Quality Assessment of Electromagnetic Localizers in the Context of 3D Ultrasound

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Quality Assessment of Electromagnetic Localizers in the Context of 3D Ultrasound

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Abstract: Electromagnetic spatial localizers represent low cost and flexible solution for clinical free-hand three dimensional ultrasound system. Their performances condition the accuracy of the calibration and the ultrasound reconstructed volume and the robustness of the acquisition stage. In this study, we evaluate the resolution and the accuracy for translations and rotations of two widespread localizers in quite metallic environment: Fastrak and Flock of Bird. Our experiments show that their resolution for position is under $0.2mm$ at $60cm$, and their resolution for orientation is around 0.06 degrees. For translations below $30cm$, their position accuracy is around $1.5mm$, and the angular accuracy is under 1 degree. These results show that theses devices provide sufficient accuracy for use in a clinical context.

Key-words: magnetic tracking device, three-dimensional ultrasound system accuracy.

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Évaluation de capteurs électromagnétiques dans un contexte d'ultrasons 3D

Résumé : Les systèmes de repérage électromagnétiques représentent une solution souple et peu onéreuse pour les systèmes d'imagerie ultrasonore 3D. Leurs performances conditionnent fortement la précision de la phase de calibration, du volume reconstruit ainsi que la robustesse de la phase d'acquisition des images. Dans cette étude, nous évaluons la reproductibilité et la précision en translation et en rotation pour les deux systèmes les plus répandus : le Fastrak et le Flock of Bird. Nos expériences montrent que la reproductibilité en translation est inférieure à $0.2mm$ à $60cm$, et la reproductibilité en rotation est d'environ 0.06 degrés. Pour des déplacements inférieurs à $30cm$, la précision en position est d'environ $1.5mm$, et la précision angulaire est inférieure à 1 degré. Ces résultats montrent que ces systèmes de repérage ont une précision suffisante pour une utilisation dans un contexte clinique.

Mots-clés : système de repérage électromagnétique, précision d'un système ultrasons 3D.

1 Introduction

Three-dimensional (3D) ultrasound is becoming popular and some commercial systems had already appeared in hospital ([6]). Classical 2D ultrasound is commonly used for clinical exams because its non-invasive nature, its real time capability and its relatively cheap cost of acquisition. The purpose of three-dimensional ultrasound is to dismiss the main drawback of traditional two-dimensional ultrasound imaging which is its weak capability of issuing quantitative accurate morphometric information. Furthermore, 3D ultrasound facilitates extensive investigation and allows accurate measurements of organ volumes ([14]).

Spatial localizers provide the positions and the orientations of a sensor with regard to a transmitter. These systems are very used in augmented or virtual reality, in surgical applications and also in 3D reconstruction of images. In free-hand 3D ultrasound imaging, spatial localizer is mounted on the scan probe and is used to know the positions and the orientations of the B-scans with respect to the fixed transmitter. After the calibration step of the 3D ultrasound system, this knowlegde permits to reconstruct a volume with the set of B-scans. This framework encompasses our study of spatial localizers. Various spatial localizers are used in 3D-US imaging, four of the main used systems are :

Acoustic sensor This system uses sound broadcasting stations and microphones ([11]). The principle is based on the measure of the propagation time of sound signal, knowing the propagation speed in the air. The problems concern the variation of propagation speed of the signal in the air (due to variations of temperature, pressure and humidity), and a possible cut of the signal when the line between broadcasting station and microphone is blocked.

Mechanical arm The probe is fixed at the end of a mechanical arm ([17]), thus measures are not disturbed by the environment. The constraints imposed by a rigid mechanical device may complicate scanning of some structures. However, the problem results from the trade off between freedom of movement and precision.

Optical sensor It is the same principle as acoustic device but using optical sensors ([8, 4, 18]). There is no interference with the environment. Furthermore, by placing properly distributed marker on the probe, and adding cameras, we can expect to eliminate the line of sight problem. This type of system offers a very good precision but is very cumbersome.

Electromagnetic sensor This system consists of two elements : a sensor placed on the probe and a transmitter. Using the magnetic field created by the transmitter to determine spatial positions and the orientations of the probe, this system is sensitive to metallic environment. However, this type of spatial localizer is very simple to use and does not disturb the manipulation of the probe. A lot of teams use electromagnetic sensor: [2], [5], [7], [9], [12], [16], [20].

