Virtual Locomotion: Walking in Place through Virtual Environments

Article *in* Presence Teleoperators & Virtual Environments · December 1999

DOI: 10.1162/105474699566512 · Source: DBLP

3 authors:

James N. Templeman
United States Naval Research Laboratory

Patricia S. Denbrook
United States Naval Research Laboratory

Linda Sibert

James N. Templeman
templeman@itd.nrl.navy.mil
Code 5513
Naval Research Laboratory
Washington, DC 20375-5337

Patricia S. Denbrook
Independent Software Developer

Linda E. Sibert
Naval Research Laboratory

Virtual Locomotion:
Walking in Place through Virtual Environments

Abstract

This paper presents both an analysis of requirements for user control over simulated locomotion and a new control technique designed to meet these requirements. The goal is to allow the user to move through virtual environments in as similar a manner as possible to walking through the real world. We approach this problem by examining the interrelationships between motion control and the other actions people use to act, sense, and react to their environment. If the interactions between control actions and sensory feedback can be made comparable to those of actions in the real world, then there is hope for constructing an effective new technique. Candidate solutions are reviewed once the analysis is developed. This analysis leads to a promising new design for a sensor-based virtual locomotion called *Gaiter*. The new control allows users to direct their movement through virtual environments by stepping in place. The movement of a person's legs is sensed, and in-place walking is treated as a gesture indicating the user intends to take a virtual step. More specifically, the movement of the user's legs determines the direction, extent, and timing of their movement through virtual environments. Tying virtual locomotion to leg motion allows a person to step in any direction and control the stride length and cadence of his virtual steps. The user can walk straight, turn in place, and turn while advancing. Motion is expressed in a body-centric coordinate system similar to that of actual stepping. The system can discriminate between gestural and actual steps, so both types of steps can be intermixed.

1 Introduction

Natural human locomotion is the self-propelled movement of a person through the real world, typically performed on foot. Natural locomotion provides a high level of maneuverability over a wide range of terrain, with speed limited by a person's strength and agility. Natural locomotion differs from vehicular motion in which a person pilots a mobile platform containing the user's viewpoint.

Virtual locomotion is a control technique for allowing a person to move in a natural way over long distances in the virtual environment (VE), while remaining within a relatively small physical space. Ideally such an interaction technique will allow users to perform the same coordinated actions and move with the same agility in VE as in the real world.

Virtual locomotion can be used for:

Training and Rehearsal in executing skills, tasks, strategies, and navigation that involve moving through an environment on foot;
Planning activities that involve moving through a target environment;

Presence, *Vol. 8, No. 6, December 1999,* 598–617

Evaluating the ergonomics or aesthetics of structures designed for human habitation, or of devices intended for use by people while walking;
Communications between people at different locations when they want to relate to each other in a way that involves locomotion; and
Entertainment experiences that involve moving through a VE.

All of these activities can involve several people interacting with each other.

The ability to realistically simulate walking around in the environment is a key element that is missing from most of today's fully immersive VEs. A number of sensor-based techniques are widely used to control movement through VEs, but they introduce artifacts into the interaction. Mechanical motion platforms have also been employed to surmount these difficulties, but they exhibit different but equally troublesome side effects. We will further review these techniques once we have presented our framework for analysis.

Virtual locomotion is an enabling technology that will allow more realistic team training systems to be built. The applications that most clearly justify the development of virtual locomotion are those that impose the greatest demand on realistic control. Training people to perform hazardous tasks is an obvious application for a fully immersive simulator, for that would allow the user to experience a realistic scenario without risking bodily harm. Virtual locomotion is essential for constructing individual combatant simulators in which the soldier interacts directly with the surrounding environment. Fully immersive simulators can be used to train soldiers in team operations and tactical doctrine. They can be used to familiarize a group with a specific environment and to plan and rehearse operations in that environment. An accurate VE model of an embassy could be used to train a team to carry out an evacuation.

Developing virtual locomotion to support infantry combat simulation is quite challenging. Infantry operations place high demands on both the facility of control over movement and the compatibility of this control with other actions that the user makes while moving. The users must be able to both cover large distances across varied terrain and maneuver with agility through tight spaces. Combat situations demand that the soldier pay careful attention to the environment being traversed and be able to react quickly (reflexively) to unexpected conditions. Individual combatants need to be able to move, navigate, shoot, take cover, clear buildings, communicate with other team members, and so forth.

Previous military simulators have focused on vehicular weapons platforms where motion was controlled through the same kinds of control devices that were used to pilot the actual vehicle. Actual or reduced-cost versions of the controls used to pilot aircraft or drive a tank can be used in flight and tank simulators. This made it relatively straightforward to attain a high level of realistic interaction. A locomotion simulator requires a fundamentally different approach. The user's physical body is the control device, and the representation of the user's body in the VE is the "vehicle" being controlled. The development of such a direct body interface calls for new analysis and design techniques to simulate a natural range of capabilities.

Many other simulation tasks do not demand the level of fidelity of an infantry combat simulator. However, in satisfying the requirements for the more demanding task, we have come up with a system that supports movement in a natural, body-centered frame of reference and allows the user to express himself and experience environments at a personal scale. The features that resulted from meeting the requirements of the more demanding task yield subtle but significant advantages for a wide variety of application areas.

1.1 Interactive Realism

To what extent can an infantryman learn to engage in urban combat by playing a desktop computer game like *Quake II*? Some things can be learned, such as the layout of a building or even simple tactics like hugging the wall to minimize exposure, but many other tactical aspects of the situation are not conveyed. A person's immediate relationship with the 360/180 degree space surrounding him and his ability to sense the enemy and coordinate with teammates is degraded. Not just "what," but "how" a person does things changes when experienced from within a body-centric framework. It seems important to actually carry a rifle and aim through the rifle's sights rather than align a cross hair using a joystick or mouse. Sometimes there is no substitute for being inside the dynamic situation and controlling one's actions directly. How close can we get to this for first-person simulators using VEs?

The realism of a virtual locomotion system can be assessed in a number of ways. The user-interface control can be examined from either side of the sensory-motor feedback loop. First, consider the actions the user must perform to exert control (computer input). In terms of high-level control, does it provide the user the same capability he has in the real world; i.e., can he perform the same tasks? At a lower, fine-grain level, does the control allow the user to react at the same rate, with the same accuracy, degree of effort, and coordination—and effectively in the same way as he would in real world situations? Second, consider the sensory feedback received in response to the user's actions (computer output). Does the user pick up the same information as he would in the real world? Information should be interpreted in terms of how it affects the user's decision making, that is, how it influences his future course of action. A virtual locomotion control influences how the user moves through the VE, which in turn shapes the user's perceptions, producing a simulated experience. Thus, interactive realism can also be viewed in terms of the user's actions—how similar the user's actions in the VE are to those he would perform in the real world.

2 Simulating Natural Locomotion: a Framework for Analysis

Our goal is to find a virtual locomotion control technique as similar to actual locomotion as possible. But exactly how should it be similar? We approach this question through analysis of the interrelationship between natural and control actions.

2.1 Specifying Control in Terms of Action and Effect

It is useful to divide a control technique into two parts: the control action made by the user and the controlled effect produced by the computer system. Since in this case the control technique is used to mimic an action performed in the real world, there is a corresponding natural action and natural effect. In the context of a human's virtual movement, the natural action is perambulation (walking, running, sidestepping, and so on), the natural effect is real locomotion (the displacement and turning of the whole body through space), and the controlled effect is virtual locomotion. Many alternative control actions can be used for virtual locomotion, and they will be considered in terms of the analytical framework developed in this section.

2.2 Components of Locomotion

Locomotion control will be divided into two components: control over the direction of motion (steering) and the rate of motion (speed control). With natural locomotion, steering includes turning the body to redirect forward motion and oblique stepping (that is, displacing the body in a direction other than where the torso is oriented, as in side- and back-stepping). Within the context of our analysis of locomotion, the orientation of the pelvis, or more specifically the pelvic girdle, will be adopted to describe the body's orientation.

2.3 Interaction with other Natural Actions

Natural locomotion interacts with a wide variety of other actions. These actions include looking (directing both the head and eyes), manipulation (typically involving the hands, as in pointing a rifle), posturing (moving parts of the body for purposes other than looking, manipulation, or locomotion), and thinking. Thinking is included because it is something the user does which interacts with other actions, including locomotion. The expression *cognitive load* can be used to describe how thinking can limit or be limited by the performance of other actions.

2.4 Simulating a Natural Capability

The goal of simulated locomotion is to provide a control for moving through a VE as naturally as possible. We now have the terms to state this requirement more formally, in terms of action, component actions, interaction, and effect.

