ALO: an Ultrasound System for Localization and Orientation based on Angles

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Abstract:

This paper presents a low cost system based on ultrasound transducers to obtain the localization and orientation information of a mobile node, such as a robot, in a 2D indoor space. The system applies a new differential time of arrival (DTOA) technique with reduced computational cost, which is called ALO (Angle Localization and Orientation). Instead of directly calculating its position, the system calculates the direction of arrival of the received ultrasonic signal and, through it, its position and orientation. A prototype of a robot has been built in order to show the validity of the method through experimental results.

Keywords:

DTOA, DOA, location, orientation, ultrasonic, triangulation, robot, Field Programmable Gate Array

1 Introduction

In the last years, localization systems for indoor spaces have been deeply studied. The advantages obtained by outdoor localization systems, like GPS, and the problems to adapt these systems to indoor environments have been the base for the research of alternative localization methods suitable for indoor environments.

For indoor localization, there are many systems already developed and tested. From RFID [1] localization systems, based on measuring the strength of the received signal and the knowledge of the position of the transmitters, to systems based on image recognition [2, 3], where the system must identify patrons on the floor, ceiling or walls, there are a lot of techniques that can be used. The selection is done in function of the computational capacity of the system and the accuracy requested by the application. Some of the most extended localization systems for indoor applications are the ones based on ultrasonic technology. This is because this technology allows high accuracy with low cost and low computational effort.

The main advantage of ultrasonic signals is their low propagation velocity, at least when compared to electronic circuits processing speed. This characteristic allows

capturing the propagation delay between known points with high precision and using relatively low frequency counters.

Two main approaches are used when using ultrasonic technology: "time of arrival" (TOA) localization techniques, in which the system estimates the propagation delay between transmitter and receiver; and "differential time of arrival" (DTOA) techniques, in which the system estimates the propagation delay between multiple receivers but not between transmitter and receiver. TOA systems based on ultrasonic transceivers need an auxiliary radiofrequency signal in order to know both the time of transmission and reception, while DTOA systems can use only ultrasounds because they only need reception times.

TOA localization systems usually calculate the position of the mobile node with the intersection of spheres, whose radii are the measured distances and whose centers are the positions of some known points, called anchor points. These anchor points can be either the transmitters (passive architecture) or the receivers (active architecture). Examples of systems that use this technology are the BAT Ultrasonic Location System [4], The MIT Cricket Indoor System [5, 6], the system developed at the UAM [7, 8] or the Single Compact Base Station system [9]. In all these proposals, the anchor points are deployed in the ceiling, except in [9], where the three transmitters are included in a compact platform. This simplifies deployment, but at the cost of obtaining less precision.

DTOA localization systems are divided in two main groups. The systems of the first group, called multilateration systems, calculate the position of the mobile nodes with the intersection of hyperboloids where the focuses are the anchor points, while the systems of the second group estimate the direction of arrival (DOA) of the reference signal.

The multilateration systems have been implemented in multiple proposals, like the one developed in the Univ. of Bristol [10, 11], Decca Navigator System [12] or LORAN-C [13]. Their main disadvantage is their high computational cost, so when they are implemented in low cost robots they are usually implemented using linearized equations [14] or with minimization functions [15].

The DOA algorithms allow obtaining both the position and orientation of the mobile node. The main problem of these systems is their high complexity because they use complex trigonometric equations. An example of DOA based in DTOA techniques is the MUSIC algorithm [16] that allows estimating, simultaneously, the reception angle of

different signals from multiple transmitters, checking the correlation of the received signal in the array of receivers. Other example, but using audible signals instead of ultrasounds, is presented in [17]. Although the algorithm is simplified, it still uses FFT (Fast Fourier Transform) apart from other calculations.

In this paper, a new localization and orientation DTOA system, ALO (Angle Localization and Orientation), is presented, which is based on the angle of reception of an ultrasonic signal in a mobile node moving in a 2D space (i.e. the floor). This allows obtaining the position of the node and its orientation. The main novelty of the proposed system is that it uses low complexity calculations, so it can be implemented in low cost devices. The rest of the paper is organized in five main sections: "Angle Estimation", where the base of the system and the mathematical equations are described; "Localization and Orientation", where the localization and orientation technique based on angles is presented; "Implementation", where the implementation of the system can be found; "Error Analysis", section that describes the main error sources and their effect on the precision of the localization system; and "Results", where the experimental results are presented.
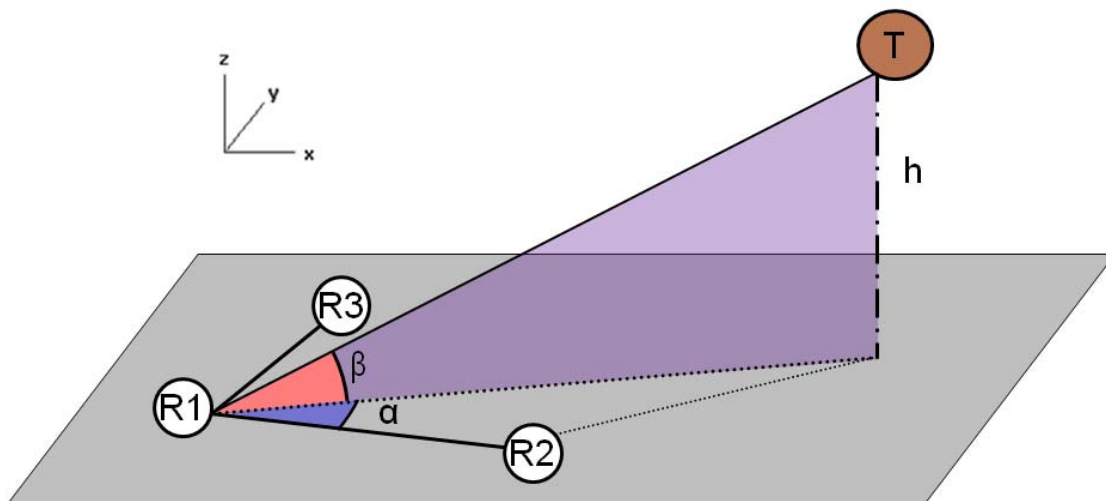
2   Angle Estimation

Fig. 1 - Angles in the receiver

To estimate the reception angle to any transmitter, it is only necessary to measure the time elapsed between the receptions of the same ultrasonic signal in different points. The only assumption of our proposal is that all the receivers see the transmitter under approximately the same angle. This is true if the distance between the transmitter and

the receivers is much greater than the distance between receivers. With this condition, the approximation error on the angle of the proposed method is negligible.