The electromagnetic devices provide a flexible and low-priced solution. Moreover, contrary to the others systems, EPOM (electromagnetic position and orientation measurement) devices have a great freedom of movement. The only constraint is to ensure that the sensor lies within a certain range relative to the transmitter (about $1m$). Indeed, mechanical arm has limited movement, optical and acoustic devices have the "line of sight" problem : there must not be any occlusion during the exam. At this time, EPOM devices seem to be the most appropriated solution for routine applications in hospital.

2 EPOM device

A EPOM device is composed of a transmitter, a sensor and an electronic controller which manages the connection between the system of localization and the workstation. The transmitter and sensor contain three orthogonal coils. The transmitter coils generate three orthogonal magnetic fields, which induces electrical currents in the sensor coils. The relative forces of induced currents are used to calculate the position and the orientation of the sensor with respect to the transmitter.

There are two types of devices : AC devices and pulsed-DC devices. The differences result of the way that how magnetic fields are generated and detected. But, these two types of devices are very sensitive to interferences with metal, sources of magnetic radiations like monitor or ultrasonograph.

The precision of spatial localizer affects directly the precision of images registration during the 3D reconstruction step, and therefore becomes a very significant factor for accuracy of the 3D ultrasound system.

The EPOM devices sensitivity to interference in certain environments has led to caution in their acceptance for use in clinical US applications. For instance, metallic beds used in hospitals provoke distortions of magnetic fields produced by the system of location, and can create important errors of localization ([13], [15]).

Furthermore, during clinical exam, it is necessary to optimize sensor position with regard to the transmitter. Indeed, the device should not be too far from the studied region (0.5m to 1m, [5] and [1]) to avoid interferences, but also to be the more precise as possible.

3 Experiments

3.1 Framework

To measure the EPOM device precision , we have used a R0P6 Afma robot[1] which was able to be used as reference for measures. Its static resolution is $0.1mm$, and its static accuracy is $0.5mm$. The figure (1) shows the environmental conditions of our experiments. Unlike [1], measures could be taken in a large workspace. One can suppose that these conditions are close to clinical conditions, even worse with regards the possible magnetic interferences

[1] http://perso.wanadoo.fr/afma.robots

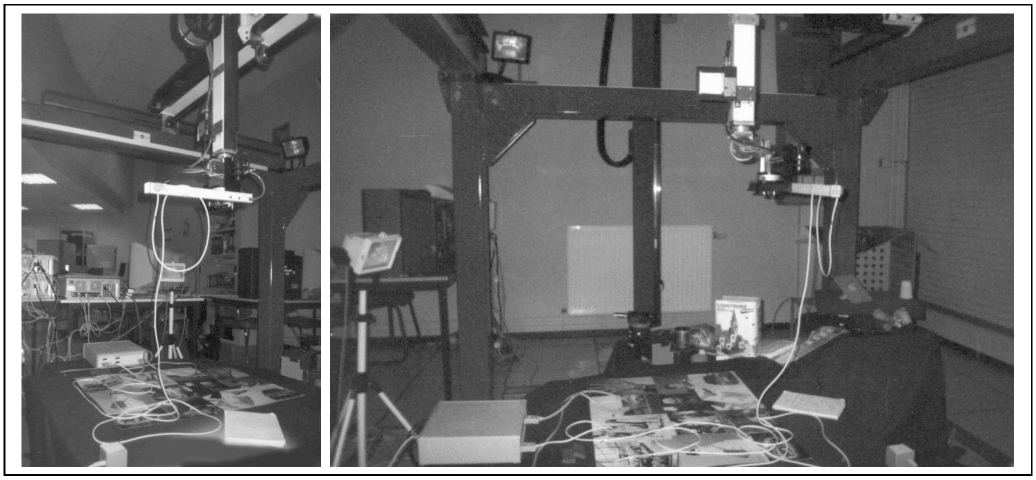

Figure 1: Robotic and Mechanical Environment of the Experiments.

caused by presence of metal in the room (monitors closed to the robot do not disturb EPOM measures because the distance between magnetic sensor and monitors is upper to $1m$ ([15])). We positioned the sensor on a plastic stalk to take it away from the metallical arm of the robot. So, it is possible to evaluate the mangetic sensor accuracy for the three translation and the three rotations. Transmitter and electronic controller are arranged on a wooden table, in the center of the working space.