(1) The control action should be similar to the natural action with respect to its intrinsic properties (constraints on movements, caloric energy expenditure, and so on).
(2) The components of the control action (steering and speed control) should interact with each other as the components of the natural locomotion interact.
(3) The control action should interact with other actions (looking, manipulation, posturing, and thinking) in a similar manner to the way the natural locomotion interacts with other actions (for example, freeing the hands for manipulation and allowing a normal level of coordinated head, arm, and leg movements). It should also be compatible with actual locomotion over short distances.
(4) The controlled effect should be similar to the natural effect. The rate and precision of movement should match, and there should be no inappropriate side effects (such as having to be careful to avoid falling over).

This is clearly a tall order for any virtual locomotion control to meet, but it provides a basic set of criteria with which to evaluate all candidate techniques. These criteria are summarized in Table 1 and further developed in the following topics.

Table 1. Summary of Requirements for the Interactive Realism of Virtual Locomotion

Similarity of Natural and Control. . .
1. Actions
• Part of body performing action
• Attributes of action: orientation, motion, force, etc.
Motion attributes: direction, extent, timing
• Effort and caloric energy expenditure
2. Interaction between Component Actions(A)
• Steering: turning and sidestepping
• Speed control
3. Interaction with Other Actions(B)
• Look—pointing the head and eye
• Manipulate—free hands for manipulation
• Think—cognitive load
• Move—compatibility with other body motions
One- and two-footed pivots—to quickly turn
Actual steps—to local displacement of body
Special purpose motions: bending, crouching, etc.
4. Effects
• Rate and precision of movement
• Trajectories taken
• Constraints on movement

(A) implies the components of motion control interact with each other as the components of natural motion interact. (B) implies the motion control interacts with other actions as natural motion interacts with other actions (coordinated head, arm, and leg movements).

2.5 Compatibility with Turning the Body

A great deal of compatibility with other natural actions can be achieved by having the user turn in the VE by physically turning his body. This allows actions like turning the head, pointing the hand, or wielding a weapon to be performed as a natural coordinated motion. It also allows the reflexive orientation a person might make towards or away from a stimulus to be used effectively (such as turning one's head to view the source of an unexpected sound). Another advantage of using the natural action of turning is to avoid a potential sensory conflict. People sense turning through their visual, aural, haptic, and vestibular systems. Peoples' vestibular sense of motion contributes to their ability to navigate through virtual environments (Chance, Gaunet, Beall, & Loomis, 1998). They build up a sense of their orientation in an environment through the temporal integration of this information.

It is therefore advisable to incorporate the natural action and effect of turning the body directly into the virtual locomotion control, without altering the way turning is performed. In other words, for turning, the control action should be equivalent to the natural action, and the controlled effect should be equivalent to the natural effect. Although this eliminates the need for special actions to control turning, it imposes the constraint of having the control action be compatible with physical turning. The user should be able to perform virtual locomotion while turning, and the path traversed should vary accordingly.

The body can be turned in several different ways. Most of the time, people step to turn: lifting and planting the feet in a different direction on each successive step turns the body to face in a new direction. People also pivot on their feet to turn. Here the foot is turned while it continues to support a person's weight. There are one- and two-footed pivots. Pivoting provides a means of turning the body that is more economical in terms of both time and space than stepping to turn, particularly critical in martial situations. Pivots are often used in tight, awkward spaces or in executing time-critical actions. People also turn while jumping. Turning the body is not the only way of achieving steering with natural locomotion. A system intended to offer the full set of capabilities provided by natural locomotion must also support moving in a direction other than where the body is oriented forward (that is, side-, diagonal-, and back-stepping).

2.6 Walking with the Head Turned is Separate from Sidestepping

In addition to turning, people can move in one direction while looking in another. There are two ways of doing this:

(1) A person can step in any direction even though his hips remain oriented in a fixed direction. Thus, one can walk forward, backward, sideways, and diagonally without turning.

(2) A person can turn his head and upper torso to a degree determined by the flexibility of his spine, while maintaining a relatively constant gait and hip orientation.

This allows one to walk forward while looking to the side, or to scan back and forth while continuing to walk forward. Thus, there are two means of moving laterally to one's direction of gaze or aim point. The first is to side-step; the second is to walk forward while twisting the upper body.

2.7 Independence of Control

The human body consists of many parts. The head and torso may be oriented in different ways, and the movement of both legs working together moves the body over ground. When constructing a hand-operated motion control for the desktop, it is convenient to collapse control over these different elements into control over a single orientation. Even if one had a control capable of expressing more degrees of freedom, it is not clear that the user would want the added responsibility of having to control all the additional control states this freedom implies, at least not by overloading the duties of the hand.

2.8 Compatibility with Other Real Motions

It is highly desirable for the virtual locomotion control to be compatible with other sorts of postural movements like bending at the waist or crouching down. These may be thought of as special-purpose actions, essential for certain tasks. A user might bend to look around a corner, or crouch to hide behind an embankment. It would be desirable if those motions could be made in a natural manner while performing virtual locomotion. Users should not have to learn an entirely new vocabulary of control actions just to allow them to move in different postures.

It is also desirable to allow virtual locomotion to be intermixed with natural locomotion. The user could move forward in a VE by making control actions or by taking actual steps (albeit over a limited range). Physical movements can work well in VEs, but must remain within tracker range and within the available space.

2.9 Consequences of Unrealistic Interaction

What happens when the requirements for interactive realism developed above do not hold; when similarity of action, component actions, interaction, or effect are not fully attained? The actions must be the same for the user to develop the right set of coordinated reflexes. The capability (effect) must be the same for users to learn when to apply it, to incorporate it into strategies, and to avoid changing their strategy to compensate for its absence. Compensation is bad because it means that users are adopting different practices and approaches in the VE than they would use in the real world.

In terms of isolated capabilities—capabilities can be lost in the VE, new capabilities can be gained, and the control action can alter the way a capability is used. All of these cases are departures from realistic task performance. If a control lets the user effortlessly move at a rapid speed, the user might carry out rehearsal missions in the VE that would be impossible to accomplish in the real world. In terms of interacting capabilities—the control action can preclude other capabilities (for example, not being able to stop quickly may discourage a rapid motion), the control action can free the user to perform extra actions (for example, a technique that supports backwards motion while the user stands at rest would allow the user to aim a rifle accurately while retreating from the enemy), and the control action can alter the way other capabilities are used (for example, not being able to advance in a crouching posture limits the kind of ground cover one can hide behind).

3 Prior Work in Virtual Locomotion

We will now review a wide variety of locomotion controls in the context of the framework developed above. We start by considering the more conventional controls that control motion using sensors attached to parts of the upper body. We then describe a series of mechanical locomotion systems that seek to simulate the physical experience of locomotion. We conclude by describing a number of recent sensor-based controls that allow the user to express desired virtual motion using his legs, without physically moving the surface beneath his feet. This provides a rough sketch of the progression and convergence of approaches taken. Youngblut, Johnson, Nash, Wienclaw, et al. (1996) is recommended for an alternative review of virtual locomotion technology.

3.1 Conventional Sensor-Based Controls

Sensor-based controls use sensors attached to selected parts of the user's body to direct movement through a VE. The most common type of sensor used in VEs tracks the position and orientation of an object in 3-D space. Other types of sensors are used to measure other properties, such as force and acceleration. Sensor-based controls are often used to steer and set the speed of motion through the VE. This section describes conventional controls that have been employed for this purpose.

3.1.1 Steering Controls. The most obvious and widely used steering technique is that of pointing. With a vehicular control, the user's body remains fixed in the vehicle and a rate-dependent pointing device, like a steering wheel, is used to turn the vehicle. In a fully immersive VE, constructed using either an HMD or a 360 degree surround-screen display, the user can turn his body so that pointing is direct.

Head-based steering is widely used in VE systems. It is economical because the same position tracker used to determine the user's field-of-view is used to control the direction of motion. Other advantages of head-based steering are that it makes the user look where he is going, and frees the hands from having to steer. The disadvantage is that looking and moving are no longer independent. The user cannot turn his head to look to the side while moving without altering his path. Bowman demonstrated this problem by asking users to walk to a position pointed at by an arrow in a VE (Bowman, Koller, & Hodges, 1997). Users had to keep turning to look at the arrow as they moved toward the desired position; the act of looking interfered with their motion. The task was much easier to perform using hand-based steering.

Hand-based steering techniques determine direction either from where the arm is pointed, where a handgrip is pointed, or where a finger is pointed when an instrumented dataglove is worn. Hand-based steering frees the head for looking and allows the user to move sideways relative to the head or body. The disadvantage is that it interferes with manipulation. The hand is occupied so that using the hand for other tasks leads to conflicts and interruptions. The user also must remain aware of the significance of where the hand is pointed.

