ULTRASONIC MOTION TRACKING OF INSTRUMENTS IN OPERATING THEATRE

Alejandro Ibarz, Roberto Casas, Álvaro Marco, Héctor Gracia, Rubén Blasco and Jorge Falcó
Instituto de Investigación en Ingeniería de Aragón,(Tecnodiscap Group)
Universidad de Zaragoza. María de Luna 1, Zaragoza, Spain

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Abstract: The purpose of this paper is to address the design of a system to track surgical instrument's movement during an operation. Motion tracking of surgical instruments is one of the most interesting methods to survey the data needed for medical robotics, computer-aided surgery, skills assessment and training progress applications. Over the wide range of tracking technologies, low frequency ultrasound was selected to meet the system's requirements. Factors that bring about measurement inaccuracies are analysed and taken into account when developing the system. Furthermore, a localization algorithm that calculates three-dimensional position using one-dimensional distances and overriding signal blockage is presented. Moreover, experimental results of a resectoscope mock up motion tracking are shown.

1 INTRODUCTION

With the spread of minimally invasive surgery and training in this field, development of metrics for medical robotics, computer-aided surgery, skills assessment and training progress has become increasingly important.

There is a wide range of technologies for motion tracking: computerized tomography, nuclear magnetic resonance imaging, video-based imaging, ultrasound imaging, optical tracking systems, electromagnetic tracking systems, inertial, ultrasound positioning, etc. They can be characterized according its price, complexity, accuracy and drawbacks. Most of these technologies are not suitable for designing a indoor positioning system meant for operating theatres (Tatar, 2006; Bianchi 2007). However, low frequency ultrasound positioning offers promising perspective measuring one-dimensional distances. Moreover, a more thorough analysis will be done to use low frequency ultrasound for motion tracking purposes.

The purpose of this paper is to design an ultrasound indoor positioning system. It has to be able to track the motion of a surgical instrument during the operation. Furthermore, system's requirements are low-cost, low-complexity and accuracy enough to track instrument's position properly. The final and most important requirement is that devices placed on the instrument can not restrict surgeon's movements or put the patient in risk.

Concerning the exactitude of the system, the design of the electronics will be analysed, as well as the method of time of flight measurement to obtain an accuracy of millimetres. In order to obtain this accuracy, it will be necessary to analyse the influence of environmental factors and correct its effects. The ultimate goal is to objectively assess instrument localization in a realistic environment; i.e., the operating room.

2 ULTRASONIC TRACKING

Generally speaking, ultrasonic positioning systems are based on different subsystems: transducers on the mobile that needs to be located, transducers places on known positions and one or several computing units (PC, microprocessor or DSP). In order to obtain mobile's unknown position; one-dimensional distances from fixed transducers to mobile transducers have to be surveyed. After obtaining the one-dimensional data, mobile's coordinates can be calculated by a computing unit using a location algorithm.

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A generic ultrasound positioning system has been described. Afterwards, the system has to be adapted to the operating theater characteristics.

The system's architecture is as follows:

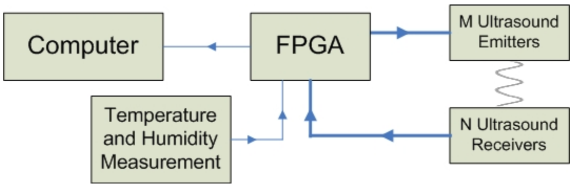

Figure 1: System's architecture.

Emitting transducers (at least 3 to determine mobile's position) need to be placed on the surgical instrument on known position (in order to compute the instrument's position).

Receiving transducers have to be placed on the ceiling to avoid non-line of sight issues. To ensure good performance of the system, the coordinates of receiving transducer should be known as much accurate as possible.

The FPGA assigns a temporal interval to each emitter module. It commands the emitter to generate ultrasound chirps; simultaneously the ultrasonic time of flight (TOF) to the receiving transducers will be computed and stored (as well as ambient temperature and humidity). After the FPGA sends all surveyed data, the computer will obtain the coordinates of all emitting transducers and the instrument's position.

2.1 Ambient Influence in Operating Rooms

In this sub chapter, several factors that may affect system's performance will be analysed. This analysis will take into account operating room (OR) ambient characteristics and several others considerations that may bring about measurement inaccuracies.

Update rate: The frequency of the measurements reported by the tracking system. The higher this parameter the better tracking results are obtained. The TOF system has a low update rate caused by the low speed of sound and the sequential triple emission of pulses.

