A survey of tracking technology for virtual environments

A SURVEY OF TRACKING TECHNOLOGY FOR VIRTUAL ENVIRONMENTS

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ABSTRACT
Tracking for virtual environments is necessary to record the position and the orientation of real objects in physical space and to allow spatial consistency between real and virtual objects. This paper presents a top-down classification of tracking technologies aimed more specifically at head tracking, organized in accordance with their physical principles of operation. Six main principles were identified: time of flight (TOF), spatial scan, inertial sensing, mechanical linkages, phase-difference sensing, and direct-field sensing. We briefly describe each physical principle and present implementations of that principle. Advantages and limitations of these implementations are discussed and summarized in tabular form. A few hybrid technologies are then presented and general considerations of tracking technology are discussed.

1 INTRODUCTION

Human exploration in virtual environments requires technology that can accurately measure the location and the orientation of one or several users as they move and interact in the environment. This is referred to as tracking users in the environment. The location and the orientation of each user are measured with respect to the virtual environment coordinate system. One common approach to tracking a user in the environment is to attach a coordinate system to his head and to measure the location and the orientation of this coordinate system with respect to a reference coordinate system. The domain of tracking systems is large and we shall focus on head tracking or the like in virtual environments. This paper most generally reviews however technologies used to track real world features at human scale. Some technologies use an external reference, others do not, which may indicate for example the scalability property of a given technology.

If tracking of other body parts beside the head was also required, their respective positions and orientations would be measured using special purpose tracking probes attached to the parts. The body parts' locations could then be represented with respect to the head coordinate system. While aimed more specifically at head tracking, the various tracking principles described in this paper could also be exploited in designing probes for tracking other body parts. Moreover, the physical principle of goniometry, extensively used in motion capture, would be considered in technology choices. While of extreme relevance and interest to tracking in virtual environments, a description of the technology that pertains to various forms of goniometry (e.g. mechanical goniometers, fiber-optics bend sensors, resistive-flex sensors, and magnetic extensometers) is beyond the scope of this paper. Furthermore, other trackers, such as those for inter-satellites spatial communications, eye tracking, or missile tracking, will not be considered in this review.

To interact effectively in a virtual environment, tracking should be conducted accurately and at interactive speed. The technology employed spans a combination of engineering fields that includes optics, electromagnetics, electronics, and mechanics, and this multi-disciplinary combination often makes the working principle challenging to understand. We propose a top-down perspective on the technology that emphasizes the underlying physical principles of operation and the types of measurements involved. We chose such taxonomy because it allows summarizing a large body of work in a manner that we hope will stimulate going beyond the applications and the requirements for tracking and learning more about the various underlying technologies themselves. We also hope it will stimulate the generation of new ideas to the tracking problem.

Previous surveys of tracking technologies and their use in Virtual Reality can be found in (Ferrin, 1991; Rodgers, 1991; Meyer and al, 1992; Bhatnagar, 1993; Burdea and Coiffet, 1993; Durlach and Mavor, 1994; Fuchs, 1996). The present review brings a top-down perspective on the technology, where main principles of operation lead the classification of the various technological implementations. We distinguish between technologies that use only one physical principle and those that use a combination of principles. The latter are referred to as hybrid systems and will be treated separately. In fact, hybrid technologies usually refer to the combination of various technological implementations (e.g. optical and mechanical) rather than various operating principles (e.g. time of flight and spatial scan). To build on the current use of the word hybrid, a system will be specified as hybrid if either various principles of operation or various technological implementations are used.

The proposed classification is inspired in part by Chavel's perspective on range measurement techniques (Chavel & Strand, 1984). We identified six main principles of operation: time of flight (TOF), spatial scan, inertial sensing, mechanical linkages, phase-difference sensing, and direct-field sensing. The classification is presented along with a description of the principles involved and examples. The latter are meant as a representative rather than a comprehensive selection. For each tracking principle, a table summarizes the physical phenomenon involved, the measured variable, the characteristics (e.g. accuracy, resolution, and range of operation), as well as the advantages and limitations of the technique. The tables were assembled from published literature and available patents and while some of the numbers may become obsolete with technological progress, we hope they provide some guidelines for what the technology can provide at a point in time.

Several sub-classifications proposed in this paper are in concordance with various research publications on tracking systems (Wang and al., 1990; Ferrin, 1991; Burdea and Coiffet, 1993; Fuchs, 1996). We propose in Appendix A some definitions of terms commonly associated with tracking for virtual environments as well as symbols employed in this paper. In Appendix B, the addresses of corporations and laboratories working in the area of tracking are supplied. A few patents related to the technology of tracking encountered in our research for this review are referenced in Appendix C.

2 TIME OF FLIGHT

Time of Flight (TOF) systems rely on the measure of distance between features attached on one side to a reference and on the other side to a moving target. These distances are determined by measuring the time of propagation of pulsed signals between pairs of points under the assumption that the speed of propagation of the signals is constant.

2.1 ULTRASONIC MEASUREMENTS

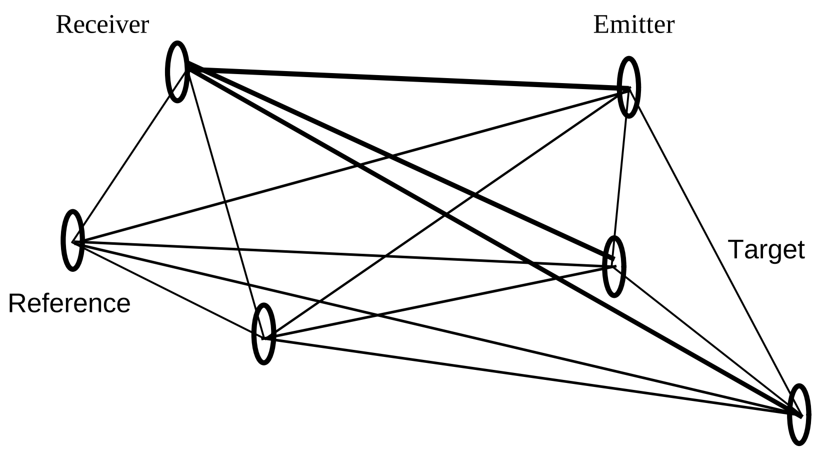

Fig. 1 *Working principle of a Time-Of-Flight (TOF) tracking system.*

Commonly used ultrasonic trackers involve three or more ultrasonic emitters on the target and three or more receivers on the reference (e.g. Logitech, 1991). The emitters and the receivers are transducers (e.g. piezo-electric ceramics, electromagnetic and electrostatic transducers, and spark-gap emitters) usually installed on a triangle structure. Details on these various transducers can be found in (Fraden, 1997). The relative spatial positions of the emitters on the target and the receivers on the reference are known. We found that the principle of operation of ultrasonic trackers is not well explained in current literature. In the scheme presented, each emitter sends an ultrasonic pulse sequentially. It is then important to note that all the receivers then detect each pulse to ensure that the emitter plane is uniquely defined within some boundary constraints. The spatial position of the emitter with respect to the plane defined by the receivers is measured by triangulation as shown in Fig. 1. After determination of the spatial position of at least three emitters, the orientation and the position of the target is known, making the overall system a six-degree-of freedom finder. The emitted frequency is above 20Khz, typically around 40Khz, to prevent the user from hearing it (Fuchs, 1996).

The advantage of the ultrasonic TOF system is that the emitting unit held by the user is small and lightweight. Moreover, the system does not suffer from distortion. Problems with such a system are multiples: first, the accuracy of the system depends on the constancy of the velocity of sound. Although, the speed of sound varies primarily with temperature, it also varies with pressure, humidity, turbulence, and therefore position. Other limitations are the loss of energy of the signal with the distance traveled that tends to limit the range of tracking, ultrasonic ambient noise, and the low update rate. Ultrasonic noise is produced by Cathodic Ray Tube' (CRT) sweeping cycles, disk drives, or reflections of the emitted signals. The low update rate results from the sequential triple emission of sound signals and the low speed of the sound.

A general approach to improve the update rate is to code the signals in order to send them simultaneously. Several frequencies may be used, for example (Arranz and Flanigan, 1994). It has also been suggested that an infrared signal may be used to trigger the ultrasonic emission, thus making the system wireless (Fuchs, 1996). The principle of operation of such a system, the US Control ultrasonic tracking system, is shown in Fig. 2.

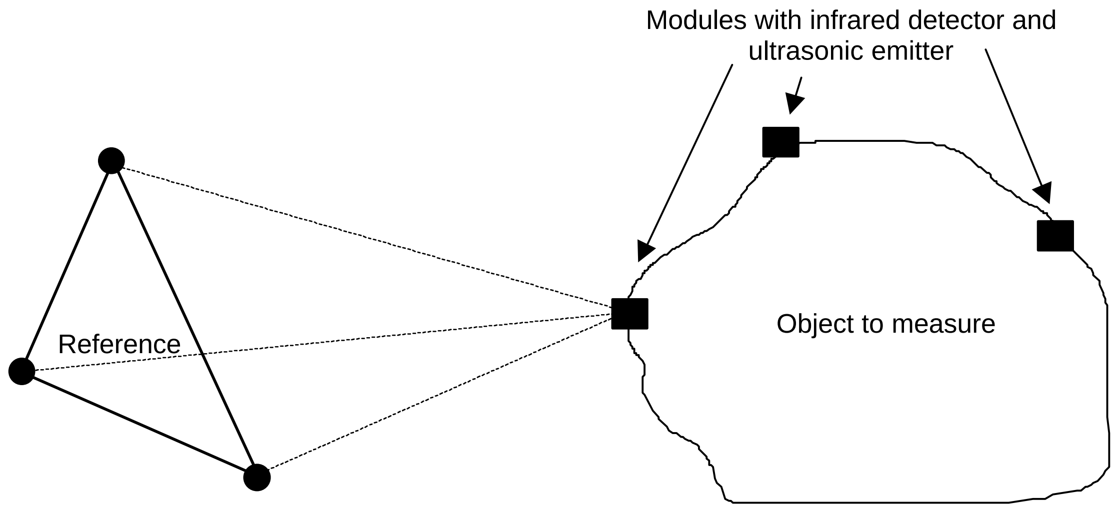

Fig. 2 *Principle of the wireless US Control ultrasonic tracking system*

Such a system is composed of an infrared emitter, three ultrasonic receivers placed on the reference, and of modules placed on the target’s features to be sensed. Each module located on the target consists of an infrared receiver and an ultrasonic emitter installed on a small chip. The association of the ultrasonic emitters on the modules and the ultrasonic receiver on the reference constitutes a time-of-flight ultrasonic tracking system. The infrared beam, sent by the reference at the beginning of each acquisition, triggers the firing of the ultrasonic signal emitted by the modules. This setup relies on the fact that the time-of-flight of infrared waves is negligibly small compared to that of ultrasonic waves. This system is able to localize the position of several modules simultaneously, making it a three degrees-of-freedom position finder.

However, if the geometry between the modules is known, the tracking system becomes a six degrees-of-freedom position and orientation finder.   This system has the same advantages and limitations of a conventional TOF ultrasonic system. Recently, InterSense Inc. implemented motion prediction using an inertial sensor in addition to a wireless ultrasound technology yielding an hybrid technology reminiscent of an hybrid videometric/inertial technology developed by Azuma, (1995; see also Section 8.2)

Table 1. *Summary table of the characteristic of TOF ultrasonic systems*

Physical phenomenon	Acoustic pulse propagation
Measured variable	Time of flight
Degrees of freedom (d.o.f)	Some system (Honeywell) measure only the orientation (2 or 3 d.o.f). Other have position and orientation capabilities (6 d.o.f).
Accuracy (position/orientation)	0.5-6 mm / 0.1-0.6 degree
Resolution (position/orientation)	0.1-0.5 mm / 0.02-0.5 degree
Update rate	25-200 Hz
Lag	40 ms
Range / Total Orientation Span	250-4500 mm / 45 degrees
Advantages	Small, light, no distortion
Limitations	Sensitive to temperature, pressure, humidity, occlusion and ultrasonic noise from CRT sweep frequency or disk drives. Low update rate.
Examples	Honeywell helmet tracking system, 3D mouse from Alps Electric, RedBaron (Logitech, 1991), Lincoln laboratory Wand (Roberts, 1966), Mattel Power Glove, Sciences Accessories Space Pen. US Control localization senssor, OWL from Kantec, Intersense Inc.

