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

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Abstract

This paper presents an analysis of the main sources of error in a 3D-positioning system using ultrasonic waves, coming to different technical improvements. We suggest a new processing algorithm that will overcome the main sources of error encountered in practice. Comparing with existing processing methods, the proposed technique shows an error reduction by a factor of 20, making the system especially robust against outliers measurements.

Keywords: 3D-Positioning system, ultrasonic, time-delay measurement.

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 xyz 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 (In [ref. 1] a full description of a predecessor of the system can be found). 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 figure 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 $\mathbf{t_i}$ from the emission to the reception (Time-of-Flight, TOF) at each receiver **i** and the distance $\mathbf{d_i}$ from the transmitting point to each receiver can be estimated using the speed of sound $\mathbf{v_s}$, 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:

$$\left\{d_i^2 = t_i^2 \cdot v_s^2 = (x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2\right\}_{i=1..3} \qquad (1)$$

Where $\mathbf{(x_i,y_i,z_i)}$ 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 $\mathbf{x_i}$, $\mathbf{y_i}$, $\mathbf{z_i}$ 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 4x4 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 of xyz that minimise expressions of the type:

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

In such techniques we have the flexibility of processing an indeterminate number of measured times $\mathbf{n}_i$ corresponding to references situated at arbitrary positions $\mathbf{(x_i,y_i,z_i)}$.

Using the minimum-required number of references (3 or 4 depending on the estimation method) results in a non-robust behaviour; 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 minimisation function, respectively. The problem is that both approaches consider a least square minimisation (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 Chi-squared minimisation 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.

Our experimental study confirms the conclusions of other authors [3] in the sense that in real situations the biggest contribution to the estimation error comes from outliers, that may come from different physical phenomena: shadowing of some receivers by an obstacle, wave interference, air turbulence, etc. Therefore it is necessary to use a redundant configuration and also a robust estimation method against any kind of noise.

The method we propose below has the flexibility of the minimisation methods with a lower and predictable computational effort and it takes especially into account the nature of the expected noise in order to maintain the errors within low limits.

Processing method

As a first step we will show that using the minimum number of references (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 **zx**-plane **(** $y_3'=0$ **)**. The set of equations (1) becomes:

$$
\begin{aligned}
d_1^2 &= (x')^2 + (y')^2 + (z')^2 \\
d_2^2 &= (x'-x_2')^2 + (y')^2 + (z')^2 \\
d_3^2 &= (x'-x_3')^2 + (y')^2 + (z'-z_3')^2
\end{aligned}
\qquad (3)
$$

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

$$
\begin{aligned}
x' &= \frac{d_1^2 - d_2^2 + x_2'^2}{2x_2'} \\
z' &= \frac{d_1^2 - d_3^2 + z_3'^2}{2z_3'} \\
y' &= \pm\sqrt{d_1^2 - x'^2 - z'^2}
\end{aligned}
\qquad (4)
$$

Making two coordinates transformations: first from the coordinates of the references $(\mathbf{x_i},\mathbf{y_i},\mathbf{z_i})$ 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 **(xyz)** 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:

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

Each receiver set, has two possible solutions symmetrical to the plane containing the receivers, we have thus **2 M** estimations for each of the coordinates **xyz**. Application of a modified trimmed mean filter (MTM) [4] allows us to get unique estimations for **xyz**. 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 summarised 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 **3 σ** window (**σ**=standard 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. Figure 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 figure 2. Note how outliers are at the extremes of the list and the correct value for x (0.5 metres 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 behaviour for both cases: gaussian noise and outliers noise. We expect that the first step (median filter) would cancel outliers while the 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.

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 figure 3 for an illustration of this phenomenon for the two dimensional case. In this figure we have the same pair of receivers ($\mathbf{R_1},\mathbf{R_2}$) with similar precision in the estimation of the distance to the transmitting points ($\mathbf{P_1},\mathbf{P_2}$), but the estimation of the **y**-coordinate of the point $\mathbf{P_2}$ would suffer from a larger indetermination. The same situations appear for three-dimensional 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.

TOF versus delay between references.

We call Time of Flight (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 synchronisation signal. Mathematically we can solve the problem of the absence of this synchronisation signal using an additional reference; again we have three equations and three variables to estimate:

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

Where $\mathbf{t_{ij}}$ 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 form of the echo-signal (that depends on the temperature [1,5]), delays in the electronic, 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.

The Transmitting element.

