ELSEVIER
Sensors and Actuators A 101 (2002) 311–321
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Estimating the 3D-position from time delay data of US-waves: experimental analysis and a new processing algorithm

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Received 26 January 2002; received in revised form 4 June 2002; accepted 17 June 2002

Abstract

This paper analyzes the main sources of error in an ultrasonic 3D position measurement system: these include shadowing of some of the receivers, wave interference, air turbulence and the effect of the wind. Some of these phenomena appear as outlier noise in the measurements, against which conventional statistical methods do not give good results. A new algorithm is suggested which improves precision and robustness, by taking advantage of the redundancy in the number of measurements and the use of a modified trimmed median (MTM) filter. The performance of the new technique is demonstrated experimentally in a robotic 3D positioning system, achieving an error inferior to 1 mm in a $3\,m \times 3\,m \times 3$ m work area.

Keywords: 3D-position measurement; Ultrasonic signals; Time-delay estimation

1. Introduction

In GPS systems, there are a number of transmitting satellites at known positions and one receiver. Measuring the time delay between the different received signals, using the known position of each satellite and the propagation speed of the electromagnetic waves, the (*x*, *y*, *z*) coordinates of the receiving point can be computed when at least four transmitting satellites are detected. In practice, a minimum of seven satellite signals is required to confirm a valid signal.

The ultrasonic local positioning system developed is based on a similar principle: there is only one transmitting element at the point whose position we want to measure and we place a number of receivers at known positions in our referential frame (see [1] for a description of a predecessor of this system). Using the position of the receiver, the measured delay times and the sound propagation speed, the position of the transmitting point can be computed (see Fig. 1).

There are several strategies to estimate the spatial location of an object of interest using time delay measurements. When we know the time elapsed t_i from the emission to the reception (time-of-flight, TOF) at each receiver *i* and the distance d_i from the transmitting point to each receiver can be estimated using the speed of sound v_s, the determination of the unknowns (*x*, *y*, *z*) can be formulated as the intersection of three spheres, i.e. solving the following non-linear system of equations:

$$\{d_i^2 = t_i^2 v_s^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2\}_{i=1,\dots,3} \quad (1)$$

where (x_i, y_i, z_i) are the coordinates of the *i*th receiver. One way to estimate the positions is by algebraic computation, which is not easy if the receivers are placed at arbitrary positions. In order to simplify calculations, many authors require the receivers to be located at very precise points along orthogonal axes on the reference system to make some of the (x_i, y_i, z_i) terms to be zero [1,2]. The use of pseudo-inverse techniques transforms the system of non-linear equations into a linear expression using a 4×4 matrix and a dummy variable [3]. This approach implies that it is necessary to use one receiver more than the number of variables to estimate.

Iterative methods [2], such as Gauss–Newton or Marquant Levenberg iteration, are more time-consuming but are very flexible, giving good results as long as the iteration does not find a local minimum. They look for the values (*x*, *y*, *z*) that minimize expressions of the type:

$$\sum_{i=1}^{n}\left(t_i v_s - \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}\right)^2 \quad (2)$$

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0924-4247/02/$ – see front matter © 2002 Published by Elsevier Science B.V.
PII: S0924-4247(02)00211-X

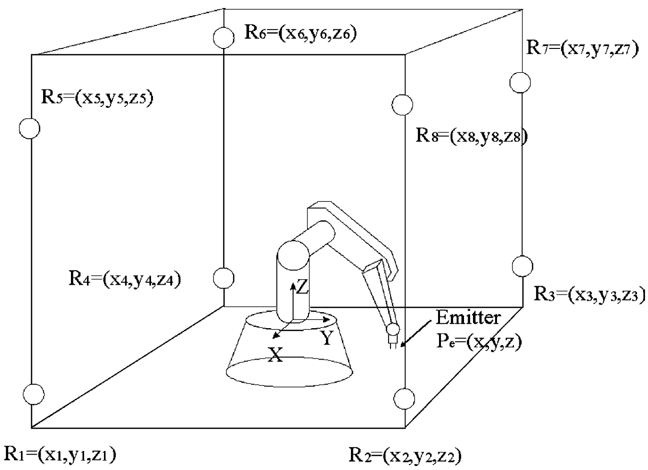

Fig. 1. Geometric setup of the measurement system.

In such techniques we have the flexibility of processing an indeterminate number of measured times n_i corresponding to references[1] situated at arbitrary positions (x_i, y_i, z_i).

Using the minimum-required number of references ([3] or [4] depending on the estimation method) results in a non-robust behavior; the position estimation is very sensitive to bad estimation of a single TOF. In order to improve the reliability, it is usual to employ a redundant set of references, i.e. to use more references than variables to estimate ($n > 3$).

Both, pseudo-inverse and iterative methods, admit this redundancy in their algorithms by increasing the size of the matrix or increasing the set of data points in the sum of the minimization function, respectively. The problem is that both approaches consider a least square minimization (LSM). It is known that LSM is not robust against outliers, therefore, the redundancy in the system works well when only Gaussian noise is present on the TOF measurements. A χ^2 minimization can be formulated, giving less weight to TOF measurements with higher standard deviation. These estimation algorithms perform better under outlier noise but do not cancel errors completely.

In ultrasonic range measurements, we have found experimentally the presence of outliers caused by: (a) shadowing of some receivers by an obstacle; (b) wave interference; and (c) air turbulences. The importance of these phenomena in the position measurement error has been acknowledged by other authors [3]. These outliers invalidate some of the measurements times t_i of a given set, and cause a large deviation in statistical methods. Thus, the need for a combination of a redundant configuration and a robust estimation method.

