Position trackers for Head Mounted Display systems: A survey

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ABSTRACT

The paper is a survey of existing position tracker technologies for Head Mounted Display (HMD) systems. The four major categories of position trackers, magnetic, acoustic, optical and mechanical, are discussed. The chief characteristics, advantages, disadvantages and examples of each category are described. A set of metrics for comparing the performance of position trackers is identified. The expected future trends in the field are also discussed.

1. INTRODUCTION

A position tracker is an important part of a Head Mounted Display (HMD) system. It is the device (or system of devices) that is responsible for reporting the position and orientation† of the HMD (the target object) to the host computer that generates the virtual environment images displayed in the HMD. These images represent the view that a wearer of the HMD would have seen if he or she were present in the virtual environment at the position and orientation reported by the position tracker. Since these images are strongly affected by the reported position and orientation, the performance of the position tracker plays an important part in determining the quality of the virtual environment experienced by the wearers of the HMD.

Many different kinds of position trackers have been designed in the past

† Position and orientation refer to the 3-dimensional position coordinates (x,y and z) and the 3 Euler angles (the pitch, yaw and roll angles) respectively.

twenty-five years for HMD applications. These can be broadly classified into four categories: magnetic, acoustic, optical and mechanical. Each of these has its own advantages, disadvantages and spheres of application.

This paper surveys the current position tracking technologies. It first discusses metrics for comparing the performance of position trackers. Then it discusses each of the four major categories of position trackers, providing a general description of their working principles, their advantages and their limitations, without delving too deep in the technical details. Finally it discusses the future trends in the field of position tracking.

The paper does not assume that the readers have any prior knowledge of position trackers. However, it does assume that they have adequate knowledge of high-school physics.

2. CRITERIA FOR MEASURING POSITION TRACKER PERFORMANCE

A common set of metrics is needed to evaluate the performance of the many different kinds of position trackers that are available today. These are listed below.

- *Accuracy:* This is a measure of the error in the position and orientation reported by the tracker.
- *Resolution:* This is the smallest change in position and orientation that can be detected by the tracker.
- *Update rate:* This is the rate at which position and orientation measurements are reported by the tracker to the host computer.
- *Lag* (also known as *latency*): This is the delay between a change in position and orientation and the report of the change to the host computer.
- *Working volume:* This is the volume within which the tracker can

measure position and orientation with its specified accuracy and resolution.

A good position tracker should have high accuracy, fine resolution and high update rate. Its latency should be low and its working volume should be large. Ideally, it should not need any specialized environment for operation. In addition, the parts of the tracker that need to be worn should be small and light in weight, to ensure user comfort.

3. MAGNETIC TRACKERS

Magnetic trackers can be classified into two categories, Alternating Current (A.C.) magnetic trackers and Direct Current (D.C.) magnetic trackers.

3.1. A.C. magnetic trackers

A.C. magnetic trackers contain a source transmitter and a receiver. The source consists of three mutually perpendicular electromagnetic coils and is mounted at a known fixed position in the environment. The receiver has a similar construction and is mounted on the target object to be tracked.

When A.C. signals are supplied to the three coils in the source, they produce a rotating magnetic field. This field, in turn, induces currents in the three receiver coils. These currents vary as a function of the position and orientation of the receiver with respect to the source. They are measured and are used to compute the position and orientation of the receiver [Raab et al., 1979].

In the presence of metallic objects, A.C. magnetic trackers suffer from the problem of eddy current distortion. In accordance with Faraday's law, the rotating magnetic field generated by the source induces eddy currents in metallic objects in the environment. The eddy currents, in turn, generate their own magnetic fields, which interact with the magnetic field of the source and distort it. As a result of this distortion, the tracker reports inaccurate position and orientation in the vicinity of metallic objects. This imposes severe limitations on the environment in which A.C. trackers can be used.

A series of A.C. magnetic trackers has been produced and marketed by Polhemus (formerly Polhemus Navigation Systems). They report that their latest product, Fastrak, has a latency of 4 ms and an update rate of 120 Hz when operating with one receiver. When the separation of the transmitter and the receiver is less than 30 inches, Fastrak has a reported accuracy of 0.03 inches in position and 0.15 degrees in orientation. The corresponding figures for resolution are 0.006 inches and 0.025 degrees. The tracker is capable of tracking target objects within a range of 5 ft from the source.