First, an object must be defined as a group of receivers located in a plane. This object will have a reference receiver (R1 in Fig. 1) and one or two auxiliary receivers (R2 and R3 in Fig. 1). All the angle estimation process will make reference to this reference receiver, using the auxiliary receivers to measure the propagation delay and direction of the reference wave.

This object, which moves in a plain (which will be the floor in the real world), has two main orientations with respect to any point in the space: the first orientation, that will be called horizontal orientation (α in Fig. 1), makes reference to the angle that forms the north of the object (R1 to R2 direction) with the projection of the vector that joins the reference receiver and the transmitter on the receiver's plane. The other orientation, called vertical orientation (β in Fig. 1), makes reference to the angle between the plane that contains the receivers and the vector that joins the transmitter and the reference receiver.

To calculate the localization of the object, the vertical angle must be always obtained, while the horizontal angle has only two possible values (0º or 180º) when the object moves in a 1D space (a line), but can have any value when the object has 2 or 3 degrees of freedom.

2.1 Estimating the reception angle in a 1D space

If the object can only move in a line, a plane that contains that line and the transmitter can be defined. In this plane, the axis X will be the same as the movement line, and the axis Y will be a line perpendicular to the movement line and that contains the transmitter (see Fig. 2). In this case, if the system north reference is +X, the horizontal angle can only be 0º (if R2 is nearer to X=0 than R1) or 180º (if R1 is nearer to X=0 than R2), and given that the object can't rotate, once the object is deployed it can be deduced in function of the receiving order of the reference wave. This allows calculating the sign of the X position of the receiver R1 (positive for 0º, negative for 180º). To estimate the vertical angle, the system must measure the difference in the time of arrival between the two receivers.
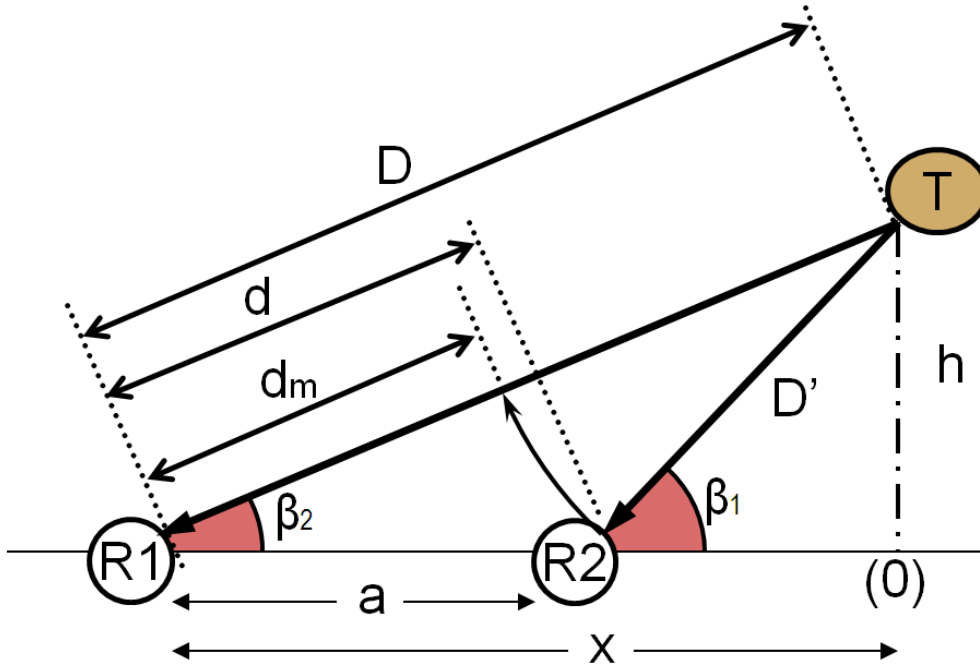
Fig. 2 - Angle estimation for 1D space system

For this example, the transmitter will be in the position (0, h), the reference receiver (R1 in Fig. 2) in (x, 0) and the auxiliary receiver (R2 in Fig. 2) in (x-a, 0). If the transmitter is omnidirectional and there are not obstacles in the space, the propagation delay from the transmitter to the receivers will be proportional to the distance between the transmitter and each receiver (D and D' in Fig. 2). As both receivers are in different positions, the difference in the time of arrival (d_m in Fig. 2) can be measured counting the number of clock cycles between the arrivals of the ultrasonic signal in each receiver (N_{clk}).

If the distance between the transmitter and the receivers is much greater than the distance between the receivers ('a' in Fig. 2):

$$D >>> a \quad D' >>> a \Rightarrow \beta_1 \approx \beta_2 \quad d_m \approx d \quad (1)$$

This difference can be considered as a cathetus of a right triangle (d in Fig. 2). In this right triangle, the hypotenuse is the distance between the receivers (a), that is known, so the reception angle can be easily estimated as:

$$\cos(\beta_1) = \frac{d}{a} \approx \frac{d_m}{a} \quad (2) \qquad d_m = \frac{V \cdot N_{clk}}{f_{clk}} \quad (3)$$

Where V is the propagation speed of the reference wave (speed of sound), f_{clk} is the frequency of the counter that measures the difference in the times of arrival and N_{clk} is the number of clock cycles measured.

2.2 Estimating the reception angle in a 2D or 3D space

If the object can move in a 2D or 3D space, the system needs to estimate two angles in order to calculate its position and orientation. In these cases, a third receiver is needed, and to simplify the future localization process, the three receivers should be placed in a right isometric triangle distribution.

If we define a plane as the surface that contains the three receivers, the axis X will be the line that contains R1 and R2 (Fig. 1) while axis Y will contain receivers R1 and R3 (Fig. 1). The axis Z is orthogonal to the XY plane. In this distribution, R1 will be defined as the reference receiver, with position (0, 0, 0), while R2 and R3 will be the auxiliary receivers with positions (a, 0, 0) and (0, a, 0) respectively. The transmitter will be placed at (Tx, Ty, Tz).