We have tested three different transducer arrangements (see figure 4) as transmitter: A sparking device (A), a set of piezoelectric ceramic discs (B) and a PVDF cylindrical transmitter (C). The experimental tests show that each of them have advantages and disadvantages that we describe below.

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, its design together with the teflon cover are optimised to produce more stability forcing the spark to be confined in a reduced region. The amplitude signal generated is relatively lower than for the other transmitting elements and it has a lower precision 1mm (standard deviation). On the other hand, the generated wave has an exact spherical behaviour, the signals detected and the times measured do not show dependencies 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 volt), the audible sound generation and the e.m.-interferences that it can produce. The signal produced can be incremented with a longer distance between electrodes and the application of higher voltage, but it would increase also the instability.

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=0.1mm) and it has also the highest signal. As disadvantage we have a distance measurement error with a maximum value of 1.5mm coming from the discrete placement of the individual transducers. The behaviour with the inclination is worse than for the sparking device and better than for the PVDF element, we have an angle of 100º (α in figure 5) before the system shows ambiguities equivalent to a wavelength (aprox. 8mm.). 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 (40Khz Omni-Directional Transmitter US40KT-01 from Measurement Specialities inc.) has a better cylindrical behaviour than the PZT set, it does not present appreciable differences with orientation. It has less signal (1/3) than the piezoelectric elements and its also more instable (precision =0.3mm). It is more sensitive to the inclination of the transmitting element, we have only a reliable measurement space enclosed by α=70º (see figure 5) in which we can measure before the differences in form of the sound signals makes that the system error rise above one wavelength (8mm.).

In Table I, we present a comparison of the three transmitting elements tested.

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 40Khz., The use of narrowband 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 above 20m. The receivers (see figure 6) are mounted in a small box with a simple preamplifier circuitry that avoid losses and reduces interference's in the long cables used for transmitting the signal to the central processor unit.

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 maximisation of the cross correlation yields an optimal estimation, in the sense that: a) it is not biased; and 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 inconvenient of having a large computational load, growing as the square of the sampling frequency; recently, some optimised 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.

The Speed of Sound.

The speed of sound varies with the temperature (aprox. 0.61 m/sºC) [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 the equations of (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 unnecessary the instability of the coordinates-estimations due to the fact that the system has one additional degree of freedom. Using the fact that the speed of sound changes slower than the position, we finally suppose an initial estimate for the speed of sound and then estimate the coordinates as described above, using this estimation $(\hat{x}, \hat{y}, \hat{z})$ and the coordinates of the receivers we make an estimation of the actual sound speed using least-squares according to (2) for each triplet of receivers.

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

See figure 7 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 $\mathbf{v_s}$ and introduce it into a low-pass filter, whose output would be used as the improved estimation for the next measurement. At the start of the system, we have a time (less than a second) that the system is looking for the correct estimation but hereafter we have a very good estimation and a better precision in the coordinate estimation.

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

Calibration of the references positions.

One of the problems we found while testing the system is to measure the exact position of the receivers due to the long distance between them. We solve the problem creating a fixed aluminium frame that we can put in the workarea. Bringing the transmitting probe to known points in that frame, we can invert the problem proposed in [3] and calculate the positions of the receivers knowing the transmitting positions. In fact, a minimum of three calibration points is needed but, again, the use of more points would result in a better estimation of the position of the receivers.

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 longitudinal components have an influence that depends on the direction. Using $\mathbf{v_{sa}}$ for the actual propagation speed having a transversal air movement of $\mathbf{v_{at}}$ and a longitudinal air motion of $\mathbf{v_{al}}$, we find:

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

It is easy to calculate that for expected wind velocity (between 1 m/s and 10 m/s), the longitudinal influence is 60 to 600 times greater than the transversal contribution. At a distance of 10 metres, wind of 1 m/s (aprox. 3 Km/h) would produce an error in the distance estimation of 30 mm. Probably at this moment, this would be the most important source of physical errors of the system.

We have explored different ways to reduce the error caused by this phenomenon.

