Immersive Escape-Route Scenario with Locomotion Devices

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ABSTRACT

The simulation of damaged buildings is of great interest. Virtual-reality technologies allow us to experience such a situation. A main concern here is escaping from the building. To simulate this scenario, a model of the environment and an interface for locomotion are needed. Locomotion inside virtual buildings requires special input devices. This paper discusses several simulation methods for human locomotion in an escape-route scenario. We present some results for a new locomotion device for escaping from of a virtual house that is on fire.

KEYWORDS: Locomotion, full-motion-interface, escape-route scenario, cost-efficient device

INTRODUCTION

Technological advances in the areas of computer-graphics hardware and virtual-reality technology have made it possible to develop virtual environments for a wide class of applications. One of these application areas is architectural design.

Escape Route Scenario

Buildings and architectural sites can be simulated visually to enable future users to inspect buildings during the planning phase. If users detect weak points during a virtual walkthrough, the design of the building can be changed, thus avoiding costly reconstruction measures.

To detect weak points, the relevant properties of the building have to be simulated. For instance, to check the lighting conditions at a particular workplace, all the characteristics that influence illumination (daylight, artificial lighting, transparency of building materials, diffuse interreflections, etc.) have to be properly simulated.

A key concern when planning a new building is user safety. Escape routes have to be carefully planned to ensure that visitors can leave the building quickly in case of an emergency. One such situation is a building that is on fire. Burning buildings can be visualized and inspected interactively (e.g. [1]).

In what follows we discuss how escaping from such a building can be simulated by means of immersive visualization and interaction technology. Users are placed in a virtual burning building with which they have no previous acquaintance. They are instructed to leave the building as quickly as possible following the escape-route signs.

If the perception of users in the virtual environment and in reality were identical, users would not be able to distinguish between the simulation and reality and their behavior could be transferred to a real-life situation. To enable users to forget that they are moving in a virtual environment the degree of immersion must be as high as possible. One main concern, then is to simulate the visual (e.g., impairment of vision by smoke) and auditive stimuli as realistically as possible. Another concern is supporting the realistic impression of locomotion.

Locomotion scenarios using vehicles (e.g., flight simulation, driving simulation) can be simulated in acceptable quality using an existing human-machine interface. Since there is a real cockpit in most flight-simulation systems, cutaneous stimuli do not have to be simulated. The system only simulates vision, audio and aircraft dynamics.

There is no consensus on how to technically realize natural human locomotion (e.g., walking, running). One approach designed to enhance the quality of perception is intersensory integration. The human sensory apparatus is able to combine information incoming from several sense modalities to create a single, coherent sensation [2]. Even where the same environmental status is channeled across multiple modalities, the redundancy is not wasteful [3, 2].

Virtual Reality Technology

In multimodal virtual environments, not only the visual sense but also the auditive, cutaneous, kinesthetic or vestibular
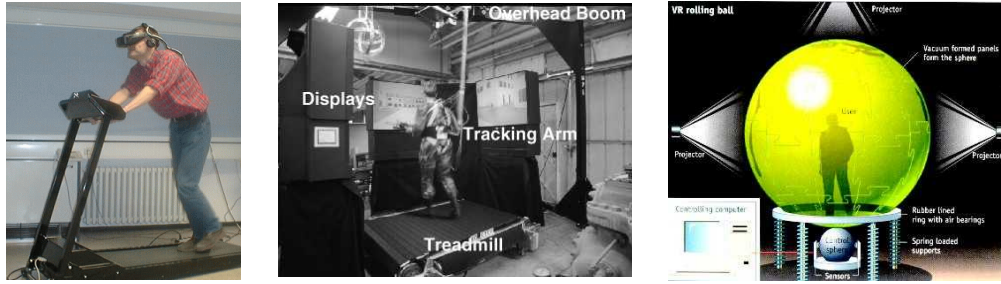
Figure 1: Full-motion interfaces: (a) Spatial Navigator, (b) Omni-directional treadmill [15] (copyright by Darken et al.), (c) Cybersphere [16] (copyright by Findlay Publications)

senses may be stimulated to enhance immersion. The visual, auditive and cutaneous senses can be stimulated directly by means of technical devices (display, headphones, haptic devices, etc.), but the kinesthetic and vestibular stimuli can only be achieved indirectly because the receptors are inside the human body.

