3. TRACKING INTERFACES

Tracking, also called Position and Orientation Tracking or Position Tracking and Mapping, is used in VEs where the orientation and the position of a real physical object is required. Specifying a point in 3-D requires the transition position, that is, the Cartesian coordinates *x*, *y*, and *z*. However, many VE applications manipulate entire objects and this requires the orientation to be specified by three angles known as pitch (elevation), roll, and yaw (azimuth). Thus, six degrees of freedom (DOF) are the minimum required to fully describe the position of an object in 3-D.

Trackers are used to measure the motion of the user's head or hands, and sometimes eyes. This information is then used to correlate visual and auditory inputs to the user's position. In this way, trackers are one part of a visually coupled system that Kocian and Task (1995) define as a special subsystem integrating the natural visual and motor skills of an operator into the system he is controlling. For example, in the case of magnetic sensors, a receiver is placed on the user's head so that when the head moves, so does the position of the receiver. The receiver senses signals from the transmitter which generates a low frequency magnetic field. The user's head motion is sampled by an electronic unit that uses an algorithm to determine the position and orientation of the receiver in relation to the transmitter. In addition to magnetic head trackers there are mechanical, optical, acoustic (ultrasonic), and inertial head trackers. These types of trackers also can be mounted on glove or body suit devices to provide tracking of a user's hand or some other body part, see Section 5.1. Some include special facilities to augment the tracking function with 3-D mouse-like operations. Eye trackers work somewhat differently; they do not measure head position or orientation but the direction at which the users' eyes are pointed out of the head. This information is used to determine the direction of the user's gaze. Eye trackers use electroocular, electromagnetic, or optical technologies.

Trackers also are used in augmented reality applications. In these systems, the user sees the real world around him with computer graphics superimposed or composited with the real world. One of the big obstacles to widespread use of artificial reality is the registration problem in correctly aligning real and virtual objects. Because of lags in the time interval between measuring the head location and superimposing the corresponding graphic images on the real world, virtual objects may appear to swim around real objects. Since the human eye is very good at detecting even very small misregistrations, errors that can be tolerated in immersive VE are not acceptable in augmented reality, though registration is a tracking issue for all types of applications when multiple moving objects are involved.

This section starts by discussing trackers under the heading of head tracking although, as indicated above, many of these trackers also can be used for hand and body tracking. It then moves on to look at eye tracking. The final part of the section presents some projections for how tracking capabilities, as a whole, may evolve over the next few years.

3.1 Head Tracking

Several researchers have investigated the value of head tracking for promoting a sense of immersion in VEs. One study compared head tracking and hand tracking for an experimental task that required subjects to visual scan a room and locate targets consisting of two-digit numbers; in both cases, the method of tracking was used to control the visual scene displayed (Pausch, Shackelford, and Proffitt, 1993). The results of this experiment showed that subject using head tracking were nearly twice as fast in located targets as those using hand tracking (a mean of 1.5 seconds per target for head tracking versus 2.6 seconds per target for hand tracking). Hendrix (1995) reports that the use of head tracking, together with a stereoscopic visual display, significantly increased the reported sense of presence in a VE and subjects' subjective assessment of their performance in performing spatial judgements, although actual performance measures showed no increase in judgement accuracy.

As previously stated, there are several tracking technologies in use, although the most common are magnetic, acoustic, and optical technologies. Table 3 provides an overview of the different technologies and their advantages and disadvantages.

Head trackers can be described with respect to a small set of key characteristics that serve as performance measures for their evaluation and comparison. Meyer et al (1992) define these characteristics as resolution, accuracy, and system responsiveness (additional characteristics of robustness, registration, and sociability are not considered here).

- Resolution. Measures the exactness with which a system can locate a reported position. It is measured in terms of inch per inch of transmitter and receiver separation for position, and degrees for orientation.
- Accuracy. The range within which a reported position is correct. This is a function of the error involved in making measurements and often it is expressed in statistical error terminology as degrees root mean square (RMS) for orientation and inches RMS for position.
- System responsiveness. Comprises:
  - Sample rate. The rate at which sensors are checked for data, usually expressed as frequency.
  - Data rate. The number of computed positions per second, usually expressed as frequency.
  - Update rate. The rate at which the system reports new position coordinates to the host computer, also usually given as frequency.

Table 3. Tracking Technologies

Technology	Description	Strengths	Weaknesses
Mechanical	Measure change in position by physically connecting the remote object to a point of reference with jointed linkages	Accurate Low lag No line of sight (LOS) or magnetic interference problems Good for tracking small volumes accurately	Intrusive, due to tethering Subject to mechanical part wear-out
Magnetic	Use sets of coils (in a transmitter) that are pulsed to produce magnetic fields. Magnetic sensors (in a receiver) determine the strength and angles of the fields. Pulsed magnetic field may be AC or DC.	Inexpensive Accurate No LOS problems Good noise immunity Map whole body motion Large ranges - size of small room	Ferromagnetic and/or metal conductive surfaces cause field distortion Electromagnetic interference from radios Accuracy diminishes with distance High latencies due to filtering
Sourceless, Non-inertial	Use passive magnetic sensors, referenced to the earth's magnetic field, to provide measurement of roll, pitch, and yaw, and as a derivative, angular acceleration and velocity.	Inexpensive Transmitter not necessary Portable	Only 3 DOF Difficult to mark movement between magnetic hemispheres
Optical	Use a variety of detectors, from ordinary video cameras to LEDs, to detect either ambient light or light emitted under control of the position tracker. Infrared light is often used to prevent interference with other activities.	High availability Can work over a large area Fast No magnetic interference problems High accuracy	LOS necessary Limited by intensity and coherence of light sources Weight Expensive
Acoustic (Ultrasound)	Use three microphones and three emitters to compute the distance between a source and receiver via triangulation. Use ultrasonic frequencies (above 20 kHz) so that the emitters will not be heard.	Inexpensive No magnetic interference problems Lightweight	Ultrasonic noise interference Low accuracy since speed of sound in air varies with environmental conditions Echoes cause reception of "ghost" pulses LOS necessary
Inertial	Use accelerometers and gyroscopes. Orientation of the object is computed by jointly integrating the outputs of the rate gyros whose outputs are proportional to angular velocity about each axis. Changes in position can be computed by double integrating the outputs of the accelerometers using their known orientations.	Unlimited range Fast No LOS problems No magnetic interference problems Senses orientation directly Small size Low cost	Only 3 DOF Drift Not accurate for slow position changes

- Latency, also known as lag. The delay between the movement of the remotely sensed object and the report of the new position. This is measured in milliseconds (ms).

Another pertinent characteristic is repeatability. The accuracy of the measured 3-D position and orientation between bodies is based on the composite effects of the measurement separability (that is, variance) and the measurement of offset (that is, measurement errors that cannot be removed by collecting more data). Thus, repeatability refers to the resulting distribution spread of several repeated measurements of, for example, a single stationary point. It provides a gauge of measurement precision and can be expressed in inches, degrees, or microns.Drift is problem specific to inertial trackers. These trackers combine measurements from accelerometers and gyroscopes to calculate 6 DOFs relative to the starting position.Since the measurement is relative, rather than absolute, drift can cause errors in reading that require an absolute position for re-calibration.

These characteristics provide some guidance for tracker performance. One of the most important is latency. Durlach (1994) states that delays greater than 60 msec between head motion and visual feedback impair adaptation and the illusion of presence. Latencies of greater than 10 msec may contribute to simulator sickness. Bryson (1993) considers systems with latency longer than 0.5 second not to be real-time interactive. On the other hand, in the case of non-immersive VEs systems where the VE is viewed through a CRT, Ware and Balakrishnan (1994) found latency in the head-tracking system to be relatively unimportant in predicting performance, whereas latency in the hand-tracking system was critical. Latency between systems are difficult to compare because they are not always calculated the same. Bryson (1993) identifies several sources of latency: delays in the tracker signal, delays in communication between the tracker and the computer system, delays due to computations required to process the tracker data, and delays due to graphical rendering. However, several manufacturers contacted for this report suggested that 1/frequency as the preferred measure.

With respect to responsiveness, Durlach (1994) contends that head movements can be as fast as 1,000°/sec in yaw, although more usual peak velocities are 600°/sec for yaw and 300°/sec for pitch and roll. The frequency content of volitional head motion falls off approximately as $1/f^2$, with most of the energy contained below 8 Hz and nothing detectable above 15 Hz. Tracker to host reporting rates must, therefore, be at least 30 Hz.

Where the information was available, data on resolution, accuracy, and system responsiveness are given for all the commercial tracking products described below. An additional important characteristic that is included is working volume or range, which may be bound by intrinsic limitations such as mechanical linkage or signal strength. This is the volume in which a position tracker accurately reports position. It is variously expressed in feet or meters, inches or feet in diameter, or as some portion of a geometric shape such as a sphere.