Introducing the influence of the longitudinal component of the air movement in equation (1), we found:

$$t_i = \frac{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}{v_s\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}+v_x(x-x_i)+v_y(y-y_i)+v_z(z-z_i)} \qquad (9)$$

Where $(\mathbf{v_x},\mathbf{v_y},\mathbf{v_z})$ are the three components of the wind velocity. If we have a minimum of six receivers we can calculate the six unknowns: $(\mathbf{x},\mathbf{y},\mathbf{z},\mathbf{v_x},\mathbf{v_y},\mathbf{v_z})$. 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. Let us see this in detail for one dimension. In the configuration of figure 8, the measuring times considering the influence of the air speed $\mathbf{v_x}$ along the x-axis is:

$$t_1 = \frac{x-x_1}{v_s-v_x}; \quad t_2 = \frac{x_2-x}{v_s+v_x} \qquad (10)$$

Bringing us to the system of equation:

$$\left\{\begin{array}{c} x+t_1v_x = t_1v_s + x_1 \\ x+t_2v_x = -t_2v_s + x_2 \end{array}\right\}$$

These are the equations of two straight lines, the system becomes indeterminate when $\mathbf{t_1}$ is equal to $\mathbf{t_2}$ and is not well determined when both times are similar which is the case in the situation of figure 8a, the transmitter approximately in the middle of the receivers. The system will have a reasonable solution for the configuration of figure 8b, but this last solution implies, in practice, the need to set extra receivers just within the measurement space reducing the workability of the system. Instead of that, we have placed a second single transmitter in the middle of the measurement space at a well-known position. We use these transmitter for estimate the three components of the wind, correcting continuously the time measurements and reducing the errors. These estimation is used also to assure that the wind conditions stays within a reasonable minimum that allows to measure with an adequate precision, especially important in outdoor measurements.

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 viceversa. 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.

Experimental Tests

We have tested the 3D positioning system using a robot (STAUBLI RX90) with repeatability of 0.02 mm and accuracy of 0.1mm., in a scenario shown in figure 9. The volume defined by the cubic frame is 3x3x3 metres, which is enough to cover the working volume of the robot.

The prototype has been put in a room of 12x10 metres with doors of 3x4 metres, people going in- and out. The room has also air conditioning machines (with fans) that commonly work only by day. The stability tests taken during several days at very different positions show that the absolute accuracy of the system is 0.5 mm, including all sources of errors described. Figure 10 shows one of this long-time tests carried out, a improving of more than 20 times is verified compared to previous tests. For same measurements we have incremented the distances up to 20 metres.

Outliers in the measured TOF's, that could appear due to multiple causes, such as shadowing of several receivers, ultrasound reflections on near-by objects, failures in fine TOF calculation due to noise or low amplitude pulses, air turbulence (specially low and non-uniform air flows that affect some paths between emitter and receiver), are rejected succesfully by the robust algorithm described.

As we have noticed before, the transmitter used has an influence on the non-linearity errors. Using the spark generator as transmitter the non-linearity errors are minimal, although we observed those kind of errors when the transmitting point has an orientation to the receiver of more than 70 degrees (in practice, when it is close to the walls), reducing the useful space. The use of the algorithm described minimises also those errors; only when a majority of the receivers are seeing the transmitter under angles above 70 degrees, the final estimation would be affected.

Conclusions

We have analysed the main difficulties encountered in practical 3D-position measurement systems; especially those based on ultrasonic TOF measurements.

An empirical study is carried out, identifying the main error sources and analysing its behaviour, finding finally adequate solutions for most of the problems studied.

A new algorithm for robust 3D-position estimation has been described. This algorithm reduces considerably the error present in practical conditions where gaussian and outliers-type noises are present.

Additionally, the algorithm uses an algebraic solution approach to solve a non-linear system of equations reaching a significant reduction in the computing time and making this time predictable.

A prototype is designed and implemented capable of measuring the 3D-position of an ultrasonic probe with a estimated precision of 3 mm in a measurement space of 12x10 meters.

The combination of techniques applied to the system presented, makes it especially robust and reliable in most of the environmental conditions tested.

The paper also suggests possible technological solutions to investigate in order to increase the precision of the system and reduce the influence of the wind.

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BIOGRAPHIES

José Miguel Martín Abreu, 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 twenty 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.

Antonio R. Jiménez, graduated in Physics, Computer Science branch (Universidad Complutense de Madrid, June 1991). He received the PhD degree also in Physics from the Universidad Complutense de Madrid in October 1998. From 1991 to 1993, he worked in industrial laser applications at CETEMA (Technological Center of Madrid), Spain. Since 1994, he is working as a researcher at the Instituto de Automática Industrial, CSIC, Spain. His current research interests include advanced sensory and processing technologies for localization, tracking and extracting features of objects in sectors such as robotics, vehicle guiding, inspection and machine-tool.

Fernando 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

Leopoldo 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.

José L. Pons, received a B.S. degree in Mechanical Engineering from the Universidad de Navarra Engineering in 1992, the M.S. degree in 1994 from Universidad Politécnica de Madrid and a Ph.D. 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.