2.2 PULSED INFRARED LASER-DIODE

Pulsed infrared laser-diode tracking uses TOF techniques with an infrared laser beam. This principle was used in a hybrid system that will be described in Section 8.5.

2.3 GPS

The GPS (Global Positioning System) tracking principle uses a total of 24 satellites and 12 ground stations spread around the world (Elliot, 1996). Each satellite has an atomic clock that has a drift of about 0.1 msec per year. The drift yields errors on measured distances in the order of 30 km. Each ground station controls the orbital drift of the satellites and recalibrates their atomic clock every 30 sec. Theoretically, the system can determine the position of a user having a GPS receiver by the reception of a signal from each of at least three satellites and the computation of their respective times of arrival (TOAs). In practice, however, the receiver clock is not precise and has an unknown bias. Four measurements of TOA of signals from GPS satellites must be taken, from which it is possible to solve for the position of the receiver and the clock bias. The resolution accomplished with such a system is in the order of 10 meters. A more precise system, the differential GPS, uses emitting ground stations that refine the resolution to the order of the meter (Noe and Zabaneh, 1994). Drawbacks of GPS systems are their poor accuracy and resolution, and the failure of the technology if the direct lines of sight to the satellites are occluded.

2.4 OPTICAL GYROSCOPES

Gyroscopes are used to make angular velocity measurements. Optical gyroscopes operate on TOF principle. They use laser light (Fiber optics gyroscopes or FOG, Ring laser gyroscope or RLG) and time of propagation to extract angular velocity of a target. They are light, durable, and low in power consumption. A FOG relies on interferometry. Let's consider a free space interferometer shown in Fig. 3. The same principles apply to that of a fiber optic system. A laser beam is divided in two waves that travel within the interferometer in opposite directions. For no rotation, both waves combine out of phase because of the consecutive pi phase shifts at mirror reflection.[1] For a clockwise rotation of the device, the wavefront propagating counter-clockwise travels a shorter path than the wavefront propagating clockwise, producing interference at the output. The number of fringes is proportional to the angular velocity. (Meyer-Arendt, 1995). A RLG is a ring laser cavity. It resembles the FOG except that it has an amplifying medium within the cavity to make it a laser. Upon rotation of the device, two waves of slightly different frequencies propagate in opposite directions. The frequency of the signal at the output of the laser is the difference in frequencies of the two waves. The angular velocity of the target can be extracted based on the output signal frequency (Fraden, 1997).

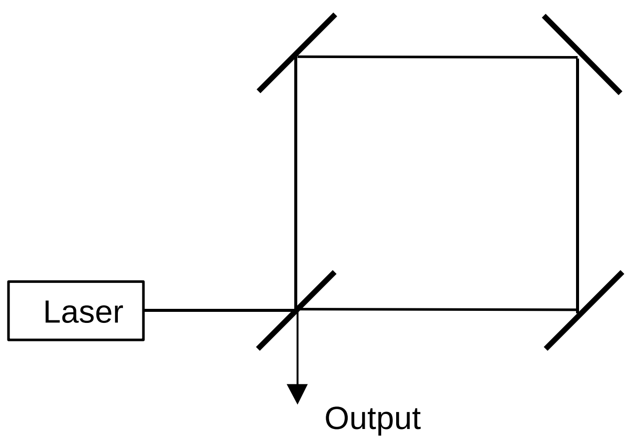

Fig. 3 *Schematic view of a FOG gyroscope.*

3 SPATIAL SCAN

The principle of spatial scan trackers is based on either the analysis of 2D projections of image features or on the determination of sweep-beam angles to compute the position and the orientation of a target. The optical sensors are typically cameras (e.g. CCD), lateral-effect photodiodes, or four-quadra detectors (4Q). A CCD is an array detector receiving an in-focus or out-of-focus image on the focal plane of a camera depending on the application. A lateral-effect photodiode is a 1-D or 2-D array that directly reports the location of the centroid of detected energy (Wang et al., 1990; Chi,

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[1] Note that there is a pi phase shift upon each mirror reflection. For the half-silvered mirror, however, there is a pi phase shift on one side only. This results in a phase shift difference of pi between the two paths.

1995). A 4Q detector is a plane component that generates two signals specifying the coordinates of the estimated centroid of the incoming out-of-focus light beam on its surface. These 4Q detector signals are useful to control directly two axes of some pointing system gimbals (see Section 8.4). Any device that estimates centroids is designed to work optimally with out out-of-focus imagery.

A possible sub-classification of the optical systems is outside-in versus inside-out. Wang first proposed this terminology for a subclass of optical trackers that use beacons as target features (Wang, 1990). We propose to extend these two classes to pattern recognition and beam sweeping systems, to indicate and emphasize their common physical principles. In the outside-in configuration, the sensors are fastened to the fixed reference. In the inside-out configuration, the sensors are attached to the mobile target. All systems share the properties that light propagates in straight line through a linear medium and that the links between emitters and sensors constitute the lines of geometrical construction.

Optical systems typically have good update rates because of the speed of light. The measurement accuracy and resolution tend to decrease with the distance of the target to the sensor (a function of the working volume), because the relative distance between two points on the sensor becomes smaller as the target gets farther away, thus making the points harder to resolve spatially. Optical noise, spurious light, and ambiguity of the sensed surface are sources of errors. Most of the systems use infrared light to minimize some of these effects. Moreover, if too many target features are occluded, the system may fail to report correct data.

3.1 OUTSIDE-IN

Outside-in systems employ video cameras that are placed on the reference and record features of the target. This technique is widely employed. Two methods, multiscopy and pattern recognition, are typically used.

We refer to *multiscopy* as an outside-in technique that employs multiple imaging sensors. The simplest multiscopy system uses only two cameras (stereoscopy) as shown in Fig. 4. A simple example of such a system is the human visual system that perceives 3D shapes of objects from two viewpoints (i.e. right and left eye position). Multiscopy, therefore, will employ two or more video cameras to compute the spatial position of a target feature by triangulation. The measurement of several features allows determining the orientation of the target. A tracking system may always use additional views either to refine a measure using an appropriate sensor fusion technique or to compensate for potential occlusions. Most of the systems define a plane on the target by detecting several features to measure the orientation and the position of the target (6 DOFs) (Horn, 1987). Some systems, however, could measure a subset of the DOFs to meet the needs of an application.

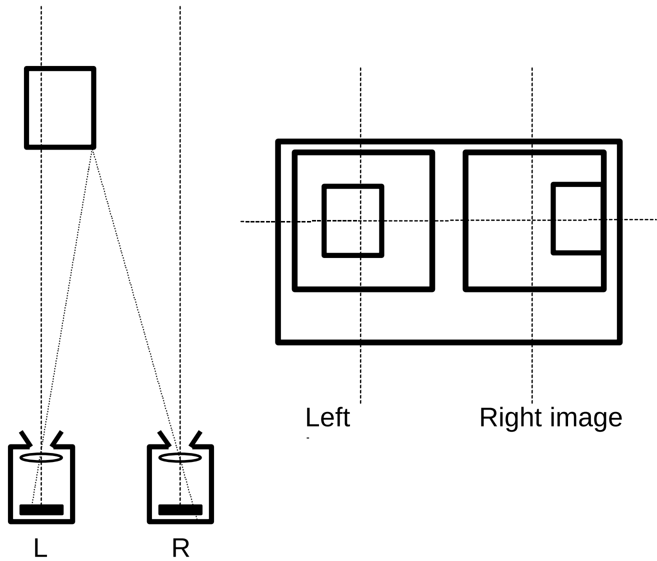


Fig. 4. *Principle of the optical stereoscopic tracking-system*

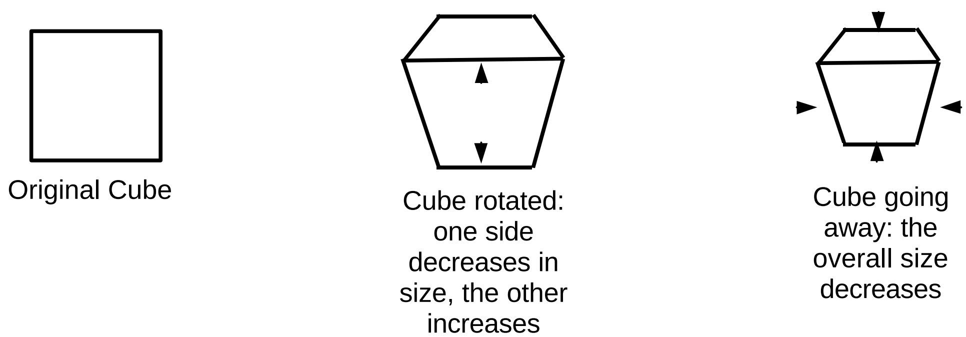


Fig. 5. *Pattern recognition method. The 3D shape of the features of the cube is known and the image analysis allows reconstructing position and orientation.*

Pattern recognition uses one camera and a known geometrical arrangement (pattern) of a set of features on a target (Gennery, 1992; Horn, 1987). The recorded 2D pattern on the image is a function of the position and orientation of the target. For example, considering a cube structure originally placed perpendicularly to the visual axis, the slant of the cube can be detected by the size of one side compared to the other, as shown in Fig. 5. If the cube is moved further away from the camera, the overall size is reduced. The combination of these analyses can be used to calculate the orientation and position of the cube. In this example, the tracking system constitutes an orientation and position finder (6 DOFs).

Pattern recognition is also used to reconstruct the motion characteristics of the human body (Simon et al., 1993; Barret et al., 1994; Regh and Kanade, 1994). To this end, numerous algorithms have been developed most often without use of landmarks or sensors on the target. If no landmark is used, this method needs complex algorithms to recover the position and orientation from the image of the object. To reduce the processing time, these algorithms can be implemented in electronic circuitry (Okere, 1995) or as artificial neural networks (ANN) rather than in software (Chan, 1992; Colla, 1995).

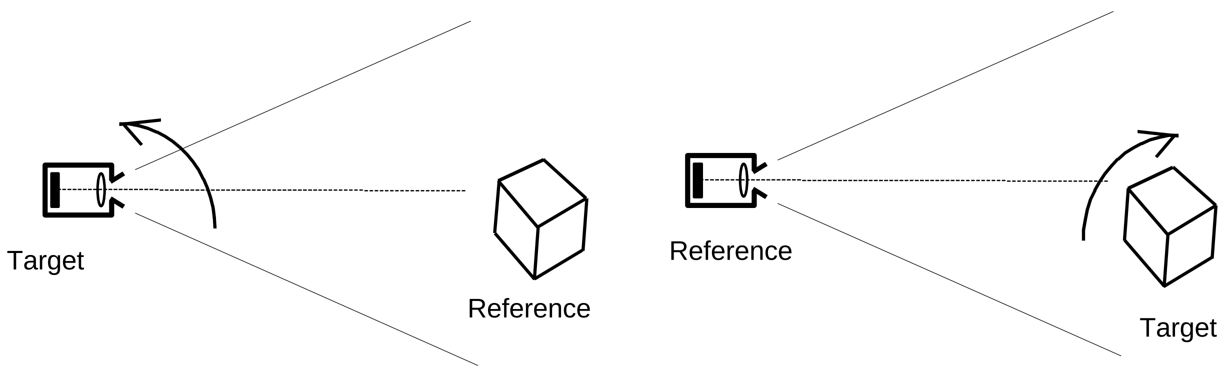
Another approach to pattern recognition is forming a regular pattern in space by mean of some optical effect. The pattern is projected on the tracked objects and imaged by the camera. The shape of an object can be determined by analysis of the projected pattern. There are two ways of producing regular patterns of light in space. A first method is to produce the interference between two or more laser beams (Dewiee, 1989). The strong points of this method are the opportunity to produce fringes with a very small spatial period and an equal spacing between the fringes in the region where the beams overlap. The smallest possible period is half the wavelength when two interfering beams go in opposite direction forming as a result a standing optical wave. There are several disadvantages to producing a spatial pattern by interference. The first disadvantage is that the region where the beams overlap is small, making it difficult to track objects in large environments. The second problem is that of forming a pattern with specific geometry.