3.2. D.C. Magnetic trackers

D.C. magnetic trackers follow a working principle that avoids eddy current distortion in the vicinity of metals. Eddy currents are generated by changes in the transmitted magnetic field. D.C. trackers avoid eddy currents by using a static magnetic field.

D.C. trackers use a transmitter similar to that used by A.C. trackers, but, instead of exciting it with A.C., they supply short D.C. pulses to the transmitter. Once the perturbances caused by the rising edge of a D.C. pulse settle, the magnetic field generated by the transmitter remains static till the end of the pulse. The static field is measured by the receiver. The measurement, however, includes a significant component of the effects of the earth's magnetic field. In order to eliminate this undesirable component, a measurement of the earth's magnetic field is made before exciting the transmitter. This measurement is subtracted from the subsequent measurement of the transmitted field and the result is used for computing position and orientation of the target object.

While D.C. trackers avoid the distortion caused by induction of eddy currents in metals, they remain vulnerable to the the effects of ferromagnetic materials. If present in the vicinity of the tracker, these materials distort the transmitted magnetic field by reflection. As a consequence, the position and orientation reported by D.C. trackers in the presence of ferromagnetic materials are inaccurate.

A series of D.C. trackers has been produced and marketed by Ascension Technology. This includes the Bird, the Big Bird and the Flock of Birds. The manufacturers report that the update rate for the Bird is 100 Hz. Its lag, in the absence of noise filtering†, is reported to be 17 ms. Lack of noise filtering, however, produces inaccuracies in the output; hence the the reported lag may not be achievable with acceptable levels of accuracy. With the transmitter and receiver separated by 12 inches, the Bird has a reported accuracy of 0.1 inches in position and 0.5 degrees in orientation. The corresponding figures for resolution are 0.03 inches and 0.1 degrees. The maximum permissible range of the Bird is only 2 ft. However, the Big Bird has a larger range, namely 8 ft. While both the Bird and the Big Bird can track only one target object at a time, the Flock of Birds can track a maximum of six target objects simultaneously; it uses one transmitter and six receivers, one for each target. This simultaneous tracking does not affect the update rate of the tracker. However, if the targets are not equidistant from the transmitter, the data reported for all but the nearest target do not meet the reported

† In most magnetic trackers, the 'raw' signals measured by the receivers have to be passed through hardware and/or software filters to reduce the noise in the signals. This is known as noise filtering.

accuracy specifications.

3.3. Advantages and disadvantages of magnetic trackers

3.3.1. Advantages

• The sensors of magnetic trackers are small and light in weight. Hence they can be worn comfortably by the users.

• Magnetic trackers do not have any line of sight problems. They can track even if there is an obstruction between the transmitter and the receiver, provided that the obstruction is not metallic or ferromagnetic.

• Unlike acoustic and optical trackers, each magnetic tracker unit requires only one transmitter and receiver, thus adding to the convenience of use.

• Many magnetic trackers with high update rates are available 'off the shelf'; thus they are suitable for users who cannot afford to develop tracker systems on their own.

3.3.2. Disadvantages

• The main disadvantage of magnetic trackers is that of distortion. Distortion problems of A.C. trackers in the vicinity of all metals and those of D.C. trackers in the vicinity of ferromagnetic materials have already been discussed. In addition, both kinds of trackers are adversely affected by distortions caused by external electromagnetic fields, e.g., those from CRT displays.

• While the Big Bird system with its range of 8 ft provides a large working volume, I believe that this is close to the upper limit of the range that can be provided by a single-transmitter magnetic tracker. The intensities of the magnetic fields required for greater ranges are too high to guarantee the safety of the users. One possible alternative is to use multiple low intensity transmitters, each covering a portion of the working volume. However, such a scheme suffers from the problem of severe inaccuracies in the reported position and orientation at the boundaries of the regions covered by different transmitters. Unless some method for overcoming this problem is devised, magnetic trackers cannot provide much bigger ranges than those offered by the existing products.