Torso-based steering frees the head for looking and the hands for manipulation, but it does not support sidestepping. Often people move in the direction where the front of their torso is pointing, but sometimes they do not. A soldier aiming a rifle across his chest may prefer to advance in the direction he is aiming.

Another set of techniques uses leaning the body to specify the direction of motion. Three approaches to lean-based steering are tilting the upper torso, shifting weight relative to one's feet, and shifting one's weight relative to a platform. All three kinds of leaning provide hands-free operation and can support sidestepping. Fairchild, Lee, Loo, Ng, et al. (1993) implemented a system based on shifting the user's head position by tilting his upper torso (bowing). This control is incompatible with the user tilting their torso for other purposes, such as looking under a table. The second approach, shifting weight relative to the feet (that is, to the basis of support), is of limited use because the continuity is broken when a user steps to turn.

The third type of lean-based control is shifting one's weight relative to a platform. Max Wells at the University of Washington's HIT Lab developed such a system (Wells, Peterson, & Aten, 1996). Motion is controlled by moving one's body locally, relative to a central neutral position. When immersed wearing a head-mounted display, the user might lose track of where he stands with respect to the neutral position. The direction and rate of optical flow provides one indication of where the user is situated. A set of elastic straps attached to a ring around the user's waist can be added to give haptic feedback, pushing the user back towards the neutral position. The directional coordinate frame is relative to a fixed external point in space, an unnatural condition that produces interesting side effects. This makes turning the body and controlling the direction of motion even more independent than they are with natural locomotion. The user may choose to move in one direction and then turn to face in another, making it as easy to "run" backwards as forward. This approach is incompatible with physical locomotion, because velocity is controlled by relative position of the body.

3.1.2 Speed Controls. Speed can be controlled using finger pressure or by the degree of leaning (when leaning is used for steering). With finger pressure, a pair of binary switches attached to a hand control are used to invoke either forward or backward virtual motion. This is a widely used technique, easy and inexpensive to implement. We have tried using pressure-sensitive buttons and recommend their use because it provides a smooth way of varying speed. A major advantage of hand controls is that they work independently of head, torso, and leg movement and are thus compatible with a wide range of physical motions. The primary drawback of using the hand to control speed is that it interferes with using the fingers for manipulative tasks. As VEs become richer and engage the user in more complex tasks, they require a greater commitment of the user's hands for manipulation. This is most evident for combat systems in which the user needs to hold and aim a weapon both at rest and in motion. A second drawback of using hand controls with head-mounted displays is that the user cannot directly see how his hand holds the grip or how fingers touch the buttons. This limits the number of buttons the user can deal with.

Slater, Usoh, and Steed (1995) developed a novel speed control based on detecting the gesture of walking in place. A six degree-of-freedom (DOF) magnetic sensor attached to the HMD tracked the user's head motion. Recorded motion data was used to train a computational neural network to recognize walking in place versus other activity such as bending or walking around.

Head-based steering was used, so the single six-DOF head tracker fully controlled virtual locomotion (a very economical approach). This technique was a significant advance toward leg-based locomotion control, but it does not provide a full range of natural movement. A user cannot walk in one direction while looking in another, and it is unclear whether the network has enough information to discriminate a gesture for advancing while turning from simply turning in place.

3.2 Mechanical Locomotion Systems

Mechanical locomotion systems enhance the simulation of the physical experience of locomotion by linking the action of the user's legs to his movement in the VE. These systems characterize the direction and speed of virtual movement by using the motion of the body in conjunction with an external mechanical apparatus.

3.2.1 Unidirectional Systems. Unidirectional systems limit movement to one direction and require a special control action for turning the virtual world around the user. An early system in this category is the treadmill used at the University of North Carolina in their Architectural Walkthrough System (Brooks, Airey, Alspaugh, Bell, et al., 1992). It uses a handle in front of the user to steer. They report that the treadmill is disorienting, probably because there is no true sense of turning (which is helpful for route learning). Spinning the virtual world about the user produces an odd transient effect. Other unidirection systems are likely to suffer from the same difficulty. Sarcos Research Corporation developed the TREADPORT, a large treadmill that allows the user to stand, kneel, sit, and lay prone (Youngblut et al., 1996). Treadmills allow the user to move using a more realistic gait, as long as the user moves at a constant speed and direction. They make a superior sports simulator for long-distance runners. OSIRIS, developed by the US Army's Night Vision Laboratory, is a stair-stepper device (Lorenzo, Poole, Deaso, Lu, et al., 1995). It can present forward motion only, and a hand control is used for steering. The Individual Soldier Mobility Simulator (ISMS) was developed by Sarcos Research Corporation in conjunction with the Army Research Institute. The user stands on two robotic-arm boot plates that create the sense of walking or running over different terrain, and ascending or descending stairs (Youngblut et al., 1996).

3.2.2 Multidirectional Systems. Other mechanical systems allow the user to move in any direction. Sarcos Research Corporation's UNIPORT is based on a unicycle (Youngblut et al., 1996). The user remains in a seated position and turns around a pivot point by applying torque to the seat. This engages a motor to turn in place at a controlled rate. (This system is at the borderline between a vehicular and locomotion control.) The user's hands are free to hold a gun or other objects.

The Virtual Perambulator (Iwata & Fujii, 1996) uses a sliding motion of the feet to indicate walking. The user wears sandals with low-friction film on the middle of the sole and a rubber brake pad at the toe. The user glides on a low-friction surface by sliding his feet while pushing against a rigid frame surrounding his waist. Position sensors attached to each ankle and contact sensors on the bottom of each foot allow the system to recognize the length and direction of each step to specify movement in the VE. An earlier version used roller skates instead of the low-friction film. The placement of the hoop at waist level does not allow a user to hold an object by his side.

The Omni-Directional Treadmill developed by Virtual Space Devices, Inc., (Darken, Cockayne, & Carmein, 1997) allows the user to walk in any direction. The mechanism consists of a pair of conveyor belts nested one inside the other. Each track moves horizontally, and the tracks are oriented perpendicularly to each other. The outer track has rollers on it so that it transmits the motion produced by the inner track. Thus, the rollers can convey motion in any direction to the user's feet resting upon it. The active surface of the motion platform measures 50 in. $\times$ 50 in. A control system is used that seeks to keep the user centered in the middle of the platform. The system is very effective at allowing a user to walk in a straight line in any direction, and people have little difficulty accelerating to a fast walking speed along a straight path. Turning while accelerating can lead to a misalignment between the user's direction of translation and the centering motion of the mechanism, which is apt to make the user lose his balance and stumble. Even turning in place can be difficult because the tracking system registers the motion and compensates for it by moving the surface under the user's feet. Sometimes the dynamics of natural locomotion go beyond what the ODT can support. People can decelerate very quickly, coming to a full stop in a single step, and if they pivot while walking fast they can redirect their motion even more rapidly.

Inertia is another factor that makes it difficult to simulate acceleration using a motion platform. The inertia due to a person's mass, distributed throughout the body, resists acceleration. Hollerbach added an active tether to the Sarcos TREADPORT (Christensen, Hollerbach, Xu, & Meek, 1998) that pulls back on the user's harness as the user accelerates on the treadmill. This simulates the effect of the inertia encountered during normal linear acceleration. An active tether capable of pulling and pushing the user in any horizontal direction would be necessary to provide this resistance for the Omni-Directional Treadmill. People sense linear and angular acceleration using their vestibular system. A user immersed in a VE while standing on a "perfect" motion platform would have the sensation that his vestibular perception of linear acceleration was "turned off." This alone would make it difficult to perform certain actions, even if the dynamic response of a motion platform were ideal.

3.3 Leg-Based Virtual Locomotion Systems

A new trend has been developing that combines the sensor-based approach of the conventional steering and speed controls with the use of the legs to control motion as pioneered in mechanical locomotion systems. Sensor-based systems that use the leg motion as the control action to initiate forward virtual motion have been built and already demonstrate a number of advantages. They are especially well suited for locomotion tasks that require a high degree of maneuverability, both in terms of turning and rapid starting and stopping.

3.3.1 Independently Developed Leg-Based Systems. Several leg-based virtual locomotion techniques have been independently developed, seeking a more natural interface. The U.S. Army Research Institute in conjunction with the University of Central Florida's Institute for Simulation and Training (Knerr, 1998; Singer, Ehrlich, & Allen, 1998) developed a foot-based system in which forward virtual motion is triggered by lifting the foot above a vertical threshold. Steering is controlled by the horizontal orientation of a magnetic tracker worn on the back, between the shoulder blades. The user can turn while advancing through the VE by raising his feet above the threshold while stepping to turn (physically in place), or turn in place in the VE by not raising his feet above the threshold. To move backward, one foot is placed or slid behind the other a predefined distance, with both feet flat on the floor. This gesture moves the user one step back at a time. Gestural side-stepping is not supported. Grant and Magee (1998) developed a sensor-based virtual locomotion control in which the user moves forward in the VE by sliding his foot either forward or backward over the floor. The direction of motion is determined by the averaged direction of where both feet point (in terms of the foot's orientation rather than its movement). Foot motion outside of a 45 deg. corridor about this direction is treated as actual motion, so gestural side-stepping is not supported. Both of these leg-based systems have been used effectively in studies of user navigation and search through large-scale VEs. Since these systems rely solely on magnetic trackers with limited accuracy for measuring foot movement, they are not accurate enough to determine when or where the foot makes or breaks contact with the floor. The trackers' inaccuracy makes it difficult to characterize other properties of a person's gait, thus limiting the design options for control techniques.