There are two main approaches for implementing immersive virtual environments: spatially-immersive displays (SIDs) and head-mounted displays (HMDs). A SID is a display that physically surrounds the viewer with a panorama of imagery [4] (e. g., the Cave Automated Virtual Environment [5]) Auditive stimuli may be supplied via multiple loudspeakers. An HMD [6] consists of two small displays mounted on the head in front of the viewer's eyes. Auditive stimuli may be supplied via headphones. In both approaches, head tracking is used to determine the viewer's location and orientation for image generation.

Some research is currently being done on olfactory stimulation for virtual environments [7], but the realistic simulation of odors for virtual buildings that are on fire has not yet been achieved.

The cutaneous senses may be stimulated via a haptic interface. It applies force feedback to the user's skin while they are interacting in these environments. There are some approaches that apply force feedback to the user's hand or arm (e.g., [8, 9]), because most manipulations of the environment involve use of the hand.

Burdea and Coiffet [10] propose using a light-weight force-amplifier suit called "Jedi" to apply force feedback to the whole body. However, there is currently no implementation of whole-body force feedback in virtual environments. For navigation tasks, force feedback may be neglected. For example, doors can be opened automatically and feedback in collision situations can only be rendered by sound.

During a virtual walk-through, it is the kinesthetic and vestibular senses that are adressed. To properly stimulate these senses, users have to perform similar motions to those in a natural environment. Human beings are able to perceive po-

sitions and accelerations of their limbs as well as acceleration in space, rotation and orientation in the gravitational field. To achieve realistic simulation, the exertion caused by movements should be similar to natural locomotion.

LOCOMOTION IN VIRTUAL ENVIRONMENTS

In many applications, the virtual environment has larger dimensions than the physical workspace. A device has to transform physical motions into motions in a virtual environment. Manual navigational control (e.g., using the mouse, keyboard, or joystick) is provided for many applications. Motion interfaces that involve other parts of the human body relieve the hands of the task of navigational control, leaving them free for other more natural manual manipulations.

Sufficient-motion interfaces activate the kinesthetic and vestibular senses [11] such that self-motion cues are sent to the brain through the initiation of the appropriate muscular contractions and translational and rotational accelerations [12, 13]. One such interface is the Virtual Motion Controller (VMC) [11]. Participants stand on a platform, controlling the motion direction by changing their center of gravity. Head orientation is tracked by a magnetic tracking system, enabling independent control of gaze and travel direction. Peterson showed, that wayfinding is influenced by the motion interface. Users performing a survey-related wayfinding task with the VMC in a spatially complex environment are faster than those using a joystick device [14]. Peterson suggests incorporating the natural walking motion to reduce participants fatigue and increase naturalness of interaction.

Full-motion interfaces

Full-motion interfaces promise a more natural involvement of most of the integrated modalities. The implementation of the interface depends on the desired motion. In fact, there are four types of full-motion interfaces for human walking: treadmills, foot followers, cybersphere and sliding devices.

The simplest type of treadmill, which is used for navigating in virtual environments, is a user-driven uni-directional treadmill (e.g., [17, 18], see Fig. 1(a)). The user holds on to a steering bar while walking on the treadmill.
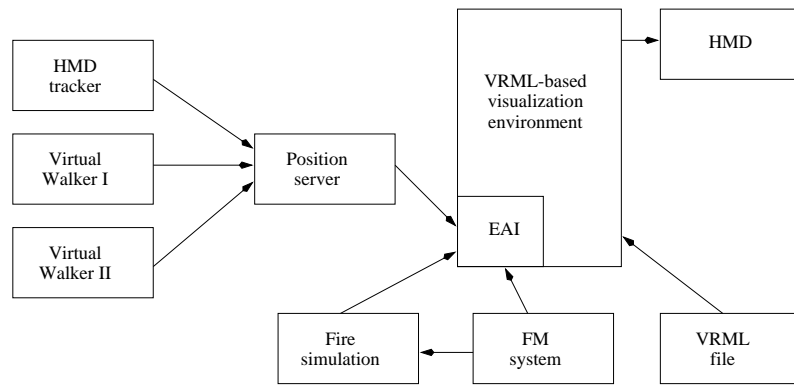
Figure 2: Architecture of FACIT system

If the position of the user is tracked, the treadmill can be driven by a motor. It is than not necessary to hold on to a bar. The system must always bring the user back to the center of the device. If the user changes speed, the speed of the belt has to be adapted accordingly. Abrupt changes in the speed of the belt result in unnatural forces, which may cause the user to stumble. Users must learn to handle this device. Treadmills can also be used to simulate sloping ground and force feedback [19].