Table 4. Characteristics of Commercially Available Tracking Devices

Technology	Product	Vendor	DOF	Frequency	Latency	Resolution	Working Volume	Price
Mechanical	BOOM3C	FakeSpace, Inc.	6	>70 Hz	200 msec	0.1°	6 ft diameter, 2.5 ft high	$95,000[a]
	PUSH	FakeSpace, Inc.	6	>70 Hz	200 msec	0.1°	2 ft diameter	$45,000[a]
	ADL-1	Shooting Star Technology	6	240 Hz	0.35 - 1.8 msec	0.25 in, 0.15 - 0.3°	35 in diameter, 18 in high	$1,299
	WrightTrac	Vidtronics, Inc.	6	300 Hz	3.3 msec	0.1° per axis	1/4 sphere, 40 in diameter	$795
Magnetic	Fastrak	Polhemus	6	120 Hz/number of receivers	4 msec[b], 8.5 msec[bc]	0.0002 in/in, range 0.025°	10 - 30 ft	$6050
	Isotrak II	Polhemus	6	60 Hz/number of receivers	20 msec[b] 40 msec, 23-45 msec[b]	0.0015 in/in, range 0.1°	5 ft	$2,875
	Insidetrak	Polhemus	6	60 Hz/number of receivers	12 msec[b]	0.0003 in/in, range 0.03°	5 ft	$999
	Ultratrak	Polhemus	6	30 - 60 Hz	12 msec[b]	0.05 in at 5 ft range, 0.25 ft at 15 ft range 0.1° RMS	2 - 15 ft	$23,250 - $32,250
	Ultratrak 120	Polhemus	6	60 - 120 Hz	12 msec[b]	0.15 in at 5 ft range, 0.25 ft at 15 ft range 0.1° RMS	2 - 15 ft	$39,500 - $71,500
	Flock of Birds	Ascension Technology Corp.	6	Up to 144 Hz	7.5 msec [b], 39-47 msec	0.1° RMS at 12 in	3 - 8 ft	$2,695 basic system, $8,090 ERT system
	PC/BIRD	Ascension Technology Corp.	6	Up to 144 Hz	10 msec	0.08 in translation, 0.15° rotation	4 ft	$2,475
	SpacePad	Ascension Technology Corp.	6	120 Hz/number of receivers	<8 msec[c]	Not available	16 x 16 ft	$985
Sourceless, non-inertial	CyberTrack 3.2	General Reality Company	3	30 Hz	<50 msec	0.15° heading, 0.12° tilt	360° horiz, ±55° tilt	$850
	Wayfinder - VR	Precision Navigation, Inc.	3	30 Hz	33.3 msec[d]	±0.1° heading, +±0.1° tilt	360° horiz, ±20°, ±50° tilt	$599 - $699

Table 4. Characteristics of Commercially Available Tracking Devices

Technology	Product	Vendor	DOF	Frequency	Latency	Resolution	Working Volume	Price
Sourceless, non-inertial	CyberMaxx	Victor Maxx Technologies	3	75 Hz	29.6 msec	0.1° vertical, 0.1° horiz	360° horiz, ±45° tilt	$799
	Mouse-Sense 3D	RPI Advanced Technology Group	3	8 Hz	125 msec[c]	±1° heading, ±1° tilt	360° horiz, ±25 - 55° tilt	$750
Optical	SELSPOT II	Selcom AB	6	10 KHz	Not given	0.025% of millirad	Up to 200 m	$29,980
	OPTOTRAK 3020	Northern Digital, Inc.	6	600 Hz	Not given	0.01 mm at 2.25 m	Not given	$57,400
	MacReflex	Qualisys, Inc.	6	50-200 Hz	Not given	Not given	0.5 - 30 m (indoors), 0.5 - 9 m (outdoors)	$38,500 - $48,500
	DynaSight	Origin Instruments Corporation	3	64 Hz max	16-31 msec	0.1 mm cross range 0.4 mm down range	0.1 - 1.5 m for 7 mm target, up to 1 - 6 m for 7 mm target	$2,195
	RK-447 Multiple Target Tracking System	ISCAN, Inc.	6	60 Hz	16 msec	Not given	Not given	$36,800
Acoustic (Ultrasonic)	Head/Hand XYZ Tracker	Fifth Dimension Technologies	3	20 Hz	Not given	Not given	Up to 3 m	$345
	GP12-3D (Free-point 3D)	Science Accessories Corp.	3	150 Hz/number of emitters	Not given	0.002 in	3.25 x 3.25 x 3.25 ft up to 16 x 8 x 8 ft	$4,995 - $6,995
	Logitech 3D Mouse and Head Tracker	Logitech	6	50 Hz	72 msec[e]	1/250 in (linear), 1/10° angular	5 ft long, 100° cone	Not given
Inertial	MotionPak	Systron-Donner	6	60 Hz	Not given	0.004°/sec.	Not given	$10,000
	GyroPoint	Gyration, Inc.	3	Not given	Not given	0.2°	75 ft	$299

a. Includes visual system.
b. Unfiltered
c. (Adelstein, Johnston, and Ellis, 1995)
d. Calculated as 1/Frequency and converted to milliseconds.
e. (Ware and Balakrishnan 1994).

3.1.1 Commercially Available Trackers

This section presents over twenty five different tracking devices. Some tracking systems are integral parts of a display system and these are described in the Section 2.2 of this report. Specifically, the Fakespace, Inc. BOOM 3C and PUSH are described in Section 2.2.14 and Section 2.2.17, respectively; and the VictorMaxx Technologies CyberMaxx is described in Section 2.2.4. Additional products, Sensor Applications Inc.'s CG93 and SPAR non-inertial sourceless sensors and MVR, Inc.'s Optical Head Tracker could not be included for lack of adequate information. Table 4 presents summary information for all the described devices, except BioVision, by Optimum Human Performance Center, Mandala Virtual Reality Systems from the Vivid Group, and REALWare VR System by CCG Meta-Media, Inc. These were included in the text, but excluded from the table for lack of specific tracking information.

In addition to the following products, Crossbow Technology has recently announced the availability of a new tracking technology. Designed for use in 3-D games, this technology employs small, low-cost, silicon micromachined accelerometers and silicon-based magnetic sensors (a patent is pending on these microsensors). It supports roll, pitch, and yaw tracking with a resolution of less than 0.1°, and a speed of less than 10 msec. Crossbow Technology has demonstrations available for a 3-axis orientation tracker, called the TRK300, and a 2-axis analog joystick system. The company develops custom designs to meet specific user needs, and currently is looking for OEMs to license the base tracking technology.

3.1.1.1 ADL-1

ADL-1 by Shooting Star Technology is a 6 DOF mechanical head tracker. The user wears a headband attached to the lightweight arm while seated before a video display for non-immersive VR, or can attach the tracker to a HMD for conventional immersive VR. Sensors mounted on the arm measure the angles of the joints of the arm. A microprocessor uses the angles to compute the head's geometry and sends the data to a host computer via a serial connection. Specification details for the ADL-1 are given in Figure 27. ADL-1 costs $1,299.

Specification	
Update Rate	Max. 240 Hz
Sampling Rate	240 Hz
Latency	0.35-1.8 msec
Accuracy	0.2 in
Linear Resolution	~0.025 in
Angular Resolution	0.15 -0.3°
Work Volume	Half cylinder, ~36 in diameter. 18 in height
Repeatability	0.1 in

Figure 27. ADL-1

3.1.1.2 Vidtronics Wrightrac

Specification	
Update Rate	300 Hz
Resolution	0.1°
Work Volume	1/4 sphere, ~ 40 in diameter.
Repeatability	0.1 in

Figure 28. Wrightrac

Wrightrac, by Vidtronics, Inc. is a 6 DOF mechanical tracker designed for use with PCs and desktop VR systems. It consists of an aluminum arm and boom. It has microprocessor-based control and a potentiometer-based position/orientation system. The Wrightrac uses serial RS-232 data transmission and comes with a DOS interface. Some specification details are given in Figure 28. Wrightrac costs $795.

3.1.1.3 Fastrak

The Polhemus Fastrak was developed based on a redesign of the vendor's Isotrak product. Isotrak was one of the first trackers developed for use in VEs. It used older analog technology that produced large latencies, sensor range was small, and signal noise large. These problems were solved in the redesign by using a digital signal processing architecture. Each Fastrak can accept data from up to 4 receivers and up to 8 systems can be multiplexed to allow up to 32 receivers. Further details are given in Figure 29. Fastrak costs $6,050.

Specification	
Update Rate	120 Hz ÷ no. receivers
Latency	4 msec
Linear Accuracy (RMS)	0.03 in
Angular Accuracy (RMS)	0.15°
Resolution	0.0002 in/in, 0.025° orientation
Range	Up to 10 ft, 30 ft with Long Range transmitter

Figure 29. Fastrak

3.1.1.4 Isotrak II

The Polhemus Isotrak II is a lower cost tracking system with slightly reduced performance from Fastrak. It consists of an electronics unit, a single transmitter, and 1 or 2 receivers. One of these receivers can be the Polhemus 3Ball, a 3-D positioning/orientation input device that incorporates hand and body motion into a mouse. This optional receiver costs $800 in addition to $2,875 for the basic Isotrak II. Specification details for the Isotrak II are given in Figure 30. In an independent study of lag and frame rates of VE systems, Ware and Balakrishnan (1994) found the device lag for the Isotrak II to be 45ms.

Specification	
Update Rate	60 Hz ÷ no. receivers
Latency	20 msec (unfiltered)
Accuracy (RMS)	0.1 in for x, y, and z, 0.75° for receiver orientation
Resolution	0.0015 in/in, 0.1° orientation
Range	Up to 15 ft

Figure 30. Isotrak II

3.1.1.5 Insidetrak

Specification	
Update Rate	60 Hz ÷ no. receivers
Latency	12 msec (unfiltered)
Accuracy (RMS)	0.5 in *x*, *y*, and *z*, 2° for receiver orientation; < 30 ft range
Resolution	0.0003 in/in, 0.03° orientation
Range	Up to 5 ft

Figure 31. Insidetrak

Insidetrak, by Polhemus, is an even smaller version of the Fastrak sensor, compressed to fit on a PC-card that plugs into 386 or 486 PCs. Specification data for Insidetrak are given in Figure 31. Testing by Burdea and Coiffet (1994) found that Insidetrak sensing data is much noisier than Fastrak. In June

1995, Polhemus announced a drop of price for Insidetrak from $2,250 to $999.