4. ACOUSTIC TRACKERS

Acoustic trackers use ultrasonic waves for determining the position of the target object. They can be classified into two categories, the Time of Flight (T.O.F.) trackers and the phase coherent trackers.

4.1. Time of Flight (T.O.F.) trackers

T.O.F. trackers compute position and orientation of the target object by measuring the time taken by ultrasonic pulses to travel from a set of transmitters to a set of receivers. A typical system might consist of three transmitters and three receivers. The transmitters are mounted on the target object and the receivers are arranged at known fixed positions in the environment. The transmitters emit ultrasonic pulses at regular intervals with only one transmitter emitting at any given time. The receivers detect these pulses and record their times of arrival. Since the times of transmission of the pulses are known, this measurement permits the computation of the times of flight of the pulses, which are then used to compute the distances between the transmitters and receivers by multiplying the times of flight by the speed of sound in air. These distances and the known positions of receivers constitute sufficient information for computing the position and orientation of the target object. A series of computations is performed on these data and the position and orientation are obtained [Ferrin, 1991].

One of the major problems with T.O.F. acoustic trackers is that their update rates are limited by the low speed of sound in air. The variations in the speed of sound with temperature, pressure, humidity and turbulence cause an additional problem. However, this problem can be overcome if the speed of sound is measured while tracking, by a dedicated transmitter-receiver pair, set a fixed distance apart. (The remedy is based on the assumption that the speed of sound is constant over the entire working volume; this may not be true in certain extreme cases.)

One of the first T.O.F. trackers was the Lincoln wand [Roberts, 1966]. Capable of measuring only position, it had an update rate of 25 Hz, a resolution of 0.02 inches and an accuracy of 0.2 inches. It was adversely affected by external ultrasonic noise. More recent examples include Honeywell's ultrasonic tracker, which is used to track head orientation in a cockpit. It is reported to have an accuracy of 0.3 to 0.6 degrees [Ferrin, 1991].

Some T.O.F. trackers are available commercially. A position tracking system produced by Scientific Accessories Corporation is an example. The manufacturers report that the system has a resolution of 0.004 inches and an update rate of 100 Hz. Its working volume is a 9-foot cube.

4.2. Phase Coherent trackers

Phase coherent trackers track position and orientation by comparing the phases of emitted acoustic waves with the phase of a reference wave. Transmitters of acoustic waves are mounted on the target object and receivers are set up at fixed positions in the environment. The receivers periodically measure the phase difference between the waves emitted by the transmitters and a reference wave. Since a phase angle of 360 degrees is equivalent to a distance of one wavelength, the difference between the two successive measurements of phase difference for an emitted wave can be translated into the distance moved by the transmitter of the wave between the two measurements, provided that this distance is less than one wavelength. The receivers measure phase difference at a rate fast enough to meet this condition; hence, they are able to estimate the movements of the transmitters. These movements are used to compute the changes in position and orientation of the target object. The computed changes are used to update the previous position and orientation to obtain the current position and orientation. The system is initialized by measuring the initial position and orientation with some external source.

Since phase coherent trackers operate by updating the initial position and orientation with computed changes, the errors in the changes accumulate over time, leading to inaccuracies in the reported position and orientation. Hence, these trackers have to be corrected from time to time by some external source to rectify the accumulated errors.

I do not know of any recent trackers that use this technique.

4.3. Advantages and disadvantages of acoustic trackers

4.3.1. Advantages

- Both kinds of acoustic trackers are small and light in weight; hence they are comfortable for the users.
- Unlike magnetic trackers, acoustic trackers do not suffer from distortions in the presence of magnetic fields.
- They do not require a specially designed environment for operation.

4.3.2. Disadvantages

- Both T.O.F. and phase coherent trackers are unable to function correctly if there are obstructions between the transmitters and the receivers.

• Echos and external noise create spurious measurements in both systems, leading to inaccuracies in the reported position and orientation.

• T.O.F. trackers have low update rates.

5. OPTICAL TRACKERS

Optical trackers have been designed using a wide variety of technologies. While most of them can be classified as beacon trackers [Wang, 1990], there are some types of optical trackers which do not belong to this category. Notable among these are the laser ranging trackers.