Misalignment between transducer pairs: Due to the quantity of receiving transducers and the wide range of mobile's movements, we cannot expect to have perfect alignment between transducers pair (emitter-receiver). It has been stated (Lamancusa, 1990) that misalignment between transducer pairs will bring about a distance measurement error.

Ultrasound wave reflection on surfaces: Reflections on surfaces has been used in ultrasound distance measurement systems, using echoes to determine distances to surfaces. Nevertheless, considering the number of medical instruments in OR (lamps, monitors, tables), echoes might bring about measurement errors to our system and affect system's robustness. Therefore, reflection on surfaces should be analyzed and taken into account in system's design.

Airflows: Most of these systems are based on calculating the ultrasound TOF and multiplying it by the sonic air speed to obtain the distance. Therefore, airflow will modify the speed which the ultrasound moves in the air.

Temperature: The temperature is an environmental factor to consider when designing an accurate ultrasound positioning system, as it affects the speed of sound (Liao et al, 2004).

Relative Humidity: The relative humidity modifies the speed of sound, affecting distance measurement (Liao et al, 2004).

Table 1: Inaccuracies due to ambient factors.

Parameter	Accuracy	Max. Error
Temperature	0.3 º C	1.77 mm
Humidity	1.8 % RH	0.4 mm
Misalignment	---	1 mm
Airflows	---	1.3 mm
Total	---	4.4 mm

2.2 Distance Measurement

Once analysed the environmental factors (table 1) that influence distance measurements, we will analyse the measurement process. This part includes: generation of ultrasonic chirps, reception and treatment of the signals; and determination of TOFs.

TOF is the time elapsed between the transmission of a pulse and its reception, from which the target distance can be calculated multiplying speed of sound in air by TOF. Using TOF to measure the distance, the system errors are primarily due to amplitude degradation of the received signal, and uncertainty in the speed of sound.

There is a close relation between generation of ultrasonic chirps and the method to determine TOFs and distances (Tatar, 2006; Huang et al, 2002). Moreover, the chirp generation method can affect system's performance. For example, some methods require longer chirps, lowering system's update rate and making them less robust to reflections on surfaces.

The chosen method of emission was based on self-interference (Cai, 1993), using short chirps and giving the signal in reception a specific form that will take be used to determine TOF and afterwards the one-dimensional distance. Allocating an event on the signal close to its start will make the method more robust to reflections on surfaces.

The method implemented in the FPGA consists on storing several time stamps of the moments when the signal exceeds a predefined threshold. These data are processed through an algorithm in the FPGA to determine where the event is located, and afterwards this time is corrected to obtain the TOF.

Experimental tests were done to assess the precision of determining the TOF using this method. Placed both emitter and receiver at a fixed distance, the distances obtained had a standard deviation of 300 µm and a resolution of 7 µm. The system was also able to measure distance between transducers with a high degree of misalignment.

2.3 Location Calculation

2.3.1 Problem formulation

We have to solve the classic multilateration problem. Calculate the position of the transmitter (x_P,y_P,z_P) from the estimation of several distances (d_i) to emitters having known coordinates (x_{bi},y_{bi},z_{bi}). Distances have been estimated as indicated in previous subsection.

At least three distances are required to solve the aforementioned trilateration problem. Unfortunately, this is not typically the case in real operations where one or more of the distances may contain large errors produced by multipath effects and the blockage of the ultrasonic signal.

2.3.2 Location Algorithm

Our aim is to solve the proposed problem when it is not possible to use any prior information to solve the multilateration. It is not possible to identify the measurements affected by error, or whether there are any. In the end, there is redundant data within unidentified, erroneous information, which must be filtered out to compute the best solution.

Robust estimators provide methods for detecting outliers, and they obtain trustworthy results even when a certain amount of data is contaminated. The LMedS method used (Casas, 2006) searches in the space of solutions obtained from subsets of the minimum number of data. As we require a minimum of three distances to compute the location and there are a total of n, we make m subsets of three distances:

$$m = \frac{n!}{3!\,(n-3)!} \qquad (1)$$

For each subset Si of distances (du, dv, dw), we compute a location Pi (xi, yi, zi) by solving the system of equations of using any traditional technique such as least squares:

$$\left.\begin{aligned} d_u &= \sqrt{\left(x_i - x_{BSu}\right)^2 + \left(y_i - y_{BSu}\right)^2 + \left(z_i - z_{BSu}\right)^2} \\ d_v &= \sqrt{\left(x_i - x_{BSv}\right)^2 + \left(y_i - y_{BSv}\right)^2 + \left(z_i - z_{BSv}\right)^2} \\ d_w &= \sqrt{\left(x_i - x_{BSw}\right)^2 + \left(y_i - y_{BSw}\right)^2 + \left(z_i - z_{BSw}\right)^2} \end{aligned}\right\} \qquad (2)$$

where i = 1,…,m and (xBSj, yBSj, zBSj) are the coordinates of BSj being j = u, v, w.