3.3.2 Our First Attempt at Using Walking-in-Place. The first virtual locomotion system we implemented and tested used a combination of torso-based steering and step-based speed control. Side-stepping was not supported. A position tracker was attached to the user's waist and force sensors (Wertsch, Webster, & Tompkins, 1992) were mounted under the ball and heel of each foot on the insoles of their shoes. The basic idea was to initiate virtual motion when the user took an in-place step and use the rate of stepping to control speed. The system also had to be able to distinguish between stepping to turn and stepping in-place to initiate virtual motion. Forward and backward virtual motion were indicated by pushing off the ball or heel of the foot, respectively. Flat-footed steps produced no virtual displacement and were used for stepping to turn. The user could also turn while advancing in the VE by pushing off the ball of his foot while stepping to turn in place. This was easy to do when the user concentrated on it, and the computer had no problem recognizing these distinctions. But users tended to get a little "sloppy" when they started thinking about something other than how they stepped. Although ninety percent of their steps indicated their intention, the remainder was enough to spoil the technique. Unintentionally moving or missing a step was quite disconcerting.

3.3.3 Expressiveness of Stepping Gestures. While these locomotion controls show the promise of the leg-based approach, the application of force sensors alone or magnetic position trackers alone severely limits how well leg motion can be characterized. The result is that the user is required to make exaggerated gestures to ensure clear gesture recognition. The leg motions of a person stepping in place can be very expressive. It is up to the user interface to derive as much information as possible from what is expressed. This may require a richer combination of sensors and a more sophisticated pattern-recognition system to achieve, but it holds the promise of a more responsive interface.

4 Virtual Locomotion Using Gaiter

4.1 Our New Locomotion Control

We have developed a second-generation locomotion control that allows users to more easily control their movements in the VE; it also addresses many of the criteria presented earlier for achieving a higher level of interactive realism. We call the new system *Gaiter*. Its design is based on a generalized classification of human gait that integrates control actions with natural actions in a seamless manner. The control actions in Gaiter are various forms of excess leg motion, which, in its purest form, is simply stepping in place. The corresponding natural actions include forward and backward walking, stepping to turn, and side-stepping. The controlled effect is virtual locomotion, which is the horizontal displacement of the user's virtual body in a VE.

Virtual motion in Gaiter is controlled by gesturing with the leg. It is indicated by the excess motion of the legs while stepping in place, or by extra leg motion added to steps that turn or displace the user. *Excess leg motion* is defined as any motion of the legs that does not participate in the physical displacement of the body. For example, when the knee rocks (swings out and back) while stepping in place, the direction and extent of the knee movement is used to compute an implicit horizontal displacement of the person's body in the VE. Here and in the remaining discussion, the term *virtual body*, or just *body*, is used to describe the location of the user in the VE. It links the perspective imagery to the user's perception of where he is in virtual space (sometimes referred to as a person's *egocenter*).

The combination of several characteristics set Gaiter apart from other leg-based locomotion controls.

(1) It is sensor based and does not rely on an external motion platform.
(2) The control is characterized by excess motion of the legs.
(3) The direction, extent, and timing of the excess leg motion controls the locomotion of the virtual body.
(4) Excess leg motions can be flexibly intermixed with other natural actions (such as actual steps, head and hand movements, pivots, crouches, and leaps).

The current implementation of Gaiter employs a hybrid sensor system (Figures 1 and 2). Six-DOF (x, y, z, roll, pitch, and yaw) sensors attached to the knees track the translation of the knee and rotation of the lower leg. Force sensors placed on shoe insoles under the ball and heel of each foot register approximate ground-reaction forces. Gaiter uses the data from the knee trackers to compute displacements of the body in the VE. The force sensors help determine the timing of each step, allowing

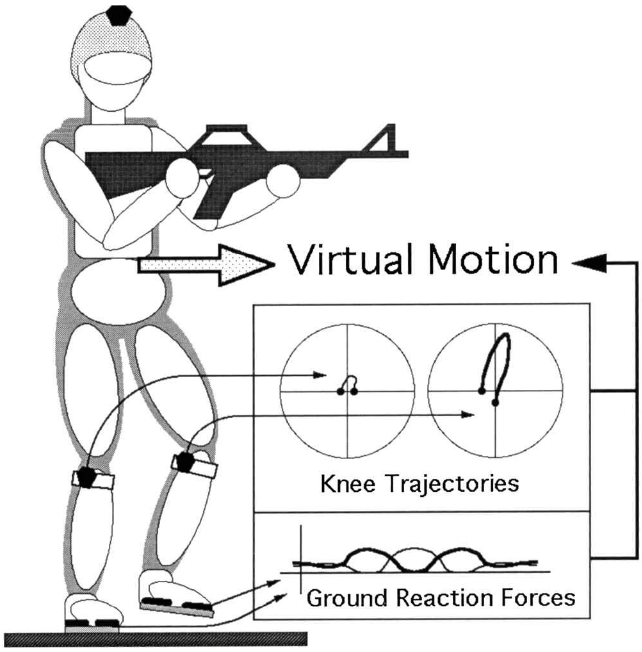

Figure 1. Gaiter: Steps are characterized using a combination of position and force sensors.

successive steps to be segmented. Pattern-recognition software distinguishes between in-place steps, turning steps, and actual steps. Since the system can distinguish between these, it allows the user to intermix gestural steps (control actions) with actual steps (natural actions). Purely gestural steps move the body virtually. Actual steps move the body the same distance in both the virtual and real world. While actual steps provide the most natural and accurately judged movements, their range is limited, so gestural steps are used to cover large distances in the VE.

Sensors are also placed on the head, waist, and handgrip to track the physical position and orientation of the view point, trunk, and hand. The virtual displacement (an accumulated horizontal offset from the starting position) is computed from the gestural stepping motion of the legs, then added to the sensed positions of these body parts to derive their positions within the VE. This approach allows tracked body parts to move independently, yet remain linked to the position of the virtual body. In Gaiter, the head tracker controls the viewpoint, the waist tracker controls the position and orientation of the central body, and the handgrip tracker allows for manipulation of a hand-held object, such as a weapon. Since the head, body, and hand share the same virtual displacement, they remain "attached" and move as parts of a single body through virtual space. Of course, additional body parts (such as the other hand or elbows) could be similarly tracked.

4.2 How It Works

Virtual motion in Gaiter is controlled by in-place stepping. Virtual steps (or, more precisely, the virtual displacements generated by gestural steps) move the virtual body, including the viewpoint, in the VE while the user remains localized in the real world. The user can move in a given direction by rocking his legs in that direction (Figures 3 and 4). Forward virtual motion is achieved by simply walking in place; in this case, the knees swing forward then back. To take a virtual sidestep to the right, the user swings his right leg to the right and then drops it back down (to the left); the left foot is nominally raised and lowered on alternate steps, mimicking the way the alternate foot follows the lead foot in an actual sidestep. Backward virtual steps are taken by swinging the feet backward then forward while keeping the knees relatively stationary. (Backward steps may also be taken by swinging the entire leg backward then forward in a "Nordic track" style, although this gesture is more awkward for most users.) In a similar fashion, the user can move diagonally forward or backward through the VE by rocking the knees or feet along a diagonal path. In a forward step, the direction of locomotion follows the knee, whereas in a backward step the path follows the foot.

Since the control action in Gaiter is the excess leg motion derived from rocking the legs during in-place stepping, any other motion of the legs is interpreted as a natural action. In particular, this means that Gaiter is compatible with the natural action and effect of turning the body. People typically do not make excess leg motions when stepping or pivoting to turn. Therefore, the user may easily turn in place. Gaiter does not conflict with a wide variety of natural movements, including jumping, crouching, and other types of posturing.