Walking in any direction is supported by omni-directional treadmills (ODTs). Darken et al. built an ODT using two perpendicular treadmills [15] (see Fig. 1(b)). The top belt consists of freely rotating rollers which are driven by another, orthogonally oriented, belt below. Maximum user velocity is 2m/sec. Darken et al. observed that users turn slowly and do not suddenly accelerate or decelerate when using the ODT in order to avoid unexpected system responses. Darken et al. state that "skill level plays too important a role in determining the usability of the system." [15].

Foot followers consist of two small movable platforms. In simple types of foot-following systems, the platforms are foot-driven. Examples of such devices, called "Virtual Walker", are given in the next section.

Latham suggests using a more sophisticated foot-following device in which small platforms move automatically to the positions users want to step on [20]. Systran Cooperation propose a device called LocoSim. Boot plates, which are connected to the users' feet, can be moved individually to various positions. The device is able to support walking, running and crawling over different terrains as well as ascending or descending stairs [21]. There are, to our knowledge, no publications so far on the implementation of these two proposals.

A cybersphere is a large rotating sphere driven by a user walking on the inside. Images of the environment are projected onto the surface of the sphere. The user can walk in any direction. Movement is detected by another ball pressed against the underside of the sphere. An implementation of the cybersphere, with a diameter of 3.5m, was developed by J. Eyre (see Fig. 1(c)). It weights 270 kg and presents about twice the inertia of a man starting or stopping walking. Abrupt changes of speed are therefore not possible with the current demonstrator. Eyre plans to integrate a servodrive system. The ball should be rotated by the system according to the movements made by the user [16].

Iwata and Fujii developed an omni-directional sliding device called the "Virtual Perambulator" [22]. Users have to wear special shoes with a low friction film on the sole. Rubber soles attached to the top of the shoes are used as brake pads. Users can physically walk and turn inside a hoop with a diameter of 70cm. Users must hold the hoop to keep their balance. Trained users may push their waists against the hoop while walking [22].

Relation between gaze direction and motion direction

One basic requirement of motion interfaces is that users are able to control the motion direction. Most of the described interfaces (e.g., [15, 16, 22]) allow users to look in any direction while moving forward.

Independent control of gaze and travel direction was a basic design goal of the VMC [14]. Peterson asserts that people frequently walk along a straight path while rotating their heads to the left and right to scan the environment. However, he observed that participants did not attempt to use the independent control of gaze and travel direction provided by VMC. Participants actually become disoriented if gaze and travel direction are misaligned while they are moving [14].

Pausch et al. fielded a virtual environment at the EPCOT center for a period of fourteen months, during which they observed the reactions of over 45,000 guests. Most users refrained from turning their heads much while flying a virtual magic carpet [23]. Pausch et al. assume that users did not exploit this possibility because head tracking is far enough
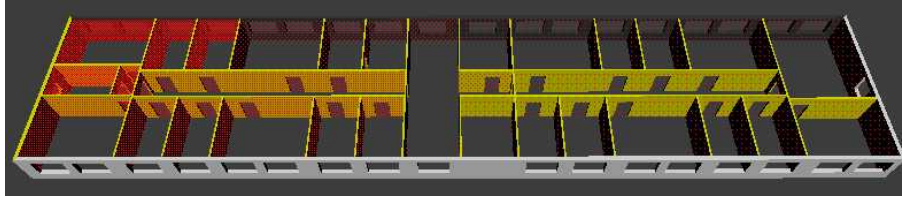
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Figure 3: Bird-eye view of spread of temperature in a simulated floor

from most guests' experience with film and television. Another explanation is that users piloting a vehicle usually look in the direction they are moving in.