For each location Pi, we obtain the residues Ri as:

$$\begin{aligned} \mathbf{R_i} &= \left(\left(d_1 - \hat{d}_{i1}\right)^2, \left(d_2 - \hat{d}_{i2}\right)^2, \ldots, \left(d_n - \hat{d}_{in}\right)^2\right) \\ \hat{d}_{ik} &= \sqrt{\left(x_i - x_{BSk}\right)^2 + \left(y_i - y_{BSk}\right)^2 + \left(z_i - z_{BSk}\right)^2} \qquad (3) \\ k &= 1, \ldots, n \end{aligned}$$

And compute the median Mi of the residues Ri.
The final solution P (x, y, z) is that with the minimum median Mi.

2.4 Instrument's Localization

As an experimental implementation (figure 2), a motorized resectoscope mock up have been used. The distances between emitters and receivers were processed by the computer through the localization algorithm in order to obtain the instrument's unknown position.

According the results (figure 3), can be stated that the system has a good dynamic behavior. Moreover, can be stated the good performance of localization algorithms and solution filtering.

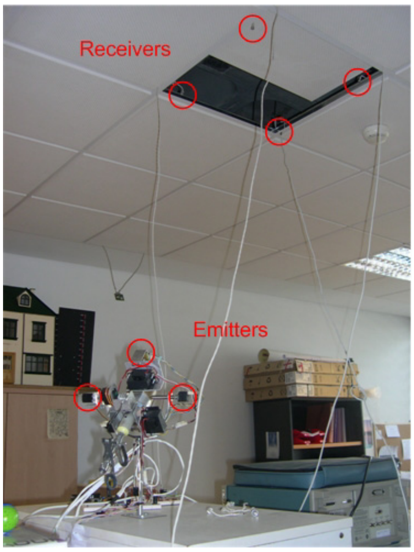

Figure 2: Mock up implementation.

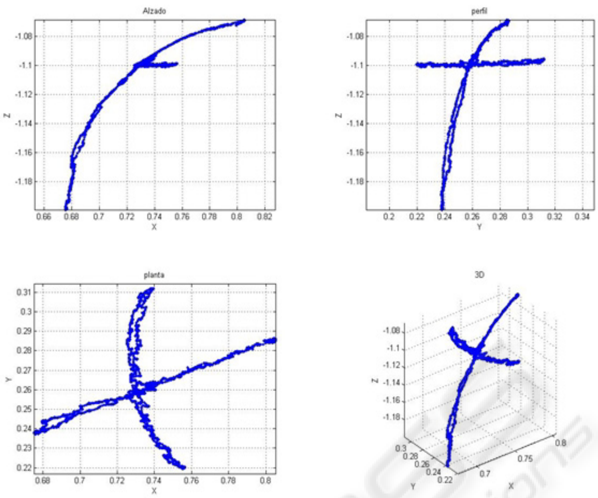

Figure 3: Motion tracking.

3 CONCLUSIONS

As result of this research, a low-cost and low-complexity indoor positioning system has been designed. It meets the requirements stated previously, to fit in a motion tracking application.
The method of determining TOF has a good precision for fixed distances (300 µm) and good performance with high misalignment between transducer pairs. Adding all sources of one-dimensional distances' inaccuracies (worst case scenario), the error might reach 5 mm. This error translated to three-dimensional positioning would mean 8 mm.

Regarding the reliability of the system, with the inclusion of the controlled emission, the system has been able to create signals in reception with a characteristic form. This effect brings about advantages when dealing with reflection on surfaces, important factor in an operating room. In addition, the system will be more robust to external noises in the work frequency. In terms of scalability, the developed system is able to capture the data from up to 20 receiving modules. Observing the obtained results, we can conclude that the system performs in a satisfactory way the motion tracking of the instrument's position and movement.

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