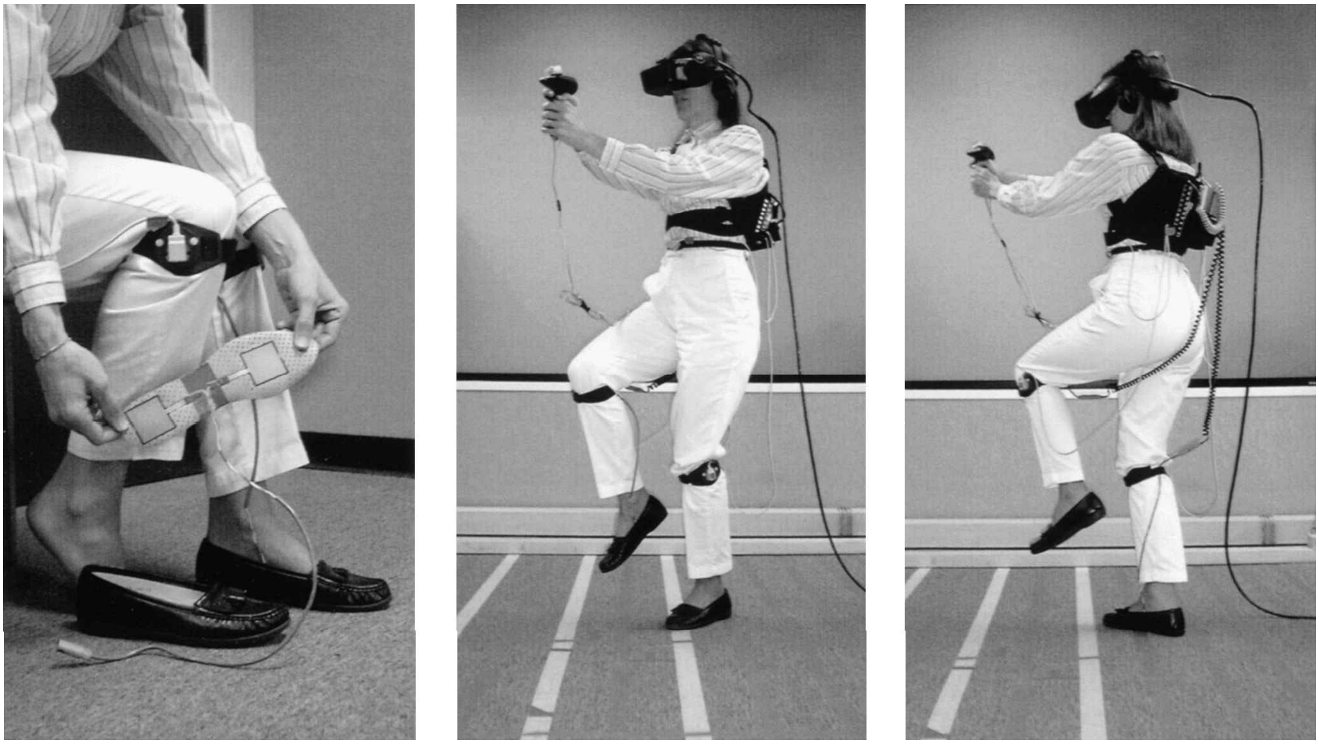

Figure 2. Gaiter: A sensor-based locomotion control that allows the user to move through a VE by walking in place. The motion of the legs is characterized by force sensors placed on shoe insoles and six-DOF trackers attached to the knees. Additional sensors attached to the waist, head, and handgrip track the motion of the body, viewpoint, and handgun.

With Gaiter, natural and control actions can be intuitively combined. Perhaps the best example of this is walking along a curved path. By introducing excess leg motion (like rocking the knees forward) while stepping to turn, the user advances while turning. In a similar manner, the user can also walk backwards or laterally while turning to execute a wide variety of tactical movements (although some of these are more awkward than others as compared to their natural counterparts).

4.2.1 Virtual Displacement. Virtual displacement is key to understanding how Gaiter works. Each in-place step contributes to the virtual displacement. This contribution is a function of the direction traveled by the knee during its outward swing and the distance traveled when it reverses direction and swings back to its starting point. (For simplicity, this discussion focuses on forward in-place steps.) Both the excursion (outward swing) and reversal (inward swing) of the knee are excess leg motions during an in-place step, since they generate no physical displacement of the body. In an actual step, the body physically moves in the direction of the knee motion. There is very little (if any) reverse motion of the knee, and the contribution to the virtual displacement is negligible. Since both actual and gestural steps involve an excursion of the knee, it is easy to discriminate gestural steps by the knee reversal.

Steps may generate a combination of physical and virtual displacement. In general, *Physical Leg Motion = Primary Leg Motion + Excess Leg Motion.*

Primary leg motion generates physical displacement of the body and is dominant in actual steps, whereas excess leg motion is dominant for in-place steps. When tracking the motion of the knee, hybrid steps are evident when the distances covered by the outward and reverse swings of the knee are unequal.

The position at any point in time of the user's body in the VE is its physical position offset by the accumulated

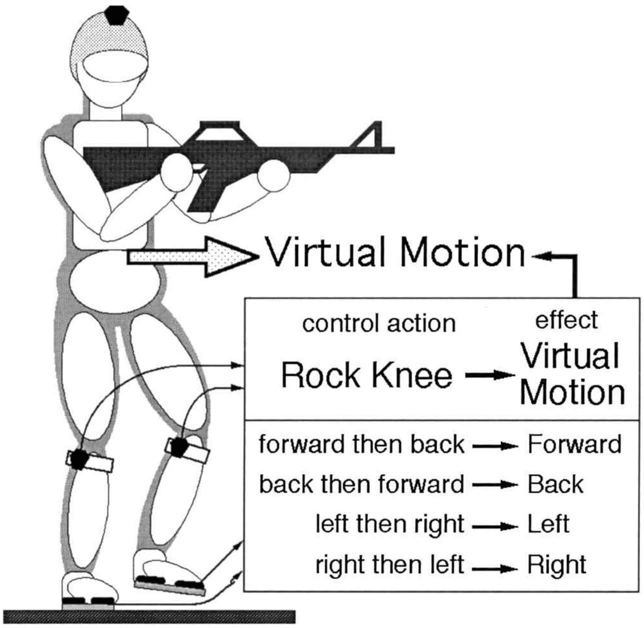

Figure 3. Gaiter: The excess motion of the legs generated by rocking the legs is used to move the body through a VE.

virtual displacement: *Virtual Position = Physical Position + Virtual Displacement.*

Actual steps update the physical position but do not alter the virtual displacement. In-place steps update the virtual displacement but not the physical position. In each case, the virtual position is altered, so the virtual body moves through the VE. The virtual displacement is added to each (physically tracked) part of the user's body to translate it in the VE. The virtual position of the waist, head, and hands are all computed in this manner, while their orientations are tracked directly. Visually representing the position and orientation of the avatar's legs in the VE is more difficult, since a physical in-place step must be transformed into a translational step in the VE. We have yet to unravel the combination of primary and excess leg motions to the point where we can depict them as natural-looking stepping motions.

4.2.2 Gaiter Stepping Phases The definition of a step must cover both in-place and actual steps taken to translate or turn the body in a given direction. Traditional definitions found in the biomechanical literature are often limited to describing walking or running on a straight or curving track. There has been little reason to treat other kinds of stepping actions, such as side-stepping, stepping to turn in place, and (especially) stepping in place. In the current implementation of Gaiter, the start and end criteria for all kinds of steps are based on the forces underfoot. Steps occur only when a foot breaks contact with the floor. This allows the system to avoid responding to knee movements that occur when the feet are down and to determine the position of the knees at the start and end of each step. Although steps are defined by the foot breaking and remaking contact with the ground, a more complete analysis also takes into account the shifting balance of weight that precedes and follows each step.

Gaiter analyzes a series of steps by monitoring the stepping state of each leg. At any point in time, a leg is in one of three phases: down (D), excursion (X), or reversal (R). The X and R phases occur when the foot is off the ground and the knee is swung outward and back, respectively. The excursion and reversal of the knee characterize the excess motion of the leg during a virtual (in-place) step; the reversal serves as the discriminator since it occurs only during a virtual step. In an actual step, the phases alternate between D and X, whereas in a virtual step the phases alternate between D, X, and R (in that order).

In a normal walking gait, the phase sequences for each step (D, X or D, X, R) alternate, usually with a period in-between where both feet are down. Representing the combined phases for each interval as ‹left›-‹right›, the natural walking pattern is D-D D-X D-D X-D D-D. . . .

When stepping in-place, the pattern is D-D D-X D-R D-D X-D R-D D-D. . . .

In a running gait, the phase sequences overlap, with a period in which both feet are off the ground simultaneously and no period in which both feet are down simultaneously. A natural running pattern is D-D D-X X-X X-D X-X D-X. . . .

The pattern for in-place running is D-D D-X D-R X-R X-D R-D R-X D-X D-R. . . .