3.1.1.6 Ultratrak

The most expensive of the Polhemus offerings is the newly introduced Ultratrak, an integrated motion capture system designed to meet the needs of applications requiring full-body motion tracking.

Ultratrak consists of a 486-based Motion Capture Server unit which contains 4 to 8 motion capture boards (each board can support 2 receivers), a VGA controller, external synchronization board, and communications card. The base system comes with 8 receivers and up to an additional 8 receivers may be added to the system. Moreover, multiple systems can be networked. Ultratrak comes in a 60 Hz version and a 120 Hz version (Ultratrak 120). Both come with the Long Ranger transmitter (optional equipment for Fastrak and Insidetrak) that allows tracking and capturing a subject in an area in excess of 700 square feet. Further details for Ultratrak are given in Figure 32. Ultratrak costs $23,250 for an 8 receiver system and up to $32,250 with all 16 receivers. An Ultratrak 120 costs between $39,500 and $71,500, depending upon the number of receivers.

Specification	
Update Rate	60 Hz up to 8 receivers, 30 Hz up to 16 receivers
Latency	20 msec (unfiltered)
Linear Accuracy (RMS)	0.1 in at 5 ft, 3 in at 15 ft
Angular Accuracy (RMS)	0.75°
Resolution (RMS)	0.005 in at 5 ft, 0.25 in at 15 ft; 0.1° orientation
Range	Up to 15 ft

Figure 32. Ultratrak

3.1.1.7 Flock of Birds

Flock of Birds is a 6 DOF tracking system by Ascension Technology Corporation. It is intended for tracking human motions in character animation, biomedics, and VE applications. In particular, Flock trackers are used for head tracking in flight simulators/trainers; head, hand, and body tracking in VE games; and full body tracking for character animation, performance animation, virtual walkthroughs, and sports analysis. Flock of Birds has full 360° coverage without blocking or echoing problems and a fast measurement rate—up to 144 position and orientation measurements per second. It can simultaneously track up to 60 separate independent points out to 8 feet with the Extended Range Transmitter option. Each standard-range transmitter allows operation in about a 3-foot radius. Ascension claims it has the lowest lag of all trackers when tracking multiple points. Specification details can be found in Figure 33. The Flock of Birds emitter radiates a sequence of DC pulses, in effect switching the emitted field off and on. This design is intended to reduce the effect of distorting eddy currents

Specification	
Update Rate	Up to 144 Hz
Angular Accuracy (RMS)	0.5°
Translation Accuracy (RMS)	0.1 in
Angular Resolution (RMS)	0.1° at 12 ft
Translation Resolution	0.03 in
Translation Range	±3 ft (8 ft optional) any direction
Angular Range	±180° yaw, roll; ±90° pitch

Figure 33. Flock of Birds

induced by changing magnetic fields in metallic objects. While it minimizes the effect of conductive metals, the Flock of Birds remains sensitive to ferromagnetic metals.

A Flock of Birds system with one receiver costs $2,695. With the Extended Range Transmitter, the system costs $8,090. Additional receivers for either configuration cost $2,245.

3.1.1.8 PC/BIRD

PC/BIRD is a new offering from Ascension Technology Corporation that uses the same patented pulsed-DC magnetic technology employed in the other Ascension tracking products. Intended for use with PCs, this tracker is configured as an ISA-compatible board, a receiver that can be mounted on any nonmetallic object, and either a standard or extended range transmitter. With the standard range transmitter, PC/BIRD operates with a range of 4 feet, the extended range transmitter allows a range of up to 10 feet. Measurements are made at the rate of up to 144 per sec. Additional cards and receivers may be used to track multiple objects simultaneously. Further details are given in Figure 34.

Specification	
Update Rate	Up to 144 Hz
Latency	10 msec
Translation Accuracy	0.08 in
Angular Accuracy	0.15°
Range	Up to 4 ft, 10 ft with extended range transmitter

Figure 34. PC/BIRD

An optional mouse, with three programmable buttons, is available for providing user inputs in 2-D or 3-D. The list price for the basic PC/BIRD is $2,475. The extended range transmitter cost is $5,845, and the 3D mouse option, in lieu of a receiver in a shell, is $345.

3.1.1.9 SpacePad

Another recent product from Ascension Technology Corporation is a low-cost magnetic tracker, SpacePad, intended for use by VE game developers and designers of interactive experiences. SpacePad measures the position and orientation of one or more lightweight receivers attached to a person. SpacePad makes 120 measurements per second in its single receiver mode (up to four receivers can be used). Lag is less than 8ms, as shown in Figure 35. Since the SpacePad is intended for use in an immersive environment, Ascension considers accuracy and resolution to be less important than update rate and lag. Consequently, Ascension has not calculated those parameters. Range is configuration dependent; the larger the antenna loops (up to 16 x 16 feet), the greater the tracking volume. A single-receiver board set costs around $985.

Specification	
Update Rate	120 Hz for 1 received, 60z for 2 receivers 30 Hz for 4 receiver, s
Latency	8 msec
Translation Range	Configuration dependent
Angular Range	±180° azimuth, roll, ±90° elevation
Range	Up to 16 x 16 ft

Figure 35. SpacePad

3.1.1.10 CyberTrack 3.2

Specification	
Sampling Rate	Max 30 Hz
Latency	<50 msec
Accuracy	±1.25° heading, ±0.25° tilt
Resolution	0.15° heading, 0.12° tilt
Range	360° horizontal, ±55° tilt
Repeatability	0.25° heading, 0.25° tilt

Figure 36. CyberTrack 3.2

CyberTrack 3.2 is General Reality Company's sourceless 3 DOF tracker that mounts on the Cyber-Eye HMD. The tracker is 3 x 2.5 x 1.5 inches, and weighs 2 ounces. Further details are given in Figure 36. It features automatic soft and hard iron correction, temperature compensation, automatic distortion detection, and automatic calibration. The CyberTrack 3.2 costs $850.

3.1.1.11 Wayfinder-VR

Precision Navigation, Inc.'s Wayfinder-VR is another low-cost, sourceless head tracker. It is a passive attitude detection system based upon a proprietary triaxial magnetometer system and a biaxial electrolytic inclinometer. It uses a 3-axis magnetometer to sense the earth's magnetic field and a 2-axis tilt sensor to measure pitch and roll. It combines these data to mathematically compute orientation and output heading, pitch, and roll data via RS-232 serial link. In addition, a mouse emulation mode that maps yaw to left-right motion and pitch to up-down motion is available. Specification details are given in Figure 37. The device costs between $599 and $699 depending on the tilt range required.

Specification	
Sampling Rate	Max 30 Hz
Accuracy	±2° heading, ±1° tilt
Resolution	0.1° heading and 0.1° tilt
Range	360° horizontal, ±20°, ±50° tilt
Repeatability	1° heading and 0.5° tilt

Figure 37. Wayfinder-VR

3.1.1.12 Mouse-Sense3D

Specification	
Update Rate	8 Hz (higher rates available as custom option)
Accuracy	±1° heading, ±2° tilt
Resolution	±1° heading, ±° tilt
Tilt Range	±25° (±55° option available)

Figure 38. Mouse-Sense3D

RPI, Advanced Technology Group, has produced the Mouse-Sense3D. This product is described as a low-cost ($750.00), high-end, multi-use position sensor for head tracking, body tracking, and three-space gesture tracking. It weighs 2.75 ounces and its dimensions are 2.375 x 4.25 inches. Further details are given in Figure 38.

3.1.1.13 Selcom AB, SELSPOT II

SELSPOT II is a commercial tracking system marketed by Selcom AB, a Swedish company. A camera registers light pulses from LEDs attached to the object being tracked. Located between the lens and electronics of the camera is the SELSPOT sensor, a patented photodetector made by SiTek Laboratories and consisting of a flat semi-conductor disc. Each side of the diode has a light-sensitive coating to produce a high resolution, two-axis field. When a light pulse from one of the LED's passes the lens system in the camera and strikes a point within this field, the electronics registers the *x* and *y* coordinates in the two-axis field. Two or more cameras are required to analyze movements in three dimensions.

Specification	
Sampling Rate	10 kHz
Resolution	0.025% of milliradians
Number of Cameras	Up to 16
Number of LEDs	Up to 120
Range	Up to 20 m, 200 m with LED 9

Figure 39. SELSPOT II

The motion analysis system is capable of analyzing two or three dimensional motion in real time. Specification details are given in Figure 39. Prices start at $29,980.

3.1.1.14 OPTOTRAK 3020

The OPTOTRAK 3020 by Northern Digital Inc. is an infra-red (IR)-based, non-contact position and motion measurement system. Small IR LEDs (markers) attached to a subject are tracked by a number of custom designed sensors. The 3-D positions of the markers are determined in real-time or post hoc, up to 256 markers can be tracked. The position sensor consists of three 1-D charged coupled device (CCD) sensors paired with three lens cells and mounted in a 1.1m long stabilized bar. Within each of the three lens cells, light from the LED is directed onto a CCD and measured. All three measurements together determine the 3-D location of the marker, which is calculated and displayed in real time. Specification details are given in Figure 40.

