Tracking Systems and the Value of Inertial Technology

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ABSTRACT

This paper intents to add to the literature on 3D position and orientation tracking systems by describing TNO's experience with the InterSense tracking system that uses a combination of inertial and ultra-sound technology. From the results of a performance evaluation study and our practical experience with this system in military applications, the value of the system and its underlying inertial technology based hybrid concept is determined. The performance figures addressed in the study include noise and registration error characteristics. Orientation and position tracking performance results are provided for the InterSense system. The figures are compared with the figures for the Polhemus FASTRAK system. The hybrid tracking system concept as introduced by InterSense is of great value to virtual environment applications. The filter algorithms included in the InterSense tracking system to combine the two different sensor types result in a system that is both fast and noise free. The system is very well suited for most immersive applications. Registration error, however, is rather large, causing the system to be inadequate for augmented reality applications in its current implementation. TNO feels that the concept will evolve to an inertial technology based system combined with high accuracy auxiliary trackers that will meet the requirements for augmented reality applications.

Keywords: virtual reality, virtual environments, tracking systems, position tracking, orientation tracking, inertial sensors

1. INTRODUCTION

1.1. Background

Driven by application requirements from the field of military simulation, the TNO Physics and Electronics Laboratory conducts a research program on Virtual Environment (VE) technology with a focus on Head Mounted Display (HMD) based simulators. Being the enabling technologies for new simulator concepts, both head mounted displays and tracking systems are at the same time often the limiting factor in the engineering reality of VE technology applications.

The quality of an HMD based VE system heavily relies on the performance of the tracking system that provides position and orientation data of real world objects. Most commonly, the position and orientation of the HMD and some kind of pointer device (e.g. a 3D mouse or a glove device) are required. The *ultimate* tracking system will have the following features[1,2]:

- measurements are reported with very high resolution and without noise, i.e. very small changes in position are measured by the tracking system and reported with a minimum error range;
- the tracking system reports position and orientation data without registration error, i.e. the reported data corresponds to the actual position and orientation of the real world object being tracked;
- the tracking system instantaneously provides new position and orientation data of the tracked object as it moves, i.e. new data is computed and output at high rates with a neglectable delay;
- performance figures are guaranteed for a large working volume in which the tracked object can move around;
- performance figures are not constrained by any environmental and operational conditions (like visual occlusion, interfering magnetic fields, mechanical constraints, etc);
- the tracking system can track a large number of objects simultaneously.

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Position and orientation tracking systems have been commercially available for years now. A large palette of technologies has been applied to strive for the ultimate tracking system as good as possible. Among these, the systems based upon electro-magnetic fields are the most widely spread. Almost any player in the field of VE applications will have at least one of the popular electro-magnetic tracking systems from either Polhemus or Ascension. Although very popular, the electro-magnetic tracking systems limit the practical use of virtual environment systems because of noise, registration and delay characteristics inherent to these systems. In 1996, the company InterSense introduced a new commercially available tracking system, based on a hybrid concept of inertial and ultra-sound technology that would solve the shortcomings of electro-magnetic tracking systems. TNO was one of the early buyers of the InterSense system in its search for more effective tracking solutions.

1.2. Purpose of this paper

Literature already covers a lot of aspects of VE tracking systems. A number of surveys describe the available tracking technologies and their advantages and disadvantages.[1,2,3] Performance figures on electro-magnetic tracking systems are also addressed.[4,5] This paper intents to add to this by describing TNO's experience with the InterSense tracking system as being a solution to the problems inherent to electro-magnetic tracking systems. Based upon our practical experience with the InterSense tracking system in military applications and the results of a performance evaluation study, the value of inertial tracking technology and in specific the InterSense tracking system is determined.

2. INERTIAL SENSOR BASED HYBRID TRACKING

2.1. Problems in Electro-Magnetic Tracking

Electro-magnetic tracking systems are advantageous in the fact that they are affordable and easily applied in many situations. The systems have no restrictions with respect to line-of-sight between source and sensor. The sensors, being small and leightweight, are integrated without trouble with most objects that are to be tracked. Accuracy and resolution are quite good in a relatively small working volume around the electro-magnetic source.