5.1. Beacon trackers

Beacon trackers use a set of optical beacons. These beacons may be either active (i.e., transmitters of light) or passive (i.e., reflectors of light). A set of sensors such as cameras or lateral effect photodiodes† is used to sense these beacons.

Depending upon the position of the beacons and the sensors, beacon trackers can be divided into two categories: the inside-out and the outside-in systems. Inside-out systems place the beacons at fixed places in the environment and the sensors on the target object. On the other hand, outside-in systems place the beacons on the target object and the sensors at fixed places in the environment.

The working principles of both kinds of systems vary slightly from implementation to implementation. Hence, their working principles are described in the examples that follow.

† A lateral effect photodiode is a special kind of photodiode; upon being non-uniformly illuminated, it generates a current that varies as a function of the position of the centroid of the illuminated area.

5.1.1. Inside-out systems

The optoelectronic ceiling tracker of the University of North Carolina at Chapel Hill (UNC) is a very successful inside-out system. This system uses infrared light emitting diodes (LEDs) as beacons. A large number of these LEDs are mounted at known fixed positions in a specially designed ceiling. Four lateral effect photodiodes and their accessory lenses serve as sensors. These are mounted on the target object. Both the LEDs and the sensors are controlled by a host computer.

When the system operates, the LEDs in and around the field of view of the sensors are lit momentarily, one at a time, under the control of the host computer. The lenses in the sensors form images of the lit LEDs on the lateral effect photodiodes, which, in turn, measure the 2D positions of these images. Each measured 2D position defines a 3D vector from a sensor to a visible LED. The set of vectors and the known positions of the visible LEDs are used to compute the position and orientation of the target object by a photogrammetric technique called Space Resection by Collinearity [Azuma & Ward, 1991].

A notable feature of the optoelectronic ceiling tracker is its large working volume. The system can track the target object at all places under the LED studded ceiling. So the entire volume under the ceiling serves as the working volume. The system is scalable and can be expanded to any size by merely increasing the size of the ceiling. The current version at UNC allows tracking in a 10 by 12 ft area. Work is in progress to expand it to 18 by 30 ft.

The update rate of the optoelectronic ceiling tracker is between 30 and 100 Hz, depending upon the height and position of the user. Typical update rates are between 50 and 80 Hz. The lag varies between 20 and 80 ms with a typical value of 30 ms. The resolution is 2 mm and 0.1 degrees. There are no firm numbers available as yet for accuracy.

A major drawback of the optoelectronic ceiling tracker is its inability to track if the target object is positioned in such a way that very few or no LEDs are visible to the sensors. In addition, the sensors are quite heavy and hence the system is uncomfortable for the user.

Another example of an inside-out tracker is Honeywell's rotating beam system for tracking the orientation of a target object. In this system, "thin, fan shaped rotating" infrared beams are generated by beacons that are at fixed positions in the environment. The sensors, which are mounted at fixed positions on the target, record the times at which the beams pass through them during rotation. These times, when multiplied with the known speed of rotation of the beams, yield the angles through which the beams have rotated when they cross the sensors. These angles and the known positions of the sensors relative to one another constitute sufficient information for computing the orientation of the target object. A series of computations is carried out to obtain the orientation. The resulting data have an accuracy of 0.1 to 0.6 degrees [Ferrin, 1991].

5.1.2. Outside-in systems

The Honeywell LED array system is an example of an outside-in system. It uses an array of four infrared LEDs arranged in a prescribed pattern on the target object. A camera is mounted at a fixed position in the environment and the LEDs are energized one at a time. An image of each energized LED is formed in the focal plane of the camera. The camera measures the 2D positions of these images in its focal plane. Each such measured 2D position defines a vector from an LED to the camera. The vectors of all four LEDs and the knowledge of their positions relative to one another are used to compute the position and orientation of the target object [Ferrin, 1991].

A variant of this system is the Honeywell videometric system [Ferrin, 1991]. In this system, instead of the infrared LEDs, a unique reflecting pattern is placed on the target object. This pattern is illuminated by an external infrared source to make it visible to the camera. This avoids the use of active beacons on the target object. The camera measures the 2D positions of certain distinctive features in the image of the pattern. These positions are then used to compute position and orientation of the target object using techniques similar to those used for the LED array system.