To estimate the horizontal and vertical angles, the next procedure is followed. Given that the distance between receivers, *a*, is negligible with respect to the distance between transmitter and receivers, the ultrasonic signal will be received as a plane wave, with a normal vector as the difference of position between the transmitter and the reference receiver. In this case, the normal vector of the reception plane is (-Tx, -Ty, -Tz).

With 3 receivers it is possible to take two differential time measures, t1 and t2, counting the number of clock cycles between the arrival at the auxiliary and reference receivers. These two time measures can be transformed into distances, d1 and d2, because the propagation speed of the reference signal is known. The propagation speed of an ultrasonic signal is the speed of sound, which is ~343 m/s.

These distances can be considered as the radii of two spheres (S2 and S3 in Fig. 3, which is an orthographic projection showing the top and front views) centered in the reference receiver (R1) and that are tangential to the ultrasonic wave when it reached the auxiliary receivers (R2 and R3). With one measure, the intersection of the possible planes that contain the secondary receiver R2 and are tangential to the sphere S2 are limited to a circumference, C2, over the surface of the sphere S2. The direction of arrival can be any of the lines joining the reference receiver, R1, and the circumference, C2, which forms a cone. Using the second distance, the circumference C3 over the sphere S3 is obtained with the planes that contain R3 and are tangential to

S3. This second circumference gives other cone of possible directions of arrival. The intersection of both cones gives only two possible directions of arrival. However, as the receivers are in the floor, the direction that goes below the floor can be discarded, so the direction of arrival is completely defined.
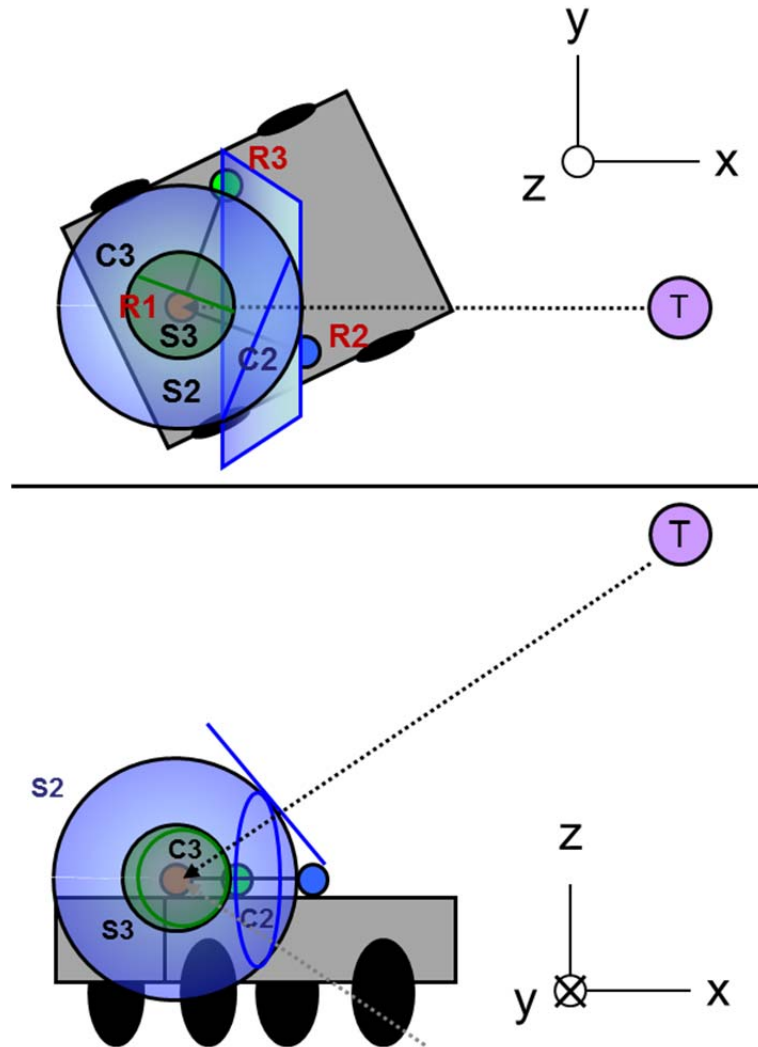

Fig. 3 - Angle estimation for 2D space, top view (top) and front view (bottom)

To conclude, the last operation consists in extracting the horizontal and vertical angles of the direction of arrival. It can be deduced that:

$$\cos(\alpha) = \sqrt{\frac{d_1^2}{d_2^2 + d_1^2}} \qquad \sin(\beta) = \sqrt{1 - \frac{d_2^2 + d_1^2}{a^2}} \qquad (4)$$

The sign of α can be deduced taking into account the reception order of the ultrasonic signal in the different receivers, while the sign of β can be only positive because our receivers can only capture the ultrasonic wave from above the floor.

3   Localization and Orientation

3.1   Localization for 1D space

If the object can only move with one degree of freedom, it limits its possible positions to a line. This enables to limit the complete space to a plane, where the object can be in any position of the X axis (x, 0) and the transmitter is fixed at the point (0, h). The object must have at least two receivers at positions (x, 0) and (x-a, 0) to calculate its position (see Fig. 2).

After estimating the reception angle as seen in the previous section, the process to calculate the position of the object is:

$$h = D \cdot \sin(\beta) \Rightarrow D = \frac{h}{\sin(\beta)} \qquad (5)$$

$$h^2 + x^2 = D^2 \Leftrightarrow x = \pm h\sqrt{\frac{1}{\sin^2(\beta)} - 1} \qquad (5)$$

$$x = \pm h\sqrt{\frac{1}{1 - \cos^2(\beta)} - 1} = \pm h\sqrt{\frac{d^2}{a^2 - d^2}} \qquad (5)$$

The sign of x can be deduced according to the reception order in the two receivers of the ultrasonic signal. For example, in Fig. 2, R2 receives the reference signal earlier than R1, so the robot knows that R2 is nearer to X=0 than R1, so the horizontal angle is 0º (see section 2.1) and X is positive. In the opposite case, the horizontal angle would be 180º and X would be negative.

The last expression of equation (5) is the one implemented in the robot, avoiding the use of trigonometric functions.