Notice that in virtual locomotion (walking or running) there are no X-X or R-R combinations. This means that jumping—which contains X-X and (occa-

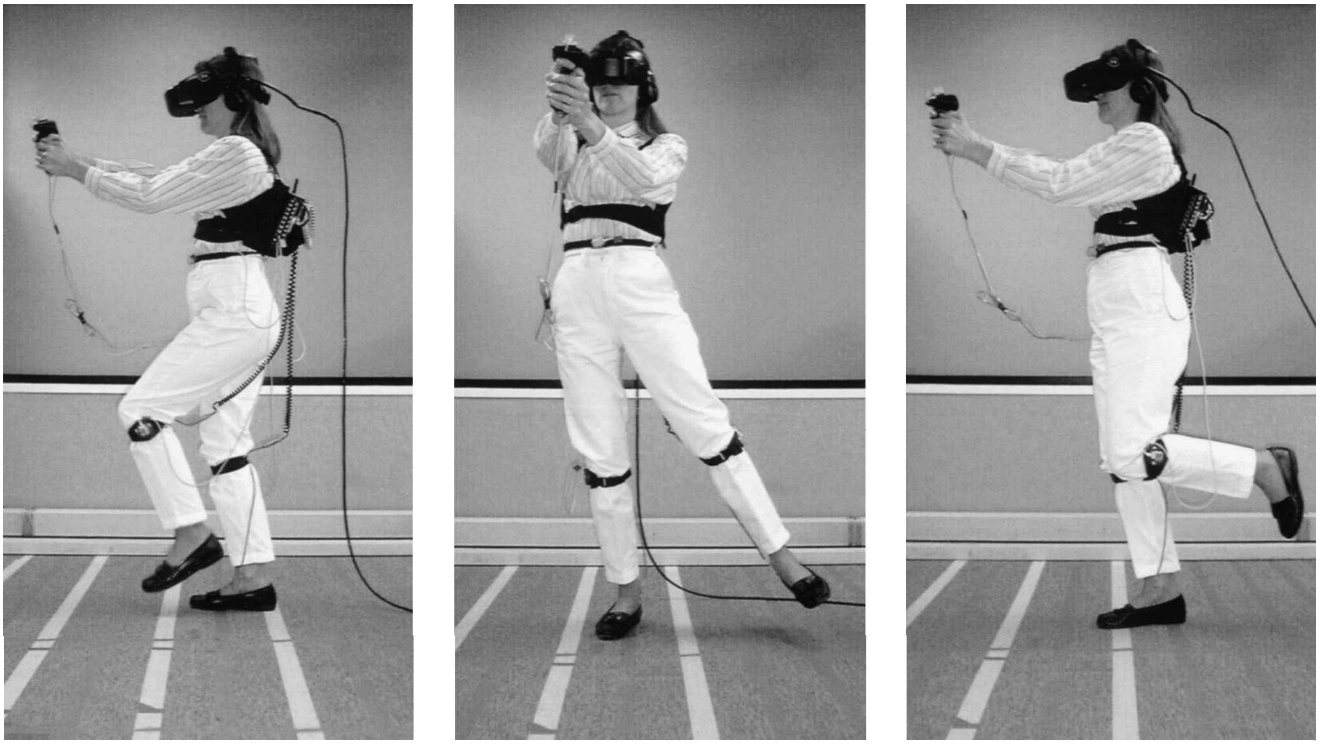

Figure 4. In-place stepping gestures move the body virtually forward, sideways, and backward while the user remains localized in the real world.

sionally) R-R states—is always physical and will not generate a virtual displacement.

These patterns show how discrimination of the reversal phase is key to generating virtual movement. The direction of movement is determined by the outward path of the knee at the point of reversal, and the extent of the virtual displacement is a function of the distance traveled by the knee as it swings back to the start position of the step. The timing is dependent on the ability of the software to accurately discriminate the beginning, ending, and reversal points of each step.

4.2.3 Characterizing Steps. The characterization of excess leg motion involves a timing issue that affects responsiveness of the locomotion control: At what point does the system determine that a virtual step is being made? In our reversal technique, the intent can be determined before the gestural step is completed, resulting in only minor lag at the beginning of a sequence of steps and even less within a series of steps.

Since the motion of the legs is tracked at the knees, a scaling factor is applied to the horizontal component of the knee as it makes its outward swing during the excursion phase. The geometry of an in-place step (Figure 5) suggests that scaling the knee excursion distance by a factor of four provides a good approximation of the displacement of the body over the course of a step. Our experience with Gaiter supports this. The scaling factor can be modified for different styles of gait and for individual differences, as well as to simulate stairs, grades and inclines, and various types of terrain.

In natural locomotion, steps are rarely taken as single units but instead occur as sequences of alternating steps that propel the body in a given direction. Biomechanical literature typically defines a step in terms of one leg swinging from a position extending behind a person to its extension in front of him (illustrated in Figure 5). When a person starts walking from rest with his legs together and stops by bringing his legs together again, the initial and terminal steps are actually half-steps. This de-

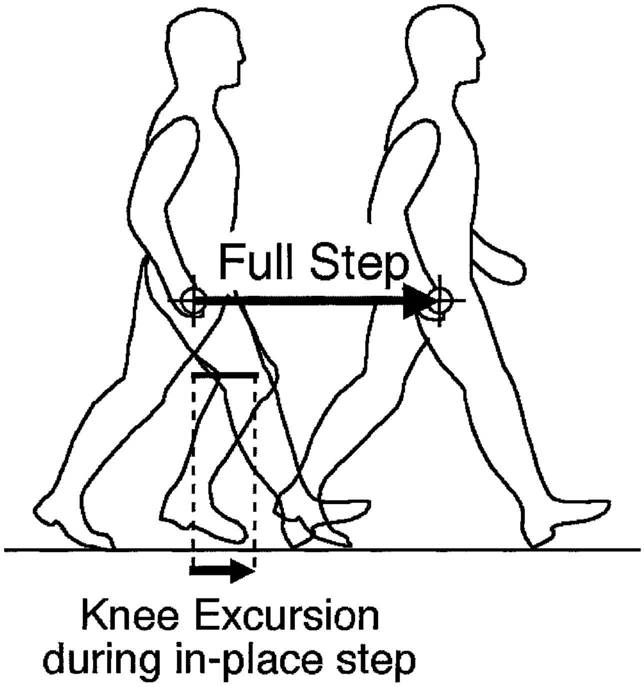

Figure 5. Body and leg displacements during actual and in-place steps. Knee excursion during an in-place step covers about a quarter of the distance traversed by the pelvis in a full step.

tail has an important effect on the timing and smoothness of the virtual movement, since the alternate foot is engaged in a "catch-up" phase with the forward foot during a series of steps. The virtual displacement resulting from the excess motion of a single in-place step must therefore be retained and applied over the excursion phase of the next alternating step to produce a more continuous, natural style of locomotion.

4.3 Hardware Architecture

The current implementation of Gaiter runs on a 200 MHz dual processor Pentium PC under Windows NT. The software performs pattern recognition on sensor data input from the feet, knees, waist, and handgrip. The computed virtual displacements (together with the transformed virtual positions of the legs, waist, and hand) are sent over a serial link to an SGI Onyx2 that performs modeling, collision detection, and visual rendering of the VE using an in-house software development system (Dandekar, Templeman, Sibert, & Page, 1998). To minimize viewing lag, the physical position and orientation of the head is tracked directly by the Onyx2, then combined with the virtual displacement sent from the Gaiter PC to generate the virtual viewpoint. The virtual position and orientation of the body is used in collision detection, and the handgrip is used for aiming and firing a simulated weapon.

Two different six-DOF tracking systems are supported for the real-time input of position and orientation data. Our initial development employed a pair of Polhemus 3SPACE FASTRAK magnetic tracking devices, supporting up to four sensors each. Position and orientation data from the knees, waist, and handgrip are collected from one of the FASTRAK devices and sent to the Gaiter PC over a serial channel. The other FASTRAK is connected to the Onyx2 for tracking the position and orientation of the head. In this configuration, signals from the insole force sensors are passed through an analog-to-digital converter and sent to the Gaiter PC over a separate serial channel.

The biggest drawback to the FASTRAK is its tethered operation and short range (under 4 ft. in diameter). As the user turns to maneuver in the VE, cables quickly get tangled, and the user must be constantly recentered as he drifts to the edges of the physical operational range. To avoid these problems, our current development uses a wireless MotionStar tracking system from Ascension Technology. The MotionStar is another type of magnetic tracking device that can support up to twenty sensors attached to a body-mounted electronics unit. Position and orientation data are transmitted through an antenna to a base station, and then on to the Gaiter PC and Onyx2 rendering system over an Ethernet interface. By channeling the force data from the insole pressure sensors through an auxiliary serial port on the MotionStar backpack unit, we have eliminated all tethers used to sense the motion dynamics.