Another outside-in system forms a part of the CSRDF flight simulator developed by the NASA Ames Research Center. It uses four cameras mounted in the environment to track head motion. The cameras scan a set of LEDs on the pilot's helmet and measure the 2D positions of the LED images formed in their focal planes. The system uses the measured image positions to compute head position and orientation. [Cook, 1989].

Other examples of outside-in systems include CoSTEL [Macellari, 1983], OP-EYE [Bishop, 1984], Twinkle Box [Bishop, 1984] and SELSPOT [Bishop, 1984].

5.1.3. Outside-in vs. Inside-out systems

An inside-out system can compute angular orientation of the target object with greater accuracy than an outside-in system that uses comparable technology. This can be illustrated by a simple example.

In a typical HMD system, the distance between the surface of the target object (the head) and the axis of rotation (the neck) is about 20 cm. The distance between the target object and the remote fixed locations where the sensors or beacons may be placed is typically about 2 m (i.e., 200 cm). Let us consider a 0.1 degree rotation of the target object.

In an outside-in system, the beacons are on the target object. When it rotates by 0.1 degrees, each beacon moves by $20 \times \pi/180 \times 0.1$ cm, i.e., 0.035 cm. Hence, in order to be able to observe the rotation, a sensor placed 200 cm away needs to notice a movement of 0.035 cm at a distance of 200 cm.

In an inside-out system, the sensors are on the target object. When the target object rotates, the sensors rotate with it and see an apparent movement of the beacons. A 0.1 degree rotation is seen by the sensors to be an apparent movement of the beacons by $200 \times \pi/180 \times 0.1$ cm, i.e., 0.35 cm. So the sensors need to be able to detect a movement of 0.35 cm at a distance of 200 cm.

Hence, in our example, the sensors for the inside-out system may be ten times less sensitive than those for the outside-in system. If the sensors in both systems are comparable, the inside-out system can have ten times greater resolution and accuracy than the outside-in system.

In general, the behavior of beacon tracking systems follows a principle similar to the lever arm principle. The farther away the beacons are from the axis of rotation, the greater is their apparent movement with the rotation of the target object. So, for any given rotation, an inside-out system, which places the beacons farther away from the target object than a comparable outside-in system, observes a larger apparent movement of beacons than the outside-in system. Hence an inside-out system is able to track orientation more accurately than a comparable outside-in system.

5.2. Other optical trackers

5.2.1. Laser ranging trackers

Laser ranging trackers use the fringe patterns generated by the diffraction of laser beams for computing the position and orientation of the target object. When a diffraction grating is illuminated with laser light, a fringe pattern appears on objects placed beyond the grating. The fringe pattern has a property called *contrast ratio*, which depends on the intensity modulation of the fringe pattern. This property varies as a function of the distance between the pattern and the grating and can be used to estimate the same. In order to obtain the contrast ratio, a video camera is used to scan across the fringe pattern and measure the intensity at different points on the pattern. The measured data are then used to compute the contrast ratio and from it, the distance between the diffraction grating and the target object on which the fringe pattern appears. Multiple gratings are needed to get sufficient distance data for computing the position and the orientation of the target object [Chavel, Strand, 1984].

Laser ranging trackers have small working volumes. As the distance between the target object and the diffraction grating increases, the intensity of the diffraction pattern diminishes. This prevents accurate measurements for large working volumes.

5.3. Advantages and disadvantages of optical trackers

5.3.1. Advantages

- Optical trackers have high update rates, which are limited mainly by the speed of the processors used in computations. Hence their update rates would improve as processors become faster.

- Working volume of optical trackers varies from system to system but can be very large as demonstrated by UNC's optoelectronic ceiling tracker.

• Optical trackers do not suffer from distortion effects in the presence of metals.

5.3.2. Disadvantages

• All optical trackers suffer from line of sight problems. Their performance suffers if there is an obstruction in the path from a sensor to some of the beacons. The problem can be partly mitigated by using multiple sensors and beacons.

• The performance of existing optical trackers is adversely affected by ambient light and infrared radiation. So the surrounding environment has to be designed carefully to reduce ambient radiation.

• Existing inside-out optical trackers require elaborately designed environments. Hence they are not very portable and are expensive.