3.2 Tested devices

We tested two different EPOM devices : Polhemus Fastrak (AC)[2] and the Ascension Technology Flock of Bird (Pulsed-DC) [3].

In both cases, we positioned the sensor on a plastic stalk which was hooked up on the arm of the robot. Each system provides positions of the sensor in the Cartesian coordinate system of the transmitter, and three angles (Eulerian representation) for its orientation.

For both devices, to compare directly the unprocessed measures, we did not use the manufacturers filters which can slightly correct measures. Forty points are taken for each measure. The distance between the sensor and the transmitter is in between $30cm$ and $1m$. The update rate of the sensor does not vary during the experiments. We used the built in default rate: 103 measurements/second for the Flock of Bird and 120 measurements/second for the Fastrak.

[2]http://www.polhemus.com
[3]http://www.ascension-tech.com

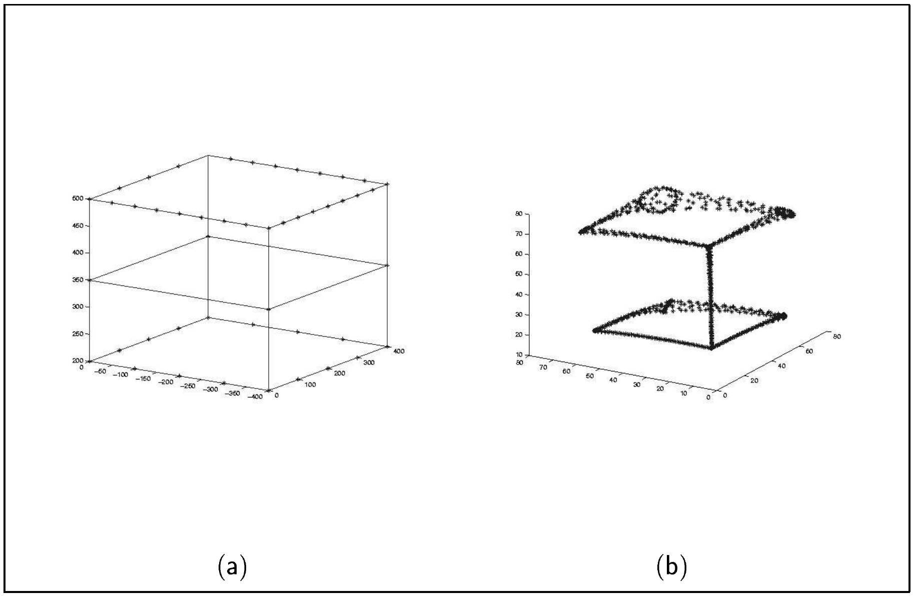

Figure 2: (a) : Distribution of points in the workspace (dimension of the box : 40x40x30 (cm); (b) : Example of a trajectory given by a EPOM device in the workspace (scale is in cm)

The figure 2(a) shows the tested points distribution in the workspace, and the figure 2(b) shows the position of points measured by the EPOM device according to the trajectory performed by the robot.

3.3 Method

Static resolution permits to assess the repeatability of each electromagnetic device. As it has been said previously, the performance of spatial localizer is crucial because it strongly determines the quality of the calibration step and the accuracy of the reconstructed ultrasound volume. So, as high accuracy is required for final results, it is necessary to estimate the accuracy of each spatial localizer.

3.3.1 Static Resolution

Static resolution is given by the average error of the device for a given point. It is calculated with a point set, for various positions and different orientations.

We took for each tested point about forty measures. For each sample, the standard deviation is calculated for the three axes. It gives us information about the system ability to reproduce the same measures.

3.3.2 Static Accuracy Position

The precision of the spatial localizer is measured by the calculation of distances. Calibrate motions can be carried out with the robot and compared with those obtained by the EPOM device. Therefore, it is possible to calculate distances between all the points of the set. Thus, the locations given by the robot are compared with the locations calculated from the data given by the EPOM device.

$$d = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \tag{1}$$

$$d' = \sqrt{(\overline{x'_i} - \overline{x'_j})^2 + (\overline{y'_i} - \overline{y'_j})^2 + (\overline{z'_i} - \overline{z'_j})^2} \tag{2}$$

where :

