7. FULL BODY MOTION INTERFACES

While full-body motion is commonly viewed as the most challenging VE interface technology to be developed, it is important to note that some types of full-body motion are feasible with current technology. Consider first those cases where a user is passively moved through a VE in a vehicle. Here, the usual practice is to build a “cabin” that represents the physical vehicle and its controls, mount this cabin on a motion platform, and generate virtual window displays and motion commands in response to the user’s operation of the controls. These systems tend to be specialized to a particular application, for example, flight and tank simulators, and have been in use by the Department of Transportation, the Department of Defense, and the airline industry for many years. Indeed, cabin simulators represented the first practical VE applications.

Recent years have seen the exploitation of this technology by the entertainment industry for interactive VE adventure rides. Examples include IWERKS Entertainment’s Loch Ness Expedition where, in a player-controlled submarine with periscope and robotic arms, six players try to save Nessie from bounty-hunters. Magic Edge, Inc. has developed a ride that sends twelve players, led by a squadron commander, on strike missions in X-21 hornets. In Galaxian-3, another Magic Edge adventure, players crew a star ship in a space battle. Greystone Technology, Inc. has developed the Mercury VR Platform, a futuristic flying motorcycle used by players to participate in the MagBall team game, using simulated magnetic fields generated by their craft to manipulate a ball and score goals. Other Mercury rides include Canyon Runner, a game where players participate in a futuristic Gauntlet League race using guns to eliminate rival competitors and simulated kinetic fields to deflect enemy shots and beams from canyon-mounted pulse cannons. Chameleon Technologies, Inc. use a centrifuge-based system with cabins, suspended from up to ten arms, capable of full 360° movement. Three Chameleon games are currently available, a futuristic space game called Labyrinth Rangers, a drive-and-shoot race car game called LazerDrive, and the MERCS supersonic aircraft mercenary game; players continually interact with each game, for example, executing aircraft barrel roles and dives in accordance with the game objectives.

For many kinds of VE applications, however, more active self-motion is required. With the limiting constraint of a stationary surface under the user that naturally provides all necessary kinesthetic cues, simple in-place user movements in a VE only require the generation of appropriate visual displays. If the surface is uniform but moving, a motion platform can be used to provide the necessary motion cues. Even locomotion through a *small* (typically around 10 x 10 feet) virtual space poses no significant problems, as long as there is a surface that can provide the necessary kinesthetic cues. The major challenges for full-body motion in a VE arise whenever any of the following are required: locomotion through a large virtual space, locomotion over varying surface characteristics, and motion in a direction other than horizontal.

This section starts with a brief look at the relevant human sensory capabilities. The following two sections deal with interfaces that, respectively, support active and passive motion through a VE. The final part of this section presents expectations for the development of full-body motion technology in the next five years.

7.1 The Human Motion Sense

Many systems play a role in a human's capability to sense motion and control posture (orientation and balance), the two primary systems being the visual and vestibular systems. Some details about the visual system have already been presented in Section 2.1. In the context of motion, however, it is important to note that the visual system is both a sensory and motor system. In the former case, it signals the position and movement of the head with respect to surrounding objects, and provides information about the direction of the vertical. As a motor system, the visual receptors that sense slipping of the retinal image supplement compensatory eye movements through a tracking mechanism called the optokinetic reflex.

The vestibular system also is both a sensor system and a motor system. In its role as a sensory system, the vestibular system provides information about movement of the head and the position of the head with respect to gravity and any other acting inertial forces. It uses two types of sensory organs. The first of these are the semi-circular canals in the inner ear that provide information about the angular velocity of head movements. These canals are fluid-filled and the inertia of this fluid causes head rotations to increase, or decrease, activity of specialized hair cells that fire neural signals to excite the vestibular nerve. The neural firing in the vestibular nerve is proportional to head velocity over the range of frequencies in which the head commonly moves, that is, 0.5 to 7 Hz. However, the semi-circular canals provide the best response in the first second or so, and output decays exponentially with a time constant of about 7 sec. The set of three canals on each side of the head work in a complimentary push-pull relationship, with the canals in each set being aligned perpendicularly to each other. This alignment allows the two vertical canals to signal forward and backward head rotations, while the horizontal canal signals rotations about the vertical axis. The second type of vestibular sensory organ is the otolith organ. There are two otolith organs associated with each set of semi-circular canals and they provide information about linear acceleration and head tilt with respect to the gravitational axis. The saccular otolith provides information about vertical linear acceleration of the head, and the utricular otolith responds to horizontal accelerations. There can be ambiguity in, for example, determining whether an anterior head rotation signalled by the semi-circular canals was the result of head flexing on the neck or body flexing at the waist. Signals from the visual and other systems are used to resolve these ambiguities when they occur. In general, the semi-circular canals respond best to rapid head movements, while the otoliths are most sensitive to slow movements.

As a motor system, the vestibular system plays an important role in posture control, that is, orienting to the vertical, controlling center of mass, and stabilizing the head. To this end, output from the vestibular system goes to the spinal cord to serve the vestibulo-spinal reflex. This reflex generates compensatory body movements to maintain head and postural stability. Output from the vestibular system also goes to the ocular muscles serving, in this case, the vestibular-ocular reflex that generates eye movements that enable clear vision while the head is in motion.