Aside from the advantages, problems do arise under most typical application conditions. The sensors to be tracked are usually about a meter (just beyond the tracking range for standard electro-magnetic tracking systems) separated from the source and the operational environment is polluted by all sorts of magnetic fields. As a result of this, in the practice of VE systems using electro-magnetic tracking we have to deal with a lot of noise on position and orientation data and significant registration errors.[4] Filtering will decrease the noise problem, but increases the delay problem.[5]

2.2. A Hybrid Tracking Solution

As an answer to the problems inherent to electro-magnetic tracking systems, InterSense came up in 1996 with a new hybrid tracking solution.[6,7] The basic idea of the system is that tracking is done via integration of gyro data providing angular rate and translational acceleration. Gyro technology is very fast, thus providing a low latency, high rate data stream. However, the integration of gyro data inevitably leads to drift errors. The essence of the InterSense solution lies in the use of a hybrid concept to solve the drift problem. The integrated gyro data is fused with data from more accurate tracking systems to compensate for drift errors. The software component included in this concept, to implement the data fusion filter, relies on complex Kalman filtering techniques and is a crucial factor in the value of the tracking system.

InterSense made the hybrid tracking concept available in a commercial product.[8] In this system, the drift errors in the gyro integration for orientation tracking are compensated for by using an inclinometer (to provide correct roll and pitch values) and a mechanical compass (to provide correct heading). The inclinometer and the compass are packaged, with the gyro's and an auxiliary thermometer, in the sensor of the system (see Figure 1).

An ultrasonic position tracking system is used to compensate for drift errors in the accelerometer data integration. The ultrasonic system uses three beacons that are mounted on calibrated positions. The beacons emit an infrared pulse to the transponder beacons (see Figure 1) that are attached to the object being tracked. Upon reception of the infrared pulse, the transponder emits an ultrasonic pulse which is received by the three beacons. For the position tracking,

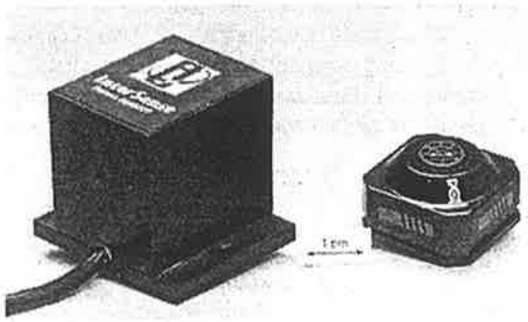

Figure 1. The InterSense tracking sensors. The main sensor (left) is packed with three rate-gyros, three accelerometers, three magnetometers, an inclinometer, a mechanical compass and a thermometer. The auxiliary transponder beacon (right) is equiped with an infrared receiver and an ultrasonic emitter.

3. EXPERIMENT DESIGN

3.1. Goals

The goal of this study is to evaluate the performance of the InterSense tracking system. Rather than providing just absolute numbers to express this performance, our goal is to assess the value of this new hybrid concept to the community of VE technology appliers that are dependent on commercially available tracking solutions. Therefore, we compare the figures for the InterSense tracking system with the figures for the commonly used Polhemus FASTRAK electro-magnetic tracking system.

Our performance evaluation study addresses the following aspects:
- *Noise* - The standard deviation in measured output data when the sensor is in a fixed position and orientation.
- *Registration error* - The difference between measured output data and actual real world position and orientation data.

A third aspect was planned to be included in the performance evaluation study as well: registration delay. However, the measurement method planned to be used appeared to be inadequate to provide valid information. This is deferred to later work.

3.2. Methods

To achieve the goals of this study, two methods are applied:
- A *static performance analysis* is performed. This is done by acquiring and analysing the tracker output data that is generated when the tracker sensor is in a known, fixed position and orientation.
- An *application test case* is analysed. The experiences in a military simulation application in which both the InterSense and the FASTRAK system have been used are described.

4. EXPERIMENT IMPLEMENTATION

4.1. Tracking systems used

Throughout the experiments, three position and orientation tracking systems have been used. The InterSense system and the Polhemus FASTRAK, that are subject of study, and a mechanical reference system that is used to provide reference position and orientation values. Details of these three systems are described in this section.

4.1.1. InterSense 6DOF tracking system

The InterSense system used for this study was from the first series that was delivered. The system used was an IS-300 PRO model with one sensor attached to it, in combination with the V-Scope VS100 ultrasonic position tracking system. In later versions of this 6DOF tracking system, the V-Scope system is fully integrated in the InterSense product, providing a dedicated construction that holds the beacons at calibrated positions. For our test system, we made our own construction to attach the beacons to the ceiling of our laboratory and position them precisely at the corners of a right triangular shape.