. d : distance calculated with the data given by the robot,

. d' : distance calculated with the data given by the EPOM device,

. i et j : relative indexes to two points in a couple,

. $\overline{x'_i}$: average of the coordinates measured by the system for the point i on the x-axis. $\overline{x'_i} = \sum_{i=1}^{N} x'_i$

3.3.3 Static Accuracy Orientation

Arm rotation can be expressed with a rotation around the helical axis. When the arm of the robot revolves around an axis according to an angle x, we want to estimate this angle with the measures of EPOM device. x is calculated by using transformation which allows to pass from the rotation matrix M to the rotation vector. The following formula gives us the value of x according to M ([19]):

$$x = \arccos\left(\frac{Tr(M) - 1}{2}\right) \tag{3}$$

where :

. $Tr(M) = m_{11} + m_{22} + m_{33}$.

. $M = \begin{bmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma \end{bmatrix}$ where α is the rotation around the z-axis, β around the y-axis and γ around the x-axis.

Rotation between two coordinate systems is affected by first rotating through γ around the x-axis, then through β around the y-axis, and finally through α around the z-axis.

If $\sin(x) \leq \frac{1}{2}\sqrt{2}$, it would be better to use the following expression :

$$x = \arcsin\left(\frac{1}{2}\sqrt{(m_{13} - m_{31})^2 + (m_{21} - m_{12})^2 + (m_{32} - m_{23})^2}\right) \tag{4}$$

Calculating the static accuracy orientation of the EPOM device only needs to compare the angle given by the EPOM with the angle given by the robot.

4 Results

4.1 Experimental Study

4.1.1 Static Resolution

Figures 3(a) and (b) show Fastrak and Flock of Bird static resolution results obtained for translation in x, y and z.

This study shows that the Fastrak system give slightly better results than Flock of Bird. However, these two devices behave very well: at about 70 cms from the transmitter, standard deviation is less than 0.5 mm for the position and less than 0.4 degrees for the orientations. Results of both systems are very similar.

To evaluate the static resolution, Barratt *et al.* ([1]) have introduced the Δ criterion :

$$\Delta D = \sqrt{(x - \overline{x})^2 + (y - \overline{y})^2 + (z - \overline{z})^2} \tag{5}$$

with :

. (x, y, z) : measured position vector,

. $(\overline{x}, \overline{y}, \overline{z})$: mean position vector.

In fact, this criterion is less accurate than the one defined in 3.3.1 because the three position vector elements given by the EPOM device are analaysed together. Reproductibility error have to be isotropic but this is not necessary the case. Figure 4 shows the evolution of ΔD for all the tested points.

4.1.2 Accuracy

Figure 5 show accuracy assessment. These results are summarised in the table 1. The mean error and the standard deviation are calculated for various distances (10cm to 60cm). For translation below $30cm$, Fastrak error is below $1.733mm$ and the Flock of Bird error is below $1.312mm$. In 3D ultrasound exams, for volume measurements, the probe motion is often

