noise reflected off the floor and noise coming from the noise enclosure box. Sound-absorbing foam was placed on the floor under the ODT and under the noise enclosure to isolate it from the floor. Noise measurements at waist height above the ODT showed that this had no effect on the ultrasonic noise; it was still 65 dB at 40 kHz.

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[13]Trackd is a registered trademark of VRCO (not an acronym), Inc., Virginia Beach, Virginia.

Next, the sensing station was reoriented and sound-absorbing foam was put around it to block reflected noise. The sensing station had been attached to the belt around the user's waist and the receivers were pointed downward right into the source of the ultrasonic noise. To solve this problem, the sensing station was moved to an aluminum plate that was attached to the back of the belt around the user's waist. It was oriented so that the receivers pointed up to the transmitters on the grid above the ODT. Also, the foam that was wrapped around the sensing station extends slightly above the sensing station receivers in order to reduce the amount of reflected ultrasonic noise that reaches the receivers (see figure 36). Reorienting the sensing station and shielding the receivers with foam solved the interference problem.

Currently, the ODT is configured as shown in figure 37. The user wears a harness that is attached to a safety strap. If the user should fall, the safety strap becomes taut and the pin on the safety switch (which is sewn into the safety strap) is pulled out. This opens the circuit to the servomotors, thus stopping the ODT. The sensing station that gives the user's position and direction is attached at the back of the belt around the user's waist. Speakers provide a three-dimensional audio environment for the user. The Onyx computer generates the virtual environment that is displayed on the screens of the RAVE II. The improvements in the ODT's control system, including the application of a non-contact sensor system, bring it closer to being an ideal mobility interface device (i.e., one that allows the postures and movements that are common to infantry Soldiers). Table 12 lists the postures and movements possible with the improved control system, compared to the original control system.

Figure 36. Sensing station surrounded by foam.

Figure 37. ODT in IES.

Table 12. User's capabilities on the ODT.

Action	Improved Control System	Original Control System
Walk	✓	✓
Run	✓	✓
Side Step	✓	
Rotate	✓	
Crouch	✓	
Kneel	*	
Squat	*	

*If the safety strap is lengthened

8. Conclusions and Recommendations

The ARL team made considerable improvements in the ODT. We improved the ODT in each of the four areas on which we focused this project: tracking system accuracy, computational latency, control algorithm development and implementation, and reduction of audible noise. The tracking system's accuracy was improved after we replaced some components, modified others, and developed new calibration procedures. Because of these changes, the standard deviations of the signals entered in the control computer were reduced by more than 80%. We reduced computational latency in the control computer by creating look-up tables that eliminated the need for the control software to make some calculations. Changing to the MS-DOS operating system eliminated periodic interruptions that delayed signals to the ODT's drive motors. The new control algorithm allows users to move more naturally on the ODT. Users can side step, and the "skating effect" has been reduced. From observations of Soldiers at the culminating events, it was apparent that false starts and overshooting stops were greatly reduced in comparison to the original control system. Although the control system improvements were substantial, users still experience difficulty with sharp turns and fine movements such as maneuvering inside a building. The audible noise from the ODT was reduced. The reduction was not enough to relax the requirement for hearing protection within 4 m (13 ft) of the ODT, but it is a noticeable difference.

In addition to the improvements in the focus areas of the project, we made other improvements that make the ODT a more useful system. We replaced the mechanical linkage with a non-contact sensor to identify the user's position on the active surface. Thus, users are not restricted to a rigid upright posture. This makes using the ODT more natural. We were also successful in integrating the ODT into the TESF. As the user moves on the ODT, the scene on the screens surrounding it change to give the visual feedback that s/he is moving through the virtual environment. This gives us a unique research simulator for dismounted Soldiers to use.

Even with all the improvements in the ODT, it still has several shortcomings. These need to be addressed by building a new ODT. The following recommendations should be incorporated into the new ODT:

1. The active surface needs to be larger. This will allow users to go prone and crawl. These are common actions for dismounted Soldiers. To accommodate a tall Soldier with a weapon, the active area should be approximately 2.4 m by 2.4 m (8 ft by 8 ft).

2. The ODT should be quieter. The user, operator, and any visitor observing the ODT should not need to wear hearing protection when the ODT is operating. When the ODT is operating at top speed, it should be quiet enough that the user and the operator can easily communicate, and it should be quiet enough that the user can easily hear sounds played through the speakers in the TESF. To accomplish these things, the ODT should operate within the noise criterion curve, NC-55, printed on page F-6 of Hirschorn (1982).

3. Users should not be tethered in any way (i.e., to a position-sensing system or a safety system), or at least they should not perceive that they are tethered. This will allow them to assume the postures and perform the movements that are common to dismounted Soldiers. For example, they should be able to stand, crouch, squat, kneel, sit, and lie prone. They should also be able to lie prone and roll left or right, crawl, side step, walk, run, and jump.

4. The control algorithm still needs improvement. Users should be able to make sharp turns and fine movements easily. This may require sensing multiple points on the user's body. It may also require prediction algorithms that anticipate the speed and direction of the user so that the ODT can accommodate them. Also, if possible, the system that tracks the user should track the user's head and weapon accurately so that his or her interaction can be displayed realistically in the virtual environment.

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Appendix A. Acronyms and Abbreviations

AAR	after-action review
AC	alternating current
A/D	analog to digital
ANOVA	analysis of variance
APG	Aberdeen Proving Ground
ARI	U.S. Army Research Institute of Behavioral and Social Sciences
ARL	U.S. Army Research Laboratory
COM	center of mass
DBBL	Dismounted Battlespace Battle Lab
DC	direct current
DI	distributed infantry
DISim	dismounted infantry simulation
DT	dynamic terrain
FITT	Fully Immersive Team Training (Research System)
FOV	field of view
FY	fiscal year
HMD	helmet-mounted display
HRED	Human Research and Engineering Directorate
IES	immersive environment simulator
I/O	input-output
IR	infrared
ISMS	individual soldier mobility simulator
LID	locomotion interface device
MOUT	military operations in urban terrain

MPTT	Mission Planning and Training Tool
ODT	omni-directional treadmill
PI	proportional-integral
PID	proportional-integral-derivative
RPE	rating of perceived exertion
SAF	semi-automated forces
STO	science and technology objective
STRICOM	U.S. Army Simulation, Training and Instrumentation Command
SVS	Soldier Visualization Station
TESF	Tactical Environment Simulation Facility
TTES	Team Tactical Engagement Simulator

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