Specification	
Max. Data Rate	3500 Hz (raw), 600 Hz (real-time 3-D)
Accuracy (RMS)	0.1 mm for x, y and 0.15 mm for z, at 2.25 distance
x, *y* Resolution	0.01 mm at 2.25 m distance
Max. Markers	256
FOV	1.28 x 1.34 m at 2.25 m distance, 2.6 x 3.54 m at 6 m distance

Figure 40. OPTOTRAK 3020

The standard OPTOTRAK 3020 system includes one position sensor unit, a kit of 24 markers, a system control unit, standard data collection, display, and utility software, together with cables and other hardware. It costs $57, 400. Additional sensors are $47,500 each and up to 8 position sensors can be used per system.

3.1.1.15 MacReflex Motion Measurement System

The MacReflex Motion Measurement System, by Qualisys, Inc. also is designed to measure the 3-D motion of subjects in real-time. The system is comprised of (1) one or more MacReflex position sensors (a 3-D system uses from two to seven position sensors), (2) software to enable the user to set up and calibrate the field of view of the position sensors, and process the measured spatial coordinates of the target markers that are attached to the subject being tracked, (3) passive reflective target markers, (4) a calibration frame for 3-D measurements, and (5) a Macintosh computer system. The position sensor has two components: a CCD digital video camera, and a video-processor. The camera views up to 20 markers in real-time. It then sends the video image to the video processor which determines the centroid of each marker and determines its x, y coordinates. A program converts the x, y coordinates to enable cal-

Specification	
Sampling Rate	50-200 Hz
Max. Markers	20
Range	0.5-30 m indoors, 0.5-9 m outdoors

Figure 41. MacReflex

culation of position, displacement, velocity, acceleration, angles, angular velocity, and angular acceleration. Some specification details are given in Figure 41.

A complete 60 Hz system costs $38,500. A 120 Hz system costs $48,500. Additional position sensors are $13,500 and $17,500 for 60 Hz and 120 Hz, respectively.

3.1.1.16 DynaSight

The Origin Instruments Corporation tracking product, DynaSight, is an electro-optical sensor with integrated signal processing that performs 3-D measurements of a passive, non-tethered target. A two-color LED on the front of the sensor indicates the tracking status to the user. In a typical application, the sensor is mounted just above the viewable area of a real-time graphics display. The sensor's field of view is a nominal 75° cone, and the sensor is pointed such that this field covers the comfortable range of head/eye positions for the user of the display. The sensor measures and reports on the 3-D movements of a tiny target that is referenced to the user's forehead. The passive target itself can be mounted on eye glasses, stereoscopic goggles, or on the user's forehead. Larger high-performance targets are available that allow measurements at a sensor-to-target range of up to 20 feet.

Specification	
Update Rate	Max. 64 Hz
Latency	16-31 msec (operating mode dep.)
Resolution (RMS)	0.1 mm cross range, 0.4 mm down range
Accuracy (RMS)	2 mm cross range, 8 mm down range
Lock-on Delay	0.3 sec
Range	0.1-1.5 m for 7mm target, 0.3-4 m for 25 mm target, 1-6 m for 75 mm target

Figure 42. DynaSight

The Active Target Adapter enables tracking of up to four active targets tethered to the Adapter. Five DOF are achieved with two targets, while 6 DOF can be achieved by tracking three or four active targets.

DynaSight is the first in a new line of 3-D measurement products. It is planned that future systems will offer 6 DOF for HMDs using passive sensors and multiple sensors for networked operations in large virtual volumes. Specification details for DynaSight are given in Figure 42. (In this Figure, measurement parameters for resolution and accuracy are quoted for a 7 mm target at 80 cm range under normal fluorescent room lights.) The product cost is $2,195.

3.1.1.17 BioVision

Optimum Human Performance Centres, Inc. market a product designed to support animation. Called BioVision, this system uses multiple high speed cameras and lightweight retroreflective markers to capture motion at 60-200 frames per second. Motion is digitized, producing 3-D coordinates for each marker for each frame of the motion and software provides 3-D position, rotation, and scaling information for each of the body parts. The digitized data can then be viewed on a Silicon Graphics workstation or a PC running 3D Studio. BioVision provides 6 DOF information for each body part, but not in real-time. Currently, the motion capture system can go up to 25 markers, which is generally enough to cover one person. The next generation system is expected to be able to handle two people through higher resolution cameras and software that can manage up to 100 markers.

Like all optical systems, occlusion is a problem; however, since BioVision is not a real-time system, occluded markers can be edited. Other special features include the ability to edit bad or missing data, the ability to merge files together, and the ability to export data to all the major software animation packages. The system is marketed as a product, but price information is not available. More typically, a client can purchase BioVision services on a daily basis. Motion capture fees are $2,700 per day for one to three days; $2,400 per day for four to six days, and $2,200 per day for seven days and more. Processing fees, which includes tracking, editing, motion conversion, and data quality review cost $1,600 per man-day for the first twenty days and $1,300 per man-day thereafter.

3.1.1.18 Mandala Virtual Reality Systems

The Mandala Virtual Reality Systems from the Vivid Group use computer vision with video cameras as an input device to allow for motion tracking. Their software library contains a complete line of sports applications and other arcade adventures. An example is Turbo Kourier, a flying experience that allows a player to guide their Skyboard through the obstacles of a futuristic city while gathering valuable packages. Mandala offers four systems: the Mandala Virtual Reality System, the Mandala Standard Touring Unit, the Mandala Promotional Touring Unit, and the Mandala VR Module. The systems range in cost from $21,000 to $29,000.

All systems include cameras, a CPU, hard drive, specialty cards, and VGA monitor plus a choice of 4 Mandala virtual worlds (1 feature and 3 attractions). The Mandala VR module, their newest product consists of a booth (9.8 feet high, 10 feet wide, and 9.08 feet deep) which houses a virtual stage, speakers, lights, monitors, and camera.

3.1.1.19 REALWare

The REALWare VR system by CCG MetaMedia, Inc. also supports unencumbered VEs. The player interacts with the VE by wearing a colored cotton glove. A video camera focuses on a chromakeyed player standing before a blue wall and inserts the player's image into the VE, which can appear on everything from a TV monitor or a projection system, to a video-wall. As the player moves, a computer tracks the colored glove and reacts to its motion.

REALWare runs on two 486-based PCs, one for simulation and video control and the other for tracking. The optical tracking system returns the location of the centroid of the user's gloved hand 30 times per second. Participants are scanned at the beginning of a simulation to determine the colors of their clothing. Then the system selects a glove color that has the least chroma/luminance overlap with the clothing colors. Color calibration is fine-tuned in a 30 second procedure in which the participant touches a series of virtual objects. REALWare applications include Virtual Hoops (a basketball game) and T-probe (Virtual Voyage to XIA), a multilevel game. The integrated package (hardware and software) costs $35,000.

3.1.1.20 RK-447 Multiple Target Tracking System

The RK-447 Multiple Target Tracking System, by ISCAN, Inc., is a video tracking system which can track up to 64 facial points at 60 Hz with a latency of 16 msec. It is a real time digital image processor employing ISCAN's proprietary Simultaneous Multiple Area Recognition and Tracking (SMART) architecture. The ISCAN SMART processor computes the position and size of up to 256 areas that are within a particular range of intensity levels. Filtering the output of the SMART processor allows the complete system to specify targets of desired size, position, and intensity parameters from a field containing many potential targets.

After positioning the imaging sensor to include the desired field of view, the image gray level corresponding to the target may be selected. The areas of the video image whose intensity is within the gray level threshold setting are presented on the monitor as a bright overlay, letting the operator see precisely the video information being processed. For each thresholded area, size and position data are computed and stored in a data table which may be accessed by an external computer.

The RK-447 Multiple Target Tracking System divides the image signal into a 512 horizontal by 256 vertical picture element matrix. As the targets' position and size data are automatically determined over the monitor image area, the data within the azimuth and elevation coordinate table correspond to the horizontal and vertical coordinates within the video matrix. These coordinate data are updated every 16 msec and are available for input to a computer. Parametric information may be input to the RK-447 to automatically limit the data set to targets within a particular size or position range. The system costs $18,500.

3.1.1.21 Head/Hand XYZ Tracker

The Fifth Dimension Technologies' Head/Hand XYZ Tracker (HHT) is a 3 DOF ultrasonic translation tracker system. The system consists of three transmitters, a small receiver unit, a PC interface card, and two interface cables. It is capable of tracking position (*x*, *y*, and *z*) of up to three objects (e.g., head, left hand, and right hand) simultaneously. The tracking system has a worst case accuracy of 20 mm (at 2 m) with an accuracy of 4 mm when the tracked object remains stationary. It has been specifically designed to provide position tracking for the Fifth Dimension DataGlove, see Section 5.1.2.1.

Some specification details for the tracker are provided in Figure 43. The price for the basic HHT Tracker (with one receiver) is $345, additional receivers cost $85 each.

	Specification
Update Rate	20 Hz
Accuracy	20 mm worst case (at 2 m), 4 mm for stationary object
Tracking Distance	Up to 3 m

Figure 43. Head/Hand XYZ Tracker

3.1.1.22 GP12-3D (Freepoint 3D)

The GP12-3D, by Science Accessories Corporation, is an ultrasonic product with an update rate of up to 75 Hz divided by the number of emitters being tracked. It goes by the marketing name of Freepoint 3D and comes in three models. These models all provide a resolution of 0.002 inches, but vary in working volume as shown in Figure 44. Up to 4 emitters may be used together, allowing Freepoint 3D to be used for multiple-unit tracking. The cost is $4,995 - $6,995, depending on the model. Each transmitter is only tracked with 3 DOF (*x*, *y*, and *z*).