A second method is to employ a diffracted beam created by a grating. In this case, the shape of an object can be extracted by analyzing the spacing between the fringes of the diffraction pattern superimposed on the object (Chavel and Strand, 1984). The advantages of this method are the simplicity in forming a spatial pattern of arbitrary geometry using Fourier optics approaches, no restrictions on the size of the environment to be tracked, and the simplicity of the setup. The disadvantage of this scheme is the limited resolution obtained. While these methods are typically used for 3D shape extraction from a 2D view, Harding (1983) demonstrated that it could be used for motion tracking. We therefore postulate that it could be potentially extended to tracking human motion as well.

Table 2. *Summary table of the characteristics of outside-in optical trackers.*

Physical phenomenon	Projection of an optical pattern
Measured variable	Shape of target features in an image acquired via a camera. Position and orientation for most of the applications.
Degrees of freedom (d.o.f)	Position finder for each feature (3 d.o.f). Orientation and position finder if feature geometry is known (6 d.o.f).
Accuracy	0.1-0.45 mm / 1/2800 of cameras field of view / 2-15 mrad
Resolution	1/1000 to 1/65536 of cameras field of view / 0.01 to 0.1 mm
Update rate	50-400 Hz
Lag	Can be significant depending on the processing done.
Range / Total Orientation Span	Up to 6000 mm / 8.8 to 27 degrees
Advantages	Good update rate
Limitations	Sensitive to optical noise, spurious light, ambiguity of surface and occlusion
Examples	Sirah TC242 from Micromaine, CAE system (CAE Electronics, 1991), Optotrack from Northern Digital, LED array or pattern for Helmet tracking from Honeywell, Selspot tracker from SELCOM, Elite from BTS, Multitrak from Simulis OrthoTRACK and Expert Vision from Motion Analysis Corporation,Vicon 370E from Oxford Metrics, CoSTEL (Cappozzo, 1983), pattern recognition methods.

3.2 INSIDE-OUT



***Inside-out configuration:** The rotation of the camera, held by the target in this case, produces a large motion of the image of the cube on the CCD camera.*

***Outside-in configuration**: The rotation of the cube, the target in this case, produces a small motion of the image on the CCD camera.*

Fig. 6. *The outside-in and inside-out configuration*

In an inside-out configuration, the sensor is on the target and the emitters are on the reference as shown in Fig. 6. We distinguish between two techniques: one based on 2D projection of image features, referred to as videometric, and one based on sweep-beam angles, referred to as beam scanning. The videometric technique uses optical sensors (e.g. CCDs) placed on the target (e.g. head of the user), whereas the beam scanning system uses rotating beams emitted from the reference and detected by the sensors located on the target. While it is not necessarily trivial, it can be noted that both techniques rely on scanning principles. The videometric technique scans the CCD detector of a camera, whereas the rotating beam technique uses rotating mirrors to scan the working volume. Both techniques are able to measure position and orientation if the system is equipped with a sufficient number of sensors and features.

The inside-out configuration typically yields higher resolution and accuracy in orientation than the outside-in. The same rotation of a target around a point (e.g. the head of a user rotating around the neck) will produce more displacement on the CCD sensor in an inside-out than in an outside-in configuration. This can be explained by noting that the ratio of the radius of the trajectory of the features being tracked following either rotation of the target or rotation of the camera is smaller in the outside-in than in the inside-out configuration. This is illustrated in Fig. 6. In spite of their classification as inside-out configurations, systems based on beam scanning techniques do not share this advantage.

3.2.1 VIDEOMETRIC

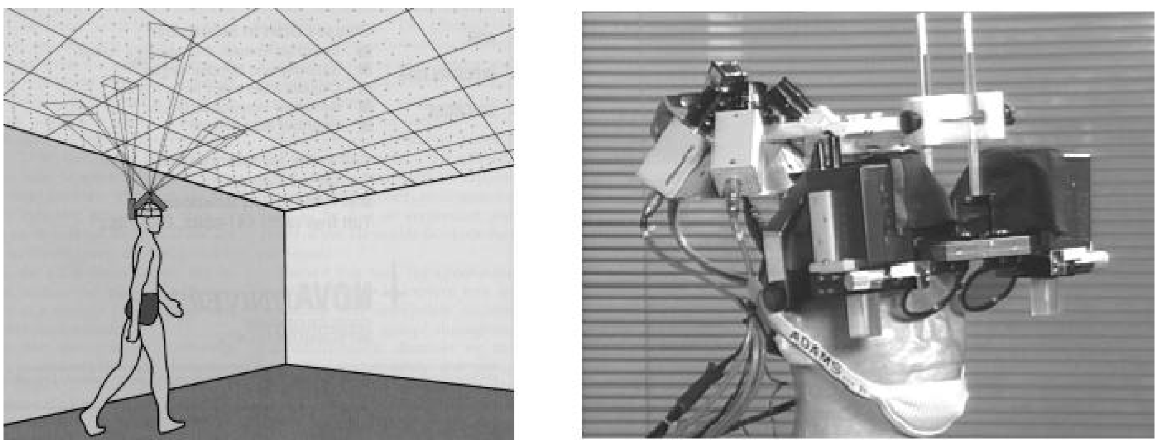


Fig. 7. *Inside-out configuration: Opto-ceiling tracking system at the Department of Computer Science at the University of North Carolina at Chapel Hill. On the left, the working principle of the tracker is shown with the fields of view of four cameras. On the right, a head-mounted display equipped with the tracking device is shown.*

The videometric technique shown in Fig. 7 employs several cameras placed on a target (e.g. the head of a user). The reference has a pattern of features (e.g. the ceiling panels) whose locations in 3D space are known. The cameras acquire different views of this pattern. The 2D projections of the pattern on the sensor can be used to define a vector going from the sensor to a specific feature on the pattern. The position and orientation of the target is computed from at least three vectors constructed from the sensor(s) to the features. The system shown in Fig. 7 has been built with four cameras located on an helmet-mounted display (target) and a ceiling (reference) covered with infrared LED sequentially fired. One camera could have been used but redundant measures improves tracking and multiple cameras allow a larger range of motion, constantly keeping the reference (ceiling) in view. A mathematical technique called “space resection by colinearity” is used to recover the position and the orientation of a target (Azuma and Ward, 1991). This tracking system has the advantage of being conveniently scaleable by adding ceiling panels. The cost of such a system becomes significant for a medium to a large volume because of the requirement that the panels be accurately positioned.

3.2.2 BEAM SCANNING

This technique uses scanning optical beams on a reference. Sensors located on the target detect the time of sweep of the beams on their surface. The time variable is transformed into a variable (e.g. angle) for extracting the position and the orientation of the target. Given a known location of the helmet, the Honeywell helmet-tracking method computes the angle of the beam on the sensor from the time of sweep (Ferrin, 1991). Fig. 8 illustrates this principle for two beams and two sensors. In this case only azimuth and elevation of the target can be measured. In more complex configurations where several emitters and sensors are used, the 3D position and orientation of the target can be computed by triangulation from the angle measurements. The Minnesota scanner tracking method employs a scanning laser beam to compute the distance between fixed sensors attached to the structure of the scanner and sensors attached to the user. The distance is computed by counting the elapsed time between the two sensors during a sweeping cycle (Cappozzo, 1983; Sorensen et al., 1989).

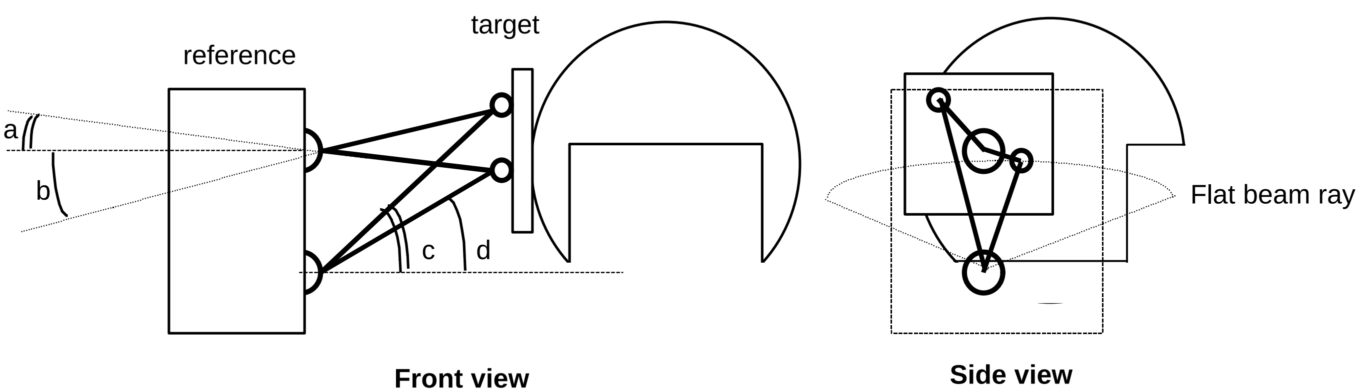


Fig. 8 *Inside-out configuration: Structure of a beam scanning tracking system used for the determination of pilots’ head-orientation in airplane cockpits (Honeywell).*

The scanning-beam technique, while an inside-out configuration, does not share the advantage of the videometric system that provides a higher accuracy and resolution in orientation of a target. Given that the receivers are on the target, which makes it an inside-out configuration, the scanning of the working volume is done from the reference. Paradoxically, we show in Fig. 9 that such a configuration can be likened to an outside-in configuration where a camera is attached to the reference and scans the scene.

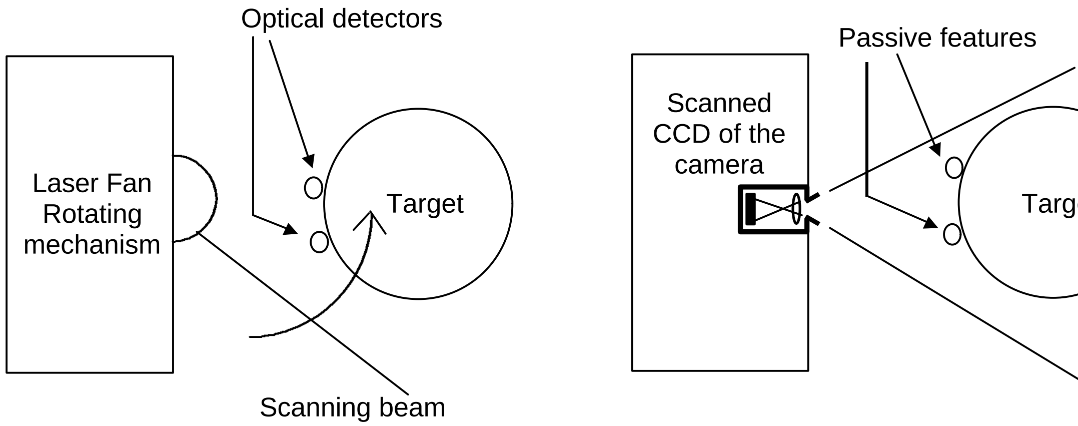


Fig. 9 *Similarity between the inside-out beam scanning (left) and the outside-in videometric (right) configurations.*

Table 3. *Summary table of the characteristics of inside-out trackers.*

Physical phenomenon	Spatial scan
Measured variable	Beam position or sweep detection
Degrees of freedom	Position and orientation
Accuracy	2-25 mrad
Resolution	Diminishes with the range of operation
Update rate	Unknown
Lag	Unknown
Range	In principle, scalability is unlimited for the UNC tracker
Advantages	Better resolution than outside-in systems, scalability
Limitations	Occlusion sensitive
Examples	OptoCeiling from UNC at Chapel Hill, Honeywell helmet rotating infrared beam system (Ferrin, 1991), LC Technology rotating mirror system (Starks, 1991), Minnesota Scanner (Cappozzo, 1983; Sorensen & al., 1989), CODA (Miller, 1987), Self-tracker project (Bishop, 1984).