Ramón Ceres was born in 1947 in Jaén, Spain. He graduated in physics (electronic) from Universidad Complutense de Madrid in 1971 and received the Ph.D. degree in 1978. After a first stay for one 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.

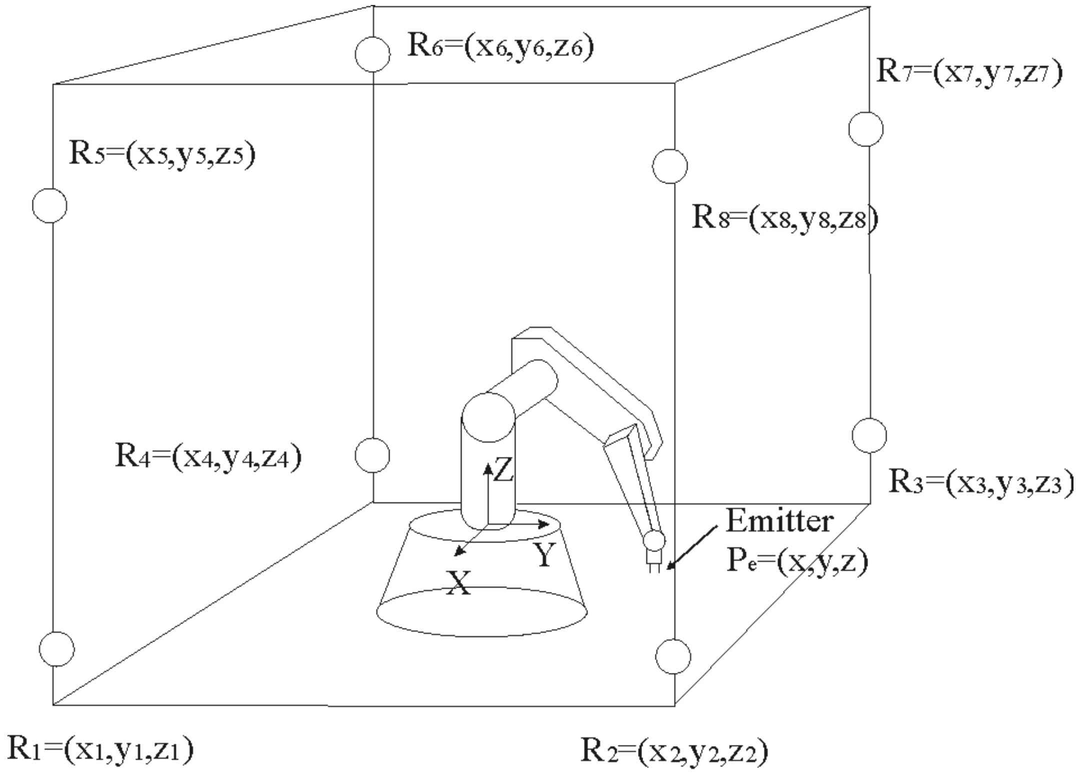

Figure 1. Geometric Setup of the Measurement System.