We claim there is a dependence between velocity and the tendency to look in the direction of motion. Users who are standing still may look around for orientation, if they are running, they always look in the direction of motion. Often, the environment is scanned by simply moving the eyes to the left or right. The orientation of the head is aligned to the motion direction. Following this assumption for an escape-route scenario, head tracking can be used for controlling motion direction, resulting in a much simpler system design.

THE FACIT SYSTEM

The FACIT project ("Extending Facility Management Systems by Immersive Rendering and Interaction Techniques") sets out to examine how tasks from the area of facility management (FM) can be performed by using an immersive user interface. Since many FM tasks can be satisfactorily performed by using simple user interfaces, there is no point in developing a new immersive FM system. Instead, an independent immersive user interface is being developed which can be connected to various commercial FM systems.

The architecture of the FACIT system is shown in Figure 2. The immersive user interface is based on a VRML97 (Virtual Reality Modeling Language)[24] browser. Various FM systems as well as a fire-simulation system can be connected via the external authoring interface (EAI)[25]. Immersive input devices modify the viewer's position in the VRML scene via the EAI, too. The browser is executed in full-screen mode. The output is displayed on an HMD.

Escape-route sceneario

We tested several FM applications with our immersive user interface. One of these was the escape-route scenario: a user has to escape from an unknown virtual building that is on fire as quickly as possible, guided by escape-route signs. The system allows us to study the impact modifying escape-route design (from changing the positions of escape-route signs to a complete redesign of floor architecture) to reduce the times needed to reach the exit (RE times). If a reduction in RE times in the virtual environment could be transferred to reality, we would have a powerful tool for planning and validating escape routes.
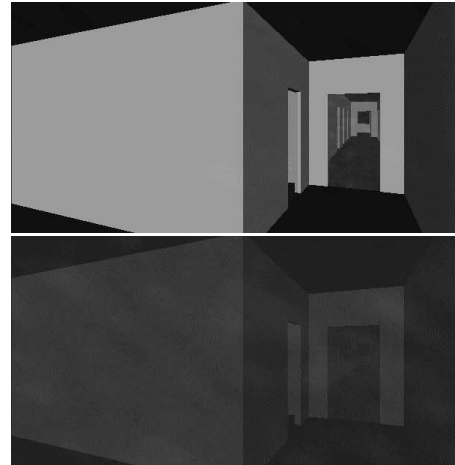

Figure 4: Smoke-filled floor after (a) 170 sec. (b) 480 sec.

The CFAST system [26] is used to compute the spread of fire and smoke. It provides a simulation of the impact of fire and its byproducts inside a building. (Figure 3 shows the spread of temperature in a virtual test floor after some minutes.)

As the user walks through the building, visibility is changed according to simulation results. We implemented smoke-filled floors by inserting semi-transparent polygons with animated textures into the scene (see Figure 4), because volume rendering is currently not supported in VRML. To increase immersion and give the user some idea of the source of the fire, a position-dependent stereo sound of crackling is supplied via the headphones of the HMD.

Locomotion devices

After conducting a few experiments, we realized that a simple hand-controlled navigation metaphor would not be realistic enough to transfer RE times to reality. We therefore decided to integrate a full-motion interface into our virtual environment. Our first attempt was to integrate a uni-directional treadmill called the "Spatial Navigator" [18] into our system. However, tests with several users demonstrated that the approximation of human locomotion was not realistic. Since users had to hold on to a steering bar, they said they felt as if they were pushing a perambulator or a trolley.

4

Figure 5: Virtual Walker I in (a) walking mode and (b) orientation mode

Later, we considered using an ODT or a cybersphere. However, neither of these systems supports running and changing speed suddenly [15, 16]. Locomotion with sliding [22] device did not appear realistic enough because users have to hold on to a hoop. We therefore began developing a new device meant to be suitable for the escape-route scenario.

The device has to be safe, easy to use and suitable for high velocities and abrupt changes of velocity. These requirements are met by fitness-training devices. We implemented two locomotion devices using mechanical parts of devices from an "air walker" and "elliptical trainer".