4 INERTIAL SENSING

The principle of inertial sensing is based on the attempt to conserve either a given axis of rotation as in the case of a mechanical gyroscope or a position as in the case of an accelerometer.

4.1 MECHANICAL GYROSCOPE

A mechanical gyroscope, in its simplest form, is a system based on the principle of conservation of the angular momentum that states that an object rotated at high angular speed in the absence of external moments, conserves its angular momentum . The wheel is mounted on a frame so that the external moments (i.e. due to friction) are minimized . This allows the target to turn around the wheel without experiencing a change in the direction of its axis, as illustrated in Fig. 10. The orientation of the target can be computed from the angles reported by rotational encoders mounted on the frame. The working principle of encoders is given in Appendix A. Each gyroscope gives us one reference axis in space. At least two gyroscopes are needed to find the orientation of an object in space.

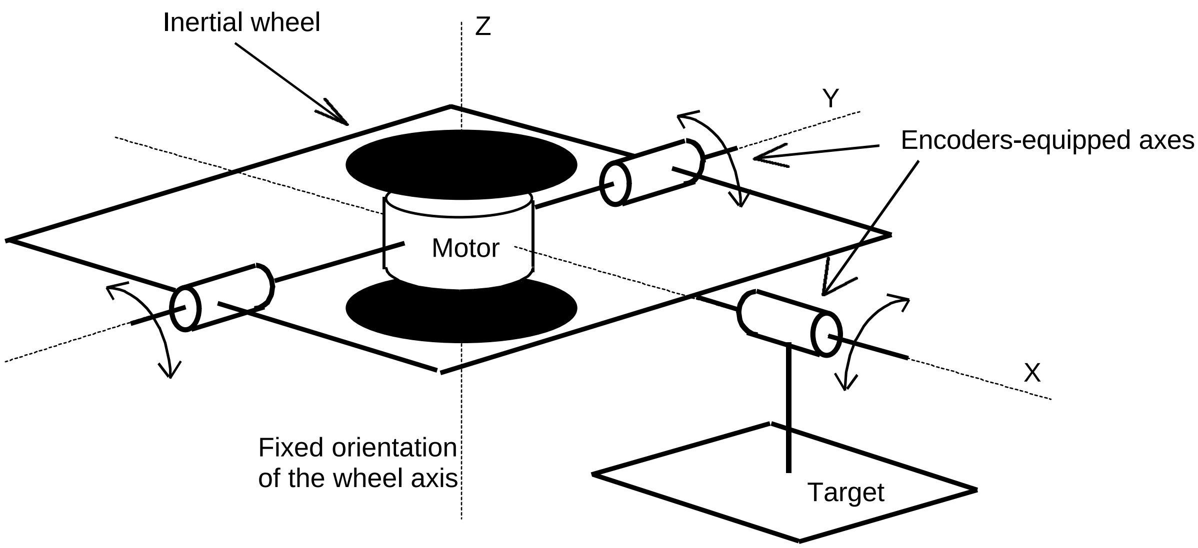


Fig. 10 *Structure of a mechanical gyroscope.*

A main advantage of this tracking system is that it does not require an external reference to work. The axis of the rotating wheel is the reference. The main problem of gyroscopes, however, is that the inertial momentum of the wheel does not remain parallel to the axis of rotation because of remaining small friction between the axis of the wheel and the bearing. This causes a drift in the direction of the wheel axis with time. Taking relative measurements of the orientation rather than absolute measurements can minimize this drift. As a consequence, the system suffers from accumulated numerical errors but a periodic re-calibration of the system will insure, more accuracy over time.

Table 4. *Summary table of the characteristics of mechanical gyroscopes.*

Physical phenomenon	Inertia
Measured variable	Orientation between the axis of rotation of the wheel and an axis attached to the target
Degrees of freedom	Orientation finder (1 to 3 DOFs)
Accuracy	0.2 degree, static drift 0.01 deg/s, dynamic drift 0.25 deg/s
Resolution	0.032 degree
Update rate	50 Hz
Lag	Unknown
Total Orientation Span	132 degrees in yaw, 360 degrees in roll.
Advantages	No reference needed
Limitations	Error increases with time since measurements are relative to previous ones leading to drift of the axis with time.
Examples	Gyrotrac2 and Gyrotrac3 from VR systems, Gyropoint from Gyration.

4.2 ACCELEROMETER

An accelerometer measures the linear acceleration of an object to which it is attached. An accelerometer can be specified as a single-degree-of-freedom device, which has some kind of mass, a spring like supporting system, and a frame structure with damping properties. It may rely for example on a mass mounted on a piezo-electric crystal and attached to the target as shown in Fig. 11. In this case, the motion of the target produces a pressure on the crystal because of the inertia of the mass. The resulting force, proportional to the acceleration, can be evaluated by measuring the voltage appearing on the sides of the piezo-electric crystal. The double integration in time of the acceleration yields the position, assuming that the initial conditions of the target (position and speed) are known. This sensor is lightweight and is reference free. Accelerometers are position finders having one degree of freedom and come in many forms including capacitive, nulling, piezo-resistive, and thermal accelerometers.

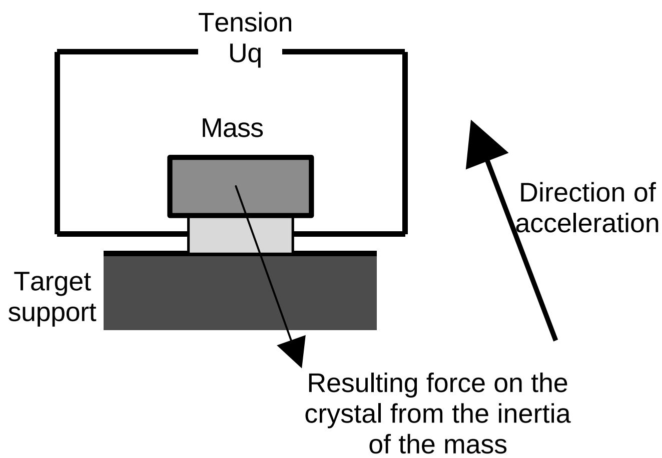


Fig. 11. *Structure of an accelerometer*.

Table 5. *Summary table of the characteristics of accelerometers.*

Physical phenomenon	Mass inertia
Measured variable	Depends on implementation.
Degree of freedom	Position along one axis only (1 DOF)
Accuracy	Unknown
Resolution	Unknown
Update rate	Depends on the processing time to integrate two times
Lag	Depends on the processing time to integrate two times
Range	Unlimited
Advantages	No reference needed; light
Limitations	Errors in position due to integration
Examples	Unknown

5 MECHANICAL LINKAGES

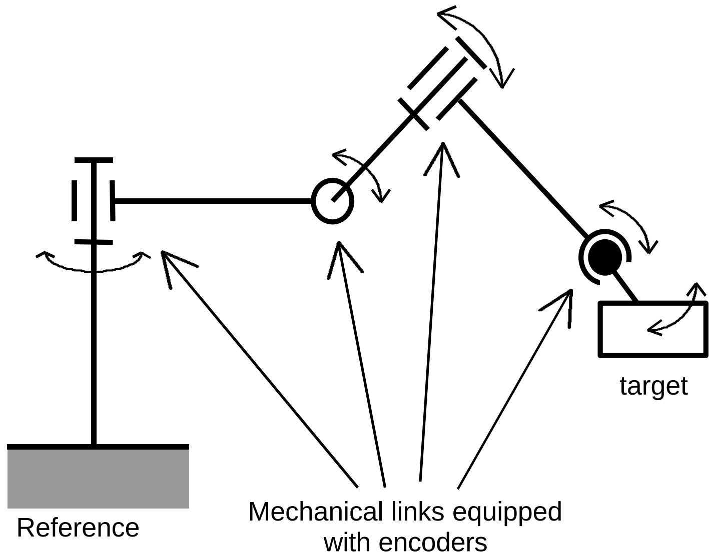


Fig. 12. *Structure of a typical mechanically linked tracking system.*

This type of tracking system uses mechanical linkages between the reference and the target (Jau, 1991). Two types of linkages have been used. One is an assembly of mechanical parts that can each rotate providing the user with multiple rotation capabilities, as shown in Fig. 12. The orientation of the linkages is computed from the various linkages angles measured with incremental encoders or potentiometers. Other types of mechanical linkages are wires that are rolled on coils. A spring system ensures that the wires are tensed in order to measure the distance accurately. The degrees of freedom sensed by mechanical linkage trackers are dependent upon the constitution of the tracker mechanical structure. While six degrees of freedom are most often provided, typically only a limited range of motions is possible because of the kinematics of the joints and the length of each link. Also, the weight and the deformation of the structure increase with the distance of the target from the reference and impose a limit on the working volume. Mechanical linkage trackers have found successful implementations among others in force-feedback systems used to make the virtual experience more interactive (Brooks et al., 1990; Massie, 1993).

Table 6. *Summary table of the characteristics of mechanical linkages trackers*

Physical phenomenon	Mechanical linkages
Measured variable	Angle measured by rotating encoder(s)
Degrees of freedom	Position and orientation (Up to 6 DOFs)
Accuracy	0.1-2.5 mm
Resolution	0.05-1.5 mm / 0.15-1 degree
Update rate	Depends on data aqusition capabilities. (about 300 Hz)
Lag	3 ms
Range / Total Orientation Span	1.8m / 40 degrees ; Limited by the weight and deformation of the mechanical structure with distance from reference.
Advantages	Good accuracy, precision, update rate, and lag. No environmental linked error.
Limitations	Encoder resolution, limitation of motion.
Examples	FaroArm(1), Phantom(1), Spidar(2), Anthropomorphic Remote Manipulator from NASA (Jau, 1991), Argonne Remote Manipulator (ARM), Fake Space Binocular Omni-Oriented Monitor (BOOM), GE Handyman Manipulator, MITI position tracker, Noll Box, Rediffusion ADL-1 (Shooting Star Technology), Wrightrac(Magellan Marketing), PROBE-IC and PROBE-IX (Immersion Human Interface), Sutherland Head Mounted Display project, University of Tsukuba Master Manipulator. Spidar II (wire tracker) (Hirata and Sato, 1995)

6 PHASE-DIFFERENCE

Phase-difference systems measure the relative phase of an incoming signal from a target and a comparison signal of the same frequency located on the reference. As in the TOF approach, the system is equipped with three emitters on the target and three receivers on the reference, as shown in Fig. 13. Ivan Sutherland's head tracking system, built at the dawn of time when it comes to virtual reality, explored the use of an ultrasonic phase-difference head tracking system and reported preliminary results (Sutherland, 1968). In Sutherland's system, each emitter sent a continuous sound wave at a specific frequency. All the receivers detected the signal simultaneously. For each receiver, the signal phase was compared to that of the reference signal. A displacement of the target from one measure to another produced a modification of the phases that indicated the relative motion of the emitters with respect to the receivers. After three emitters had been localized, the orientation and position of the target could be calculated. It is important to note that the maximum motion possible between two measurements is limited by the wavelength of the signal. Current systems use solely ultrasonic waves that typically limit the relative range of motion between two measurements to 8 mm. Future systems may include phase-difference measurements of optical waves as a natural extension of the principle that may find best application in hybrid systems. Because it is not possible to measure the phase of light waves directly, interferometric techniques can be employed to this end. The relative range of motion between two measurements will be limited to be less than the wavelength of light unless the ambiguity is eliminated using hybrid technology.