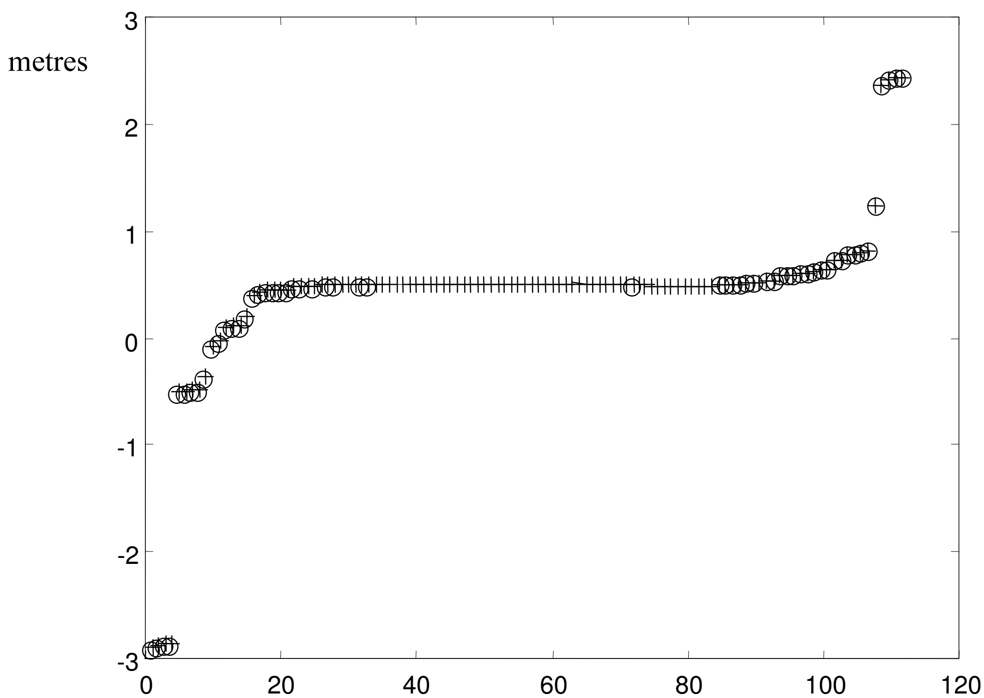

Figure 2 **Ordered set of estimations of x.**

+=all estimations o=second solution estimations.

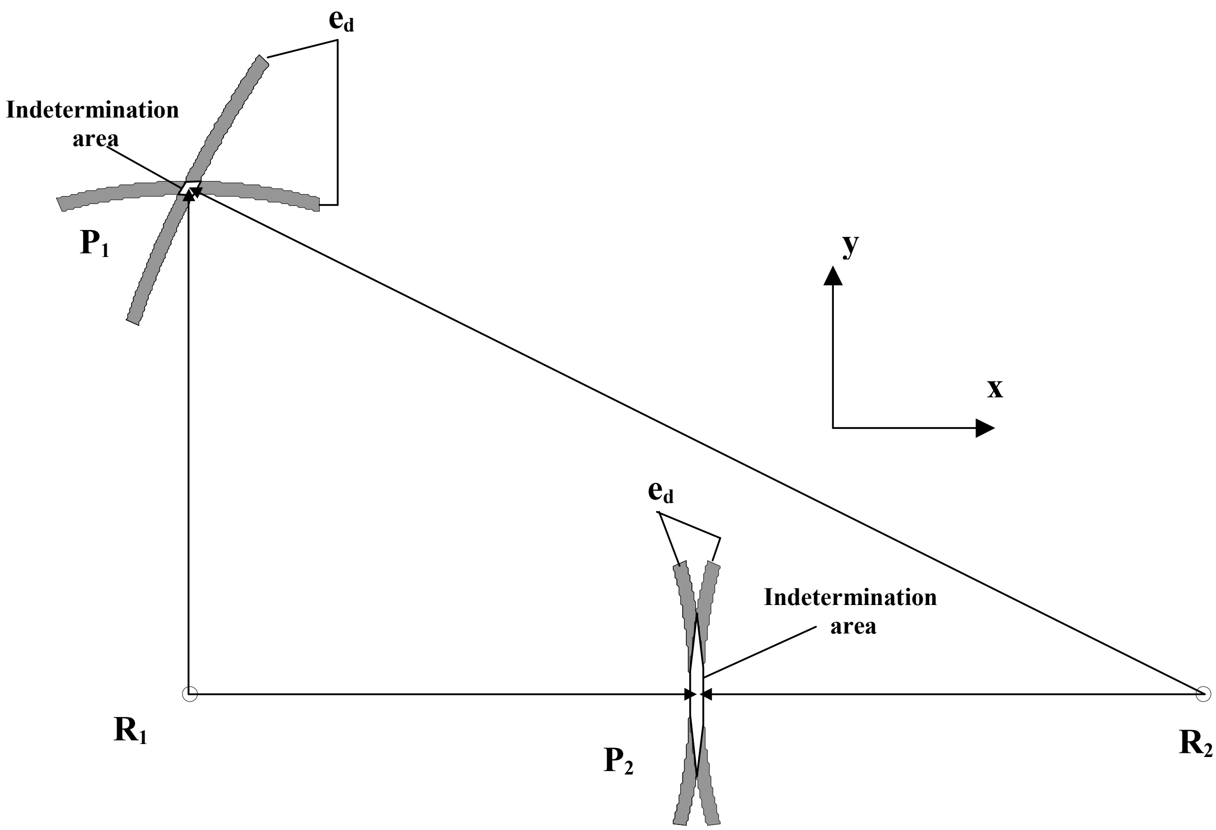

Figure 3 Illustrating the dependence of the accuracy with the position. The x-coordinate of P_1 is better determined than that of P_2, although they have the same error in the determination of distances (e_d).