Tracker	Working Volume
Freepoint 3D XL-1	3.25 x 3.25 x 3.25 ft
Freepoint 3D XL-2	8 x 8 x 8 ft
Freepoint 3D XL-D	16 x 8 x 8 ft

Figure 44. Working Volume for Freepoint Trackers

3.1.1.23 Logitech 3D Mouse and Head Tracker

The Logitech 3D Mouse enables users to provide direct inputs into a VE system. It can operate on a desktop in a similar manner to a traditional mouse, or when raised off the 2-D plane to provide 3-D spatial information. User inputs are specified by means of five buttons on the mouse. In addition the 3D Mouse supports an audio function that allows it to be used as a microphone.

With respect to its tracking function, the 3D Mouse is a low cost ultrasonic device that operates with 6 DOF. The position reference array transmitter is a triangle of three ultrasonic speakers which send signals to a receiver. The receiver itself has a triangular set of three microphones which sample signals from the position reference array. The receiver and transmitter are both connected to a control unit with a CPU that converts the receiver information into position, orientation, and button information. Figure 45 provides further details. An independent study by Ware and Balakrishnan (1994) found the device lag for the Logitech 3D Head Tracker to be 72 msec.

Specification	
Sampling Rate	Up to 50 Hz
Linear Resolution	0.004 in
Angular Resolution	1/10°
Tracking Speed	Up to 30 in/sec
Tracking Space	5 ft, 100° cone

Figure 45. Logitech 3D Mouse

A variant of the Logitech system that may be used as a head-tracker is a small triangular-shaped device that attaches to a HMD. Specification details for the head tracker are the same as those given for the 3D Mouse, with the addition that the tracking space for the head tracker is a linear 5 ft, with a 100° cone. Logitech 3D Mouse and Head Tracker currently costs $1,599.

3.1.1.24 MotionPak

MotionPak, a Systron-Donner product, is a 6 DOF inertial sensor cluster used for measuring linear and rotational motions. It is also suitable for tracking human motion. Three solid state gyros are used to sense angular rates and servo accelerometers sense linear accelerations. MotionPak weighs 32 ounces. According to Strickland et al (1994), it is both heavy and expensive ($10,000).

Systron-Donner also market the QRS and GyroChip family of sensor products that employ a pair of micro-machined vibrating quartz tuning forks to sense angular velocity through a deflecting force acting on the body in motion due to the Coriolis principle. The GyroChip weighs 100 grams and costs $1,000 in quantities of ten to fifty. It has a resolution of 0.004°/second for motion in the 100°/second range, but can handle movement up to 1000°/second. Typical drift after stabilization is reported to be 5°/hour. QRS sensors are used in the MotionPak.

3.1.1.25 GyroPoint Pro

Gyration, Inc.'s GyroPoint Pro is a mid-air mouse that operates in a functional manner similar to a mouse or trackball, but does not need a work surface on which to operate. Unlike line-of-sight IR technology, GyroPoint Pro does not need to be carefully aligned to a receiver. It is compatible with the standard Microsoft or Apple Macintosh Mouse Driver, or Philips CD-i interface. Radio technology provides wireless operation of the GyroPoint Pro within 75 feet of its receiver, even transmitting through windows and walls. GyroPoint Pro cost is $399.

The GyroPoint Pro uses the GyroEngine sensor developed by Gyration, Inc. This is a miniaturized spinning wheel gyroscope and comes in two models, the Vertical GyroEngine (Model GE9100-A) and the Directional GyroEngine (Model GE9300-C). The Vertical GyroEngine measures roll and pitch whereas the Directional GyroEngine measures heading. Both contain gimbals that are optically encoded, and digital phase quadrature output is available at the GyroEngine 6-pin connector. The Vertical GyroEngine gimbals permit freedom of movement in 360° of roll, measured on the outer gimbal, and a ±80° of pitch, measured on the inner gimbal. The Directional GyroEngine gimbals permit freedom of movement in 360° of heading on the outer gimbal, and a ±80° on the pitch and roll axes.

The sensor offers an angular accuracy of 0.1° for normal head motion, with the ability to handle head accelerations up to 1000°/second, and a drift rate of 0.5°/minute to 2°/minute. It has a 2 x 1.5 inch size and weighs 2 oz. GyroEngines cost $295 each.

3.1.2 Current R&D in Head Tracking

This section describes several R&D efforts that are underway. A topic not considered is facial tracking. For those interested, however, a notable R&D effort in this area is underway by the Interactive Systems Laboratory (INTERACT) at Carnegie Mellon University. These researchers are developing a system that tracks human faces with a computer-vision technique based on face color distributions.

3.1.2.1 NASA Ames Research Center

One goal of the research at NASA Ames Research Center, Numerical Aerodynamics Simulation Systems Division, is to study calibration methods for reducing distortions that result from magnetic trackers. This distortion is significant at distances of greater than 45 to 50 inches, and is sensitive to location since magnetic sensors are very sensitive to metal and electrical devices. The researchers, led by Dr. Steve Bryson of Computer Sciences Corporation, have looked at three methods for reducing static distortions: least-squares polynomial fit calibration, linear lookup calibration, and bump lookup calibration. Of these, 4th order polynomial fit had the best overall behavior, while the bump lookup calibration was superior for tracking very short distances. This early work suggested further study in two directions. First, pursuing the success of the polynomial technique by investigating the use of a 3-D spline calibration (a combination of global polynomials and lookup tables), and study of the weighting and interpolation for the lookup calibration. Second, refinement of the bump lookup calibration method to handle overly distorted data sets.

Current work includes studying dynamic distortion in position data. In this case, the researchers are investigating the use of calibration methods such as Kalman filters. Cross-coupling between these various distortions is also a topic of study.

3.1.2.2 Massachusetts Institute of Technology (MIT), Research Laboratory of Electronics

Dr. Eric Foxlin and Dr. Nat Durlach at MIT, Research Laboratory of Electronics, have developed a prototype inertial navigation system that uses Systron-Donner GyroChips (see Section 3.1.1.24). The goal of their research is to investigate the applications of inertial navigation systems to head tracking to overcome some of the limitations of current trackers. Tracking only orientation, not position, the prototype achieved 1 msec latency, unlimited tracking, 0.008° resolution, and 0.5° absolute accuracy (no drift). The researchers plan further work to develop a second prototype and incorporate it into a complete VE system. They also plan to extend the inertial tracker to 6 DOF tracking.

3.1.2.3 Computer Graphics Systems Development (CGSD) Corporation

A potential solution to the limitations of magnetic trackers is to use a hybrid tracker that exploits the complimentary nature of inertial and magnetic tracking. In this way, the inertial tracking can provide the short term accuracy needed to average out the noise in the magnetic tracker, whereas the magnetic tracker provides the accurate average position needed to eliminate inertial drift.

In a subtask of the Virtual Cockpit project funded by the Simulation Training and Instrumentation Command (STRICOM), Computer Graphics Systems Development (CGSD) Corporation is developing a high accuracy, low latency hybrid tracker for VEs that combines inertial sensing elements such as accelerometers and angular rate sensors with a magnetic tracker. The goal is to develop a 6 DOF tracker with low latency and increased immunity to electromagnetic interference to be used for head, hand, and foot tracking.

A key element of the development approach is the use of Kalman Filtering, from the field of aerospace systems, particularly guidance and navigation systems, to combine the data. In this way, the data from two sensors can provide better results than could be obtained from each sensor separately. For example, if the angle measurement was slightly in error, gravity would be integrated causing a position drift. The Kalman filter uses the position error derived from comparison to the magnetic tracker to assess the angle error, and correct the error accordingly.

CGSD Corporation has constructed the prototype hardware and is currently developing the software, and expect to have the completed unit ready for demonstration in early 1996. Assuming the tracker meets expectations, it could be commercialized as early as the second half of 1996. Researchers also hope to develop a hybrid inertial/optical tracker that could provide high accuracy over large areas at a cost much less than current optical-only trackers.

3.1.2.4 University of North Carolina

Under the leadership of Dr. Gary Bishop, researchers at the University of North Carolina (UNC) at Chapel Hill are conducting a program of research into wide-area tracking, also called ceiling tracking. The UNC optoelectronic tracking system features LEDs mounted in a ceiling superstructure and upward-looking position sensors, based on lateral-effect photodiodes, mounted on a HMD that a user wears when walking under the ceiling. The system works on the principles of celestial navigation using the fact that the locations of the ceiling's LEDs are known and thus serve as navigation beacons. The geometry of the sensors on the HMD is also known. When the sensors see several LEDs as the HMD wearer moves, a real-time multiprocessor system computes the position and orientation of the user's head. The optical beacon tracking technology means that data are free from the distortions commonly arising in the use of magnetic trackers. These data are then sent to a graphics application which renders the images the user sees in the HMD.

Although the optical tracker used in the wide-area tracking system gives satisfactory accuracy over a large working volume, there are various reasons why its design does not lend itself to hand tracking. One reason is the bulkiness of the cameras. Another arises from the geometry of the situation. For example, the user's body may obscure the hand's "view" of the ceiling, and the hand may not be held upright. Additionally, possible hand movements impose dynamic range requirements on photodiode sensitivity (because of changing distances from the ceiling). Since magnetic trackers usually provide satisfactory performance within a small tracking volume, the wide-area tacking system supports hand tracking by placing a magnetic source on the head mount. Thus, the optical tracker reports the head location in ceiling space and the magnetic tracking system reports the hand's location in source space. Change-of-coordinate transformations among these systems are performed to get the hand's location in ceiling space.