The main disadvantage of phase-difference ultrasonic trackers is their vulnerability to cumulative errors in the measurement process. Other limitations are their sensitivities to environmental conditions (e.g. sensitivity to temperature, pressure, humidity, and ultrasonic noise), and multiple reflections in the environment. Finally, trackers based on phase-difference measurements are limited to relative motion measurements. They will need to be associated with another measuring scheme if absolute measurements are necessary. Such a scheme will also limit cumulative errors obtained from sole relative measures.

A main advantage of phase-difference trackers is their ability to generate high data rates because the phase can be measured continuously. It is then possible to use filtering to overcome environmental perturbations. As a result, accuracy and resolution are improved compared TOF ultrasonic trackers.

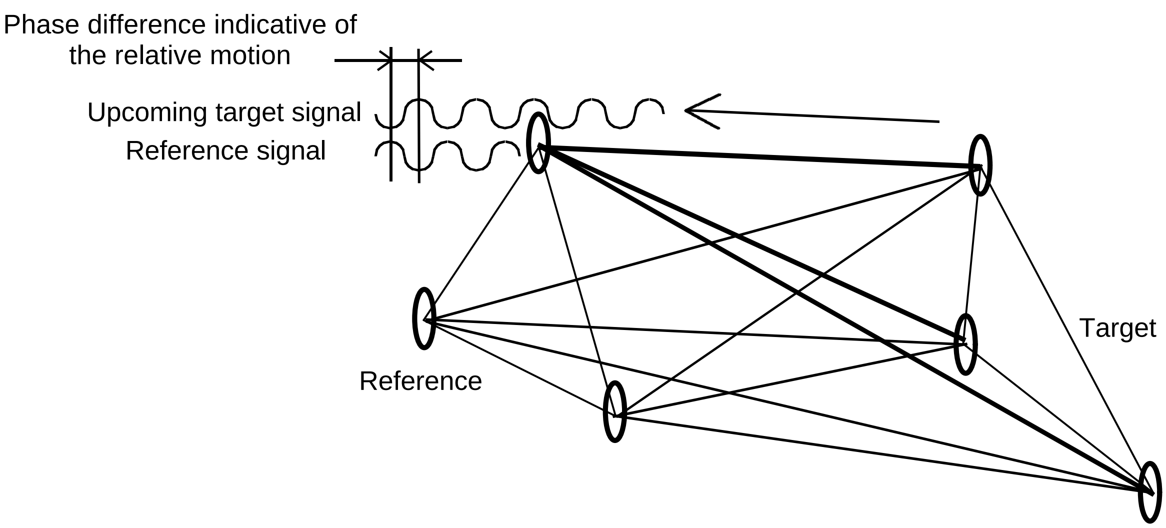


Fig. 13. *Working principle of phase coherent tracking system.*

Table 7. *Summary table of the characteristics of phase-difference trackers.*

Physical phenomenon	Phase difference sensing (e.g. ultrasonic, optical)
Measured variable	Phase difference
Degrees of freedom	Orientation and position (6 DOFs)
Accuracy	Unknown
Resolution	0.1mm, 0.1 degree, 1/32 of the maximum range
Update rate	Independent of the range of operation
Lag	Independent of the range of operation
Range	Unknown
Advantages	Less sensitive to noise than TOF systems, high data rate
Limitations	Error increases in time since relative measurements. Sensitive to occlusion. Possible ambiguity in reported measures
Examples	Sutherland-Seitz-Pezaris head mounted display position tracker (Sutherland, 1968).

7 DIRECT-FIELD SENSING
7.1 MAGNETIC FIELD SENSING

By circulating an electric current in a coil, a magnetic field is generated in the coil (Potter, 1967). The field at some distance r has the following polar components B_r (along the radial direction) and B_θ (perpendicular to the radial direction) represented in Fig. 14. If a receiver (some magnetic field sensor) is placed in the vicinity, the field induces a flux in the receiver. This is referred to as magnetic coupling between the emitting coil and the receiver. The sensor output resulting from the induced flux can then be measured (Souders, 1966). The flux in the vicinity of the receiver is a function of the distance of the receiver from the coil and of its orientation relative to the coil.

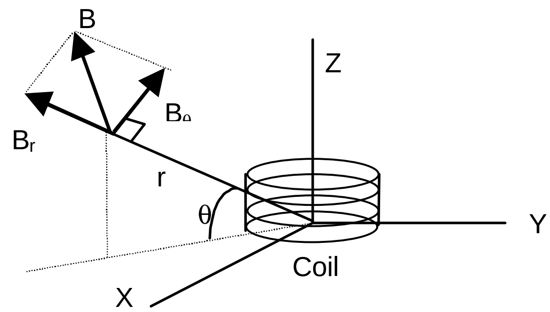


Fig. 14 *Radiating electromagnetic field components.*

To measure position and orientation of a receiver in space, the emitter must be composed of three coils placed perpendicular to each other, thus defining a spatial referential from which a magnetic field can exit in any direction. The direction is given by the resultant of three elementary orthogonal directions. On the receiver, three sensors measure the components of the field's flux received as a consequence of magnetic coupling. Based on these measures, the system determines the position and orientation of the receiver with respect to the emitter attached to the reference (Raab, 1977; Raab, 1979). It is typically required that r>>R and r>>L, where r is the distance of the receiver from the coil, and R and L are the radius and the length of the coil, respectively as shown in Fig. 14.

As stated, the position and the orientation of a receiver could be achieved simply by emitting a field along each coil of the emitting unity, but it is found with this approach, that it is difficult to solve for the position and the orientation. A practical solution actually involves the emission of three orthogonal fields: one in the estimated direction of the target and two others in the orthogonal directions (Raab, 1979).

Because magnetic trackers are inexpensive, light weight, and compact, they are widely used in virtual environments. The working volume is limited by the attenuation of the signal with the distance. However, the field cannot be increased indefinitely in order to improve the working volume because the effects of significant electromagnetic fields on humans are not completely discovered. The update rate may be limited if filtering is applied to smooth the received signals. A trade-off must be made between the working volume, the accuracy and resolution, and the update rate.

7.1.1 SINUSOIDAL ALTERNATING CURRENT (AC)

This type of magnetic tracker is based on alternating the current feeding the emitting coils. This produces a changing magnetic field (Polhemus, 1972). The current induced by the changing field in each of three receiving coils is proportional to the product of the amplitude of the magnetic flux and the frequency of the field oscillations. A problem with this system is the generation of Eddy currents in the vicinity of metallic objects that create an opposite field distorting the emitted magnetic field (Bryson, 1992) and possibly leading to tracking errors. The variation in amplitude of the signal is what produces Eddy currents by induction in metal sheets (Souders, 1966). However, if the metallic objects are static, a lookup table can be in principle pre-computed to account for the distortions.

Table 8. *Summary table of the characteristics of alternating current magnetic trackers.*

Physical phenomenon	Magnetic coupling of two coils one of which is fed with sinusoidal alternating current
Measured variable	Amplitude at the output of the receiving coil
Degrees of freedom	Orientation and position (6 DOFs)
Accuracy	0.8 mm to 25 mm (75mm at 5m) / 0.15 to 3 degrees
Resolution	0.04 mm to 0.8 / 0.025 to 0.1 degree
Update rate	15-120 Hz divided by the number of emitters
Lag	4-20 ms
Range / Total Orientation Span	up to 5000 mm / 360 degrees
Advantages	No occlusion problem, high update rate, low lag, inexpensive, small.
Limitations	Small working volume, distortion of accuracy with distance, sensitive to electromagnetic noise in the 8-1000Hz range and metallic objects
Examples	Fastrack, Isotrack, Insidetrack and Ultratrack from Polhemus (Polhemus, 1972), Honeywell, Rediffusion Zeis, Ferranti, Israeli government.

7.1.2 PULSED DIRECT CURRENT (DC)

In contrast to the previously described system, this system uses a pulsed constant current to excite the sensors. The receiver is composed of sensors capable of detecting a constant magnetic flux such as magnetrons (Ascension, 1991). During the raising front of the pulse, Eddy currents are generated as in the AC systems. However, a DC system would wait until these currents die out to take a measurement so that the distortions by Eddy currents would be eliminated. Actually one would have to wait an infinitely long time for Eddy currents to fully vanish therefore the DC systems wait the longest possible time determined by the acquisition rate of tracking before making a measurement. For instance, to make one measurement of magnetic flux per second, the DC system produces the following sequence: at t equal 0 a DC magnetic field is induced. Next, the system waits 999 ms, the longest time allowed by the acquisition rate. Finally at t equal 1 sec. the DC system measures the magnetic field. The pulsed DC method reduces significantly the influence of Eddy currents on the accuracy of measurements. A problem with this type of trackers is the distortion of the magnetic field by Ferro-magnetic objects and other sources of electromagnetic fields such as computer monitors. A calibration procedure at startup of the system should measure the magnetic field bias produced by both the Earth's electromagnetic field and other sources to optimize the system performance.

Table 9. *Summary table of the characteristics of pulsed direct current magnetic trackers.*

Physical phenomenon	Magnetic coupling
Measured variable	Amplitude in output of the receiving sensor
Degrees of freedom	Orientation and position (6 DOFs)
Accuracy	2.5 mm / 0.1-0.5 degree
Resolution	0.8 mm / 0.1 degree
Update rate	144 Hz
Lag	22 ms
Range	600-2400 mm radius of radiating magnetic sphere
Advantages	No occlusion problem, small, high update rate, low lag, inexpensive
Limitations	Small working volume, accuracy degraded with distance, sensitive to electromagnetic noise in the 8-1000Hz range and ferromagnetic objects
Examples	Ascension Bird, Big Bird and Flock of Birds (Ascension, 1972 & 1991).

7.1.3 MAGNETOMETER / COMPAS

Magnetometers measure the orientation of an object with respect to the magnetic field of the earth. Magnetic field sensors include fluxgate, Hall effect, magneto-resistive, and magneto-inductive sensors (Fraden, 1997). The most relevant magnetometers use magneto-inductive sensors. Such sensors operate, for example, on the change in inductance of a coil in the presence of an external magnetic field component parallel to the axis of coil. If the coil is used in a L/R oscillator, the output frequency of the oscillator changes. The change in frequency allows determination of the strength of the magnetic field. With three sensors, the orientation of an object with respect to the magnetic field can be determined. The other angular degrees of freedom are measured by other means for instance by inclinometers. One problem with this technology is that the Earth's electromagnetic field is inhomogeneous and yields angular errors in the orientation measurements. As noted in previous methods, relative measurements can be implemented to compensate for these errors. This technique works well if between two measurements the field is quasi-constant. Naturally, such technology is sensitive to disturbances in the ambient magnetic field. Precision Navigation uses compass for example in their product TCMVR50.

Table 10. *Summary table of the characteristics of magnetometers.*

Physical phenomenon	Magnetic field sensing
Measured variable	Depends on implementation
Degrees of freedom	Position following one direction (1 DOF)
Accuracy	1-3 degrees
Resolution	Unknown
Update rate	Unknown
Lag	Unknown
Range	Unknown
Advantages	No reference needed
Limitations	Unknown
Examples	Component of Precision Navigation (TCMVR50)

7.2 GRAVITATIONAL FIELD SENSING

An inclinometer operates on the principle of a pendulum. Common implementations use electrolytic or capacitive sensing of fluids. A simple implementation may measure the relative level of fluids in two branches of a tube to compute inclination. A common implementation measures the capacitance of a component being changed based on the level of fluid in the capacitor. Another, perhaps less common implementation is that of an optical inclinometer shown in Fig. 15. A viscous and opaque liquid is placed between two optical vertical panels (Fuchs, 1996). One of the panels produces uniform light that is received by the other panel on a linear array of photosensitive detectors. The viscous liquid surface keeps its perpendicular orientation with respect to the earth's gravitational field, and a number of photosensitive detectors are lighted while others are prevented from receiving light because of the opacity of the liquid. This number indicates the orientation of the liquid, therefore of the gravitational field with respect to the target, making it a one-degree-of-freedom orientation finder. We postulate that the problem with this sensor is the slow reaction time imposed by the viscosity of the liquid. The vibration and acceleration of the sensor also will affect the measurements.