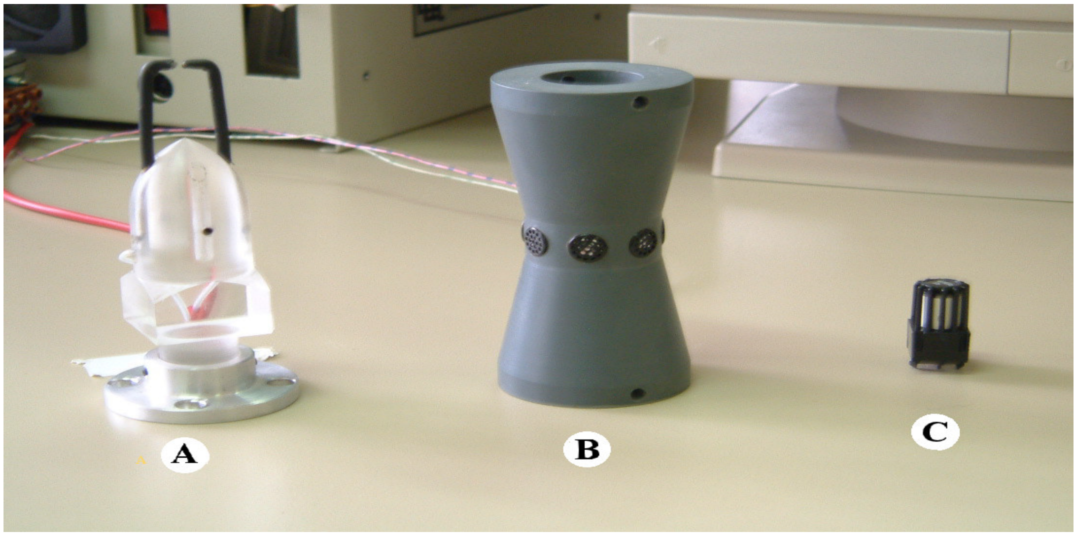

Figure 4 The three transmitters: A) Sparking unit, B) Set of piezoelectric ceramic, C) PVDF transmitter.

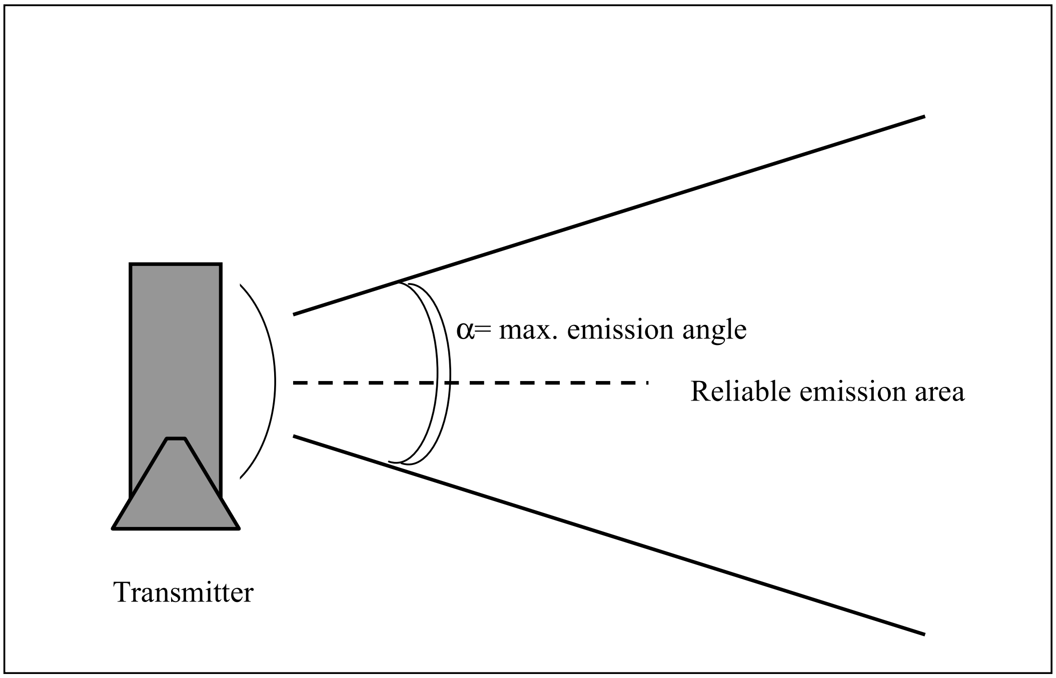

Figure 5 Reliable transmission area

Figure 6 Receiver element.