The first system, called "Virtual Walker I", was built from components of an "air walker". It was enhanced by a tracking system, that measures the excursion of the platforms. The captured data is filtered and transformed into a linear movement. Users have to swing their legs to move forward. Given the device's symmetry of motion, it is not possible to distinguish between walking forward and backward. Walking backward is therefore not supported by the device. The system supports a natural walking rhythm (step size of 73 cm, 107 steps/min.). Since the resistance of the device is low, velocity can easily be changed. As the pelvis is nearly stable while walking, hands-free locomotion is possible. While the motion paths of the thighs and feet are quite realistic, many users do not bend their knees when walking on the device.

The second device, called "Virtual Walker II", supports more realistic motion paths. The elliptical motion path of the platforms approximate the natural motion path of human feet when walking. The platforms serve as pedals, driving a flywheel. Unlike the first device, Virtual Walker II allows a

Figure 6: Virtual Walker II

distinction to be made between forward and backward locomotion. The flywheel's inertia impedes acceleration and deceleration. It takes some practice to use the device without holding on.

Controlling motion direction

Both air walker and elliptical trainer are designed for walking in a straight line. To control motion direction, we first

5

| Device | State | Immersion | | | Performance | | Subjective assessment |
		Motion paths	Acting forces	Hands free	Velocity	Changes in velocity	
Hand-controlled navigation	tested	- - -	- - -	-	+++	+++	not immersive
Spatial Navigator [18]	tested	++	- -	-	++	++	like pushing a perambulator
CyberSphere [16]	not tested	+++	-	+	++ (?)	- -	
ODT [15]	not tested	+++	- -	+	-	- -	
Virtual Perambulator [22]	not tested	++	-	- (?)	+	+ (?)	
Virtual Walker I	tested	+	+	+	++	++	like "leg in plaster"
Virtual Walker II	tested	++	-	+	++	++	like riding a bicycle

Table 1: Comparison of locomotion devices for the escape-route scenario

tried adding tracking components to the user's body (e.g., at the hip and shoulder). As the test persons using our device, were unable while walking to rotate parts of their body in one direction whil looking in another, we decided to use head tracking to control the motion direction.

We distinguish between a walking mode and an orientation mode. When users stand still, regular head tracking is executed. This allows them to look around for orientation. When users move their legs, gaze direction is employed to control motion direction. The gaze direction can be split into yaw, pitch and roll. Yaw is used to determine walking direction. As pitch and roll are still used for changing orientation, users are able to look up or down while walking through a virtual building. Yaw is mapped to an angular velocity which is combined with the linear velocity of the user according to the following equations:

$$\omega = k * yaw, k = 1$$
$$\Delta \beta = \omega * \Delta t$$
$$\vec{d}_{dir} = Rot_y(\Delta \beta) * \vec{d}_{dir}$$
$$\vec{p} = \vec{p} + v * \Delta t * \vec{d}_{dir}$$

In our current implementation, k is set to one. A user that looks straight to the left rotates at an angular velocity of 90 degrees per second to the left, for example. When maneuvering a tight turn, users have to move their legs slowly, while looking straight to the left or the right. We found that users learn to solve maneuvering tasks (e.g. turning round and walking away from a wall after collision) very quickly.

RESULTS AND FUTURE WORK
We developed safe, cost-efficient and easy-to-use locomotion devices for walking through virtual buildings at high speed.

We tried out our devices on a large number of test persons. Nearly every visitor to our institute was asked to try out the system. The participants were asked informally what they thought of the system. Table 1 gives a summary and evaluation of our observations (+++ for best assessment, - - - for worst assessment). By way of comparison, we included in the table the locomotion approaches that were not tested in our escape-route scenario, reflecting our assesment of their suitability.

As almost all the participants are able to use our full-motion interfaces after a few seconds' practice, the turning interface would appear to be intuitive. Many participants were immediately able to move through the building at high speed. To accelerate and decelerate, users have to exert extra force by using their leg muscles. Although the force pattern is not realistic, this may enhance immersion.

Our devices are still under development. One of our next steps will be to add a motor to our second device to drive the flywheel. This should help overcome some of the problems caused by the flywheel's inertia. Also, it should enable us to add force feedback.

After completing the motion interfaces, we plan to conduct systematic tests. By comparing motion paths through a virtual floor with paths captured by a tracking system on a real floor, we hope to prove that reductions in RE times due to changes in escape-route architecture can be transferred to reality.

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