3.2   Localization for 2D space

If the object can move in a 2D space (i.e. the floor), the object must be provided with at least three receivers in order to estimate its horizontal and vertical orientation with respect to the transmitters. In this case, the horizontal plane of the system that contains the axis X and Y will be defined as the plane that contains the three receivers, which is also the movement plane.

It is also necessary to use two different transmitters in order to calculate the position. The reason for this requirement is that an orientation with respect to a single transmitter is satisfied by an infinite group of points in a circumference centered in the

projection of the transmitter to the horizontal plane. Each point of this circumference will return its relative orientation identically, but with different absolute orientation (see Fig. 4).
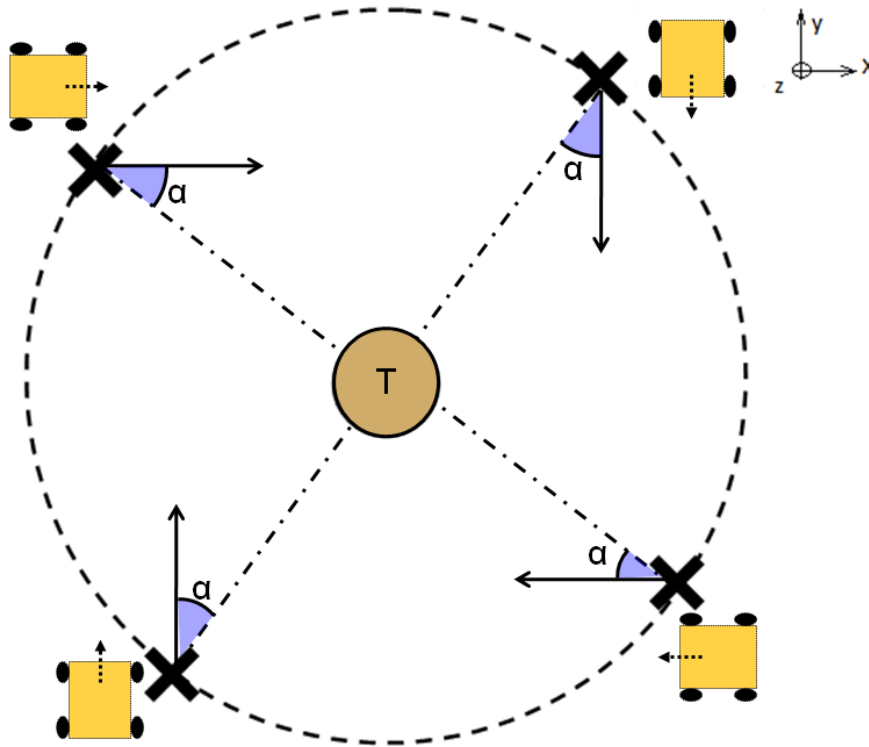

Fig. 4 - Single transmitter: undefined position

To deduce its absolute orientation and, therefore, its absolute position, a second transmitter is needed. With two orientations with respect to two different transmitters, the possible positions of the object are reduced to only two points, but only one of these two points matches both absolute orientations, so the problem is solved (see Fig. 5).
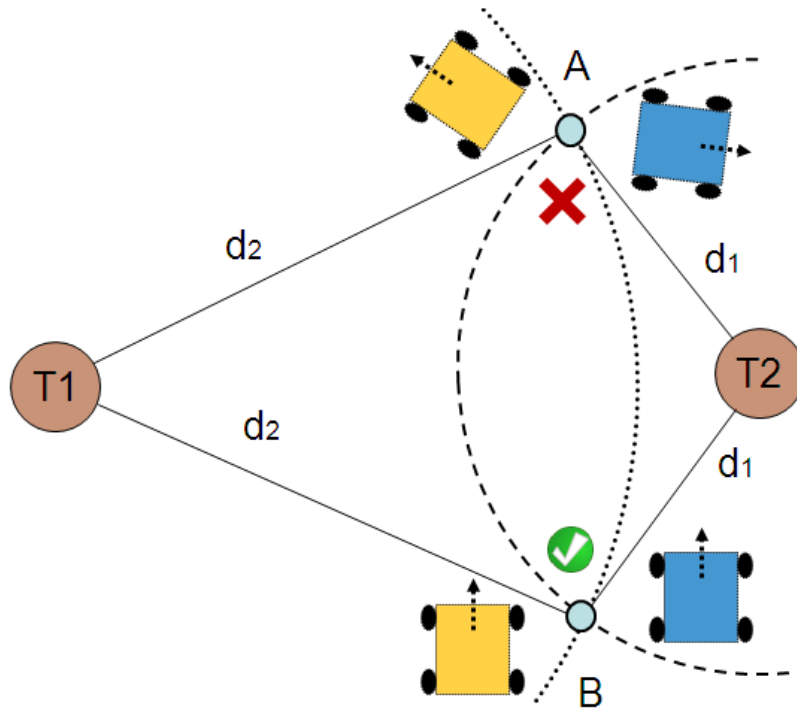
Fig. 5 - Two transmitters: position defined by distance and orientation

Mathematically, the solution is based on the intersection of circumferences, where the center of these circumferences is the projection over the horizontal plane of the transmitters. To simplify the calculus, the plane where all of the transmitters are placed is parallel to the horizontal plane, at a distance of 'h' (i.e. the height to the ceiling). The point (0, 0, 0) is the projection over the horizontal plane of the first transmitter (0, 0, h). The axis X is defined as the line parallel to the line that joins both transmitters, so the second transmitter is placed at the position (b, 0, h) (Fig. 6):
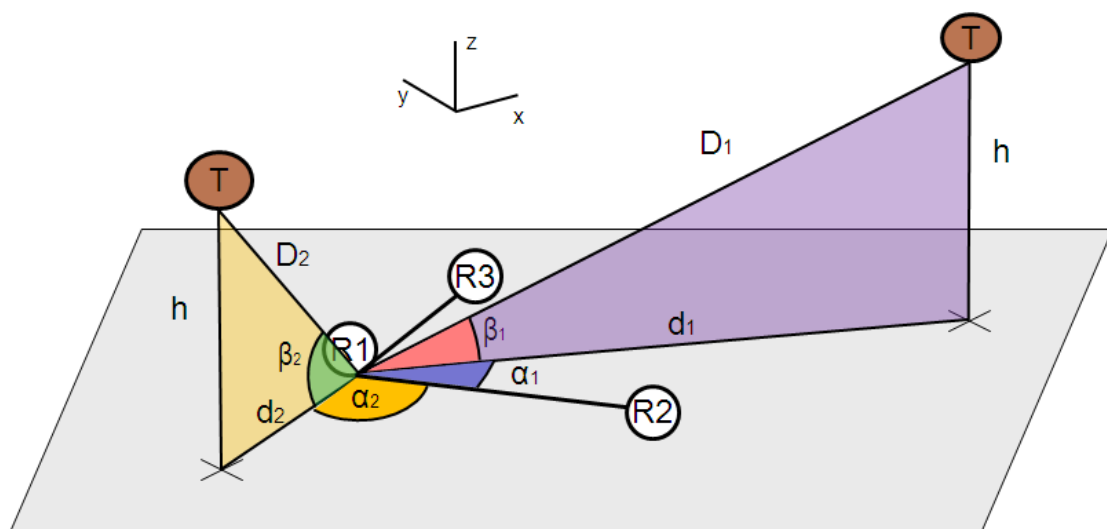