The method we propose below has the flexibility of the minimization methods with a lower and predictable computational effort, and it is shown to be more robust against outlier noise.

[1] We use the term references to account for the general situation of several emitters and one receiver (as would be the case of a GPS system) or the opposite, several receivers and only one emitter (more typical of ultrasonic ranging setups).

2. Processing method

As a first step, we will show that using the minimum number of [3] in the case of direct TOF measurement, the analytical solution is not so complex as it seems. For each three receivers we create a Cartesian reference frame, which we denote by primes. The frame is chosen as having the origin at the first reference ($x'_1 = 0, y'_1 = 0, z'_1 = 0$), the positive x axis containing the second reference ($y'_2 = 0, z'_2 = 0$) and the third reference contained in the xz plane ($y'_3 = 0$). The set of Eq. (1) becomes:

$$\left.\begin{aligned} d_1^2 &= (x')^2 + (y')^2 + (z')^2 \\ d_2^2 &= (x' - x'_2)^2 + (y')^2 + (z')^2 \\ d_3^2 &= (x' - x'_3)^2 + (y')^2 + (z' - z'_3)^2 \end{aligned}\right\} \tag{3}$$

For this case we can find the two solutions for the intersections of the three spheres as:

$$\left.\begin{aligned} x' &= \frac{d_1^2 - d_2^2 + {x'_2}^2}{2x'_2} \\ z' &= \frac{d_1^2 - d_3^2 + {x'_3}^2 + {z'_3}^2 - 2x'_3 x'}{2z'_3} \\ y' &= \pm\sqrt{d_1^2 - x'^2 - z'^2} \end{aligned}\right\} \tag{4}$$

Making two coordinates transformations: first from the coordinates of the references (x_i, y_i, z_i) to the mentioned reference system (x'_i, y'_i, z'_i) and second of the found (x', y', z') estimations to the original frame, we have the solution at the original system.

At this stage, we have a way to calculate the (x, y, z) estimation that corresponds to the minimum number of references. We repeat this procedure for all the possible combinations of references and consider each one as a different estimation. In general, all possible sets of three receivers from a group of N are:

$$M = \binom{N}{3} = \frac{N!}{3!(N-3)!} \tag{5}$$

For each receiver set, there are two possible solutions which are symmetrical to the plane containing the receivers. Therefore, we have $2M$ estimations for each of the coordinates (x, y, z), which are reduced to a set of M unique estimations by application of a filter modified trimmed median (MTM). We do that separately for each coordinate due to the fact that a triplet of receivers can give a very good estimation of one coordinate, while it fails for other, as we will see below.

The MTM filter can be summarized as follow: sort a list of values in ascending order, get the value at the middle of the sorted list (the median value), use this median value as a central value to start a mean filtering using only those values around the median within a 3σ window (σ, standard

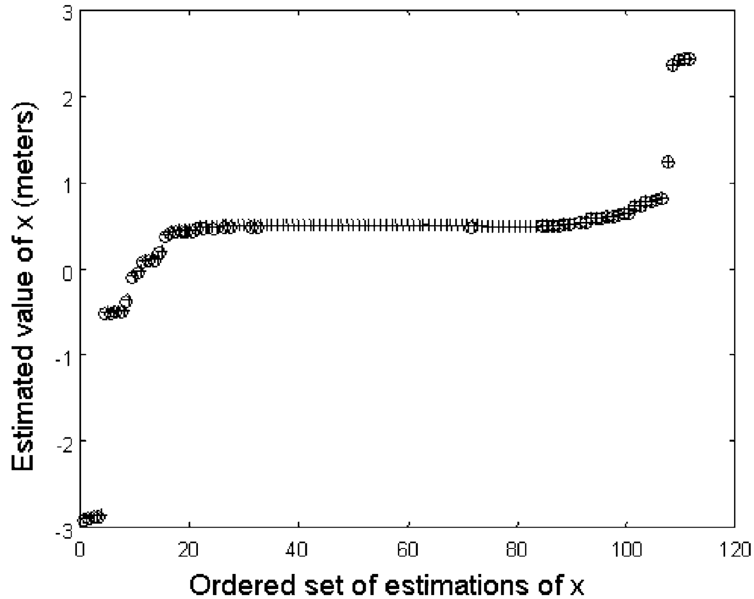

Fig. 2. Ordered set of estimations of x: +, all estimations; o, second solution estimations.

deviation). The result is that many values are not taken into account (the outliers that are at the extremes of the sorted list) but the non-outliers are averaged, therefore, providing a reliable and accurate estimation. Fig. 2 shows a set of estimations for an actual measurement.

It is important to remark that half of the elements in these lists of $2M$ elements contain implicit outliers (the non-valid solutions due to the symmetry). Considering a regular distribution of receivers around the working volume, it can be demonstrated that 25% of the implicit outliers go to the left of the sorted list, an another 25% go to the right as we can see in the Fig. 2. Note how outliers are at the extremes of the list and the correct value for x (0.5 m in this case) can be robustly estimated rejecting the non-valid solutions. Other techniques could be used to generate a list of just M elements directly, for example using the receivers orientation information to select the valid one from the two solutions, although it is not always possible to distinguish the valid one, for example when both solution are too close to each other. The arithmetic mean on these estimations would result in an optimal behavior for both cases: Gaussian noise and outliers noise. We expect that the first step (median filter) would cancel outliers while the