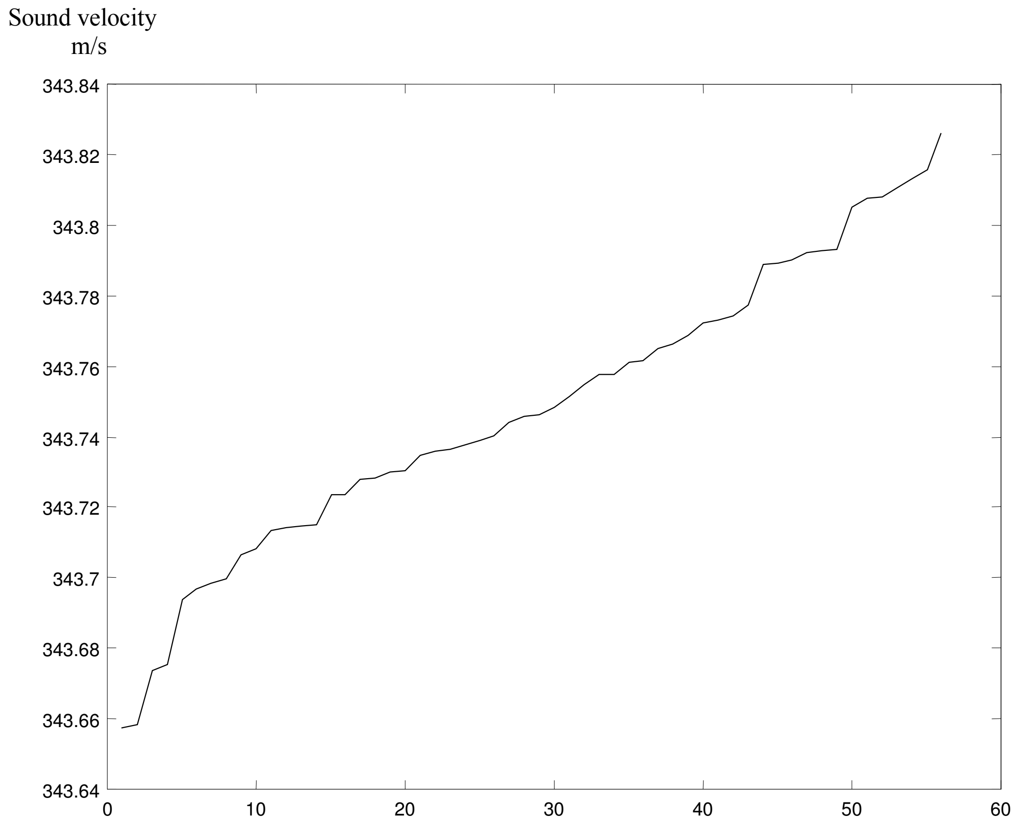

Figure 7 Set of estimations for the speed of sound.