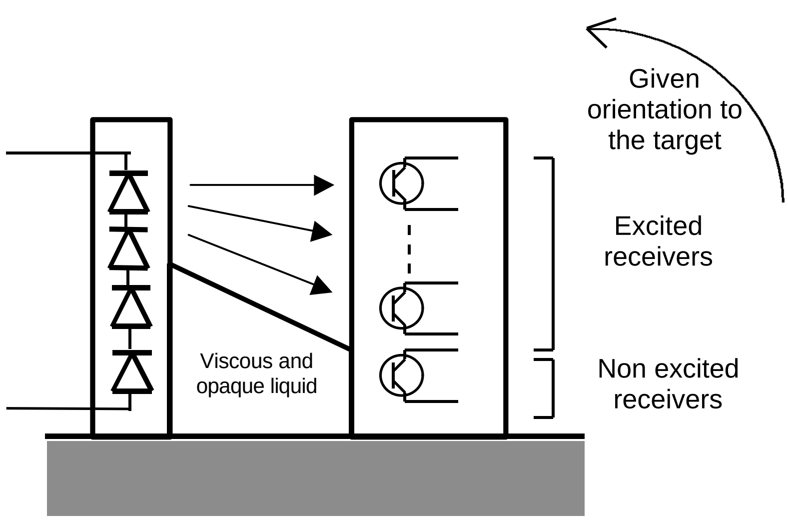


Fig. 15. *Principle of operation and structure of an optical inclinometer.*

Table 11. *Summary table of the characteristics of inclinometers.*

Physical phenomenon	Gravitational field sensing
Measured variable	relative heights; capacitance
Degrees of freedom	Orientation following one direction (1 DOF)
Accuracy	Repeatability of 0.5 degree
Resolution	Unknown
Update rate	Unknown
Lag	Unknown
Total Orientation Span	150 degrees
Advantages	No reference needed
Limitations	Reaction time degraded by viscosity of liquid
Examples	EX-TILT 2000 from AOSI

8 HYBRID SYSTEMS

Hybrid technology refers to the combination of various technologies (e.g. optical and mechanical). We would like to extend that definition to include also systems based on different principles of operation such as time of flight measurements versus phase difference measurements. While hybrid technologies increase the complexity of a tracking system and likely its cost, they are adopted either to access variables that one technology cannot easily provide (relative and absolute measurements), or to make exhaustive measurements. In the latter case, when associated with filtering and predictive techniques, sensor fusion techniques are used to associate incomplete data sets coming from different sensor types. Five examples of hybrid systems are presented to illustrate how hybrid systems may be built: inertial, inside-out/inertial, magnetic/videometric, and two TOF/mechanical linkages/videometric systems. It is beyond the scope of this paper to present a comprehensive review of all hybrid systems that have possibly been conceived.

8.1 HYBRID INERTIAL PLATFORMS

We shall present two hybrid inertial platforms. The first platform is composed of three accelerometers and three gyroscopes mounted on a target. The accelerometers measure the acceleration of the target along three independent perpendicular axes and the gyroscopes measure the orientation of the target along the same axes. Gyrometers could be used instead of gyroscopes to access the angular velocity rather than the orientation. By integration of angular velocity, orientation can be estimated. Similarly, the double integration of the measured accelerations leads to the spatial position. The main limitation of gyroscopes is drift. The main limitation of accelerometers is the integration process that leads to additional errors.

The second platform relies on three accelerometers and two inclinometers and a magnetometer. As seen earlier, a magnetometer can determine the physical North direction, thus measuring the orientation of a target along the Y-axis (Yaw). Inclinometers placed on the X- and Z-axes can provide the orientation of a target along these axes as well. These platforms without sources on a reference constitute six degrees of freedom self-trackers that are compact and light weight (Foxlin, 1996).

Table 12. *Summary table of the hybrid inertial platforms characteristics*

Physical phenomenon	Direct field sensing and inertia
Measured variables	Depends on implementation
Degrees of freedom	Orientation and position finder (6 degrees of freedom)
Accuracy	Unknown
Resolution	10 ug in acceleration, 0.002 degree in rotation
Update rate	Unknown
Lag	Unknown
Range	Up to 10 g for acceleration, 500 deg/s in rotation
Advantages	Compact and no reference needed.
Limitations	Unknown
Examples	Motion Pack from Systron-Donner

8.2 INSIDE-OUT / INERTIAL

Azuma proposed such a system as part of his doctoral thesis to improve the inside-out optical tracking system at UNC (Azuma, 1995). The improvement relied on using Kalman filtering to predict head motion. The filter inputs were the outputs of an inertial platform added to the head-mounted display. A standard Kalman filter was used for the prediction of head position while an Extended Kalman Filter was used for orientation to handle the non linearity of the quaternions used to represent orientation. The inertial sensor included three angular rate gyroscopes (i.e. gyrometers) and three linear accelerometers. The three gyrometers performed measures of a user's head angular velocities around three orthogonal axes. The linear accelerometers conducted measures of the head linear acceleration along the same axes. Azuma reported that this technique helped greatly removing what is known as the swimming of virtual images. Registration still remained a challenge. Azuma further showed improvements in the use of this technology by a factor of 5 to 10 compared to techniques using no prediction tracking and by a factor of 2 to 3 compared to techniques with no inertial sensors. This platform allowed the resolution of small fast movements in a shorter time than the original configuration would have allowed.

Table 13. *Summary table of advantages and disadvantages of Inside-out / Inertial hybrid systems.*

	Inside-out	Inertial	Hybrid
Characteristics / Advantages	Measures orientation and position, accurate.	Compact, no occlusion problems give stable solution for orientation and position predictions and small lag when output filtered by Kalman predictor.	Compact, accurate, Small lag, stable.
Limitations	Unstable, resolution may degrade with distance (implementation dependent), occlusions sensitive, processing lag.	Long term drift of the orientation.	Occlusion sensitive.

8.3 MAGNETIC / VIDEOMETRIC

This system, developed by State, was composed of a magnetic and an inside-out videometric tracker (State, 1996). The cameras of the videometric tracker as well as the receivers of the magnetic tracker were placed on the target (see Fig. 5). The system was used to measure the position and orientation of the head of a user in a virtual environment with respect to stationary objects in that environment. As a consequence we refer to the head of the user as the target, and the objects in the world as the references. The inside-out videometric system detected dual color-coded landmarks placed on the objects. Two cameras placed on the target were used because the detection of at least three landmarks was necessary to recover the position and orientation of the target.

The magnetic tracking system was used to detect the gross positions and orientations of a target and determine the field of view within which the image processing was to be performed. A global non-linear equation solver and a local least-square minimizer were used to determine the effective field of view. The calibration of the magnetic tracker was performed during a setup procedure according to the parameters given by the videometric system. The magnetic tracker was also used to remove any possible ambiguity in the occurrence of multiple solutions. Finally, it was used to verify that the solution provided by the videometric system was reasonable given instabilities that might have occurred. The system had the robustness of a magnetic tracker and the accuracy of a videometric tracker (State, 1996).

Table 14. *Summary table of the characteristics of videometric / magnetic tracking system.*

Physical phenomenon	Spatial scan and direct field sensing
Measured variables	Image analysis and electromagnetic flux
Degrees of freedom	Position and orientation (6 DOFs)
Accuracy	Unknown
Resolution	Unknown
Update rate	Unknown
Lag	Unknown
Range	Depends on the visibility of the landmarks and the distance from the receiver for the magnetic part
Advantages	Fast, accurate and robust
Limitations	Same as optical and magnetic system
Examples	State system at UNC-CH (State, 1996)

Table 15. *Summary table of the advantages and disadvantages of magnetic / videometric hybrid systems.*

	Pulse direct current (Magnetic)	Videometric	Hybrid
Characteristics / Advantages	Robust, no occlusion sensitivity, inexpensive, fast, measure orientation and position.	Accurate, insensitive to electromagnetic noise and ferromagnetic object, measures orientation and position.	Accurate, robust, insensitive to environment and occlusions, measure position and orientation.
Limitations	Non accurate, sensitive to electromagnetic noise and ferromagnetic objects.	Unstable, sensitive to occlusions, lag due to processing.	Lag due to processing of videometric data.

8.4 TOF / MECHANICAL LINKAGES / VIDEOMETRIC POSITION TRACKER

This hybrid system developed by Maykynen et al. (1992) included a pointing device and a range finder. The pointing device was based on optical technology and was composed of an infrared emitter and a 4Q (four quadra) detector. The infrared light was reflected off a feature on a target to be localized. The 4Q detector actuated a two-axis motorized gimbal that kept the feature being localized at the center of the sensor. The use of a 4Q detector allowed direct control of the motors of the gimbals by using the voltage available at the detector output. The optical axis of the pointing device was coaxial to the beam axis of the rangefinder. The rangefinder method of measurement was based on the principle of time-of-flight of infrared waves. Once the target was aimed, the range-finder measured the distance from the reference to the target by sending an infrared beam to the target equipped of a reflective mirror (e.g. sign paint and cat's eye reflector). Illustration of the principle is shown in Fig. 16. Incremental encoders attached to the axis of the pointing device determined elevation and azimuth. The TOF device determined the distance of the target thus yielding, with the elevation and azimuth measures, the position in space of the target as shown in Fig. 17.

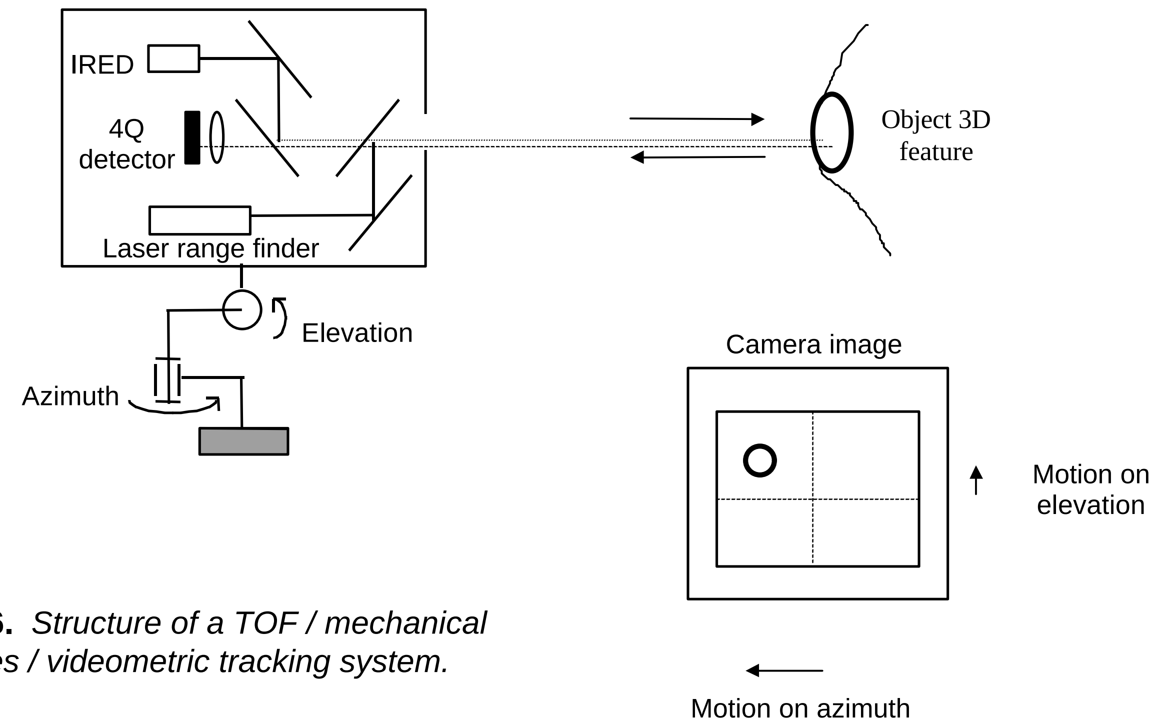


Fig. 16. *Structure of a TOF / mechanical linkages / videometric tracking system.*