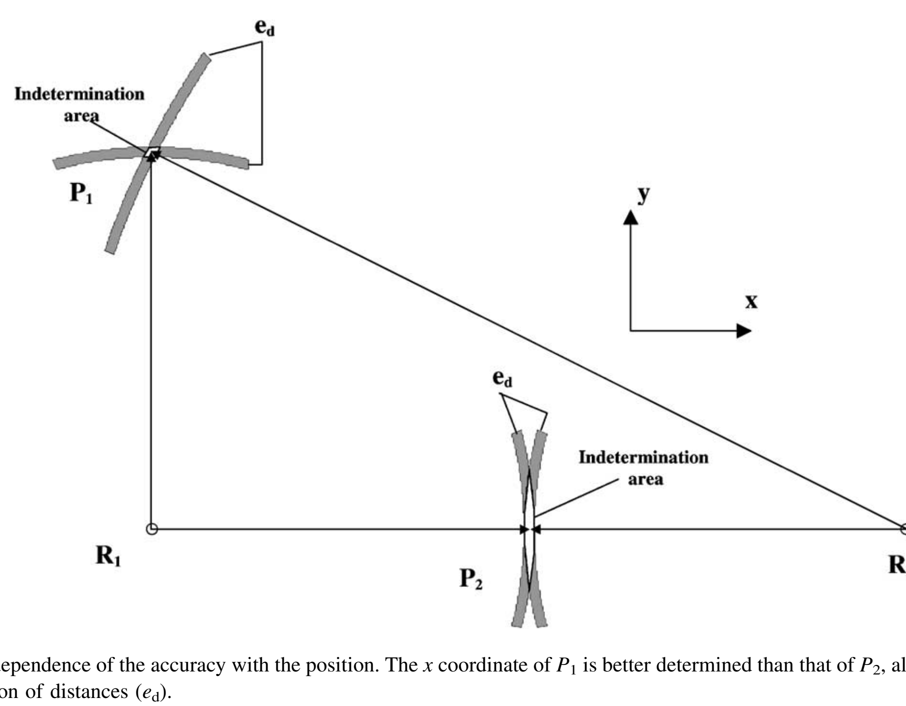

Fig. 3. Illustrating the dependence of the accuracy with the position. The x coordinate of P_1 is better determined than that of P_2, although they have the same error in the determination of distances (e_d).

second step (mean) would diminish the influence of Gaussian noise. The minimum requirement for a reliable estimation is that at least three receivers are free of outlier noise, which seems to be a reasonable request.

3. Influence of the relative position of the receivers

Another important remark about the configuration of the references is that there can be situations where small errors in the time measurement causes a big error in coordinates estimation, see Fig. 3 for an illustration of this phenomenon for the 2D case. In this figure we have the same pair of receivers (R_1, R_2) with similar precision in the estimation of the distance to the transmitting points (P_1, P_2), but the estimation of the y coordinate of the point P_2 would suffer from a larger indetermination. The same situations appear for 3D systems: the situations where the solution is found by the intersection of three spheres at perpendicular angles are more accurate than those solutions where the spheres intersect tangentially. Therefore, it is important to have more receivers than strictly needed and confirms that, even in the absence of external disturbances, some triplets would give much better results than others. It is also one of the reasons to consider the estimations for each coordinate individually, because triplets that give a reasonable result for one coordinate might do not so well for others.

4. TOF versus delay between references

We call TOF the time interval elapsed from the emission of the wave to the reception while we speak of delay between references as the time elapsed between different receptions. Absolute measurement of the TOF requests an extra synchronization signal. Mathematically we can solve the problem of the absence of this synchronization signal using an additional reference; again we have three equations and three variables to estimate:

$$\left.\begin{aligned} v_s t_{12} &= \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} - \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} \\ v_s t_{13} &= \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} - \sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} \\ v_s t_{14} &= \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} - \sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2} \end{aligned}\right\} \tag{6}$$

where t_{ij} is the delay time elapsed between the reception at receiver i and receiver j. The analytical solution is somewhat more complex but still possible. The use of delay time measurements has an important physical advantage: we can correct for many bias errors, namely, delays in the transducers or differences in the shape of the echo waveform (which is dependent on temperature [1,5]), delays in the electronic circuits, bias errors of the measurement algorithm used to estimate the times, etc. In addition, other sources of errors can be reduced, for instance dependence of the inclination of the transmitting element.

5. The transmitting element

We have tested three different transducer arrangements (see Fig. 4) as transmitter: a sparking device (A); a set of piezoelectric ceramic discs (B); a PVDF cylindrical

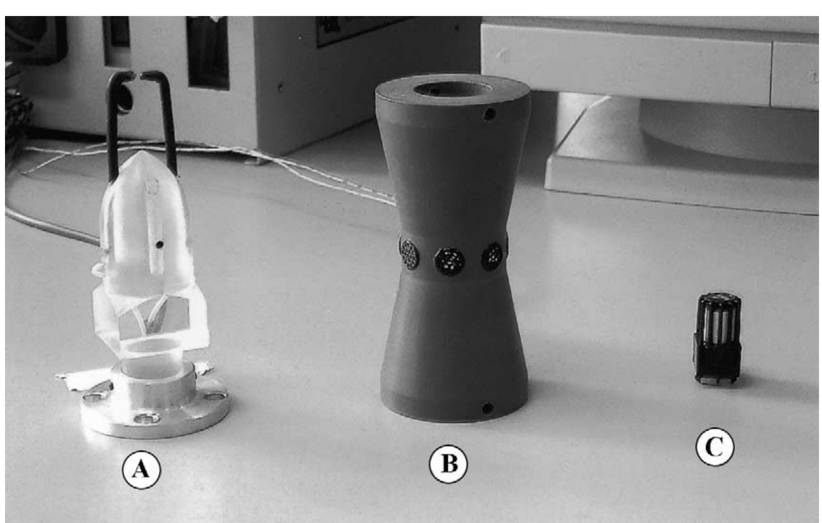

Fig. 4. The three transmitters studied: (a) sparking unit; (b) set of piezoelectric ceramic; (c) PVDF transmitter.