The only remaining cable tethering the user to the immersive VE system is attached to a V8 head-mounted display (HMD) from Virtual Research Corporation. The head-tracking sensor is attached to the HMD, which presents a dynamic perspective image of the visual environment as the user moves around within the VE. Another approach, which would eliminate tethered cabling altogether, is to place the user within a surround-screen display. In this configuration, the head-tracking sensor would be attached to a headband or helmet worn by the user. We plan to use Gaiter in such an environment in the near future (Lanzagorta, Kuo, & Uhlmann, 1998).

With the MotionStar wireless tracking system and HMD, a user may be suited up and ready to use Gaiter in a matter of minutes. A simple per-user calibration for the insole force sensors is required, which involves having the user step in place for several seconds.

4.4 Features of Gaiter

We have implemented the Gaiter locomotion control and find it easy and effective to use. Many of the realistic features of Gaiter derive from its adoption of excess leg motion as the control action:

- **Virtual motion in any direction:** People can virtually walk around freely in a VE using Gaiter. They can move forward, backward, sideways, or diagonally without turning their body. They may also move in any direction while turning their body (for example, walking forward or backward in a circle).
- **A natural coordinate system:** Gaiter operates in the appropriate coordinate frame of reference: the direction of leg movement with respect to the surrounding environment. Other parts of the body (head, shoulders, arms, pelvis, and so on) can be aligned as they are in natural postures and movements. This allows people to make use of their reflexes to direct their body in response to external stimuli.
- **Compatibility with other actions:** Since Gaiter utilizes only the parts of the body that are normally associated with walking, it does not unnaturally constrain or interfere with actions performed by other parts of the body. People are free to turn their head to look in any direction and use their hands to manipulate and point at virtual objects. Gaiter also allows users to naturally intermix a wide range of postural motions (such as crouching, jumping, and bending to look around objects) with gestural stepping motions.
- **Ease of activation:** Gaiter gestural motions are easy for a person to make with confidence. The gesture for walking forward is especially easy: simply walk in place.
- **Responsive:** The pattern-recognition system does not have to wait for a gesture to be complete before responding to knee movements. Virtual motion in response to both actual and gestural steps occurs as the step is taken.
- **Expressive:** The attributes of in-place stepping can be used to control the characteristics of natural gait as portrayed by the VE. The height and frequency of in-place steps map into the stride length and cadence of the steps taken by the virtual body. The system can be tuned to preserve metrics between physical and virtual space, as well as to match specific attributes of natural locomotion, such as perceived velocity and caloric expenditure.
- **Synergy of coupling stepping movements to optic flow:** Tying optic flow directly to leg movement makes the Gaiter interface feel like a simulation of walking rather than an indirect control over locomotion. It comes close to creating the interactive illusion of virtual perambulation, since the cadence of the stepping movements is reflected in what the user sees. This may facilitate skill learning in a wide variety of tasks that involve locomotion. Past research suggests that conflicting sensory stimuli is a primary cause of simulator sickness (Reason, 1970). With Gaiter, walking in place jostles the head in a manner similar to actual walking. This, combined with the synthetic forward motion of the viewpoint induced by virtual walking, produces sensory cues that closely match those associated with natural walking. Based on this and our experience using Gaiter, we suspect that the reduction in sensory mismatch may reduce the tendency for motion sickness.
- **Compact and cost effective:** The equipment used to implement Gaiter is compact compared to mechanical motion platforms and potentially inexpensive (with advances in tracking and immersive display technology). Of course, it requires more space and expense than a desktop joystick control. If the interaction task does not need to simulate natural

locomotion in terms of either realistic movement or coordinated head, hand, and body alignment, then a vehicular motion control might suffice.

4.5 Limitations of the Technology

A fundamental limitation of Gaiter is that walking and running in place are not the same as actual walking and running. They use somewhat different muscle sets in somewhat different ways. The user does not physically accelerate along the path of motion or build up momentum by running faster in place. (It may be possible to simulate the latter effect by increasing virtual velocity as successive strides are made, but this may make the requisite deceleration seem more artificial.) It will be possible to tune the system to match particular attributes of natural locomotion (e.g., perceived velocity, natural cadence, caloric expenditure, and so forth), but it is unlikely that one set of tuning parameters will satisfy all criteria.

Some natural actions may be misclassified by Gaiter as a control action. One example is marching in place for its own sake. Also, Gaiter does not currently provide control actions for certain kinds of locomotion, such as jumping forward or climbing a vertical ladder.

Hardware limitations also impact the Gaiter's ability to adequately characterize the motion of the legs and other body parts in real time. Gaiter is a sensor-based locomotion technique that relies on timely and accurate six-DOF position and orientation readings. While the electromagnetic trackers we use are small, flexible, and (in the MotionStar configuration) allow tetherless operation, they suffer from noisy signals and erroneous readings due to electromagnetic interference with metal and other electrical devices in the environment. Calibration and filtering of the sensor data can alleviate some of these problems, but often degrades performance in other areas, such as latency (Ghazisaedy, Adamczyk, Sandin, Kenyon, et al., 1995; Livingston & State 1997; Nixon, McCallum, Fright, & Price, 1998). Other sensor technologies are available, but each presents a different set of limitations. Optical trackers have line-of-sight restrictions and require large processing overhead. Acoustic trackers are sensitive to background noise, as well as variability in air temperature, pressure, and humidity. Inertial trackers are inherently sourceless, but provide only three-DOF orientation readings that tend to "drift" over time.

On the output side, current display-rendering systems provide limited realism of real-time imagery. Currently available HMDs that are light enough to wear while walking offer a limited field of view (typically 50 deg.), a limited display resolution (typically 640 × 480 pixels), a fixed depth of focus, and are often tethered. The lag due to sensor transmission, image generation, and display contributes to motion sickness (DiZio & Lackner, 1992).

4.6 Potential Applications

An obvious application for Gaiter is in the area of MOUT (Military Operations in Urban Terrain) training and mission rehearsal. Combat skills are mentally and physically demanding, and they require an individual to make time-critical responses under stress. As part of a comprehensive team simulator, Gaiter would allow soldiers to practice techniques and team coordination to enhance their tactical expertise. Textbook concepts, like the effectiveness of overlapping fields of fire, cover and concealment, and fire and movement can be experienced firsthand under a variety of conditions. Team coordination skills include maintaining awareness of the location of other team members, communication between dispersed units, and all-around security. The Marine instructors who have tried Gaiter appreciate the full range of motion facilitated by the control. Gaiter will complement a new training system being developed by the Marine Corps called SUTT (Small Unit Tactical Trainer, formerly the Team Tactical Engagement Simulator, or TTES). SUTT is being developed by the Naval Air Warfare Center Training Systems Division (NAWC/TSD) and Southwest Research for the purpose of training MOUT skills in deployed settings (Goodman, Porter, & Standridge, 1997).

Another potential application is shipboard firefighting. The Naval Research Laboratory's Navy Technology Center for Safety and Survivability developed a model of portions of the Ex-USS Shadwell, the Navy's full-scale fire research and test ship, to test the feasibility of using an immersive VE as a tool for shipboard firefighting training and mission rehearsal (Tate, Sibert, Williams, King, et al., 1995). Using a six-DOF joystick as the locomotion device, Navy firefighters who practiced in the three-dimensional model that included fire and smoke effects to simulate actual firefighting conditions performed better than those who practiced using only the ship's diagrams (Tate, Sibert, & King, 1997). We believe that using Gaiter as the locomotion control would allow more-realistic motion and further enhance the training effect.

4.7 Current and Future Direction

4.7.1 Testing and Experimental Evaluation. For testing Gaiter, we have been using the set of locomotion tasks described as part of VEPAB, ARI's VE Performance Assessment Battery (Lampton, Knerr, Goldberg, Bliss, et al., 1994). We also have models of the Quantico Village database developed by Paradigm, Inc., for the Team Tactical Engagement System for NAWC/TSD and the Ex-USS Shadwell ship interior developed by Tate at NRL (Tate et al., 1997). These models allow us to tune and test Gaiter in a variety of interesting virtual spaces.

We are currently designing an experiment comparing Gaiter with two other virtual locomotion controls: a head-based control (move where your head is pointed) and a desktop control (which uses a joystick to control interaction). The tasks we will use range from simple locomotion down hallways to the more complex task of clearing a building of shooters while minimizing one's exposure to them. Our hypothesis is that people will perform tasks differently using the three different controls, and the sequence of actions (including looking, moving, and manipulation) they perform using Gaiter will best match the way soldiers perform the task in the real world.