Benson (1990) has summarized the findings of several researchers on the functional thresholds of the vestibular system. He reports that, using a seat free to move in the *x* or *y* body axis, the threshold for detection of tilt from the vertical is on the order of 2°. The perception of angular motion varies with frequency, falling at around 0.2 log unit/decade between 0.1 and 1.0 Hz, and falling at -1 log unit/decade below 0.1 Hz. For stimuli shorter than 15 seconds, this perception of angular motion is related to the time, *t*, taken to detect angular acceleration, α; the product αt has a mean constant value of 3.7°/sec. For sustained rotational stimulation with prolonged acceleration (such as can occur in an aircraft), the sensory threshold for angular rotation is determined by the magnitude of angular acceleration rather than velocity change and the mean threshold for angular accelerations of the head about the *z* axis has been demonstrated as 0.32°/sec with a range of 0.05 to 2.2°/sec. With respect to the perception of linear acceleration, for a linear oscillation at approximately 0.3 Hz in the horizontal plane, the mean threshold was around 0.03 m/sec^2 for oscillations in the *x*, *y* axes and around 0.06 m/sec^2 for oscillations in the *z* body axis. The common peak angular velocity for passive nodding of the head, such as occurs during walking or running, is ±10°/sec. Volitional head movements usually exhibit a peak angular velocity of at least 100°/sec but may be as high as 500°/sec. Peters (1969) summarizes various experimental findings on the threshold for detection of motion about the vertical axis, reporting that the threshold ranged from 0.2 to 2°/sec^2. The threshold for linear acceleration has been found to range from 0.002 to 0.027 g.

There are circumstances in which other sensory systems impact the sensory thresholds of the vestibular system. For example, Huang and Young (1981) found that while the level of illumination produces no significant differences in the threshold for perception of angular velocity, the absence of illumination significantly lowers the threshold and reduces latency time.

Benson describes several functional limitations suffered by the vestibular system. Transient movements lasting less than 10 sec with a change in angular velocity below roughly 2°/sec, or peak acceleration below roughly 0.05 m/sec^2, may be undetected. Prolonged rotation of the head (over about 15 sec) with cross-coupled stimulation of the semicircular canals can cause misperceptions. Misperceptions of altitude can occur in the presence of prolonged (40 to 60 sec) linear acceleration, or deceleration, when the resultant effect of the imposed acceleration and head orientation is unaligned with the gravitational vertical. Head movements during linear accelerations over 10 m/sec^2 (1 g) also cause misperceptions of the direction of the movements, and when the acceleration increases to more than 50 m/sec^2, head movement can cause the perception of tumbling.

The different forms of illusionary passive self-motion have been studied for many years. Such perceptions can be generated by vestibular stimulation, for example, by sinusoidal stimulation of the horizontal semi-circular canals, stimulation of the cervical neck receptors, or visual stimulation. In general, visual and cervical stimulation dominate vestibular stimulation. Since only visual stimulation is likely to be used in VEs, the rest of this discussion is so restricted.

Linearvection, the illusion of linear motion in a stationary individual, is known to be generated by moving images in the visual field. In a series of experiments, Berthoz, Pavard, and Young (1975) measured image velocity and luminance thresholds for the appearance of linearvection. The thresholds of differential luminance level decreased with increases in image velocity, reaching a minimum level between 0.001 and 0.0001 cd/m^2. The thresholds of image velocity differed depending on whether the moving image was presented only to the periphery of the visual field or the entire visual field. When inducing the sensation of forward self-motion, linearvection appeared at an image velocity of approximately 0.03 m/sec in the first case and approximately 0.01 sec in the second. These figures were substantially less when inducing backwards linearvection. The velocity of the perceived linearvection increased with the velocity of the image display, reaching a saturation point when the image moved at a rate of about 1 m/sec. The latency of onset for linearvection was around 1 sec. The researchers also investigated the effects of prolonged exposure to linearvection. Here they found that the time constant of adaptation to linearvection ranged between 30 to 50 sec, after which time subjects were prone to underestimate the velocity of induced motion. Finally, in the presence of conflicting visual and vestibular cues, Berthoz, Pavard, and Young found a dominance of visual cues. More specifically, it seems that the vestibular cues dominate the short-term subjective determination of acceleration, whereas the visual cues dominate in the long-term sensation of velocity.

Visual cues can also generate the illusion of circular motion, called circularvection. Huang and Young (1981) found that the perception of self-motion is significantly more sensitive when viewing an isolated visual target that is rotating with the subject, than in the absence of a visual target. Duration of apparent motion is usually longest and perception thresholds lowest under conditions of dim illumination and plain background. In reviewing the findings of other researchers on the thresholds for perception of angular velocity, Huang and Young report no consensus on the velocity threshold for perception of vertical angular acceleration in an unilluminated environment, with experimental findings ranging from 2.0 to 16.4°/sec. Significant interaction for the duration of induced self-motion between the simulated speed of the observer and the visual angle of the display has been observed by other researchers. The duration of reported self-motion was smallest for the largest visual angle examined (21.1°) and the high speed condition. Highest depth ratings occurred in conditions in which the longest duration of self-motion was reported, possibly indicating that induced self-motion in the central visual field is dependent on relative depth information within the display. The latency of onset of circularvection is cited as ranging from 1 to 14 sec (Brandt, 1973).

Neck receptors are capable of inducing strong circular vection. (These receptors are usually stimulated by seating a subject in a chair inside a rotating drum, with the subject's head fixed in a clamp attached to the ceiling of the drum.) Both visually and cervically induced illusions of head rotation overrule the vestibular sensation of head movement when estimating head position (Bles and de Jong, 1982). Relative to the vestibular induced sensation, not only the visual but also the cervically induced sensation of head motion is strong. For stimulation of the vestibular, visual, or cervical systems separately, the size of actual head movement is generally underestimated. Pure visual stimulation can fail to induce circular vection, although combining vestibular plus visual stimulation has indicated that vision, and not the vestibular system, determines circular vection.