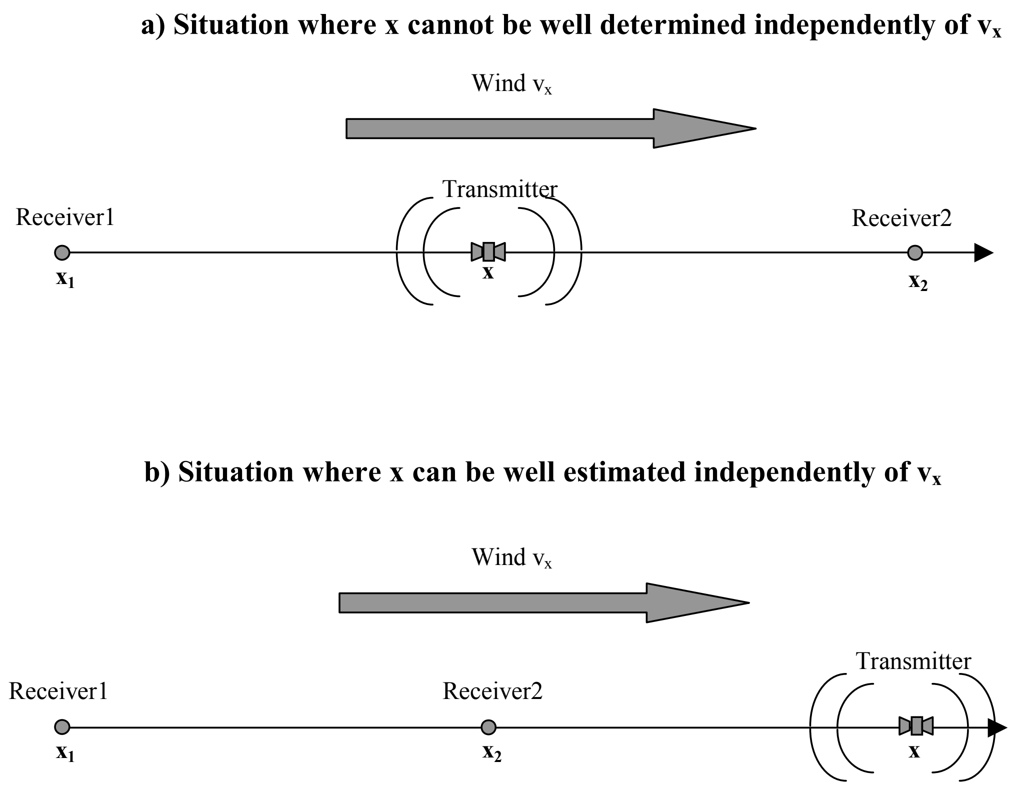

Figure 8 Influence of the position of the receivers on the determination of the wind speed.
a) bad determined b) well determined.

Figure 9 Experimental Setup.

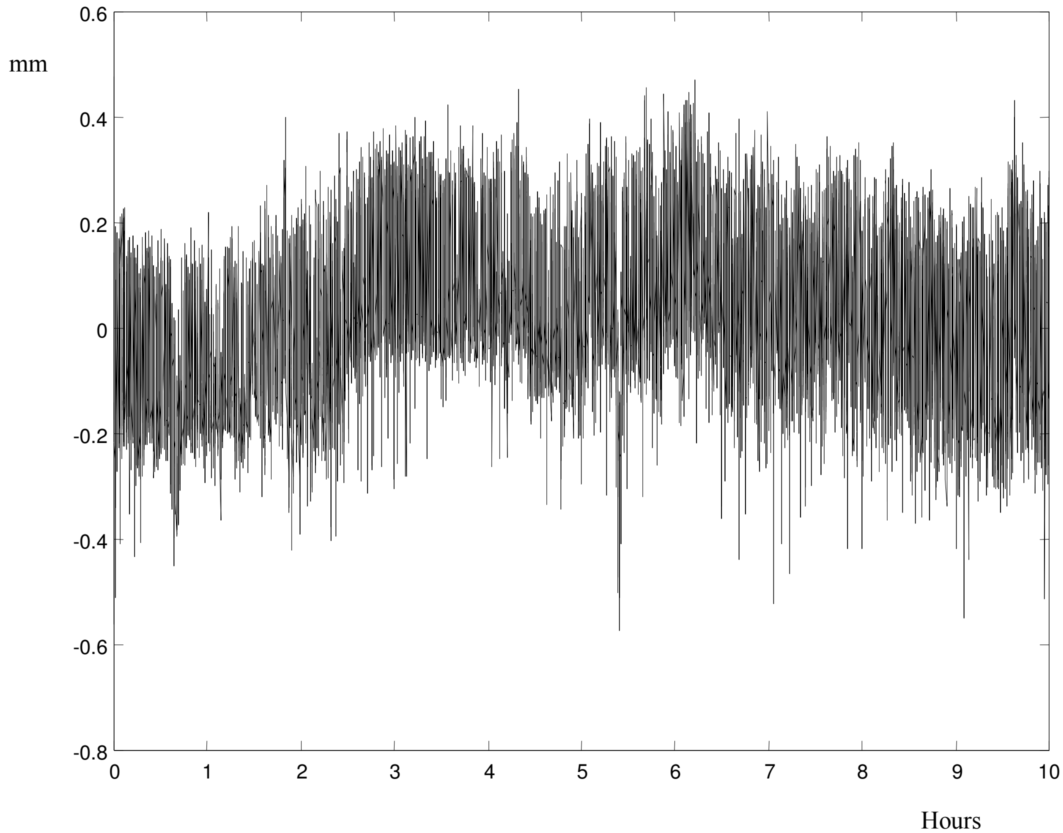

Figure 10. Typical set of measurements. Estimations of x.

Table I. Comparison of the three Transmitting elements.

	Transmitting Energy	Precision mm	Max. Measuring Angle º	Punctual Behaviour
Spark (A)	Low	1	70	Good
PZT (B)	High	0.1	120	Bad
PVDF (C)	Medium	0.3	175	reasonable