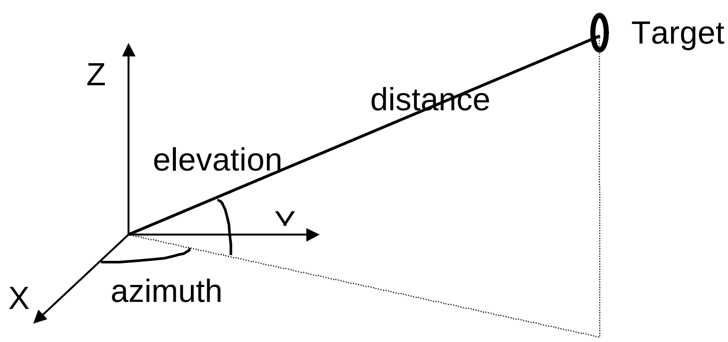


Fig. 17. *Geometrical view of the measurement method of a TOF / mchanical linkages / videometric tracking system.*

The accuracy and resolution of the system relied on the qualities of the motorized parts of the gimbals as well as on the electronics of the TOF-distance conversion. Because the speed of the measuring process was high, numerous measurements could be averaged in order to improve the accuracy of a measure. The ability to only track one feature at a time limits the system. The system has been mostly used for the measurement of large structures in outdoor environments, however we see no fundamental limitation that would prohibit its use for applications perhaps on a smaller scale. High-speed electronics is needed in this case because light passes 30 cm in 1ns, so time of flight measurements must provide nano-scale resolution or higher depending on the accuracy and resolution requirements.

Table 16. *Summary table of the characteristics of TOF / mechanical linkages / videometric system.*

Physical phenomenon	TOF, mechanical linkages, videometric
Measured variables	Time of flight, 2D projection feature, angles
Degrees of freedom	3 DOFs (position in space)
Accuracy	Depends on application
Resolution	Depends on application
Update rate	Unknown
Lag	Unknown
Range	Unknown
Advantages	Long distance measurement
Limitations	Need a reflective surface on the target. Can track one feature at a time
Examples	Large workship measurement apparatus (Makynen, 1994)

Table 17. *Summary table of the advantages and disadvantages of TOF / Videometric hybrid systems.*

	Videometric / Mechanical Linkages pointing	TOF infrared reflective range measurement	Hybrid
Characteristics / Advantages	Pointing accurate, by 4Q detector, line of sight measurement, determine azimuth and elevation.	Fast range measurement, which allows accuracy through averaging, long range, and wireless.	Position measurements, fast, accurate, long range, and wireless.
Limitations	Mechanical gimbal conditions accuracy and precision of azimuth and elevation determination.	Expensive range measurement detector can only be used for a target at a time.	Expensive, track only one target at a time.

8.5 TOF / MECHANICAL LINKAGES/ VIDEOMETRIC 5-DOFS TRACKER

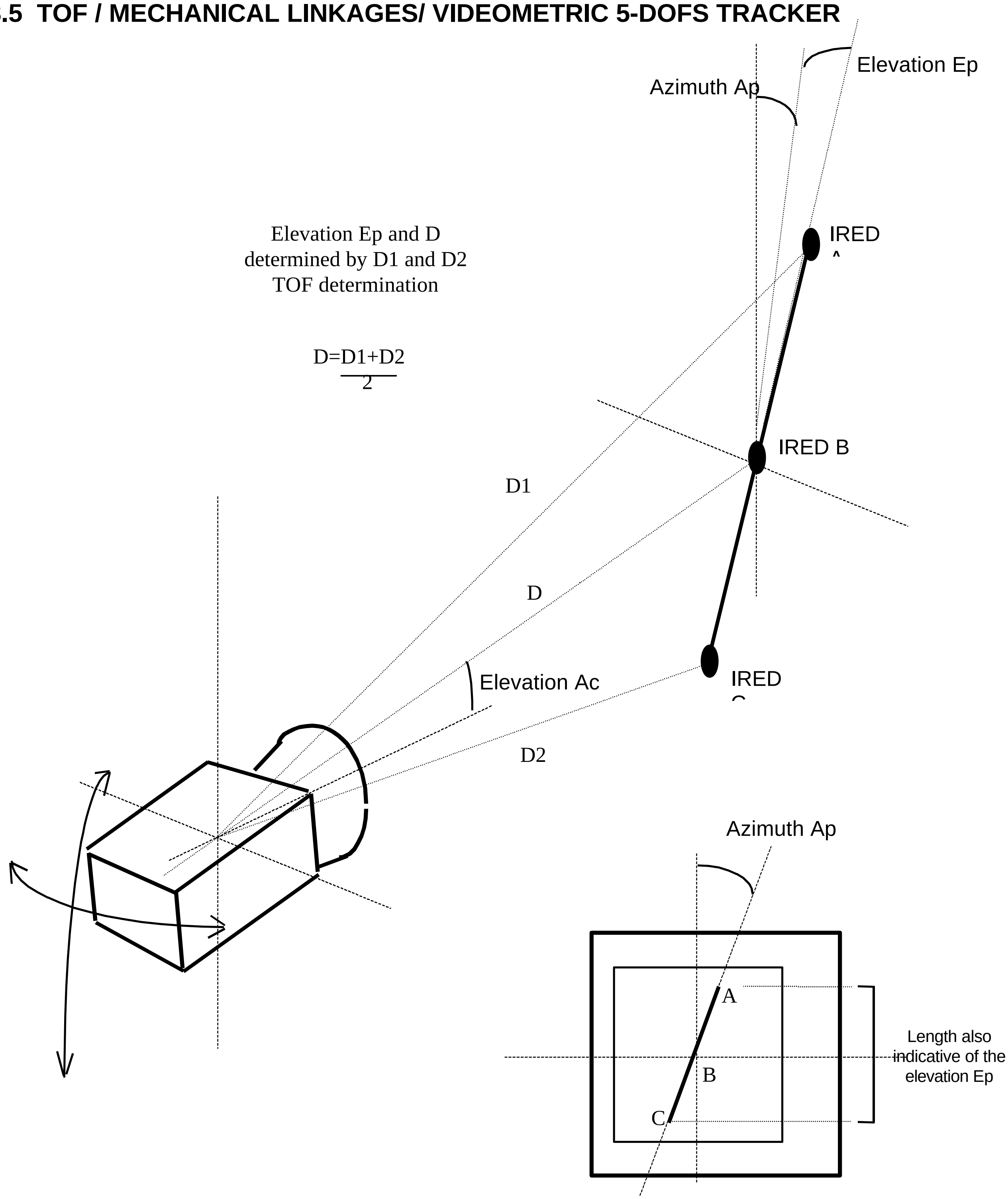


Figure 18. *Structure of a TOF / Mechanical Linkages / Videometric tracking system.*

The orientation of an object can be determined by tracking the position of at least three features with three locating systems such as those introduced in the previous section.

This TOF/ mechanical linkages / videometric 5 DOFs tracker uses an original method to perform this function with a unique device. The tracking system is composed of a TOF infrared rangefinder and a pointing device similar to the previous system. The system is illustrated in Fig. 18. This tracking system was originally proposed to teach robot paths (Mäkynen, 1995).

The target, a pen in this example, is equipped with three LEDs firing in the infrared. The pointing device aims constantly at the center of the diode, providing its elevation and azimuth to the processing unit via encoders mounted on the axis of the holding gimbal. The processing unit triggers the bottom and top tips of the pen where two LEDs are located. The TOFs of the two beams are measured by the rangefinder. The averaging of the two TOFs yields the distance of the central LED. As a result, the position of the center of the pen can be computed by the use of the elevation and azimuth variables.

Orientation in pitch of the pen is determined from the times of arrival of the infrared pulses. If the pen is vertical, the times of arrival are the same. If the pen is tilted away from the vertical, one pulse is delayed with respect to the other, and the delay is a function of the amplitude of the pitch. The actual working of the system involves a sequential firing of the two diodes with a delay Td between each firing. Such a delay is necessary in practice to distinguish between the two signals emitted. One of the signals is therefore delayed by a time Td after reception for comparison. The pointing device equipped with a CCD sensing array instead of a 4Q detector as previously adopted measures the orientation in roll. The detection of the positions of the two extreme diodes at the time they fire leads to the identification of the roll of the pen. These two orientations and the position of the central point of the pen yield a 5 DOFs tracking system.

Table 18. *Summary table with characteristic of TOF / mechanical linkages / videometric tracking system.*

Physical phenomenon	TOF, mechanical linkages, and spatial scan
Measured variable	TOF, 2D position and gimbal encoders outputs
Degrees of freedom	2 Orientation and position (5 DOFs)
Accuracy	1 mm for range-finder, 5 mm for the whole system
Resolution	1.3 mm / 0.3 deg
Update rate	Unknown
Lag	Unknown
Range / Total Orientation Span	Up to 5m / 80 degrees (field of operation of the gimbals)
Advantages	Unknown
Limitations	Unknown
Examples	Laser radar to teach robot paths (Makynen, 1995)

Table 19. *Summary table of the advantages and disadvantages of TOF / Mechanical Linkages / Videometric 5DOFs hybrid systems.*

	Videometric / Mechanical Linkages pointing	TOF infrared range finding and orientation determination	Hybrid
Characteristics / Advantages	Measures azimuth and elevation.	Determine orientation by TOF difference, fast, long range and accurate.	2 Orientations and 3 position measures, fast, accurate, long range.
Limitations	Videometric system and gimbal mechanics limit the accuracy and resolution in position.	Need wires to bring back to the control unit the received signals, expensive time detector.	Expensive, control wires needed, accuracy and resolution in position limited by mechanics of the gimbal and the quality of the videometric system.

9 DISCUSSION

After reviewing some unique advantages and disadvantages of various tracking technologies, whether in isolation or in hybrid configurations, we shall now discuss common issues to these technologies. First we shall ask and discuss whether there are fundamental limitations in aiming for finer and finer accuracy and resolution. Next we shall discuss a critical technical challenge for virtual environments, the capability for real-time operation. We shall then address the issue of scalability of the technology that is especially relevant to large virtual environments where users are physically navigating through the virtual world (e.g. larger indoors or outdoors settings). Finally, general considerations for the choice of tracking technologies are discussed.

A review of tracking devices according to their fundamental principle of operation may examine the theoretical limitations in accuracy and resolution (i.e. resolution) of these systems. Because of the way accuracy is defined, it is a measure of the absolute error of either position or orientation of an object in the tracker coordinate system. A change in coordinate system yields values of these measures in the world coordinate system. Accuracy in either position or orientation refers to an estimation of the position or orientation of an object after the system noise has been fully accounted for and in a way averaged. A measure of accuracy, therefore, assumes that a large number of samples have been collected for a given position and orientation of an object in order to yield unbiased estimates of the mean values of the underlying distributions in position and orientations. In this regard the fundamental limitation of obtaining perfect accuracy in position and orientation is the Heisenberg uncertainty relation. In our macroscopic world this limitation is negligible but for instance STM microscopy can also be considered as a tracking technology and the uncertainty relations are playing a major role in this case. Other limitations to perfect accuracy are thermal noise in the electronic circuits and quantum noise in the sensors. Cooling the circuits and detectors can minimize noise.