The InterSense tracking system software is provided as downloadable firmware. As the software of the system is the main source of system effectiveness, this is a very useful feature. The IS-300 PRO was loaded with the firmware version 2.0.5. Adjustable run-time parameters include the selection of filter quality and a setting to turn the so-called smooth filter on or off. The filter quality is related to the order of the Kalman filter that is used. It was set to the heighest quality option in all experiments. The smooth filter can be used to eliminate all jitter in the tracking. If the filter is switched off, the position and orientation measurements resulting from gyro data integration is always corrected by drift compensation data from the auxiliary tracking systems. If the smooth filter is switched on, this compensation is done gradually and only if the sensor moves. As our goal is to assess the value of the tracking system as it is commonly used in applications, we had the smooth filter switched on during our experiment.

4.1.2. Polhemus FASTRAK system

A Polhemus FASTRAK system with one sensor attached to it was used. The standard range transmitter was used as a source for the electro-magnetic field. The built-in filter of the FASTRAK was switched on during the static performance analysis experiments.

4.1.3. Mechanical reference system

A mechanical reference system was developed to setup a known position and orientation for the sensor being tracked. The sensor is attached to a rotation platform that allows separate setting of heading, pitch and roll angles in steps of 15 degrees (see Figure 4). The base of the rotation platform holds an integrated water-level indicator. The sensor is attached to a fixture that can be adjusted along the three axes, in order to align the centre of the sensor with the centre of the rotation platform (this feature, however, was not critical in our experiments).

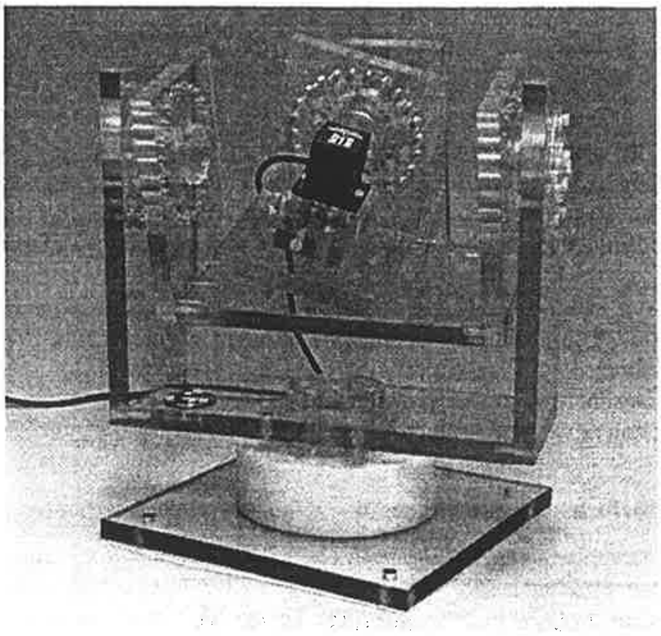

Figure 2. The rotation platform that enables the separate setting of heading, pitch and roll angles.

To set the sensor at a known position (x, y, z), the rotation platform is attached to a fixture which can be translated vertically (to set z) along a pillar. The pillar is attached to a ground fixture that can be translated on a flat board that holds equidistant grid holes to set (x, y). Three pins are inserted through the Figure 3.

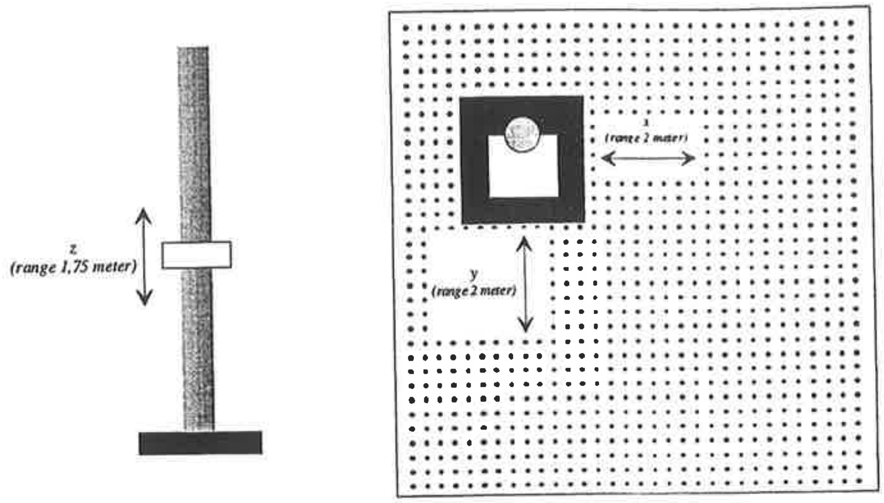

Figure 3. The rotation platform is attached to a moving fixture on a pillar (left) to select height z. The pillar is moved around on a flat board with equidistant pin holes to select position (x, y).