Table 1
Comparison of the three transmitting elements

	Transmitting energy	Precision (mm)	Vertical measurement range (°)	Point-like behavior
Spark (A)	Low	1	70	Good
PZT (B)	High	0.1	100	Bad
PVDF (C)	Medium	0.3	175	Medium

transmitter (C). A short description of each transducer as well as quantitative data of their performance follows.

We characterize each sensor by the following magnitudes: (a) precision (deviation between consecutive measurements, which is of statistical nature); (b) signal strength (actually (a) and (b) are related); and (c) vertical emission range.

The sparking element [1] is housed in a metacrillate holder especially designed to avoid interferences of the direct transmitted wave with the waves reflected at the holder. The electrodes are made of brass, showing less degradation than other metals tested, and its design together with the Teflon cover are optimized to produce more stability by forcing the spark to be confined in a reduced region. The amplitude of the generated signal is relatively lower than for the other transmitting elements, and consequently a lower precision is achieved (1 mm). On the other hand, the generated wave has an exact spherical behavior: the received signals and the measured times do not depend on the orientation, inclination or position of the transmitting element. The main problem is of practical nature: it is not friendly for the people involved in the measurement process because the high voltage needed (3000 V), the audible sound generation and the electromagnetic interferences that it can produce. The signal produced can be increased with a longer distance between electrodes and the application of higher voltage, but it would increase also the unstability.

The configuration of the set of piezoelectric discs is designed using the tool described in [6], which allows us to get a homogeneous radiation field independent of the orientation. The single elements are Piezoelectric bimorph ceramics with resonance frequency of 40 kHz (model ST40-10IN of Nippon Ceramic). It is the most stable transmitter (precision = 0.1 mm) and it has also the highest signal. As a disadvantage we have a distance measurement error with a maximum value of 1.5 mm coming from the discrete placement of the individual transducers. The behavior with the inclination is worse than for the sparking device and better than for the PVDF element, with a vertical emission range of 100°, before the system shows ambiguities equivalent to a wavelength (approximately 8 mm). Other disadvantages are that the transmitting element has a bigger size and that the approximation of being point like is not longer true, requiring an extra correction that depends on the inclination of the transmitting set.

The PVDF element (40 kHz omni-directional transmitter US40KT-01 from Measurement Specialities Inc.) has an even better cylindrical behavior than the PZT transducer, and does not present appreciable differences with orientation. The emitted signal is about one-third than that the piezoelectric elements and its also more instable (precision = 0.3 mm). It is more sensitive to the inclination of the transmitting element, with a relatively low vertical emission range (70°); outside that range the measurement error can be higher than one wavelength (8 mm). In Table 1, we present a comparison of the three transmitting elements tested.

In the remaining sections of this paper, we will refer to the spark element as the emitter transducer. The PVDF transducer shows promising characteristics, although some research should be done to correct for the effects in the position measurement of its finite size (as opposed to the almost point-like character of the spark emitter).

6. The receiver elements

We have used as receiving elements the transducers MA40A5R manufactured by Murata Inc. They are narrow-band ultrasonic receivers with a resonance frequency of 40 kHz. The use of narrow band receivers gives a very good signal-to-noise ratios and is one of the important features in order to allow the system to get operating ranges up to 20 m. The receivers (see Fig. 5) are mounted in a small box with a simple preamplifier circuitry that avoid losses and reduces interferences in the long cables used for transmitting the signal to the central processor unit.

Fig. 5. Receiver element.

7. The time-delay estimation

The relative temporal difference between two similar ultrasonic signals can be computed using time-delay estimation techniques [7]. For signals with a Gaussian spectrum in white, uncorrelated noise, it can be proved that maximization of the cross-correlation yields an optimal estimation, in the sense that: (a) it is not biased; (b) the variance of the error takes its minimum value. If needed, precision can be increased beyond the sampling time by using curve-fitting or interpolation methods [8]. Though, optimal, cross-correlation has the inconvenience of having a large computational load, growing as the square of the sampling frequency; recently, some optimized techniques have been introduced that achieve linear dependence of the number of performed operations with the sampling frequency [9]. This technique allows us to estimate the delays for eight channels with a theoretical precision of 0.01 mm.

8. The speed of sound

The speed of sound in air varies with the temperature (by 0.61 m/(s °C) approximately) [10,11] in a way that it is unacceptable for the precision we desire to achieve with this system. Different authors have proposed different method for compensation of this effect: external temperature sensor [10] or using the piezoelectric receivers as temperature sensor [11]. We consider that both estimations have not the necessary precision for this application.

We have chosen to introduce the speed of sound as an unknown variable and try to solve Eq. (2). Again our number of minimum references would be increased by one in order to be able to solve the proposed equations. We have first tried this method but we found that it increments unnecessarily the instability of the coordinates estimations due to the fact that the system has one additional degree of freedom. Using the fact that the changes in the speed of sound are slower than those of the position, we suppose an initial estimate for the speed of sound and then estimate the coordinates as described above. With this estimation of position $(\widehat{x}, \widehat{y}, \widehat{z})$ and the coordinates of the receivers, we can make a new approximation of the actual sound speed using least squares according to (2) for each triplet of receivers:

$$\sum_{i=1}^{n}\left(t_i v_s - \sqrt{(\widehat{x}-x_i)^2+(\widehat{y}-y_i)^2+(\widehat{z}-z_i)^2}\right)^2 \tag{7}$$