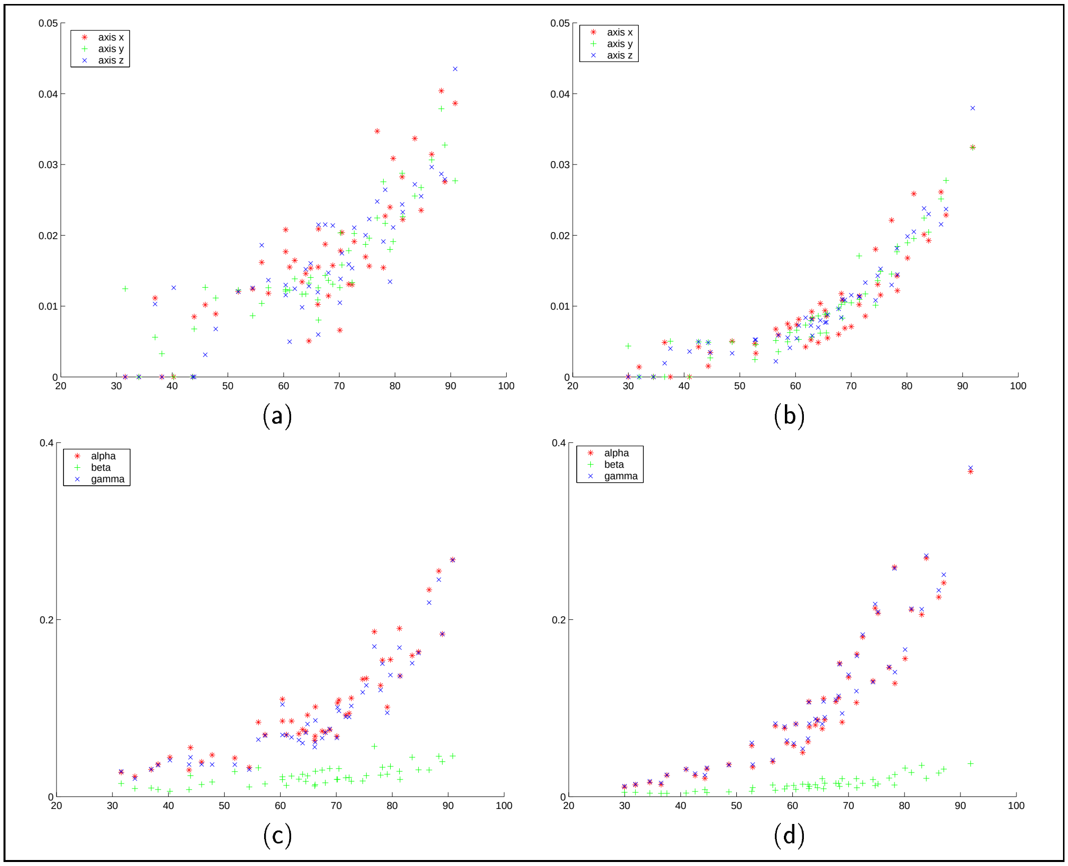

Figure 3: Static resolution for the three axes ((a) and (b)) and static resolution for orientations ((c) and (d)); abscissa : distance between sensor and transmitter, ordinate : standard deviation (cm for position and degree for orientation). (a) and (c): Flock of Bird; (b) and (d) : Fastrak.

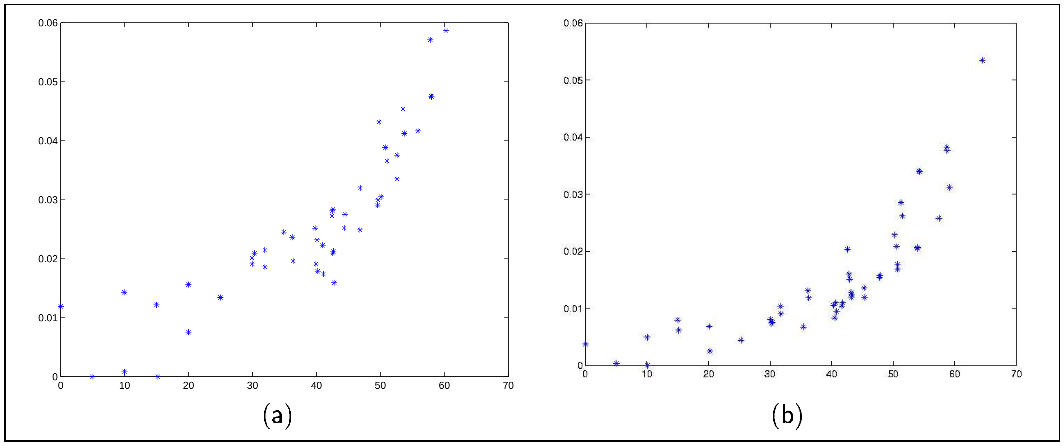

Figure 4: ((a) and (b)) : Evaluation of the reproductibility with the ΔD criterion ((a) : Flock of bird and (b) : Fastrak); abscissa : distance between sensor and transmitter (cm), ordinate : ΔD (cm).