If the settings of the mechanical reference systems are to be compared against the measurements of the InterSense and FASTRAK systems, care need to be taken in aligning these systems with the mechanical system. For the InterSense system this is done by making sure that the inertial sensors are reset before each measurement serie while the sensor is on the rotation platform in the (*heading*, *pitch*, *roll*) = (0°, 0°, 0°) setting. The ultrasonic beacons of the InterSense system are aligned with the flat board on the ground by using plumb lines. For the FASTRAK system, this is done by carefully aligning the electro-magnetic source with the flat board.

4.2. Noise and registration measurement setup

4.2.1. Basic setup

The basic setup for the data acquisition for noise and registration measurements is build around a data acquisition process that runs on a Silicon Graphics O2 host workstation. The data acquisition software is configured with the specific reference points that are to be sampled, the number of samples per series and the requested sample rate. The workstation prompts for the next orientation and position to be set on the reference system. The sensor is manually set to the required position and orientation that is prompted for. The data acquisition software is then triggered to start a data acquisition series. The sensor will remain static on the set position and orientation during the data acquisition series. The output data is stored per session for later data analysis.

All measurements were performed in a standard laboratory environment, i.e. no special precautions were taken to avoid ultrasonic or magnetic interference. Only the position tracking measurements for FASTRAK were performed in a conditioned a-magnetic environment (unfortunately, measurements in a standard environment were not available - this would have been a more fair comparison as we want to study the performance under typical circumstances).

4.2.2. Orientation tracking performance measurements

Orientation tracking performance measurements have been performed in a number of sessions. In each session, the same set of reference orientations is used. Heading is set to 0°, 90°, 180° and 270°, while for each heading, pitch is set to -60°, 0° and 60° and for each pitch, roll is set to 0°, 90°, 180° and 270°. Thus, each session consists of $4 \times 3 \times 4 = 48$ data series. Each series consists of 100 samples, sample at 10 Hz.

The measurements for the IS-300 are repeated five times to find registration error statistics, whereas this is not done for the FASTRAK. The reason for this is that the IS-300 tracking data is more dependent upon previous movements of the tracker, resulting in possible repeatability errors. For FASTRAK this dependency upon previous movements is not present - history dependency is limited to the time frame of the filter during which the sensor is held static in our experiments.

The measurements for FASTRAK are performed four times, with changing distance between electro-magnetic source and sensor: 0.2 m, 0.7 m, 1.2 m and 1.7 m.

4.2.3. Position tracking performance measurements

Position measurements have been performed in a 1.5m×1.5m×1.5m working volume. For the InterSense system, the working volume is sample at equidistant grid positions with 0.5 m spacing. Thus, for each of the 4×4×4 = 64 reference positions, a series of 100 samples is acquired. This session is repeated five times to find statistics for the registration error.

FASTRAK position tracking data is acquired for the same 1.5m×1.5m×1.5m working volume, but now with 0.25 m grid spacing (this session is not repeated, so we could afford a more dense grid). Thus, for each of the 7×7×7 = 343 reference positions, a series of 100 samples is acquired.

5. MEASUREMENT RESULTS

5.1. Noise measurements

Noise values are computed from the measurements by determining the standard deviation (1) for orientation angles and position coordinates of the output data in each series of measurement values m_i. An indication of noise quality is obtained by computing the average standard deviation over all series.

$$stddev = \sqrt{\frac{\sum_{i=1..N}\left(m_i - \overline{m}\right)^2}{N-1}} \tag{1}$$

Table 1 gives the resulting standard deviations for orientation tracking of both the IS-300 PRO and the FASTRAK. The InterSense tracker shows zero noise due to the smooth filter technique. The FASTRAK shows increasing noise when the sensor is moved away from the electro-magnetic source. Typically when a standard range transmitter is used, the distance between sensor and source will be between 70 cm and 120 cm.

Table 1. The static noise measurements for orientation angles. The FASTRAK measurement series have been repeated at four different distances between sensor and electro-magnetic transmitter.

