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CROSS-CORRELATION METHOD APPLIED TO AN ULTRASOUND SYSTEM FOR MEASURING POSITION AND ORIENTATION OF LAPAROSCOPIC SURGERY TOOLS

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Abstract- A new ultrasound wireless positioning system is developed that gives the surgeon the exact location and orientation of the instruments in the patient. The measuring system employ ultrasound markers placed on the instruments, outside of the human body. Knowing the dimensions of the usually rigid instruments it is possible to calculate their position and orientation inside the patient from the markers' positions. Using the cross-correlation method we obtained a resolution of 0.7 mm in determining the marker positions.

To eliminate wiring to the tools a wireless radio wave (RF) system is used to trigger the ultrasound sensors.

Keywords- ultrasound, 3D-detection, cross-correlation

1. APPROACH

In minimal invasive surgery usually an endoscope is used to show the surgeon what is happening inside the human body. However, this view is very limited and gives no information of instrument positions outside the camera view. Even the use of 'standard' imaging techniques like X-ray, ultrasound, MRI and CT scans, before or during the operation, do not solve this problem satisfactorily.

The system to be developed should include a marker or transmitter on the laparoscopic instrument, endoscope, and the trocar. The other part of the system will include the tracker for the markers. This piece of equipment must determine the 3-dimensional position of the different markers/transmitters with respect to each other. In addition, the systems must not interfere with the actions performed by the surgeon needed for the operation. Therefore, the markers must be small and light, preferably wireless and easy to attach to different instruments.

In our set-up two pairs of ultrasound markers (transmitters) placed on each instrument are used to measure the position and orientation of the instrument [1]. The position of a single laparoscopic instrument will be described by 2 XYZ measurements along the instrument. When the rotational position information is also required a third measurement point might be necessary. Different options exist (with the restriction that markers do not enter the patient's body). For example, one measurement can be done on the trocar and the other on the instrument handle. Together with the known length of the instrument the exact position and orientation of the instrument tip can be calculated. The detection of the marker positions is realized by an array of ultrasound receivers. Data is read at every corner of a square with the dimensions of 2x2m situated in a horizontal plane above the surgical table. In each corner a mini array of 3 to 4 receivers is placed to 3-dimensionally locate the transmitter positions. A number of 3 receivers is sufficient for using the time of flight technique of measurement. The 3D position is calculated directly from standard geometrical equations. The fourth receiver in each array will produce redundant information that can be used to check the validity of the position calculation. Figure 1 shows the schematic placement for receivers and transmitters.

We focused our efforts on the methods used for ultrasonic detection of position. The most widely used one is based on a pulse time-of-flight (TOF) estimation.

The distance between the transmitter and the receiver site is:

D = TOF *V, where V is the sound velocity, and D the distance.

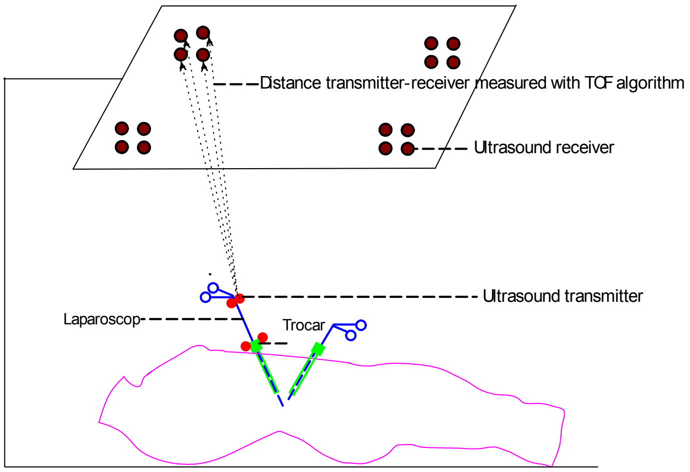

Fig.1 The positions of ultrasound transmitters on surgical instruments and the receivers in a horizontal plane situated above the surgical table.

The ultrasound transmitters are triggered by radio wave signals. For this purpose the marker modules include RF receivers that react on the correct identification code only.