See Fig. 6 for the estimations of the speed of sound from a single emission. Again we choose the MTM filter to find out the actual estimation of v_s and introduce it into a low-pass filter, whose output would be used as the improved estimation for the next measurement. At the beginning of the process, there's a short time (usually less than a second) where the algorithm is searching for a good estimation of the

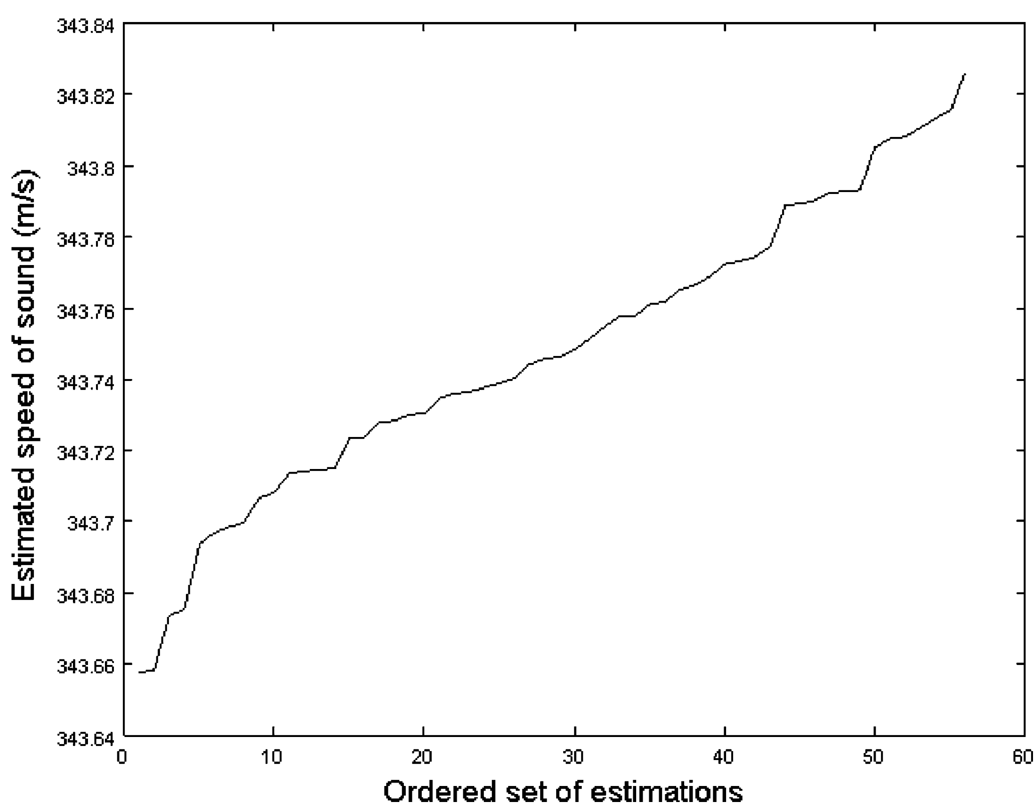

Fig. 6. Set of estimations for the speed of sound.

speed of sound, but after that the changes in its value are slow and the estimation of the coordinates has better precision.

Examining the estimation of the speed of sound, we found a correlation between the values of the sound speed and the height of the receivers, which means that our assumption of a homogeneous sound speed is not completely correct, possibly caused by a vertical temperature gradient. On the other hand, we can easily calculate that the errors coming from this assumption are lower than those from other sources.

9. Calibration of the references positions

When our position measuring system is used outside the laboratory, the problem arises of computing exactly the position of the receivers (which usually are placed several meters away). To account for this situation we built a fixed aluminum calibration frame, which was small enough to fit in the work area of the new sensor frame. By bringing the transmitter to know positions in that calibration frame, we could invert the problem posed in the system of Eq. (3) and compute the position of the receivers. Although, a minimum of three calibration points are needed, it is found again that the use of more points results in a better estimation of the position of the receivers.

10. The influence of the wind

The motion of the propagation medium (air) has a double influence on the delay times measured. Movements of the air transversal to the propagation path produces an increment in the actual measured time, while the longitudinal component may increase or decrease the TOF depending on the direction. Using v_{sa} for the actual propagation speed of sound in air with longitudinal and transversal speeds given by v_{al} and v_{at}, respectively, we find:

$$v_{sa} = v_{al} + v_s\sqrt{1-\left(\frac{v_{at}}{v_s}\right)^2} \tag{8}$$

where v_s is the speed of sound in still air. For typical wind velocities (between 1 and 10 m/s), $v_a \ll v_s$, so Eq. (8) can be approximated as:

$$v_{sa} \cong v_s + v_{al} - \frac{1}{2}\left(\frac{v_{at}^2}{v_s}\right)$$

and the influence of the transversal component of wind speed can be neglected.

To get an idea of the error caused by this phenomenon, a wind of only 1 m/s (3.6 km/h) blowing in the direction of the propagation of the sound signal would produce an error in the distance estimation of 30 mm for a range of 10 m. We believe that the presence of wind is the main cause of errors in our system at the present moment.