Tracking system	average stddev heading (deg)	average stddev pitch (deg)	average stddev roll (deg)
InterSense	0.0000	0.0000	0.0000
FASTRAK @ 20 cm	0.0038	0.0024	0.0027
FASTRAK @ 70 cm	0.0557	0.0267	0.0448
FASTRAK @ 120 cm	0.2868	0.1474	0.2266
FASTRAK @ 170 cm	1.1441	0.6128	0.8988

In order to judge the practical value of these numbers, note that 0.1 degree movement on a 42 degree field of view mapped on 1280 pixels means a movement of the image by 3 pixels!

Noise measurements for position tracking are given in Table 2. This table contains the standard deviations of the position measurements averaged over the entire 1.5m×1.5m×1.5m working volume we sampled. As FASTRAK performs exponentially worse above 1 meter, we also computed the standard deviation over all measurements with FASTRAK within 1 meter distance from the electro-magnetic source.

Table 2. The static noise measurements for position tracking.

Tracking system	average stddev x (mm)	average stddev y (mm)	average stddev z (mm)
InterSense	0.6	0.7	0.4
FASTRAK	6.6	6.0	8.0
FASTRAK @ < 1 meter	0.4	0.1	0.3

Whereas the InterSense filter software completely eliminates noise for orientation, this is not the case for position data. Table 2 shows that the average noise in position data is an order better for InterSense. The noise distribution across the working volume shall be studied in order to draw conclusions from this. Figure 4 and Figure 5 provide the necessary insight.

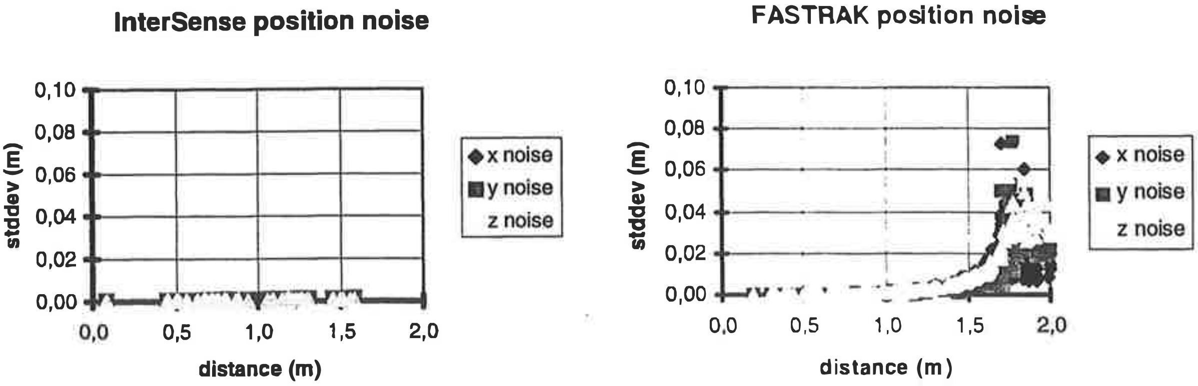

Figure 4. The noise values as a function of distance between sensor and source.

Figure 4 and Figure 5 show noise as a function of distance. Note that the distance values do not cover completely the same range for InterSense and FASTRAK. Both systems have been measured throughout a 1.5m×1.5m×1.5m working volume, but for InterSense the distance is computed between the sensor and the centre point in between the three receiver beacons and for FASTRAK, the distance between the sensor and the electro-magnetic source is computed.

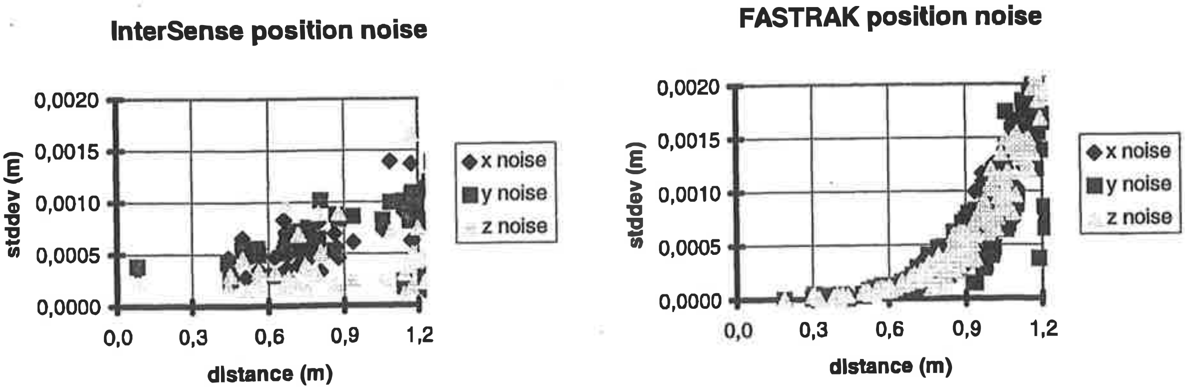

Figure 5. The noise values as a function of distance between sensor and source, detail of the working volume within 1,2 meter distance. Under typical circumstances, the sensor will be in this range.