4.7.2 Alternative Characterizations. We will be looking at other ways of characterizing leg motion and transforming it into virtual movement. Each technique involves tradeoffs between responsiveness in movement and misclassification of different types of natural movement. For example, one could use the motion of the pelvis relative to that of the knees to discriminate the excess motion characteristic. If little "forward" motion of the pelvis is detected during knee excursion, then an in-place step is being made. An advantage of this approach would be an increase in responsiveness, since a virtual step could be discriminated prior to knee reversal.

4.7.3 Avatar Development. Another major focus is the development of an avatar driven by Gaiter. An avatar has two important uses. It allows the user to see how his body fits into the VE, giving the user a better sense of immersion (Slater et al., 1995; Singer et al., 1998). An avatar also lets other people see the user's pose and location in the VE, facilitating communication and interaction in multiuser scenarios. The challenge of developing a Gaiter avatar is to match the control actions (in-place stepping) to the controlled effects (virtual stepping) in as natural a way as possible. The match will not be perfect and it remains to be seen how tolerant users will be of any kinds of mismatch.

5 Conclusions

Many interactions between perceptual-motor systems and candidate locomotion controls involve looking, manipulation, turning the body, posturing, and thinking. These interactions limit the most promising approaches to techniques that control virtual locomotion using the motion of the legs. Our first attempt at building a leg-based control put too high a burden on the user to make special kinds of steps. We then combined position trackers on the knees with the insole force sensors to create a walking simulator called Gaiter. Gaiter provides a consistent means of taking virtual steps in any direction and is compatible with a wide range of other natural actions. It is responsive, expressive, and comes close to creating the interactive illusion of virtual perambulation. Because virtual locomotion using Gaiter is so similar to natural walking, we expect that users will adopt movement strategies in VEs similar to those they would apply in the real world, and that reflexive skills practiced in a VE will transfer more fully to real-world situations.

Acknowledgments

We would like to thank Rob Page and Justin McCune who developed the interactive software implementing the virtual environment. We also would like to thank Kapil Dandekar, who pioneered development of our VE software platform; Ha Duong and Adrian Blanarovich, who developed circuits and cabling to implement Gaiter; Josh Davies, who created models for the virtual environment; and Rob Lindeman, who provided editorial comments. Gaiter has been developed and will be refined and evaluated under the ONR 6.2 Virtual Environment Technology program sponsored by Terry Allard, NRL 6.1 base funding in Controls for Synthetic Environments, and NRL 6.2 base funding in Multi-Modal Interaction.

References

Bowman, D., Koller, D., & Hodges, L. (1997). Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. *Proc. of IEEE Virtual Reality Annual International Symposium* (*VRAIS'97*), 45–52.

Brooks, F. P., Airey, J., Alspaugh, J., Bell, A., Brown, R., Hill, C., Nimscheck, U., Rheingans, P., Rohlf, J., Smith, D., Turner, D., Varshney, A., Wang, Y., Weber, H., & Yuan, X. (1992). *Six generations of building walkthrough: final technical report to the national science foundation*. (Tech. Rep. No. TR92-026). Chapel Hill, NC: Department of Computer Science, The University of North Carolina.

Chance, S., Gaunet, F., Beall, A. C., & Loomis, J. M. (1998). Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs. *Presence: Teleoperators and Virtual Environments, 7*(2), 168–178.

Christensen, R., Hollerbach, J. M., Xu, Y., & Meek, S. (1998). Inertial force feedback for a locomotion interface. *Proc. of ASME Dynamic Systems and Control Division, 64,* 119–126.

Dandekar, K., Templeman, J., Sibert, L., & Page, R. (1998). *The Hobbes, software architecture for virtual environment interface development*. (Technical Report NRL/FR/5510-98-9876). Washington, DC: Naval Research Laboratory.

Darken, R. P., Cockayne, W. R., & Carmein, D. (1997). The omni-directional treadmill: A locomotion device for virtual worlds. *Proc. of ACM User Interface Software and Technology* (*UIST '97*), 213–221.

DiZio, P., & Lackner, J. R. (1992). Spatial orientation, adaptation, and motion sickness in real and virtual environments. *Presence: Teleoperators and Virtual Environments, 1* (3), 319–328.

Fairchild, K. M., Lee, B. H., Loo, J., Ng, H., & Serra, L. (1993). The heaven and earth virtual reality: Designing applications for novice users. *Proc. of IEEE Virtual Reality Annual International Symposium* (*VRAIS '93*), 47–53.

Ghazisaedy, M., Adamczyk, D., Sandin, D., Kenyon, R., & DeFanti, T. (1995). Ultrasonic calibration of a magnetic tracker in a virtual reality space. *Proc. of IEEE Virtual Reality Annual International Symposium* (*VRAIS '95*), 179–188.

Goodman, S., Porter, S., & Standridge, R. (1997). Evaluation and assessment of a virtual environment advanced technology demonstrator. *Proc. of ITSEC,* 65–75.

Grant, S. C., & Magee, L. E. (1998). Navigation in a virtual environment using a walking interface. In S. L. Goldberg and J. A. Ehrlich (Eds.), *The Capability of Virtual Reality to Meet Military Requirements* (pp. 81–92). New York: NATO.

Horey, J., Fowlkes, D., & Reir, R. (1995). Military operations on urbanized terrain (MOUT) training in synthetic environments using the team target engagement simulator (TTES). *Proc. of the 17th Annual Interservice/Industry Training Systems and Education Conference,* 671–679.

Iwata, H., & Fujii, T. (1996). Virtual perambulator: A novel interface device for locomotion in virtual environment. *Proc. of IEEE Virtual Reality Annual International Symposium* (*VRAIS '96*), 60–65.

Knerr, B. W. (1998). Interface issues in the use of virtual environments for dismounted soldier training. In S. L. Goldberg and J. A. Ehrlich (Eds.), *The Capability of Virtual Reality to Meet Military Requirements* (pp. 171–186). New York: NATO.

Lampton, D. R., Knerr, B. W., Goldberg, S. L., Bliss, J. P., Moshell, J. M., & Blau, B. S. (1994). The virtual environment performance assessment battery (VEPAB): Development and evaluation. *Presence: Teleoperators and Virtual Environments, 3*(2), 145–157.

Lanzagorta, L., Kuo, E., & Uhlmann, J. (1998). GROTTO visualization for decision support. *Proc. of SPIE Aerosense 98,* 165–176.

Livingston, M. A., & State, A. (1997). Magnetic tracker calibration for improved augmented reality registration. *Presence: Teleoperators and Virtual Environments, 6*(5), 532–546.

Lorenzo, M., Poole, D., Deaso, R., Lu, Y., Kekesi, A., Cha, J., Slayton, D., Williams, M., Moulton, R., Kaste, V., MacKrell, W., Paddison, R., Rieks, J., Roth, W., & Wodoslawsky, F. (1995). OSIRIS. *Visual Proc. of ACM SIGGRAPH'95,* 129.

Nixon, M. A., McCallum, B. C., Fright, W. R., & Price, N. B. (1998). The effects of metals and interfering fields on electromagnetic trackers. *Presence: Teleoperators and Virtual Environments, 7*(2), 204–218.

Reason, J. T. (1970). Motion sickness: A special case of sensory rearrangement. *Advancement in Science, 26,* 386–393.

Singer, M. J., Ehrlich, J. A., & Allen, R. C. (1998). *Effect of a body model on performance in a virtual environment search task*. (Tech. Rep. 1087). Orlando: U.S. Army Research Institute for the Behavioral and Social Sciences.

Slater, M., Usoh, M., & Steed, A. (1995). Taking steps: The influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction, 2*(3), 201–219.

Tate, D. L., Sibert, L., Williams, F. W., King, LCDR T., & Hewitt, D. H. (1995). *Virtual Environment Firefighting/Ship Familiarization Feasibility Tests Aboard the Ex-USS Shadwell*. (Ltr Rept 6180/0672.1). Washington, DC: Naval Research Laboratory.

Tate, D. L., Sibert, L., & King, LCDR T. (1997). Virtual environments for shipboard firefighting training. *Proc. of IEEE Virtual Reality Annual International Symposium* (*VRAIS '97*), 61–68.

Youngblut, C., Johnson, R. E., Nash, S. H., Wienclaw, R. A., & Will, C. A. (1996). *Review of Virtual Environment Interface Technology.* (Tech. Rep. No. IDA Paper P-3186, Log: H 96–001239). Alexandria, VA: Institute for Defense Analyses.

Wells, M., Peterson, B., & Aten, J. (1996). *The Virtual Motion Controller: A Sufficient-Motion Walking Simulator.* (Technical Report: R-96-4). Seattle: Human Interface Technology Laboratory (HITLab), University of Washington.

Wertsch, J. J., Webster, J. G., & Tompkins, W. J. (1992). A portable insole plantar pressure measurement system. *Journal of Rehabilitation Research Development, 29*(1), 13–18.