Fig. 6 – Localization in a 2D space

$$h = D_1 \cdot \sin(\beta_1) \Rightarrow D_1 = \frac{h}{\sin(\beta_1)}$$

(6)

$$d_1 = D_1 \cos(\beta_1) = \frac{h}{\tan(\beta_1)} \qquad d_2 = \frac{h}{\tan(\beta_2)}$$

(6)

With these distances, the problem is reduced to intersecting circumferences:

$$x = \frac{d_1^2 - d_2^2 + b^2}{2 \cdot b} \qquad y = \pm\sqrt{d_1^2 - x^2}$$

(7)

To solve the sign of y, the system obtains the absolute orientation in both points with respect the two transmitters, and discards the point whose absolute orientations don't match.

3.3 Orientation

When the object can move in a 2D or 3D space, the horizontal orientation takes special interest. All navigation systems need to know its orientation. The angle estimation explained before only informs about the relative orientation with respect to one transmitter, but is not the robot absolute orientation.

Given that our system can obtain its absolute position and the positions of the transmitters are also known, the relative orientation can be transformed into the absolute orientation. In order to do so, the system must only calculate an orientation correction factor (θ in Fig. 7), which is the angle between the vector that represents the system north (Nx, Ny) and the vector that joins the object position and the transmitter projection (Px, Py). If this correction factor is added to the relative horizontal angle, the absolute orientation of the object is obtained.
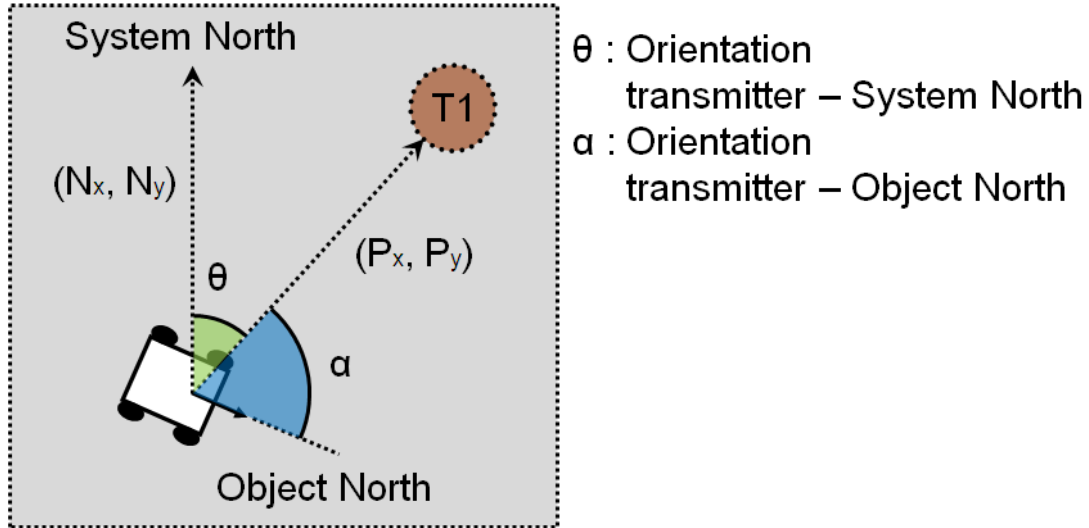
Fig. 7 – Absolute and relative orientation angles

$$\cos(\theta) = \frac{P_x \cdot N_x + V_y \cdot P_y}{\sqrt{P_x^2 + P_y^2} \cdot \sqrt{N_x^2 + N_y^2}} \qquad (8)$$

If the system north is defined as the vector (1, 0), the algorithm to obtain the position orientation correction factor is simplified to:

$$\cos(\theta) = \frac{P_x \cdot N_x}{\sqrt{P_x^2 + P_y^2}} = \frac{P_x}{d} \qquad (9)$$

4   Implementation

To test the precision of the system, two transmitters, separated by 240 cm, were placed on the ceiling of a room. The ceiling height is 280 cm. Both transmitters are connected to a unique FPGA (Xilinx Spartan3 model) that transmits sequentially each 100 ms a train of pulses at 40 kHz, one time using transmitter 1 and the next using transmitter 2. These signals are sent to drivers that increase their voltages from 3.3V to 20V, and these amplified signals are the inputs of the ultrasonic transmitters (400ST120 model). The robot, which is equipped with three receivers, is deployed in the floor of the room. This distribution allows the implementation of the localization system for 2D space (Fig. 8).
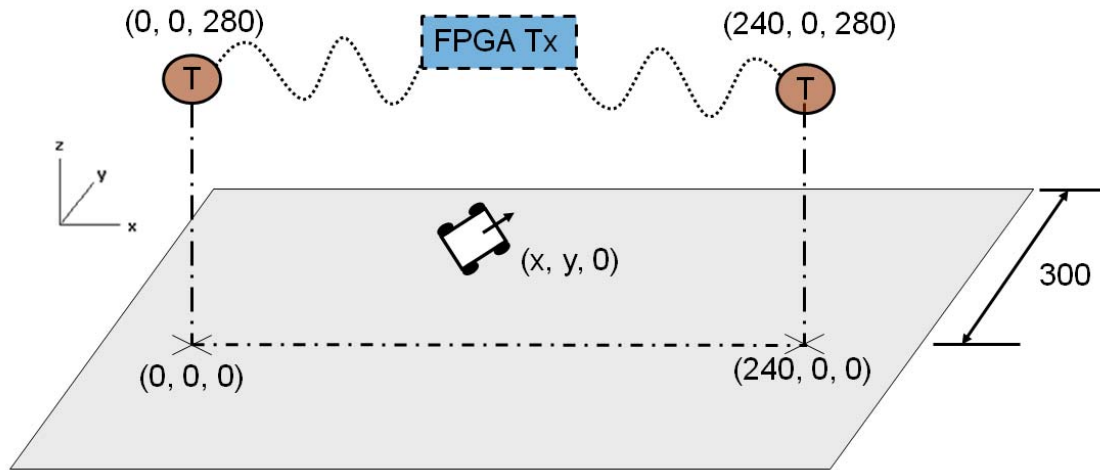
Fig. 8 - Transmitters and receivers deployment