5.2. Registration error measurements

Registration error has been measured by defining the position and orientation setting of the mechanical reference tracking system to be the 'real' position and orientation and comparing the output data of the tracking systems against these reference values. In order to so, the tracking systems need to be aligned with the mechanical tracking system. In Section 4 it was described how this was done. Registration error is computed from the output data by using the root-mean-square formula (2). The square error for all measured values m_i is computed against the reference value r_i.

$$RMSerror = \sqrt{\frac{\sum_{i=1..N}(m_i - r_i)^2}{N}} \tag{2}$$

Table 3 gives the resulting registration errors for orientation tracking of both the IS-300 PRO and the FASTRAK.

Table 3. The static registration error measurements for orientation angles. The FASTRAK measurement series have been repeated at four different distances between sensor and electro-magnetic transmitter.

Tracking system	average RMS error heading (deg)	average RMS error pitch (deg)	average RMS error roll (deg)
InterSense	5.6	1.1	1.3
FASTRAK @ 20 cm	0.5	0.4	0.6
FASTRAK @ 70 cm	1.0	0.6	1.2
FASTRAK @ 120 cm	3.9	3.1	5.2
FASTRAK @ 170 cm	11.5	10.2	14.6

When comparing the performance of the two systems, one should note that the InterSense tracker features error characteristics that are independent of position. The FASTRAK registration error increases with distance to the electro-magnetic source. Figure 6 and Figure 7 shows the error as a function of distance. For pitch and roll, the systems have about equal performance at a distance of 70 cm to 90 cm. At larger distances, the InterSense is more accurate than the FASTRAK.

For heading, the InterSense shows a rather large error. Only at distances larger than 130 cm it is more accurate than FASTRAK.

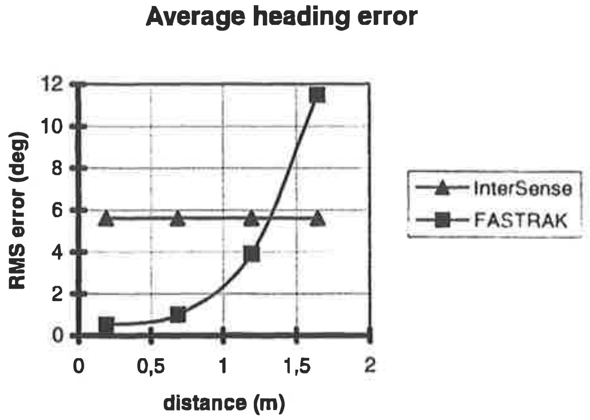

Figure 6. Average RMS error in heading tracking for both systems.

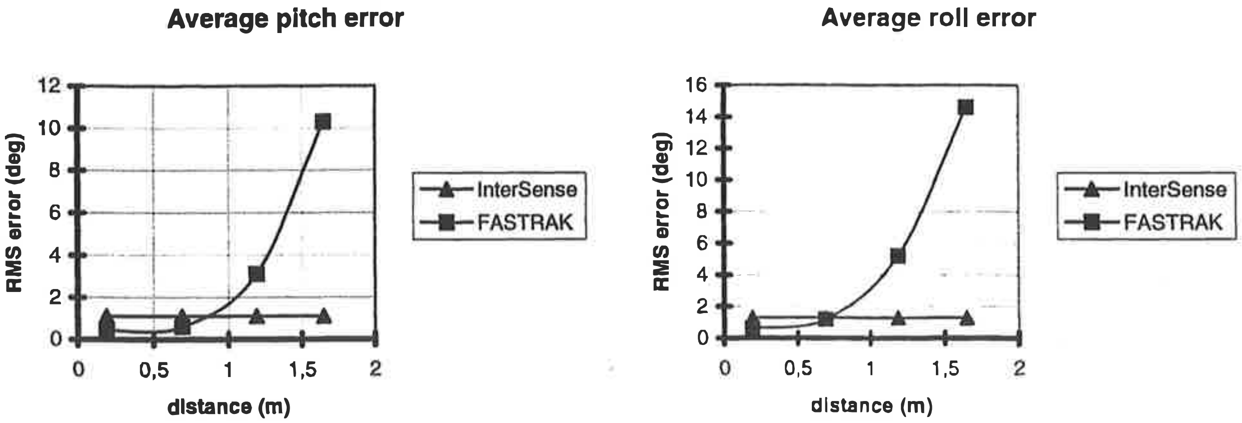

Figure 7. Average RMS error in pitch (left) and roll (right) tracking for both systems.