A measure of resolution, in the other hand, quantifies the noise of the tracking system. Resolution is a measure of the spread of an underlying distribution in either position or orientation. Resolution can thus be defined as the square root of the second central moment of the considered distribution (Frieden, 1982). All trackers are theoretically limited in resolution by a quantification unit (e.g. the size of a quantum of light in some optical trackers). At the working scale of the technology, where the application is the tracking of human scale features (e.g. the head), the resolution sought by the tracking technology considered is a lot larger than the quantification units considered (e.g. wavelength, phase, molecules size).

An exception, perhaps, is the case where secondary parameters are measured with technologies that supersede microscale technology. An example is the measurement of head acceleration with nanoscale technology developed by NASA (Tom Caudell, 1998). It has been shown that nanoscale accelerometers are limited in resolution due to interference of gravitational fields that may constitute a fundamental limitation in such measurements. As finer scale technologies are developed and investigated even beyond nanoscale technologies, other fundamental limitations are likely to be discovered. While such resolution requirements are likely beyond most applications, it is important to understand such phenomena and be able to set lower bounds on what can be achieved and what cannot. Nanoscale technology, for example, is now at the cutting edge but may be part of tomorrow every day’s technology.

In today’s' reality, two common practical limitations in resolution are brought from the state-of-the-art electronics and the manufacturing of various components of the trackers. Electronics is an essential component in the emission, detection, and processing of the measured variables (e.g. time of flight). The finite speed of the electronic signals produces a lag in the measurements. The limited bandwidth of these signals also limits the data acquisition rates. As an example, one may increase the operating frequency used in a phase coherent system with ultrasonic waves in order to increase the resolution. A limit in the case of ultrasonic wave, depending on their amplitude, may be simply the viscosity of the air: the bigger the frequency the larger the attenuation. The electronic response times would however impose a limit on the maximum data acquisition rates, thus also limiting the resolution of the tracking system. Optical data processing devices present promises for future improvements because of the larger bandwidth of the optical signals and the shorter switching times.

The manufacturing specifications of the emitting and sensing components of the tracking system often limit the resolution of current tracking technology, but not in any fundamental way. As examples, the current resolution of a CCD array, or the architectural layout and the geometry of emitting and sensing sources, limit the resolution. Achievable resolutions rely essentially on the progress of technologies including micro and nano scales electronics, mechanics, and opto-electronics. However, even if optical switching devices, for example, were to successfully replace electronic devices, and manufacturing errors were reduced to become negligible, the achievable resolution for an overall application would be limited by other components or factors of the virtual reality system, other than tracking components. For example, the resolution of the display used in the visualization and the natural occurrences of mechanical vibrations are sources of limitation as well. Finally, given the same technology, different implementations often lead to different final performances. There is no need to seek higher resolution for the tracking system than can be delivered by individual components of the overall virtual reality system.

An issue of critical importance for trackers is their real-time capability. A virtual reality system qualifies as real-time if the virtual world reacts synchronously to the actions produced by a user. Because this capability is practically not reachable the preferred term of interactive speed is commonly used. The difficulty in achieving interactive-speed results from the reception of non-synchronous signals coming from the real world (we see the real hand moving) and the virtual world (we see the virtual hand moving on the display). The signals from the real world appear as they are produced if seen directly (see the real hand), whereas the signals from the virtual world appear when the processing that produces them (time taken from end-to-end process of the virtual environment) is completed. Moreover, virtual signals are often generated following the detection of a real signal (the detection of a hand motion), thus aggravating the problem.

The total lag produced by this process comes from the establishment of the measurement conditions, the measurement completion time before availability of the measure, the filtering, the signal propagation and transmission times, and the synchronization between the tracking system, the computer, and the display. Different implementations may also have different temporal performances (Jacoby et al., 1996). To minimize the effect of lag, Kalman filtering (Kalman, 1960) has been used to predict the position of a target according to the present and past speed and position parameters (Azuma, 1995). The time of prediction can be tuned to equalize the lag produced by the system to produce virtual signals with the impression of an interactive-speed response. However, the predicted position and orientation are sole estimations produced from the last measurements and do not reflect exactly a real position. As a result, the lag problem is often replaced by noticeable registration errors.

In applications requiring registration of real and virtual objects, the lag, the update rate, and the errors in position and orientation are hindrances. Motion sickness can ensue if these variables are incorrect because of visual-proprioceptive conflicts (Kennedy and Stanney, 1997). The severity of the observed errors is a function of other system parameters (e.g. effectiveness of visual cues, use of sound) and the speed of various moving parts among others. Evaluating a tracker in the context of specific applications is a key requirement.

Another important issue of tracker technology development is the potential for scalability of the technology. In certain cases, it becomes the driving factor for adopting a certain approach to tracking. At the University of North Carolina at Chapel Hill, for example, the opto-ceiling tracker was essentially developed using an inside-out configuration because such an approach was believed to have the potential for natural scalability indoors. Such a system was described in section 3.2.1 and illustrated in Fig. 7. In this case, scalability was traded-off the need to wear three cameras on the head that appeared highly displeasing. This problem can be and is being addressed by adopting custom-made miniature camera configurations (Welch and Bishop, 1997). The first implementation of the tracking system succeeded in demonstrating tracking in a small volume (~ 10x10 feet), and the second implementation demonstrated some scalability of the system (a factor of 2 in one dimension). Practical issues however (e.g. the requirement for precise calibration of all LED-panels and associated cost) set some limit on scalability. Self-calibration was attempted to remedy this problem but the optimization becomes rapidly untractable for larger and larger volumes (Gottschalk and Hughes, 1993). Scalability is fairly challenging indeed for most technologies and theoretical as well as practical considerations have to be carefully examined. After reflecting on the scalability issues of the various technologies described in this document, we postulate that, most systems are scaleable for indoor settings if the expense is not of primary concern and hybrid technologies can be considered. Most systems are not however scalable to handle large navigation settings such as may be required for outdoors navigation. Likely, such tracking will not require the high accuracy and precision typical of most indoor settings. Generally speaking, however, scalability may imply that more complex algorithms (e.g. fusion algorithms) will be necessary as systems are being scaled and hybrid technologies are implemented.

To conclude this discussion, we shall now summarize some general considerations of tracking technology for virtual environments. TOF ultrasonic systems typically suffer from ultrasonic noise sources in the environment, while other TOF systems such as optical or GPS suffer from occlusion. In addition, current GPS systems do not yield high accuracy and resolution. Phase difference systems based on ultrasonic sources suffer from environment noise sources while those based on light sources may offer attractive solutions for relative tracking measurements. Direct field sensing trackers such as magnetic trackers seem to be most employed in virtual environments because of their robustness and their low price, even though distortions of the magnetic field typically cause large tracking errors. Spatial scan trackers give excellent accuracy and resolution, but they typically suffer from occlusion. Moreover, some of these systems are complex to implement and thus tend to be expensive. Mechanical linkages have the best accuracy, update rate, lag, and resolution, but they impose constraints of motion on certain degrees of freedom. Inertial platform and other reference-less trackers are especially well adapted for fast reaction time and long-range motion of the user, but they suffer from drift and are best used in hybrid configurations. Given an application and thus the environment (e.g. small scale versus large scale, the potential for environment noise and occlusion), a sole technology or hybrid technology may be selected for optimal performance and trade-offs.

10 CONCLUSION

This broad technical review considered existing trackers categorized according to their physical principle of operation in order to explore their similarities and differences. We briefly discussed the physical principle of each technology, as well as the technology advantages and drawbacks. Such taxonomy based on physical principle of operation was proposed to facilitate developing new and improved ways to track features of the real world, as well as assist in the choice of a tracking system that best fit some application. At present, a major limitation of state-of-the-art tracking technologies is the difficulty in achieving interactive-speed performance for complex virtual environments. The limitation is often a system limitation given that it depends on rendering speed as well as on tracking acquisition and transfer to the rendering engine. The tracker itself is often not the limiting factor.

ACKNOWLEDGMENTS

We are grateful to Tom Caudell from the University of New Mexico and one anonymous reviewer for their careful review of the manuscript, and their various insightful suggestions that have significantly contributed to improvement of this manuscript. From the university of Central Florida, we thank Jim Parsons for his help on definitions and references, and Boris Zel'dovich for his help with the geometry of the Time of Flight trackers. From the University of North Carolina at Chapel Hill, we thank Stefan Gottschalk and Gary Bishop for providing us with information on the opto-ceiling tracking system that has been developed over the last 10 years. Finally we are thankful to Warren Robinett for stimulating discussions on some aspects of this review.

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APPENDIX A: DEFINITIONS

Accuracy : Error between a real and a measured position X* for each spatial position. The extreme value of the error will be given for each system. This number is evaluated by taking numerous measures at a given location and orientation, and comparing the computed mean to the real value. A system with an accuracy A will report a position within ±A of the actual position.

Lag : Delay between the measurement of a position and orientation by a tracking apparatus and the report to a device (e.g. scene generator, force feedback apparatus) requiring the orientation and position values.

Real-time : Attribute of a virtual reality system in which the virtual world reacts synchronously to the actions of a user. This capability is practically not reachable since the processing time is not zero, so the preferred term of interactive speed is used.

Interactive Speed: Attribute of a virtual reality system that reacts "in time" according to actions taken by an user. Such a system must be fast enough to allow a user to perform a task at hand satisfactorily.

Reference : Part of a tracking system considered fixed with respect to the motion of a target.

Resolution : Smallest resolvable change in position and orientation. A measure of resolution is the standard deviation of the underlying distribution of measurements around the mean of a measured position or orientation.

User : Person interacting in a virtual world. Can be a target.

Target : Feature (e.g. object, landmark, human feature) to be localized by the tracking process.

Update rate : Maximum frequency of report of position or orientation.

Pitch : Rotation in the vertical plane including the line of sight around the X axis shown in Fig. A1. Pitch is called also heading.

Yaw : Rotation in the horizontal plane including the line of sight around the Y axis shown in Fig. A1.

Roll : Rotation in the plane perpendicular to the line of sight around the Z axis shown in Fig. A1.

Degree-of-freedom : Capability of motion in translation or rotation. There are six degrees of freedom: translation along X, translation along Y, translation along Z, rotation around X (pitch), rotation along Y (Yaw), and rotation along Z (roll).

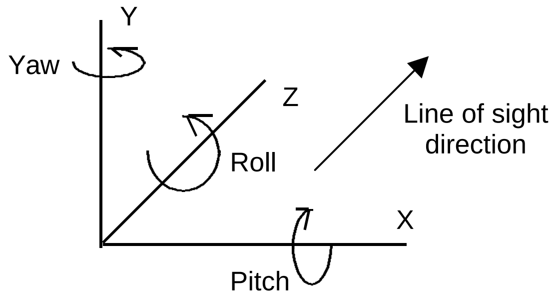
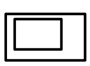


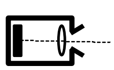
Fig. A1 *Referential commonly employed in Virtual Reality.*

CCD : Charge-Coupled Device. Sensitive photoelectric array measuring the light energy striking each pixel.

LED : Light Emitting Diode. Photoelectric emitting device used as a light signal.

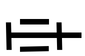
Symbols employed in this document

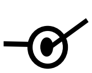
 Monitor displaying the output of a camera.

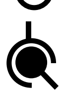
 Camera.

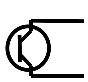
 Piezo-electric sound emitter or receiver.

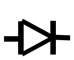
 Helmet.

 Cylinder liaison which allows rotation axially around the bearing (one degree of freedom or DOF).

 Side view of a cylinder liaison (not to confuse with the spherical or rotule liaison).

 Spherical or rotule liaison, allows three rotations (3DOFs).

 Photo-transistor or photo-receiver in general.

 LED or light emitter.

APPENDIX B: addresses of corporations and laboratories cited in this paper.

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APPENDIX C: Patents related to tracking technology.

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