These RF trigger codes are sent by a central RF transceiver and are provided by a DSP unit, which controls the whole process and derives position information from the ultrasound signals. The schematic of the whole system is described in Fig .2

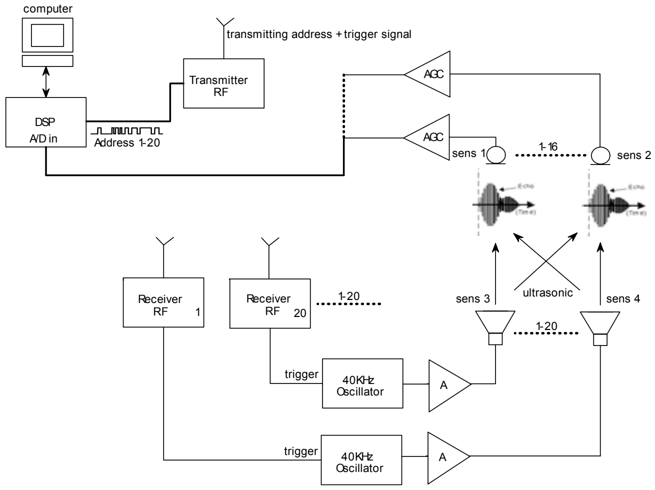

Fig 2. The schematic view of the localizing system

With preliminary TOF measurements we estimated the influence of temperature, humidity and air pressure on the velocity of sound, which is linearly correlated to the distance. While humidity and air pressure have only very little influence on the distance measurement, the temperature has a dominant effect. The temperature effect can be compensated with a simple equation that correlates variations in temperature in a surgical room with variations in sound velocity. [2]

Various methods have been developed to improve the TOF measurement accuracy. The simplest and most economical of them offer a poor resolution [3].

The goal is to investigate the possibility to improve our TOF acoustic measurements in a medical environment, using digital techniques. One of most used techniques for TOF detection is the cross-correlation method. [3]

The measurement system acquires the two digital sequences $x_T(nT)$ and $x_R(nT)$ representing the transmitted and received signals, respectively, than can be written in the form

$$x_T(nT) = s(nT) + v(nT)$$
$$x_R(nT) = \alpha\, s(nT - TOF) + n(nT)$$

where T is the sampling interval , while v(nT) and n(nT) take into account the discrepancies from the ideal model and can be considered as zero mean uncorrelated random processes.

s(t) is the signal generated by an ultrasonic transducer and is a short train of acoustic waves than can be represented in the form

$$s(t) = a(t) \sin (2\pi f_0 + \Phi_0)$$

where f_0 is the resonant transducer frequency and the pulse a(t) represents the signal envelope and has finite duration.

- α is the a factor of signal attenuation.

Figure 3 represents an signal received by an ultrasound transducer with a resonant frequency of 40 KHz.

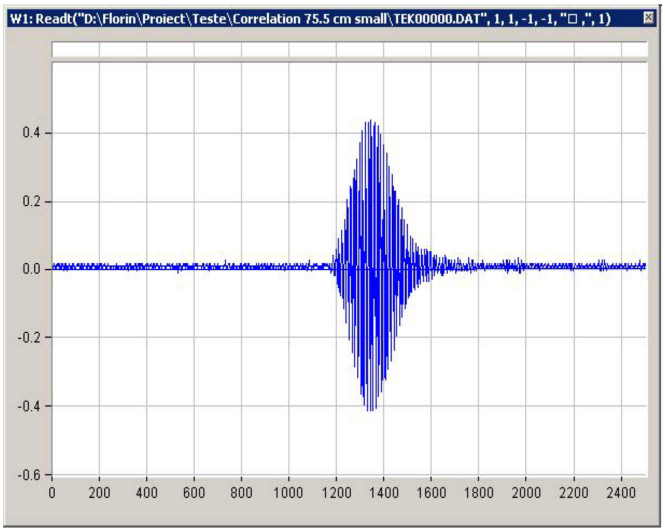

Fig. 3 Ultrasound signal received by an ultrasound transducer of 40KHz frequency

The cross-correlation of sequences is given by:

$$C(kT) = \sum_{-\infty}^{+\infty} x_T(nT)\, x_R(nT+kT)$$

The maximum values of C(kT) is localized in time close to C (TOF). [3]

Thus the TOF is estimated by searching for the maximum of C(kT).