The robot (Fig. 9) is composed by three main layers, apart from the mechanical structure including the motors and their encoders. The first level is an analog board that implements all the auxiliary circuits, while the second contains the FPGA and is responsible of the implementation of all of the logic needed to determine the localization and orientation of the robot, apart from the control of the robot. The last layer contains the ultrasonic receivers, allowing them to be deployed with a right triangle distribution and at different distances for experimental tests.
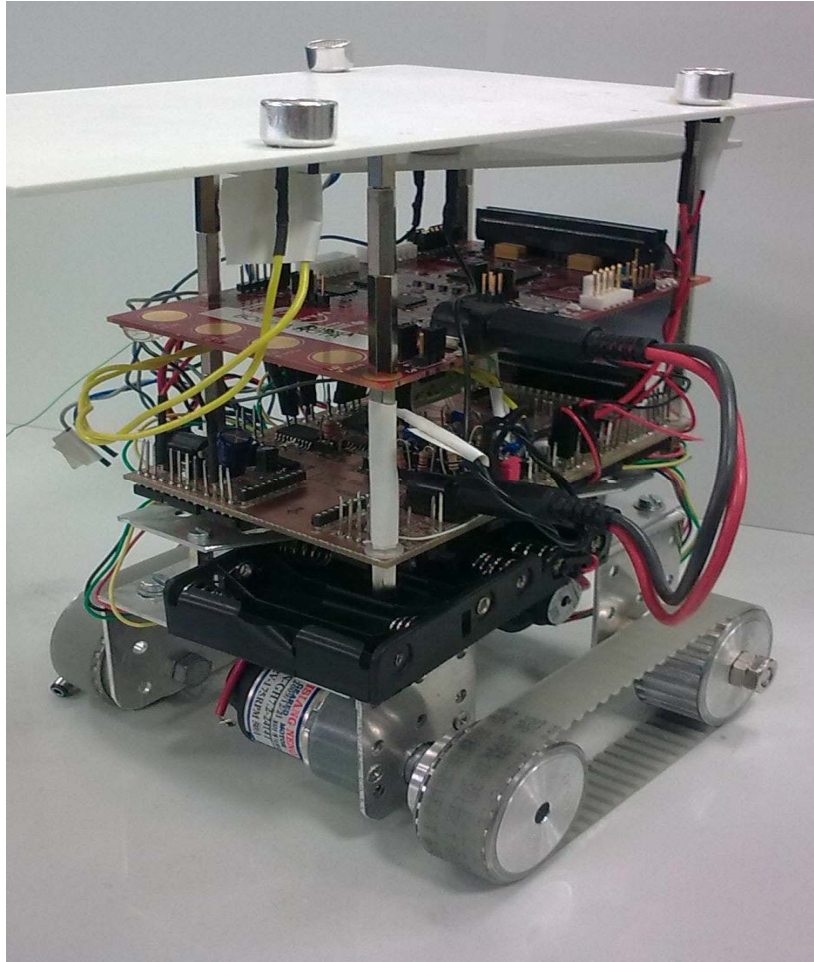
Fig. 9 - Prototype robot

The first layer (Fig. 10) is an analog board with multiple functionalities. This board includes the voltage supply to convert the battery voltage to the FPGA supply voltage, manages the voltage conversion from FPGA to motors and allows the use of infrared sensor to detect obstacles. It also has an ADC to enable the connection of analog sensors and includes RF devices to establish connection between multiple robots or to a PC. But the main functionality of this board is the amplification and digitalization of the captured ultrasonic signal by the receiver (400SR120 model).
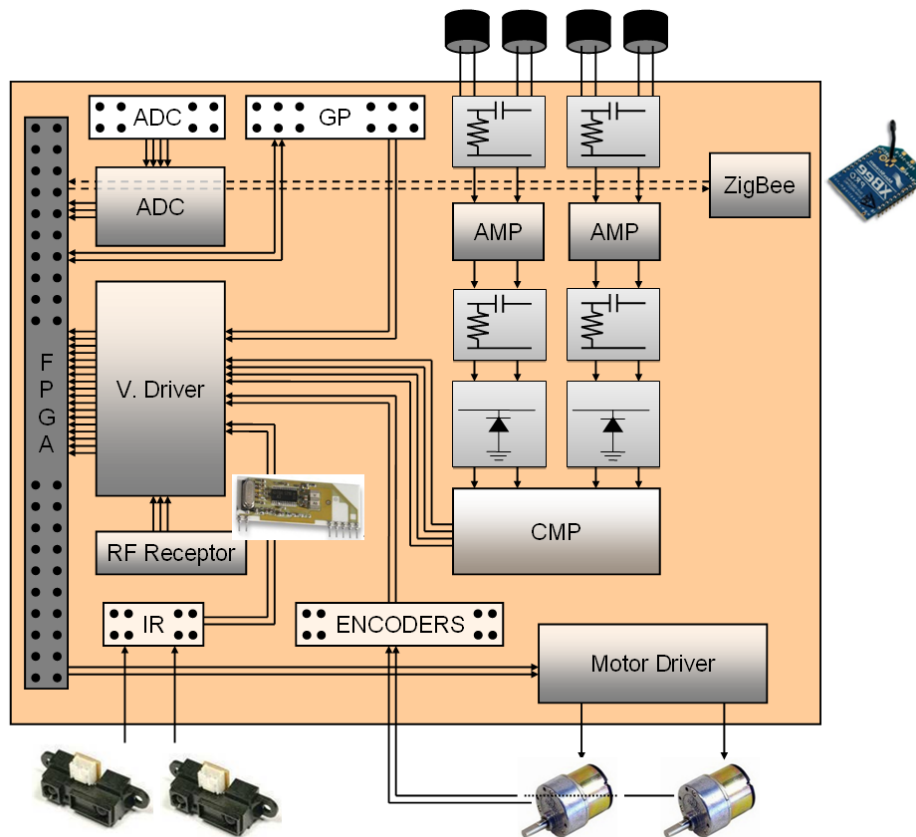
Fig. 10 - Analog board