We have explored different ways to reduce the error caused by this phenomenon. The most straightforward is to substitute the speed of sound without wind, v_s, of Eq. (1) by the corrected value of Eq. (8), neglecting the transversal influence:

$$v_{sa} = v_s + v_{al} = v_s + \vec{v}_a\vec{u}_i$$

where $\vec{u}_i = (\vec{x}_i - \vec{x})/||(\vec{x}_i - \vec{x})||$ is a unit vector going from the emitter to receiver i. This results in:

$$t_i = \frac{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}{v_s\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} - v_{ax}(x-x_i) - v_{ay}(y-y_i) - v_{az}(z-z_i)} \tag{9}$$

where (v_{ax}, v_{ay}, v_{az}) are the three components of the wind velocity $\vec{v}_a$. If we have a minimum of six receivers, in principle we can compute the six unknowns: $(x, y, z, v_{ax}, v_{ay}, v_{az})$. This simple method does not work in practice, because for the regular environment conditions we expect to find, the equations become dependent and therefore, the system shows a high degree of indetermination. To clarify this problem, refer to Fig. 7, which shows a simplified 1D situation. Let x, x_1 and x_2 be the positions of the transmitter and receivers 1 and 2, respectively, and v_x the component of the speed of wind along the x axis. Then the TOFs of the signals received at R_1 and R_2 would be given by:

$$t_1 = \frac{x-x_1}{v_s - v_x}, \qquad t_2 = \frac{x_2 - x}{v_s + v_x} \tag{10}$$

resulting the following system of linear equations:

$$\begin{bmatrix} 1 & t_1 \\ 1 & t_2 \end{bmatrix}\begin{bmatrix} x \\ v_x \end{bmatrix} = \begin{bmatrix} v_s t_1 + x_1 \\ -v_s t_2 + x_2 \end{bmatrix}$$

When the transmitter is close to the middle point of the receivers (Fig. 7(a)), and t_1 and t_2 have similar values, the system of Eq. (10) becomes singular and the x coordinate and wind speed v_x cannot be determined independently. On the other hand, for situations like the one shown in Fig. 7(b), the estimation will be accurate, but this solution implies, in practice, the need to set extra receivers just within the measurement space reducing the workability of the system.

One proposed solution is to place a second single transmitter in the middle of the measurement space at a fixed reference position. This transmitter could be used to estimate the three components of the wind speed, correcting continuously the time measurements and reducing the errors. This estimation could be also used to check that the wind conditions stay within reasonable limits that permit

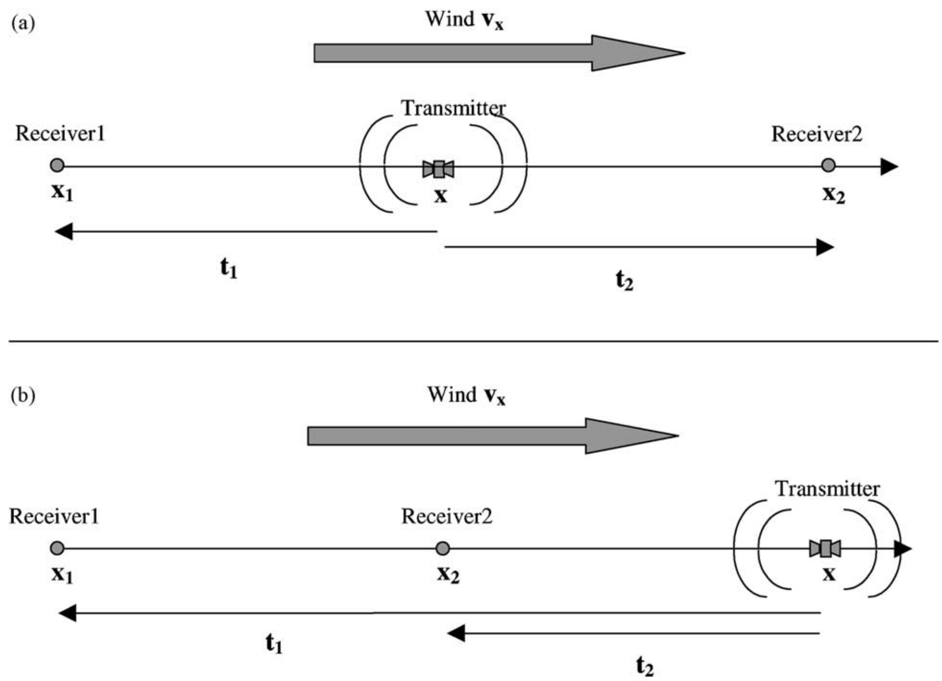

Fig. 7. Influence of the transmitter position on the estimation of the wind speed. Case (a) is prone to large errors in the estimation, while (b) is well conditioned.