The registration error measurements have been performed across the entire 1.5m×1.5m×1.5m working volume. Both InterSense and FASTRAK show error values that depend upon distance to the beacons or electro-magnetic source respectively. Hence, errors grow rather large on the boundaries of the volume. Presenting average error measurements therefore is not useful for the entire working volume. We choose to compute the average error in the inner 0.5m×0.5m×0.5m volume, this being the volume where normally the head will be positioned (at a distance of roughly 0.75 meter from the ultrasonic beacons or electro-magnetic source). The results are given in Table 4.

Table 4. The static registration error measurements for position tracking. The average is computed for the inner 0.5m×0.5m×0.5m of the measurement volume. Note the text concerning the validity of the FASTRAK measurements.

Tracking system	average RMS error x (mm)	average RMS error y (mm)	average RMS error z (mm)
InterSense	3.6	3.7	5.7
FASTRAK	17.4 (see text)	14.8 (see text)	12.2 (see text)

The registration error of FASTRAK as shown in Table 4 see way of what it should have been. After further inspection of the data it was shown that the errors measured are linearly depend upon the position within the measuring volume. This indicates that the FASTRAK electro-magnetic source was not well aligned with the mechanical reference tracking system. Unfortunately we cannot draw conclusions from these measurements.

To get an overall impression on the position tracking performance we visualised the position measurements against the reference points. Figure 8 shows this relationship. For InterSense it is remarkable that the system reports some default value when a sensor is out of range. It also strikes that this already happens for rather nearby points (the beacons are positioned about 40 cm roughly straight above the cube shown in the figure). For FASTRAK, Figure 8 clearly shows the distortion of the electro-magnetic field (the source is positioned nearby the centre of the backplane in the figure).

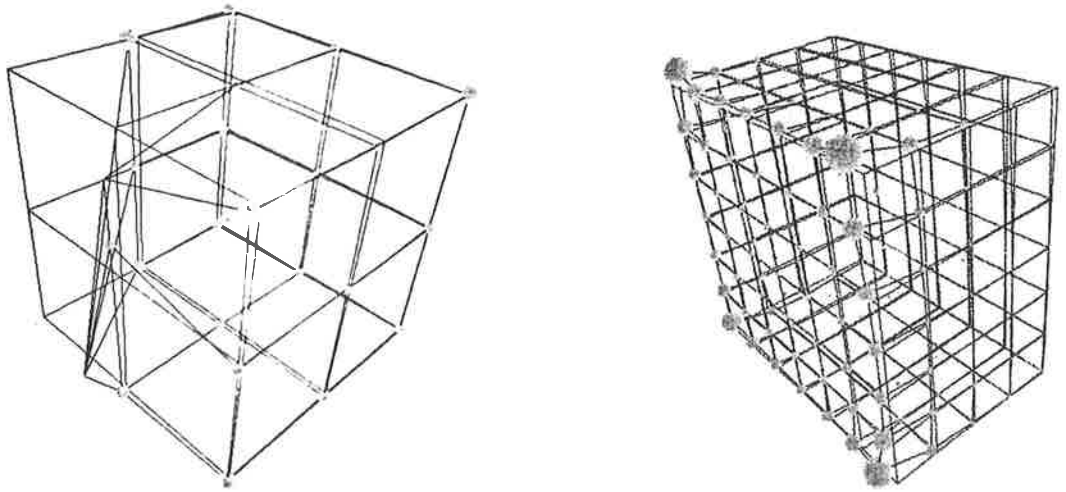

Figure 8. The position measurements over a 1.0m×1.0m×1.0m volume for InterSense (left) and Polhemus (right). The size of the spheres is proportional to noise, but does not have an absolute size (left and right image are not comparable).