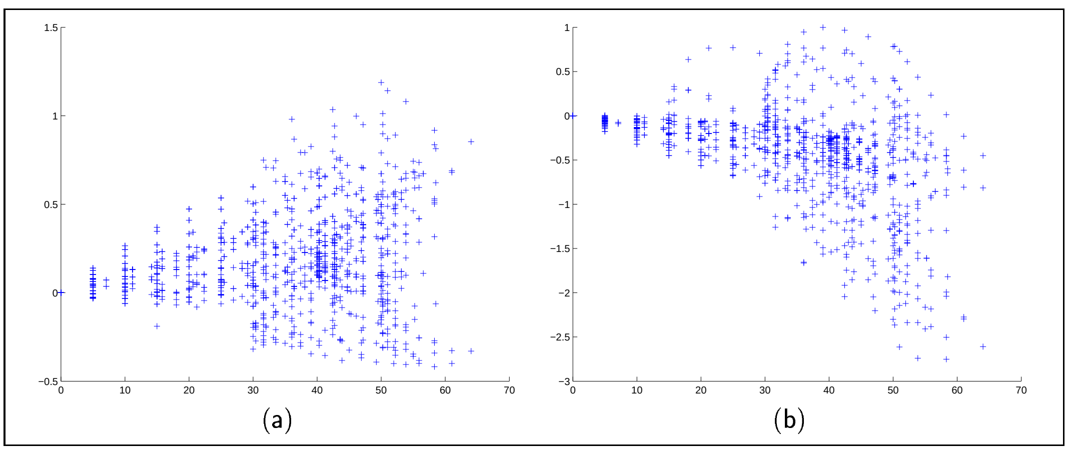

Figure 5: Accuracy assessment. Abscissa : distance between sensor and transmitter, ordinate : the difference between distance calculated with the data given by the robot and distance calculated with the data given by the EPOM device ((a) : Flock of bird and (b) : Fastrak).

Table 1: *Mean error and standard deviation (in cm) for accuracy assessment by distance calculus.*

Distance	**10cm**	**20cm**	**30cm**	**40cm**	**50cm**	**60cm**
Fastrak Mean Error	-0.0777	-0.1952	-0.2472	-0.4527	-0.8111	-1.1085
Flock of Bird Mean Error	0.0465	0.1327	0.2146	0.2625	0.2971	0.5574
Fastrak Standard Deviation	0.0058	0.0501	0.1230	0.2141	0.5259	0.6579
Flock of Bird Standard Deviation	0.0046	0.0195	0.1738	0.1595	0.2916	1.0949

below 20 or 30cm. For particular applications like carotid volume measurement, translation motions are below 10cm. For translation below 10cm, the Fastrak error is below $0.777mm$ and the Flock of Bird error is below $0.465mm$.

4.1.3 Discussion

During clinical exams, the distance between the sensor and the transmitter is contained between $30cm$ and $1m$ and the probe motion is below $50cm$. The present study results show that electromagnetic spatial localizers can be used for routine ultrasound exams.

4.2 Comparison with other studies

Table 2: *Comparison of various studies for static accuracy. The static accuracy of the Afma robot is 0.5mm.*

EPOM device	**Static accuracy for translation**	**Static accuracy for orientations**
Fastrak (manufacturer)	0.76mm RMS	0.15°
Flock of Bird (manufacturer)	1.8mm RMS	$0.5° RMS$
Barratt *et al.* ([1]) (sensor on the probe)	0.16mm @ 39cm	0.286∘ (range:$-0.842°$ - 0.868°)
Milne *et al.* ([13])	1.8%	1.6% (range:1°-20°)
Present Study/Fastrak	1.733 mm	0.54
Present Study/FOB	1.312 mm	0.59

Barratt *et al.* ([1]) and Milne *et al.* ([13]) have only evaluate the performances of the Flock of Bird. In this section, we compare the manufacturers data with the results obtained in[1] and [13] and this current study.

Table 3: *Comparison of various studies for static resolution. The static resolution of the Afma robot is 0.1mm.*

EPOM device	**Static resolution position**	**Static resolution orientation**
Fastrak (manufacturer)	0.061mm @ 30.5cm	0.025°
Flock of Bird (manufacturer)	0.5mm @ 30.5cm	0.1°
Barratt *et al.* ([1]) (with filters)	0.5mm	0.04°
Milne *et al.* ([13])	0.25mm	0.1°
Present Study/Fastrak	0.1 mm @ 60cm	0.05°
Present Study/FOB	0.2mm @ 60cm	0.06°

The results of the static accuracy can not be directly compared because Milne *et al.* report a mean error of 1.8% of the translation step size for steps of 25 to 152 mm along each of the transmitter axes. Barratt *et al.* have only tested static accuracy for very little translation ($\leq$ 90mm). For little translations, Barratt *et al.* are quite better than our results but we assess each spatial localizer accuracy in a large workspace (Barrat *et al.* estimate the accuracy for a sensor-transmitter separation equal to 39cm).