The transmitted and the received ultrasonic signal are digitized by a DSP unit, and the maximum of the cross-correlation function between these two sequences yields the TOF.

Figure 4 shows the typical cross-correlation of two ultrasound sequences delayed in time. The novelty of our approach is to replace the model for the transmitted signal with the last received digitized sequence memorized by the DSP. Since the time slot between two consecutive ultrasonic signals from the same marker is less than 100 ms, the signal envelopes will show only minor differences. This allows a more accurate correlation.

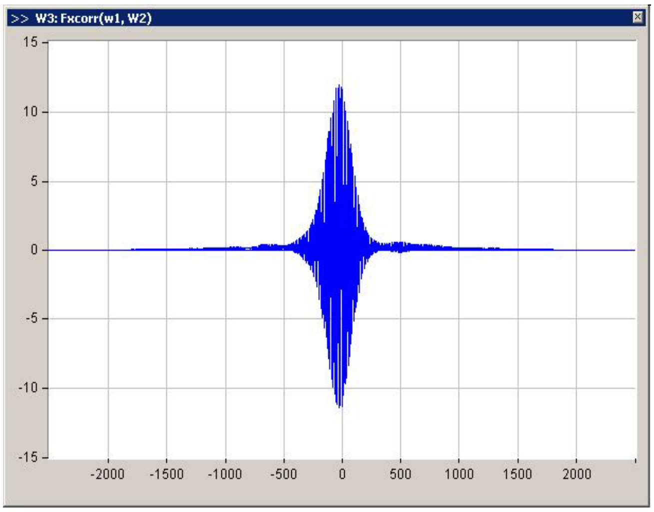

Fig.4 The cross correlation for two ultrasound signals delayed in time

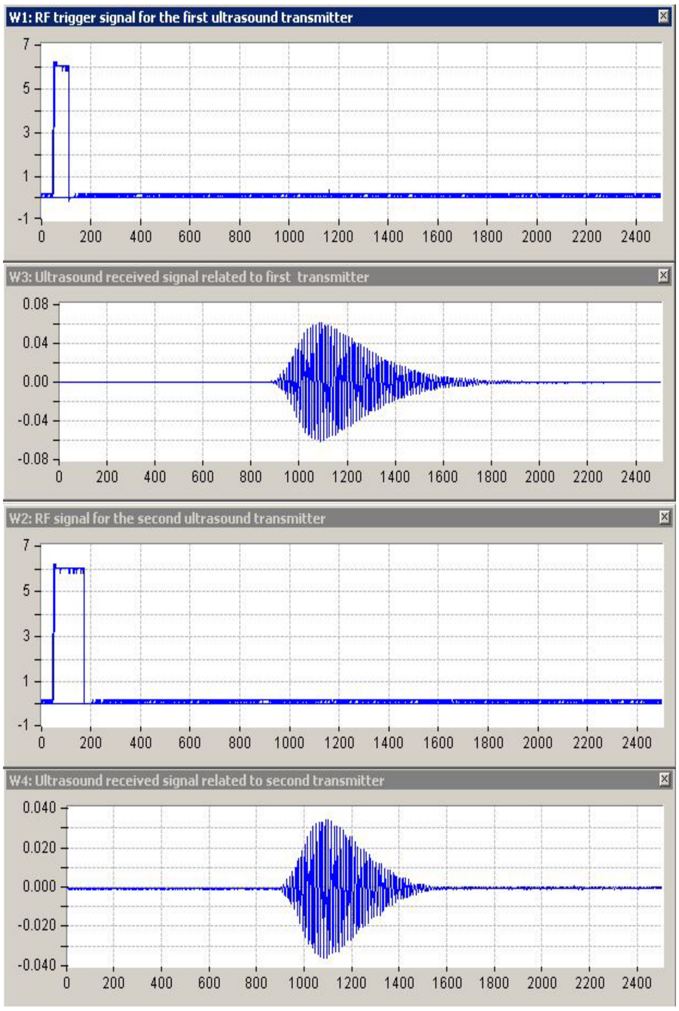

Fig.5 The ultrasound bursts received from different transmitters, triggered with different RF codes