The digitalization phase consists in four stages. In the first one, the received signal is centered at 0 V with an RC filter. After this process, the signal is amplified using an instrumentation amplifier (model INA2331), so we can obtain high amplification from a weak source. The amplified output has a continuous component that depends of each receiver, so these signals are again connected to a high pass filter, implemented with another serial RC circuit. The output is filtered with a diode to eliminate the negative part. After the diode, a comparator device (model TLC352CP) is used to digitalize the signal. The output is a logic one when the amplified signal is over a certain value, and a logic zero when it is under that value, including all the negative semicycle. Therefore, the output is a digital signal which is almost a square signal at 40 kHz when the ultrasound signal is received, and a logic zero the rest of the time. In this way, the output of the circuit can be directly connected to an FPGA (or other digital circuit), avoiding the need of an analog-to-digital converter (ADC).

The second layer contains the FPGA (XilinxSpartan-3A) where the localization and orientation algorithm is implemented. In this FPGA, a MicroBlaze embedded microprocessor (running at 52 MHz) has been implemented and a custom peripheral has been developed to capture the DTOA measure. This peripheral has the architecture shown in Fig. 11.
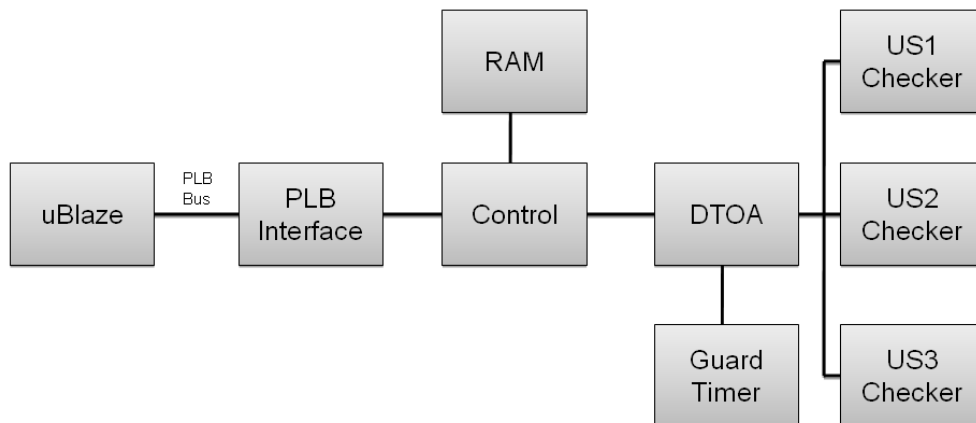
Fig. 11 - Peripheral architecture

When any of the receivers captures a signal with enough intensity to generate at least three consecutive pulses at 40 kHz, the US (ultrasounds) Checker associated to the receiver initializes a counter in the DTOA module. When the ultrasonic wave arrives to a second receiver, the counter value is registered, but the counter keeps counting until the ultrasonic wave is detected in the last receiver. This last value of the counter is also stored. These two measures are adapted to inform of the measured delay from the auxiliary receivers to the reference receiver, independently of the reception order. The measures are stored in RAM and the value at a special RAM address is updated to indicate that a new measure has been captured.

A guard timer is activated after each measure in order to avoid detecting the rebounds of the ultrasonic signal as new measures.

The MicroBlaze microprocessor can read the RAM information through the PLB interface. It periodically polls the mentioned RAM special address to detect when a new measure is available. In that case, the microprocessor starts the localization and orientation algorithm (implemented in C-code).

5   Error Analysis

Multiple sources of error that affect the precision of the localization and orientation system have been detected. Some of the error sources are inherent to the electronic implementation of the localization system (like the differences in the delay of the amplification phase for each signal or the response time of each receiver), others are the results of problems in the mechanical implementation (like the incorrect position of the receivers or the incorrect parallelization of the ceiling with respect to the floor) and

others are inherent to the system (like the fact of considering the received signal as a plane wave).

In this section, the most characteristic errors are theoretically analyzed by simulations using an environment with two transmitters, at positions (0, 0, 280) and (240, 0, 280) cm, like the one used in the experimental results (see Fig. 7). For this analysis, the robot is deployed at different positions, (x, y, 0), and it is always orientated to the system north. Experimental results are later presented in section 6.

The first error to be analyzed is the approximation of considering the received signal as a plane wave. This error can be appreciated in Fig. 2. The measured distance is considered as the cathetus of a right triangle, when the triangle has not a perfect 90º angle. This produces an error in the vertical angle estimation process that will affect the precision of the localization system. This error decreases if the distance between the receivers is small compared to the distance to the transmitter. An example of the position error for a distance between receivers of 30 cm is shown in Fig. 12.

Note: In all figures, the absolute localization error (represented in cm) is shown for each position.