In recent work, the researchers have developed new algorithms for extracting user motion from a sequence of LED sightings. This new method updates the estimate of the user position and orientation on every sighting and has allowed computing the position and orientation of the headset at greater than 1000 Hz with a delay of less than 2 msec. They have also designed a new head-mounted tracker assembly that is called the "HiBall." This apparatus is about 1 inch in diameter and integrates six cameras with digitization and communication circuitry. When the first prototype is completed, the HiBall will be used to replace the bulky off-the-shelf cameras and the custom electronics in the back pack of the old system. Besides the obvious advantages of size and weight over the old system, the new system will be much faster and more rigid. The HiBall may be useful for hand tracking, as well as head tracking.

There are several other on-going efforts in the wide-area tracking program. In one, the researchers are working to improve the tracking performance of the system from the current resolution of <2 mm in position and 0.2° in orientation, to reach their goal of tracking accurate within 1-2 mm and 0.1°. The researchers also are expanding the existing 16 x 18 foot area ceiling to cover a 16 x 30 foot area. This enlargement is based on a new ceiling panel design that fits in a standard ceiling grid without the need for a heavy metal superstructure. In additional efforts, the researchers are investigating problems for tracking in unenhanced environments (including outdoors) and have ongoing research into the use of inertial sensors in a hybrid configuration with outward looking optical sensors. Other research is investigating tracking systems based on passive targets instead of active LEDs.

3.1.2.5 Artificial Reality

In 1982, Dr. Myron Krueger proposed developing VideoDesk to Defense Advanced Research Projects Agency (DARPA) (now ARPA). In 1987, it was implemented as part of an National Science Foundation (NSF) Small Business Innovation Research (SBIR) project. VideoDesk is currently the focus of another SBIR Phase 1 study that is investigating how to present maps to blind people.

VideoDesk consists of a light table with a camera mounted above it that is aimed down at the user's hands, which rest on the desk's surface. The silhouette image of the hands appears on a monitor, also on the desk. In this way, the user's hands are superimposed on an application and, by means of a gesture interface, he can use the image of a finger to point, draw, or write.

To operate VideoDesk in 3-D, a sample plane is placed anywhere in the volume, in any orientation. Then, the live image of the user's hands is projected onto it, where they can be used to perform 2-D pointing and drawing in the sample plane. By using a second camera, it is possible to perceive the user's hand in 3-D. The most promising applications envisioned for VideoDesk are teleconferencing and teletutoring. ISDN, which enables computers to communicate over phone lines in real-time, is expected to facilitate the development of these applications.

A separate effort, the Project on Biomedical Technology, being sponsored by ARPA, includes the development of a wide-area head tracking system that can track a 30 square foot area. This tracking system combines onboard (relative) tracking and external sensors. Angular measurements will be achieved by placing sensors on people, whereas relative movement will be tracked using external sensors placed in the environment. The system will use optical sensors that the company is developing from off-the-shelf components. The goal is to reach a data rate of 200 Hz, if possible.

3.1.2.6 Massachusetts Institute of Technology, Media Lab

Using an environment for immersive virtual experience based on computer-vision techniques, the Artificial Life Interactive Video Environment (ALIVE) project at the MIT Media Lab enables interaction between people and agents via natural hand and arm gestures, without the need for HMDs and data gloves. It is under the leadership of Dr. Pattie Maes. The system uses a passive camera tracking system mounted above a projection screen to isolate the image of the user from the background room and locate the user's head, hands, and feet for interaction with the environment. The image of the user, composited with the VE, is flipped horizontally and projected onto the screen, creating a "magic mirror" effect.

Previously, the passive tracking was implemented using a special-purpose vision box by Cognex, which did background subtraction and hand tracking by direct manipulation of the bitmap. Composition of the VE and the real-world room was achieved by chroma keying, which necessarily kept the user in front of the computer graphics. Because of the nature of the ALIVE system, complex heuristics had to be handwritten for the vision system to understand different and unusual positions that people might assume for interaction with the agents. Examples include bending over to the side and squatting down; in both cases the hands are not where the system would generally expect.

The current system uses a digitizer on a Silicon Graphics Indigo2 to reimplement the background subtraction algorithm in software. This allows not only portability but also flexibility of the dependent algorithms. The resultant bitmap from the background subtraction is converted into a polygon which can be rendered into the 3-D VE, allowing occlusion of objects by a user and vice versa. As a result of this conversion process, extremities are essentially found automatically, reducing the hand tracking problem to a problem of classification. This system is not only more general than the previous one, but also drastically reduces the reliance on heuristics.

Researchers are exploring novel applications in the area of training and education, entertainment, and digital assistant interface agents. Current ALIVE worlds include a virtual dog the user can play with and video-game creatures the user can interact with. Another world where a synthetic animated aerobics instructor gives the user detailed personal feedback is under construction.

3.1.2.7 Sony, Computer Science Laboratory

Dr. Jun Rekimoto at Sony Computer Science Laboratory is working on VirtuaHead, a head tracking method using computer vision to support desktop VE. This system employs a video camera placed on top of a normal CRT monitor to capture user images and track the position of the user's head while he is seated at a desk. The user does not need to wear any special gear. The approach is based on some simplifying assumptions. First, that an approximate position of the user can be assumed to be in front of the screen and calculation of head orientation can be ignored. This allows estimation of the head position to be made in real-time using the two simple image processing techniques of frame subtraction and template matching. Frame subtraction is used to subtract a pre-stored background image from the captured image to detect the user's face area. Then a template of (part of) the user's face is matched against the remaining image to identify the center of the user's face. The resulting u, v position forms the basis for final calculation of head position.

Dr. Rekimoto (1995) reports on an experiment where these researchers looked at how their optical head tracking helped a user's 3-D perception. The VE used for this experiment presented three wire-frame trees positioned at the vertices of an equilateral triangle, one of which had a leaf on a particular branch. The experimental task was to identify which of the trees contained the leaf, comparing conditions of using head tracking or not. The data collected for six subjects showed that while subjects using head tracking took longer to report answers, they had significantly lower error rates. In addition, the researchers noticed that subjects without head tracking often gave up in difficult cases, while subjects with head tracking kept trying by repeatedly moving their heads.

Currently, VirtuaHead does not detect the distance between the screen and the user. Since this distance can change, the tracker can report inaccurate positions. The researchers are working on a solution to this problem. The approach being taken is to estimate the distance based on the size of the face image.

3.1.2.8 Siemens' Central Research and Development

Dr. Christoph Maggioni at Siemens Central Research and Development has developed a computer system called GestureComputer that is able to work in real-time on a standard workstation under noisy and changing environmental conditions, and that detects the 3-D position and orientation of the human hand, as well as the position of the head. The system uses video cameras to observe head and hand movements, relieving users from cables, gloves, helmets, or other encumbrances. Image processing algorithms perform head and hand tracking as follows. A color image is segmented to find patches of human skin by using a fast look-up table approach. The contours of the resulting binary image are traced and a new data structure is generated. This contour data is analyzed and special features are extracted in order to detect head and hand positions. Siemens expects to release GestureComputer as part of some of its products during the next three years.

3.1.2.9 Boeing Information and Support Services, CMU, Honeywell, Inc., and Virtual Vision, Inc.

As part of the ARPA Technology Reinvestment Program (TRP), Boeing Information and Support Services, CMU, Honeywell, Inc., and Virtual Vision, Inc. are using an optical inside-out videometric tracker for an industrial augmented reality application, touch labor manufacturing. The goal is to develop a position-sensing device that tracks the factory worker's head direction. With this information, the display unit can project the information through a transparent display and onto the work surface, as if it were painted on. Workers having this capability do not have to look through books, so their hands are free to work without interruption. Moreover, the system obviates the need for the expensive marking systems now used in aerospace manufacturing. A benchtop prototype was demonstrated in June 1995.

The project is to assist workers assembling aircraft cable bundles. The worker will wear a belt and headband with a high resolution display and small camera (videometric tracker) through which he will look at the board he is wiring. Graphics will be superimposed on the board, showing him where to put the wires. In order to accurately project graphics onto specific coordinates of a workplace, it is necessary to have the coordinates of the workpiece, the display's virtual screen, the position sensor, and the user's eyes in the same coordinate system. The project requires high accuracy, long-range tracking in a high-noise environment.

In order to compute the position and orientation of a camera mounted on the user's head, fiducials (or markers) are mounted in the work environment and their locations accurately measured. Based on where in the field of view the fiducials appear, the computer can calculate the position and orientation of the camera, and therefore the user's head. For the June 1995 benchtop prototype, Boeing used black paper with white spots as fiducials. For factory use, they plan to mount a bright LED on the user's head pointed towards the work piece, and attach retroreflective targets to known locations on or near the work piece. The camera will need an optical filter that will only pass light of the same frequency as the LED.

Computation involves four steps: capture, correspondence, 3-D reconstruction, and matrix computation. In the capture step, a digital representation of the field of view of the camera is obtained, fiducials from the background are extracted, and the 2-D position of the fiducials accurately computed. The correspondence phase matches each fiducial in the camera's field of view with one of the physical fiducials. Once the location of the fiducials is known on the 2-D screen of the camera, 3-D reconstruction computes the 3-D location of each camera fiducial in the coordinate system of the camera. Finally, given the 3-D locations of the camera fiducials in camera coordinates, and their corresponding 3-D location in real world coordinates, the matrix computation step computes the transformation from one coordinate system to the other. This transformation embodies the position and orientation of the user's head.