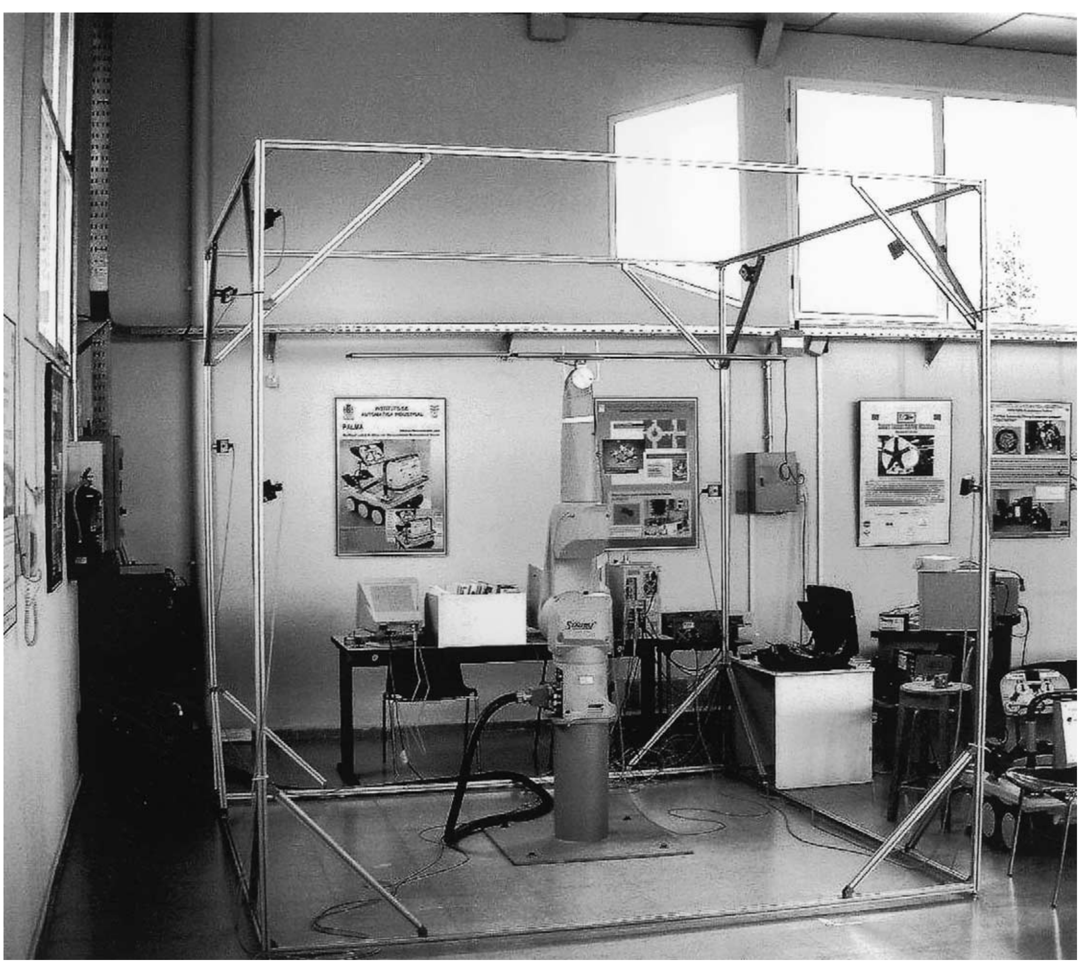

Fig. 8. Experimental setup.

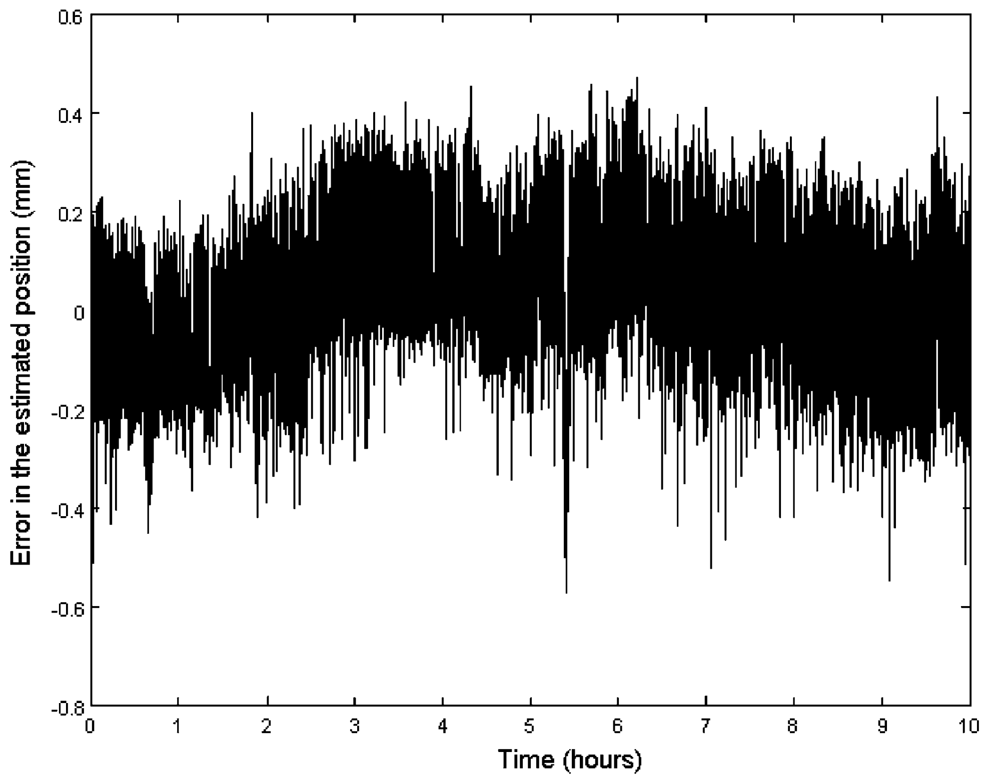

Fig. 9. Typical set of measurements of the position x.

to measure the position with an adequate precision (a precaution especially important in outdoor environments).

There is another way to reduce the influence of the wind. If we can get a two way measurement: having transmitters that are also receivers and vice versa. Because the increment in the time measurement in one direction will coincide with the decrement in the other direction. We consider this measurement method at this moment unpractical from a technical point of view; it is very difficult to distinguish the signals from different transmitters at the same receiver and an alternating transmission would cause an unreasonable increment of the measurement time. We suggest this method as a possible technical improvement for future research.

11. Experimental tests

To test the 3D positioning system we designed the experimental setup shown in Fig. 8. It consists of a cubic aluminum frame, with a volume of 3 m × 3 m × 3 m, and eight receivers which are placed close to, but not exactly at, the vertices of the cube. The emitter is moved by means of an industrial robot (STAUBLI RX90), with a repeatability of 0.02 mm and an accuracy of 0.1 mm. The workspace of the robotic arm fits completely in the cubic frame.

The prototype was tested in a large room, subject to temperature changes, air motion disturbances, etc. To test the stability of the measuring method the robot tip was taken to a fixed position and left there for several hours. The drift in the position measurement is shown in Fig. 9, which confirms that the measurement error stayed below 0.5 mm at all times.