From the two tables 2 and 3, we can see that the environment in which we make experiments interferes with the EPOM device, that decreases their performances. However, even in this environment, performances remain still satisfactory.

Unlike manufacturers specifications and the study described in [15], our experiments do not reveal any significant difference between the two systems. One explaination is that the Fastrak system is more sensitive to metallic objects like the robot than the Flock of Bird ([15]). Moreover, interferences with EPOM wires can appeared. This is the reason why, in our study, the distance between the transmitter wire and the sensor have to be above $40cm$.

5 Theorical Behavior

Distance measurement errors depend on the potential field measure. The distance between sensor and transmitter is related to the potential field [15]:

$$r \propto \nu^{\frac{1}{3}} \tag{6}$$

where s is the sensor-transmitter separation and ν is the potential field. So, distance measurement error is related to the potential field measurement error :

$$\Delta r \propto r^4 \Delta \nu \tag{7}$$

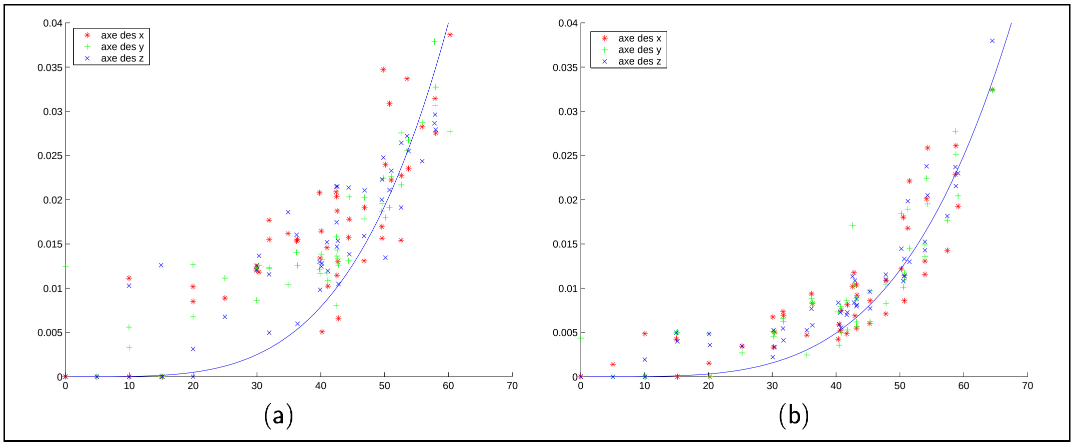

Figure 6: Static resolution for the three axes superimposed on the theorical model ((a) : Flock of bird and (b) : Fastrak).

In the case of electromagnetic spatial localizer, $\Delta\nu$ is constant. The error in the calculated position is :

$$\Delta r \propto d_{ts}^4 \tag{8}$$

where $d_t s$ is the sensor-transmitter separation.

Without any perturbations, the position error is proportional to the fourth power of the transmitter-sensor separation. So, for each tested EPOM device, we have calculated the proportionality coefficient, and we found very similar results for translation and rotation. For translation, the coefficient is around 1.6, and for rotation is around 1 (see figure 6). Even if the results seem to be very similar, the Flock of Bird performances decline faster than the Fastrak performances.

6 Conclusion

According to the studies of [1], it is possible to obtain high precision with commercial system (Flock of Bird) in spite of the presence of an ultrasonograph and in spite of the fact that the sensor was close to the probe. Furthermore, this work shows that the probe had a little influence on the results obtained with Flock of Bird. Barratt *et al.* ([1]) has noticed that for the Flock of Bird the influence of the distance between transmitter and sensor is less important than the influence of the present echograph in the operating room.

In the domain of augmented or virtual reality, EPOM device calibration is often performed, this stage allows to decrease measurement errors. Many error correction methods have been proposed ([10]). But, ultrasound exams are not always made in the same room and each room configuration is particular. Sensor calibration depends strongly on the room configuration. This explains why error correction methods are not easily applicable in clinical environment. In this context, a hybrid system for surgical environments is presented in [3]. Electromagnetic devices can not be used in surgical room, so hydrid system can be an elegant solution for surgical environments where optical trackers are already installed, but for routine exams, due to the flexibility requirement, hybrid system can barely be a solution.

The present study shows that electromagnetic devices provide sufficient accuracy for use in a 3D ultrasound system for routine exams.

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