Much work on this project remains to be done, both in constructing a production quality unit, and in characterizing the algorithm. Researchers will continue analyzing errors, introducing noise in the camera parameters, lens aberrations, and errors in fiducial placement. Measuring the resulting degradation in accuracy will help them to focus on the major sources of errors. The researchers will also develop methods to calibrate these sources of errors. Two methods that are being explored are auto-calibration and optimization calibration.

3.1.2.10 University of Washington

Recognizing the need for tracking technology which addresses some of the limitations of current head-tracking technology, such as price, accuracy, resolution, and range, the University of Washington, Human Interface Technology Laboratory (HITL), has conducted work on a fast, wide area, multi-participant tracking system. The system used a swept laser fan with multiple sensors mounted on a helmet to track position. The efforts were suspended when funding ran out two years ago, but HITL is now revising the project in hopes of attracting new funding.

HITL researchers are not sure what method of tracking they will now pursue. They are studying the requirements and looking at a number of methods, including the swept laser fan. Advantages of the swept laser fan include the ability to track multiple participants in an area (no real limit). Moreover, no feedback is required between the scanner and the object being tracked. Finally, simplicity of system setup and calibration make it an attractive method. The disadvantages are its limited update rate (60 Hz or so), the power required in the swept beam, and retaining accuracy at the far end of the range. The goal of HITL researchers is to have a system that is accurate to 1 mm over a range of 10 x 10 meters.

3.2 Eye Tracking

Eye-tracking technologies measure the direction the eyes are pointed out of the users' head by detecting the movement of the fovea. This information is then used to determine the direction of the user's gaze and to update the visual display accordingly. General approaches are optical, electroocular, and electromagnetic. The first of these, optical, uses reflections from the eye's surface to determine eye gaze. Electroocular approaches use an electrooculogram (EOG) via skin electrodes that provide measurement of the corneoretinal potential. Finally, electromagnetic approaches determine eye gaze based on measurement of magnetically induced voltage on a coil attached to a lens on the eye.

3.2.1 Commercially Available Eye Trackers

Most commercially available eye trackers are optical and those covered here are products from ISCAN Inc., LC Technologies, Hughes Trainer-Link Corporation, and Fourward Optical Technologies, Inc. BioMuse from BioControl Systems, Inc. is the exception and the only product identified that uses the electroocular method.

3.2.1.1 BioMuse

The BioControl Systems Inc. BioMuse System eye controller uses an EOG as the source signal for deriving eye movement information. The EOG itself is derived from the resting potential (known as the corneal-retinal potential) generated within the eyeball by the metabolically active retinal epithelium.

Historically, the EOG has been used as an indicator of eye movement in physiological research studies and in the clinical environment. This relatively common use of the EOG for eye movement evaluation is due to the fact that the technique is noninvasive and the most cost effective and practical of the eye tracking technologies. However, standard amplification and recording techniques present the clinician with several artifacts and technical problems in the evaluation of eye movement for diagnostic purposes. For example, eyelid movement and ocular muscle electromyogram (EMG) contaminate the EOG record. In addition, the recording baseline is unstable due to electrode drift, and repeated calibration is required with adaptation to ambient light. Further, the vertical movement record is unreliable due to eye movement associated with reflex blinking.

For these reasons, traditional EOG recording technology for simple detection of eye movement is unsuitable for an eye controlling system where the user is the initiator of action using eye movements. BioMuse resolves several of the problems by using a DC coupled amplification system to acquire a signal that can be used to indicate the steady state displacement of the eyeball. However, a DC coupled physiological recording system still exhibits an unstable recording baseline caused by electrode drift. To deal with the problems of electrode drift, BioControl Systems, Inc. has developed techniques using fuzzy classification and pattern recognition which are able to greatly reduce this problem.

With proper placement of recording electrodes, vertical and horizontal eye movements can be mapped to move video objects around the screen. The company's 2-D eye controller uses a lightweight headband to position the EOG electrodes. Three electrodes are positioned on the forehead to track horizontal eye movements, and one electrode is positioned below the eye for the vertical channel. For 3-D applications a different headband configuration is required which uses five electrodes on the forehead and two below the eyes, one on each side of the face. This configuration of EOG electrodes is necessary to create two independent horizontal and vertical channels for each eye. With individual measurements for the horizontal and vertical movements, an ocular convergence signal can be derived, and this convergence signal is the basis for the 3-D controller. As the eyes focus on a near field object, they converge, or point inward and, as the object moves into the distance, the eyes diverge slowly until they are parallel at optical infinity. The depth, or third dimension channel, is unique to this patented eye controller system.

The BioMuse System enables an individual to use their nervous system to control virtual objects. The BioMuse product and software tools (libraries) allow users to develop their own motion capture system. The software is in Version 5.0 and provides 3-D depth of field with enhanced drift control to allow greater accuracy. Also included is a Microsoft Windows MIDI (musical instrument digital interface) application that enables a user to play up to 128 musical instruments with obstinacies generated by muscles, eyes, heart, or brain. A video game interface enables users to navigate with their eyes, fire a gun by natural hand motion, and move forward by walking on the spot. The price is $19,800 for single quantity purchases.

3.2.1.2 Headhunter Head and Eye Tracking System

The ISCAN, Inc.'s Headhunter Head and Eye Tracking System employs helmet mounted eye tracking technology to non-invasively monitor the position of the subject's eye with respect to a miniature imaging sensor mounted on the helmet. This system uses the RK-426 Pupil/Corneal Reflection Tracking System, a real-time digital image processor that simultaneously tracks the center of the pupil and a reflection off of the cornea from the IR light source. RK-426 is a dark pupil tracking system which enables it to perform in high illumination environments with virtually any user. The RK-520 Autocalibration System uses raw eye position data generated by the RK-426 to calculate the user's point of gaze with respect to a scene being viewed and is included in the Headhunter. The tracking system computes eye position at a 60 Hz rate and the eye's point of regard is determine to an accuracy of better than 1° of visual angle over a ±25° range. The entire Headhunter System can cost $30,000 to $40,000. Cost for the independent RK-426 is $13,000, or $7,800 in quantities of five to ten. RK-520 Autocalibration System costs $6,800. (Other ISCAN eye tracking processors include the RK-406 Pupillometry System, the RK-416 Pupil Tracking System, and the RK-436 Pupil/Dual Corneal Reflection Tracking System).

3.2.1.3 Eyegaze System

LC Technologies' Eyegaze Development System is a workstation for both developing and running custom eye tracking applications. It is a tool for measuring, recording, playing back, and analyzing what a person is doing with his eyes. The Eyegaze System uses the Pupil-Center/Corneal-Reflection method to determine the eye's gaze direction. A video camera located below the computer screen, or below the work space if the computer monitor is not used, continually observes the subject's eye. An IR LED located at the center of the camera lens illuminates the eye, generating the corneal reflection, and causing the bright pupil effect that enhances the camera's image of the pupil. Image processing software identifies and locates the centers of both the pupil and corneal reflection. Trigonometric calculations project the person's gaze point based on the positions of the pupil center and the corneal reflection within the video image. No attachments to the head are required, however the eye must remain within the field of view of the camera.

Specification	
Sampling Rate	30-60 Hz
Gaze Cone Diameter	80° (typical)
Head Motion Tolerance	1.5 (lateral), 1.2 (vertical), 0.5 (long.) in

Figure 46. LC Technologies EyeGaze System

New eye tracking data are generated each 30th or 60th of a second in synchrony with either the frame or field rate of the video camera. To allow the eye tracking software to run concurrently with an applications program, the eye tracking software runs on an interrupt basis, receiving its interrupt from the camera's framegrabber board and executing as a stay-resident interrupt service routine. The Eyegaze Development System costs $21,500. Further details are given in Figure 46.

3.2.1.4 Dual-Purkinje-Image (DPI) Eyetracker

The Dual-Purkinje-Image (DPI) Eyetracker was developed at SRI International from 1965 to 1988. In 1988, the technology was licensed by SRI to Fourward Optical Technologies, Inc. which has continued its development and marketing. Currently, Fourward offers two Eyetracker models: the top-of-the-line Generation 5.5 DPI Eyetracker and the DPI Eyetracker 1000. Both are 2-D instruments in that they track only the horizontal and vertical movements of the eye.

The concept behind DPI is as follows. Light rays striking the eye produce four reflections, called Purkinje images, from the front and rear surfaces of the cornea and lens. The first (virtual) and fourth (real) Purkinje images lie in the same focal plane. These two images move similarly under translation, but deferentially under rotation. The change in their separation is used to determine eye rotation. Thus, the DPI eye tracker tracks the first and fourth Purkinje image; the latter is dim, so bright illumination of the eye is needed. A photocell captures the reflections and also drives a servo-controlled mirror with an analog signal, avoiding the need for discrete sampling. Figure 47 provides further details for the DPI 5.5 Eyetracker.

The monocular DPI Eyetracker 1000 costs \$49,000, whereas the binocular version costs \$99,800. For the DPI 5.5 Eyetracker, the prices are \$60,000 and \$115,000 for the monocular and binocular versions, respectively. Three accessories that are required with either Eyetracker model are the Headrest Accessory Package (\$1,000), the Model Eye with Control Electronics for maintenance, checkout, and calibration of the Eyetracker (\$2,995), and the Video Eye System turnkey system consisting of an IR camera with monitor and optics that is required for alignment and monitoring (\$2,500 when purchased with an Eyetracker).