6. DISCUSSION OF THE RESULTS

6.1. Noise characteristics

The measurement results show that the InterSense system provides solid noise characteristics that are, opposed to the electro-magnetic system, almost independent of distance. The orientation noise is completely eliminated by the InterSense system. For position noise, the comparison depends on working distance. FASTRAK performs best within the 1 meter range, whereas InterSense shows more distance independent performance and is better at ranges above 1 meter.

The fact that noise is eliminated by the InterSense system is a software issue. The smooth filter simply thresholds the angular rate data. This of course also has drawbacks. In very precise rotations, the filter may ignore the movements.

6.2. Registration error

The registration error results shows that the two systems have about equal performance when at a distance of 70 to 90 cm from the source. Again, the big advantage of the InterSense system is that orientation registration is independent of position. The heading registration of the InterSense system is, however, not to good. Apparently the mechanical compass inside the sensor is not very accurate.

The average registration error found for the InterSense system is not to bad. The working volume of the ultrasonic system was, however, was constrained to roughly a 1.0m×1.0m×1.5m working volume. Unfortunately we were not able to compare these values with the FASTRAK system (see Section 5 and below).

6.3. Validity of the measurements

A weak point of the material presented in this paper is that a reference tracking system was used for which no valid accuracy specifications are available. This has little impact upon the noise measurements, but does affect the validity of the registration error measurements. The problems with the registration error measurement for the FASTRAK system indicate that more attention should have been paid to the calibration and the validation of our systems.

In a recent publication[7], InterSense published on similar experiments as reported on here. The InterSense paper reports better performance. There are however two differences compared with this paper: we used a rather old version of the system and we measured with the smooth filter turned on (as opposed to the publication by InterSense). We want to refer the reader to this paper by InterSense for additional experiments on the performance of the InterSense system and an updated description of the latest hardware and software.

As mentioned, the measurements were performed with one of the very first InterSense systems that was produced (end of 1996). According to InterSense, hardware and software has improved since. One of the things that has changed is the calibration process of the sensors. The latest version of the InterSense tracking system, the IS-600 Mark 2, uses four ultrasonic beacons instead of three and it has the possibility to use a pair of ultrasonic transponder beacons for heading computation instead of the (inaccurate) compass.

7. AN APPLICATION TEST CASE

The measurements show that the InterSense tracker is advantageous over electro-magnetic trackers because of the elimination of noise. But how does this influence user performance in practical applications? We tested this by using both the IS-300 and the FASTRAK tracking system in an HMD-based simulator.

The test case application is a military training simulator for Forward Air Controller (FAC).[9,10] The FAC has as a task to guide pilots of fighter planes to their targets. To do this, the FAC has to perform visual perception of the terrain, the targets and the fighter. Specifically the visual task of detecting the plane and perceiving the flight orientation and direction are tasks that put heavy requirements on the visual simulation chain (including the tracking system).

The tracking task in the FAC simulator application is not very complex. The only thing that needs to be tracked is the heading, pitch and roll of the HMD. The FAC trainee is standing up and will not change position during the exercise, he is only turning his head (looking not only around, but also to above).

Our experience with the FASTRAK system is that noise kills the visual perceptive capabilities of the trainee, making fighter detection a very hard task. Only if the users remain very close to the electro-magnetic source (which was positioned on a 1.5 meter height vertical stand next to the user), visual detection of the fighter plane at reasonable distance was possible. The quality of the simulation was significantly improved by using the IS-300 system instead of the electro-magnetic system. This was judged, based upon the improved capabilities of the trainees to detect the incoming fighter plan and to determine its orientation and direction. Acceptance of the system was also improved because of the faster response and the fact that with the IS-300 tracking system, performance does not depend on distance to a source, so the users were less constrained in their movement, all resulting in a less straining situation that is more acceptable by trainees who have to wear an HMD during an exercise.

8. CONCLUSIONS

Now what is the value of inertial tracking technology to VE application builders? InterSense has shown that it is of great value if combined in a hybrid concept with some other tracking system for accurate orientation and position measurements. Key advantages in the InterSense concept is the low noise figures, small latency and constant performance across a large working volume. In its current implementation, the InterSense tracking system is a very good solution for many immersive VE applications. We feel that the next step on the evolution path of tracking systems will be a system that is based upon the hybrid concept of InterSense, however with the aid of a more accurate optical system instead of the ultrasonic system. The inertial sensors are required to get low latency tracking and effective noise reduction and motion prediction, whereas the optical system will provide accurate position and orientation values to obtain improved registration.

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