2. RESULTS

The first measurements for the received ultrasonic signals were made for a distance transmitter-receiver of 1.69 m.
Two ultrasound transmitters react to two (different) RF trigger codes generated by the DSP. Figure 5 shows the ultrasound signals acquired from the two different ultrasound transmitters. The ultrasound transmitters are reacting exactly to their specific code.
The distance transmitter–receiver for one transmitter was changed 5 times with 5mm steps and the received signals were acquired and sampled with a 500 kHz sample rate. Figure 6 is representing the two bursts for two consecutive sensor positions and the cross-correlation function between them. The last graph from Fig. 6 shows the cross-correlation function for these two received signals. The maximum value of the function is correlated with 5 mm deviation of the transmitter position. Analyzing a set of consecutive cross-correlation sequences related to a set of 5mm standard deviations of the transmitter position we obtained a resolution of 0.7 mm with a sampling rate of 500 kHz of determining the transmitter position. Increasing the sampling frequency will increase the resolution. The maximum absolute error of measurements was about 2.8 mm for a distance of 1.69 m.

In this preliminary setup the time slot between two measurements was 1-2 minutes, because displacements were made manually. In the final system the time slot will be 100 ms or less. This will decrease the relative error.

Furthermore advanced DSP filter algorithms could reduce the influence of noise and could increase the accuracy.

3. CONCLUSIONS

The principle of a wireless ultrasound system for measuring the 3D position of laparoscopic instruments was discussed. By triggering the ultrasound transmission with an RF signal and cross correlating two consecutive bursts, the relative ultrasound transmitter position could be determined with a resolution of 0.7 mm. The maximum absolute error of measurements was about 2.8 mm for a distance of 1.69 m.

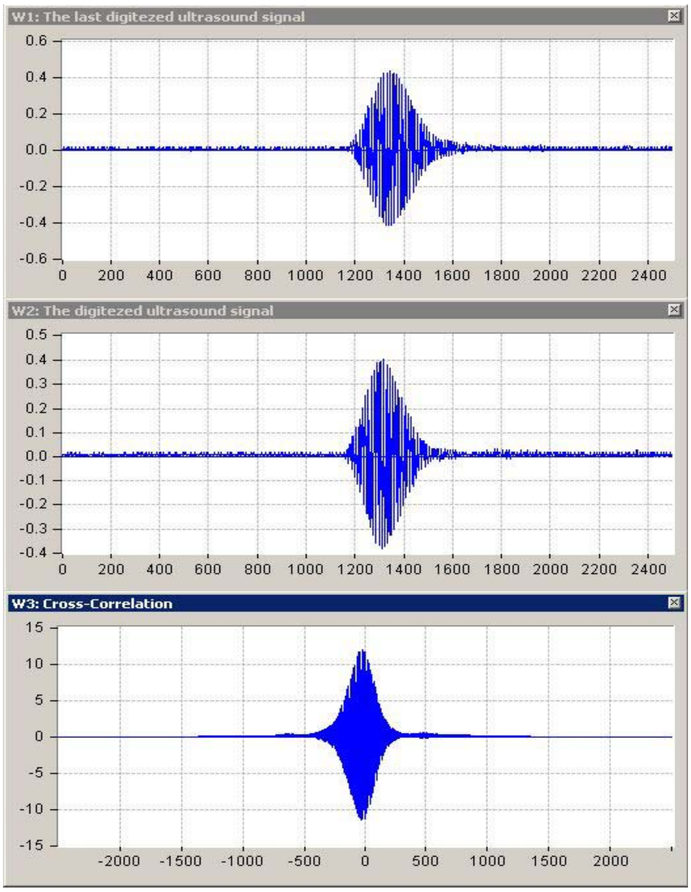

Fig 6.The cross-correlation function of two signals received after a change of 5 mm in transmitter position.

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