• Unless proper care is taken in the computations in inside-out optical trackers, the computed position and orientation undergo a slight but sudden change when one beacon leaves the field of view or another enters it. This phenomenon, known as beacon switching, is quite distracting to HMD users.

6. MECHANICAL TRACKERS

Mechanical trackers measure the position and orientation of a target object that is attached to the end of a movable mechanical arm. The arm is anchored at a fixed point of reference and is made up of several sections that can rotate and move at the joints. The rotations and movements are measured by gears or potentiometers and are used to compute the position and orientation of the target object relative to the fixed point of reference.

Little work has been done in the past few years on the development of mechanical trackers for HMDs. The few examples of this work include the Fake Space Boom and the MITI Robotics Lab tracker [Meyer et al., 1992]. A commercially available mechanical tracking system for HMDs is the ADL-1, which is marketed by Shooting Star Technologies. The manufacturers report that it has an update rate of 300 Hz, an accuracy of 0.2 inches in position and a resolution of 0.025 inches in position. However, its working volume is small — a cylinder with a radius of 1.5 ft and height of 1.5 ft.

Mechanical trackers for non-HMD applications include NASA's Anthropomorphic Remote Manipulator [Meyer et al., 1992] and UNC's Argonne Remote Manipulator [Brooks et al., 1990].

The chief disadvantage of mechanical trackers is that the user is constrained by the mechanical arm and does not have full freedom of movement. The working volume is also quite small since it is restricted by the size of the arm. These limitations are so severe that mechanical trackers are now practically obsolete for HMD applications.

7. FUTURE TRENDS

Design of position trackers remains an active area of research. Attempts are being made to build position trackers that do not have the drawbacks of the systems described earlier in the paper. Some of the notable proposed systems include natural environment trackers and inertial trackers.

Natural environment trackers do not require any specialized environment for their operation. They can track in any area without requiring any changes in the environment. The first such tracker was proposed by Gary Bishop [Bishop, 1984]. The Self-Tracker, as it is called, compares consecutive images of the environment that are seen by its sensors. It computes changes in position from the differences in these successive images. An experimental, "proof of concept" Self-Tracker was built by Gary Bishop in 1984 but this was not followed up with a full-scale system because it was too complex. However, with the subsequent advances in fabrication and analog VLSI technology, I expect that such a Self-Tracker will be implemented in the near future.

Inertial trackers use accelerometers and gyroscopes to compute changes in position and orientation from measurements of acceleration and velocity. These trackers tend to accumulate error over time and need to be updated by some external source from time to time. Researchers at the University of North Carolina at Chapel Hill are working towards the development of such trackers.

Apart from these, hybrid trackers that use two or more different technologies to complement each other are also being explored.

8. CONCLUSION

A comparison of the four major categories of position trackers is shown in table 1. The comparison and the descriptions in this paper show that none of the current technologies is a panacea for the position tracking problem. Each technology has its own advantages that make it suitable for certain applications. However, each technology also has some major drawbacks, viz., distortion and short range in magnetic trackers, low update rates and occlusion in acoustic trackers, occlusion and need for elaborately designed environments in optical trackers, and user discomfort in mechanical trackers. Hence HMD designers selecting a position tracker need to compromise between the requirements of their HMD applications and the disadvantages of the trackers that fulfill those requirements.

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	Magnetic Trackers	Acoustic Trackers	Optical Trackers	Mechanical Trackers
Accuracy & Resolution	High Adversely affected by ferromagnetic and metallic objects in the environment	High Adversely affected by ultrasonic noise	High Adversely affected by ambient infrared radiation	High
Working Volume	Small	Small	Practically unlimited	Very small
Lag	Low	High	Low	Low
Effects of obstructions	None if the obstructions are not metallic or ferromagnetic	Increase in inaccuracies; loss of tracking ability in extreme cases	Increase in inaccuracies; loss of tracking ability in extreme cases	Loss of tracking ability in areas that cannot be reached because of the obstructions
Convenience of use	Easy to use	Easy to use	Inside-out systems require special environments and are heavy. Outside-in systems are more convenient to use.	Very inconvenient User motion is restricted.

Table 1. A comparison of the major categories of position trackers.