Specification	
Frequency Response	~500 Hz
Output Delay Signal	0.25 msec
Slew Rate	2000°/sec
Noise Level	20 sec of arc RMS

Figure 47. DPI 5.5 Eyetracker

In order to track in 3-D, the tracker must know not only the 2-D angular orientation of the line of sight but also the distance from the eye to the point in space on which the eye is fixated, that is, the level of accommodation. The attachment of Fourward's Infrared Optometer enables the measurement of the subject's accommodation. This additional product costs \$29,950.

3.2.2 Current R&D in Eye Tracking

This area is seen as one with a limited application area and there is little active research. It is worth noting, however, that two of the research efforts described below do circumvent one of the biggest limitations of eye tracking technology, that is, its intolerance to head motion.

3.2.2.1 Hughes Training-Link Corporation

The Hughes Training-Link Corporation (formerly CAE-Link) Eye-Slaved Projected Raster InseT) (ESPRIT) is a simulator foveal projector eye-tracked display system that uses a bright pupil tracker. It provides a high-resolution (better than 4 arc minutes per line pair) picture in an area of interest mode of operation using a General Electric light valve as display source and a helmet-mounted occulometer from Honeywell. The scene is inset into a background by a high-speed servo that operates at a speed faster than eye saccade velocities (saccade movements can reach 700°/second and have accelerations of up to 50,000°/second). The static line of sight accuracy of the azimuth/elevation servos is better than 1 minute of arc, while the dynamic accuracy is better than 3 minutes of arc at an angular velocity of 700°/second. Latency is about 90 msec, a lag that test subjects found acceptable.

While two of these systems were built for the British, they are very expensive (in the millions of dollars) and were never produced on a commercial scale. Future development plans call for development of a proprietary occulometer by Hughes Training-Link.

3.2.2.2 Interactive Systems Laboratories (INTERACT)

Previously under the direction of Dr. Pomerleau and now under the direction of Dr. Waibe, the Gaze-Tracking Team at the Interactive Systems Laboratories (INTERACT), School of Computer Science, Carnegie Mellon University has developed an artificial neural network-based gaze tracking system that can be customized to individual users. A three layer feed forward network, trained with standard error back propagation, is used to determine the position of a user's gaze from the appearance of the user's eye. Unlike other gaze trackers, that normally require the user to wear head gear or to use a chin rest to ensure head immobility, this system is entirely non-intrusive. In his experiments, Pomerleau has achieved accuracy of 1.5°, while allowing head mobility. Average accuracy is 1.7°. In its current implementation as an input device, the system works at 15 Hz.

The researchers hope to increase the system's accuracy through several additions. When using low resolution images, the pupil and cornea do not provide enough information for the neural net to support accurate gaze tracking. In order to obtain more information from the appearance of the eye, the researchers have used the position of the cornea in the eye-socket. However, this method makes the eye tracker less invariant to head position. One method of addressing this problem is training on multiple head positions and necessitates collecting large amounts of data. In the current system, data collection requires approximately three minutes of the user visually tracking the cursor. In this time, 2000 images of the user's eye paired with the position of the cursor are gathered. If the system were to be invariant to distance from the screen, and relative position with respect to the screen, more training image/gaze location pairs would have to be gathered. An alternate method of maintaining position invariance in the eye tracking system is through the addition of extra input units to represent the head position. Because the camera used in this system has a relatively wide field of view, the same image from which the user's eye is extracted can be used to extract information about head position.

A potential method to rapidly train the neural network for new users may be to use a multiple network architecture. Several smaller expert networks, under the control of an arbitrating network, can be trained on the eye images of different users. The arbitrating network selects the expert network that is yielding the best response or combines the responses of several expert networks. Preliminary results of this approach have yielded noticeable performance improvements. Alternatively, arbitration could be through the use of metrics which estimate the output reliability. As another attempt to make the same network robust to a variety of people, preliminary experiments have also shown that training a large network with the images of several user's eyes improves the performance for each user.

Currently, the INTERACT Lab is combining the gaze tracking work of Dr. Pomerleau with its face tracking work to extract the face image first and then the focus of the eye based on the image of the face. The goal of this is to eventually extend the ability to identify gaze even for a person moving about the room freely (not only for someone sitting in front of the screen in a relatively stable position as is presently the case). Extraction of the eye image is a problem they are now trying to solve through combination of face tracking and segmentation modules.

3.2.2.3 State University of New York

The Computer Science Department at the State University of New York at Stony Brook has produced an in-house EOG-based eye tracking device from inexpensive off-the-shelf components to detect horizontal and vertical eye movements for human-computer interaction. The system is applicable for both VE systems and video games, as well as for the handicapped. For the latter, the goal is to develop an inexpensive system for use by people able to control only their eye muscles.

The project consists of the development of EOG eye tracking pick-up electrodes, electronics hardware and its fine tuning software, as well as the definition of acknowledgeable eye behavior and the establishment of basic protocols governing on-screen and both 2-D and 3-D object selection and manipulation.

The system itself includes a detecting device adapted to detect the bioelectromagnetic signals generated by eye movements. A first processor receives these signals and generates tokens corresponding to pre-defined eye gestures. These tokens indicate the direction of gaze movement, such as north, south, or north-east, the magnitude of the movement, and the type of eye movement, such as smooth pursuit, saccade, or blink. A second processor receives the tokens and generates command signals based on a token correlation protocol. Thereafter, a user interface responds to these command signals with the appropriate control function. Experiments on the ease of use and accuracy of the system were performed using a 3 x 2 two-level boxed menu driven by eye selections. Subjects were able to make correct menu selections 73% of the time. However, results improved dramatically (up to 99%) when only four corner squares were looked at, as opposed to the two center squares.

In November, a patent was issued for this eye-tracker. The system is currently in its third prototype and the developers are looking to commercialize it.

3.2.3 Summary and Expectations

To date, low-latency, high accuracy systems for head tracking in unprepared, possibly noisy environment do not exist. Most head trackers achieve a large working volume at the expense of accuracy. These are well recognized problems and, for the relatively mature technology areas of mechanical, magnetic, and acoustic tracking, expected to be the focus of near-term R&D. Improvements are particularly likely in the case of magnetic trackers which are widely used and where the field is dominated by two highly competitive companies (Polhemus and Ascension Technology Corporation). For example, the sourceless, non-inertial trackers described in Section 3.1.1.10, Section 3.1.1.11, and Section 3.1.1.12, are a new type of passive magnetic tracker that offers a cheap alternative to more traditional magnetic trackers. Clymer and Graves (1994) believe they have a strong potential to replace existing inertial, gravity, or mass-based technologies. Because the sensor is non-inertial, the viewer is not subjected to screen "slosh" where head motion has stopped, but the screen keeps moving for a period of time. Also, because it passively monitors its position relative to the earth's magnetic field, the sensor does not need to maintain its alignment relative to any other source. It is, however, difficult to mark movement from one magnetic hemisphere to another, a requirement for full 360° operation.

The most significant improvements in tracker performance, however, are expected to come from the use of hybrid trackers where many of the limitations inherent in a particular technology can be overcome by combining the best features of two of more technologies. Several groups of researchers are doing this. In May 1995, a U.S. patent (Patent No. 5,412,619) was issued for a hybrid triaxial accelerometer/ultrasonic tracking system expected to provide position sampling rates of up to several thousand Hz. Another patent (Patent no. 5,422,715), issued in June 1995 describes a hybrid of an optical localization system and independent tilt and direction sensors. While no commercial hybrid trackers are available as yet, this activity indicates that the next few years most likely will see a growing availability of hybrid trackers using inertial technology. Despite its problems, chiefly a limitation to 3 DOF, inertial tracking provides unlimited range, is fast, and free of interferences. Recent use of silicon micro-machining techniques, that has begun to produce very small inertial sensors, and is leading to an overall reduction in product size and cost, also makes inertial trackers attractive.

The number of research efforts and commercial systems that are using computer-vision with tracking implies that this will continue to be an area of slow growth. Several advances are needed. Most of these systems only deal with 2-D gestures, require complex algorithms, and need significant computing power supported by special-purpose hardware.

None of these problems, however, is insurmountable. The long standing trend toward increasingly powerful hardware at cheaper prices should quickly resolve the last problem, and several groups are working on the development of more powerful and efficient algorithms that can deal with multiple features and users. As reported in Section 3.1.2.4, UNC already has algorithms capable of supporting update rates of 1000 Hz with a delay of less than 2 msec. As the computer vision community continues to make advances in algorithms and hardware, the use of computer vision is likely to become prevalent in tracking.

Wide-area trackers are another area where commercial products are unavailable. However, researchers are demonstrating effective systems capable of both head and hand tracking and these efforts may lead to near-term products. Wide-area tracking is likely to become an increasingly important type of tracking, where the lack of tethering and ability to move freely in room sized areas will make it highly desirable for many different types of VE applications. Current limitations in magnetic, line of sight, and electromagnetic interference are being addressed by various researchers and likely to be resolved in the near future. The wide breadth of possible applications for this type of tracking is likely to encourage continued research and development.

Eye tracking is limited by both the current technology and by the nature of human eye movement. Cost and performance improvements are coming, but only slowly, probably owing to the narrow market this technology serves. Accuracy seems to be the main problem. VE applications need to consider the selection of eye-tracking carefully, since using long gaze or blinking to signal intentions is often an unnatural user interface and limited in its interpretation. The two basic approaches use either biosignals or cameras and, as yet, no one technology seems to be favored above the others. The next few years will likely see ongoing research in both areas. In this timeframe, a small number of new products may come to market, but nothing radically different from the current products.