We tried the effectiveness of the proposed robust algorithm against outliers by deliberately introducing all kinds of error sources in the emitter-receiver path. Shadowing of the ultrasonic signal, introduction of false echoes by reflecting objects within the workspace, low amplitude of the emitted pulse and the effect of air turbulences, were all successfully rejected by the algorithm as long as only a small number of receivers were subject to these disturbances.

As we noted above, the finite size of the transmitter transducer is a source of error in the measurement of position. This error is very evident for the PZT and PVDF transducers, but also appreciable in the case of the spark emitter, especially when the orientation of the emitter with respect to the receiver is higher than 70°. In practice this happens when the robotic arm is fully stretched. The MTM filter described is partially successful in rejecting those measurements, unless they affect to several of the receivers.

12. Conclusions

In this paper, we have analyzed some of the problems arising in 3D positioning systems, particularly those based in the measurement of the TOF of ultrasonic waves.

Some of the problems identified are: (a) partial or complete occlusion of one of the receivers; (b) wave interference by obstacles within the workspace; (c) air turbulences which produce local changes of the speed of sound; (d) the influence of wind. These sources of error introduce outlier noise in the measurement process, which makes application of common statistical methods difficult.

To retain high precision estimation in presence of both Gaussian and outlier noise, a robust algorithm for 3D position measurement was developed. This algorithm is a combination of an algebraic solution for the non-linear system of equations of position, and a modified trimmed mean filter (MTM), which rejects "false" measurements and provides considerable robustness against the outliers described above.

An advantage of the technique described is that its computing time is fixed, and therefore, the process is time predictable, as opposed to iterative methods, like square error minimization.

The performance of the algorithm has been verified experimentally by building a prototype consisting of a set of eight ultrasonic receivers placed in a metallic frame, while the moving element (a spark emitter) is mounted on top of a robotic arm. The prototype showed a maximum error of 1 mm within a work area of $3\,\mathrm{m} \times 3\,\mathrm{m} \times 3\,\mathrm{m}$. Its ability to reject moderate amounts of outlier noise was also checked.

Finally, in this paper we have considered the influence of uniform air motion (wind) on the measurement process and suggested algorithm solutions to estimate its speed and compensate it.

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Biographies

J.M. Martín, born in 1958 in Isla Cristina (Spain), graduated in physics and mathematics from the Universiteit van Amsterdam in 1982 and received the doctoral degree in physics in 1990 from the Universidad Complutense de Madrid. He has developed many research activities in the field of automation of processes and especially in the study of sensors (focusing on ultrasonic sensors), sensor data processing and application of sensors in industrial processes and robotic systems. He started his research activity at the van der Waals Laboratorium (Amsterdam) and, since 1985 he works at the Instituto de Automática Industrial (Madrid). He has participated in more than 20 research projects, many of them including technological transference to the industry and also in different European programmes and international congresses. Author of many scientific papers and several patents, he is referee for different national and international publications and scientific evaluator for national and international research programmes.

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F. Seco was born in Madrid, Spain. He received a degree in physics from the Universidad Complutense in Madrid in 1996, and is currently working towards a PhD degree in Science at the Instituto de Automática Industrial (IAI). His dissertation deals with the development of a linear position sensor based on the transmission of ultrasonic signals. His research interests include the electromagnetic generation of mechanical waves in metals, the propagation of sound in waveguides and the processing of ultrasonic signals.

L. Calderón was born in 1947 in Lumbrales (Spain). He graduated in physics from the Universidad de Sevilla in 1974 and received the doctoral degree in 1984 from the Universidad Complutense de Madrid. Since 1974, Dr. Calderón has been working in the Instituto de Automática Industrial developing many research activities in the field of automation of processes and especially on the study of sensors (focused on ultrasonic sensors) and their processing and application. As a consequence of this activity, Dr. Calderón has published many scientific papers and is author of different patents. He has also participated in different national and international scientific programmes and congresses.

J.L. Pons, received a BS degree in mechanical engineering from the Universidad de Navarra Engineering in 1992, the MS degree in 1994 from Universidad Politécnica de Madrid and a PhD degree in 1996 from the Universidad Complutense de Madrid. From 1994 to 1999, Dr. Pons was a research assistant at the Systems Department of the Intituto de Automática Industrial. He has spent several research stays at the Katholieke Universiteit Leuven in Belgium, Arts/MiTech Lab at the SSSUP Sant'Anna in Pisa, Teknische Universit in Munich, Germany and MIT in US. His research interests include new sensor and actuator technologies, signal processing and digital control and their application to microsystems and technical aids for the disabled. In 1997, Dr. Pons received the Fundación Artigas prize in mechanical engineering for the most outstanding doctoral dissertation in the engineering disciplines. The Consejo Superior de Investigaciones Científicas also awarded his contribution to the discipline of mechanical engineering with the silver medal award in 1998. He currently holds a research position at the Instituto de Automática Industrial, CSIC.

R. Ceres was born in 1947 in Jaén, Spain. He graduated in physics (electronic) from Universidad Complutense de Madrid in 1971 and received the PhD degree in 1978. After a first stay for 1 year, in the LAAS-CNRS in Toulouse (France), be has been working at the Instituto de Automática Industrial (IAI), a dependent of the Spanish National Council for Science Research. For the period 1990–1991, he worked in an electronics company (Autelec) as R&D director. Since the beginning, Dr. Ceres has developed research activities on sensor systems applied to different fields such as continuous process control, machine tools, agriculture, robotics and disabled people. On these topics he has published more than 80 papers and congress communications, and he has several patents in industrial exploitation. At present Dr. Ceres belongs to the Spanish Delegation of the IMT (Brite-Euram) Committee, being deputy director of the IAI.