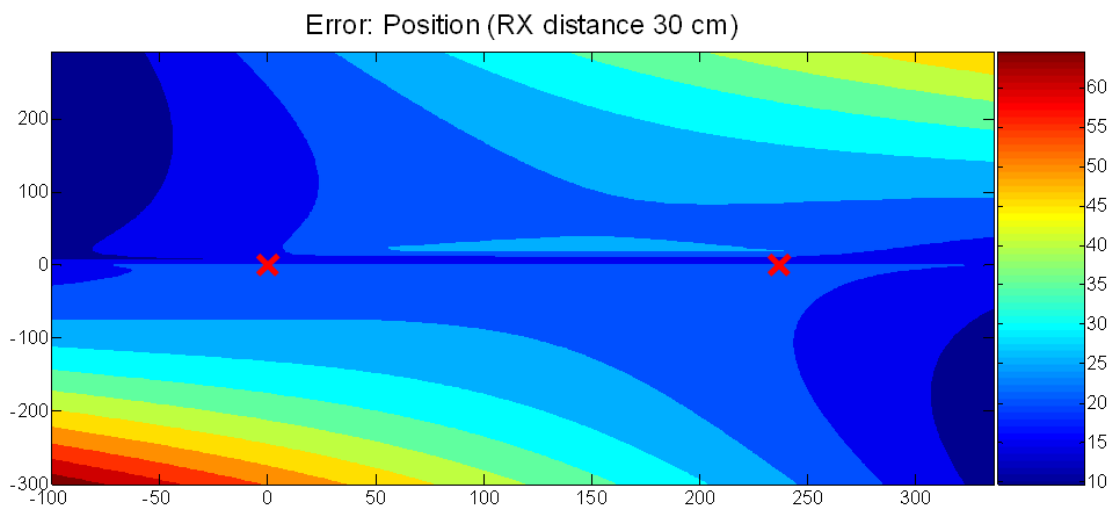Note: In all figures, transmitter positions are marked as red crosses.

Fig. 12 - Position error due to plane wave approximation (receivers distance 30 cm)

This error can be minimized reducing the distance between the receivers because, if the receivers are closer, the received wave will arrive to all receivers with a more similar angle. Fig. 13 shows the error when the distance between receivers is 3 cm.
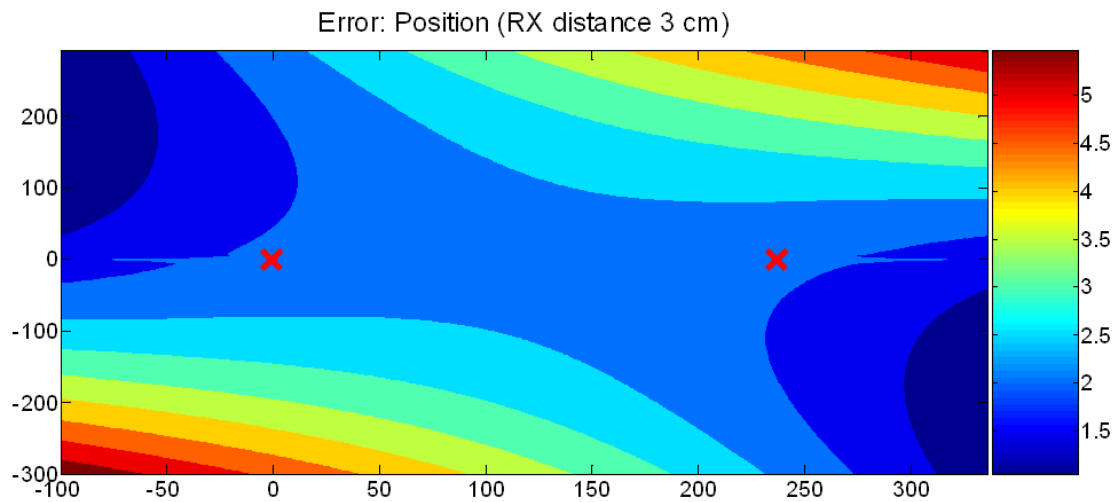
Fig. 13 - Position error due to plane wave approximation (receivers distance 3 cm)

It can be observed that, although the distribution of error is similar in Fig. 12 and Fig. 13, the error magnitude of Fig. 13 is about ten times smaller than in Fig. 12, so this error is approximately proportional to the distance between receivers. The conclusion is that the smaller the distance between receivers, the smaller the error of approximation by a plane wave.

The second error to be analyzed is the error introduced at the amplification phase. As there are three receivers, there are three similar, but different, time responses. There are also three different paths from the receiver to the FPGA input pin. These three paths contain the same components, but as in the previous case, its temporal response is not identical. The result of this process is an error that will affect the time measured by the system. For example, if time estimation error is ±500 ns, the effect in the localization process when the distance between receivers is 3 cm is shown in Fig. 14 (all other errors sources are not considered).
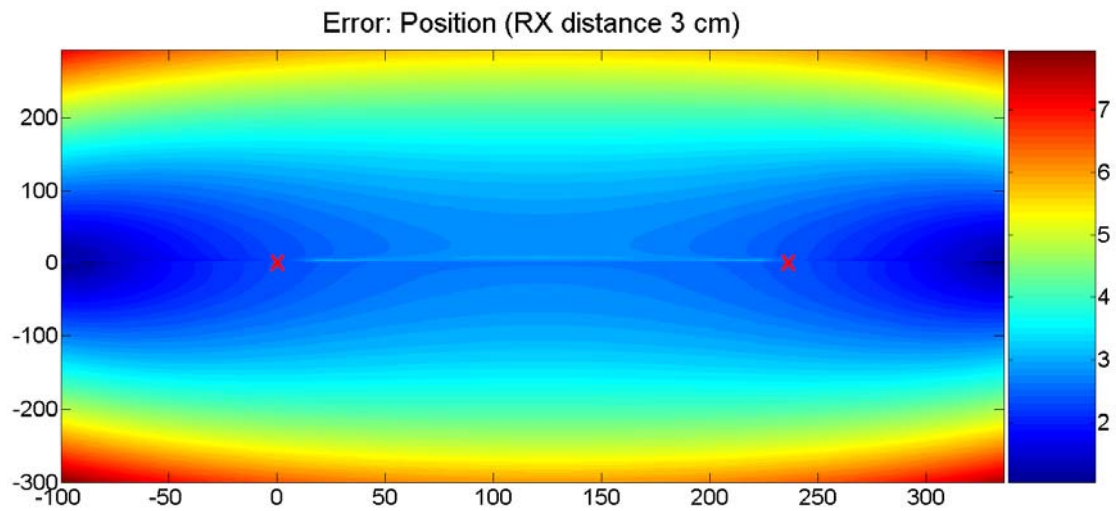
Fig. 14 - Position error due to non ideal amplification phase (receivers distance 3 cm)

In order to reduce the effect of this error, the receivers must be placed as far as possible. When the distance between the receivers is reduced, the percentage of this error respect the total time measure will be bigger and the localization error will be increased too. To show this effect, Fig. 15 represents the localization error if, with the same estimation error (±500 ns), the distance between the receivers is reduced to only 1 cm.
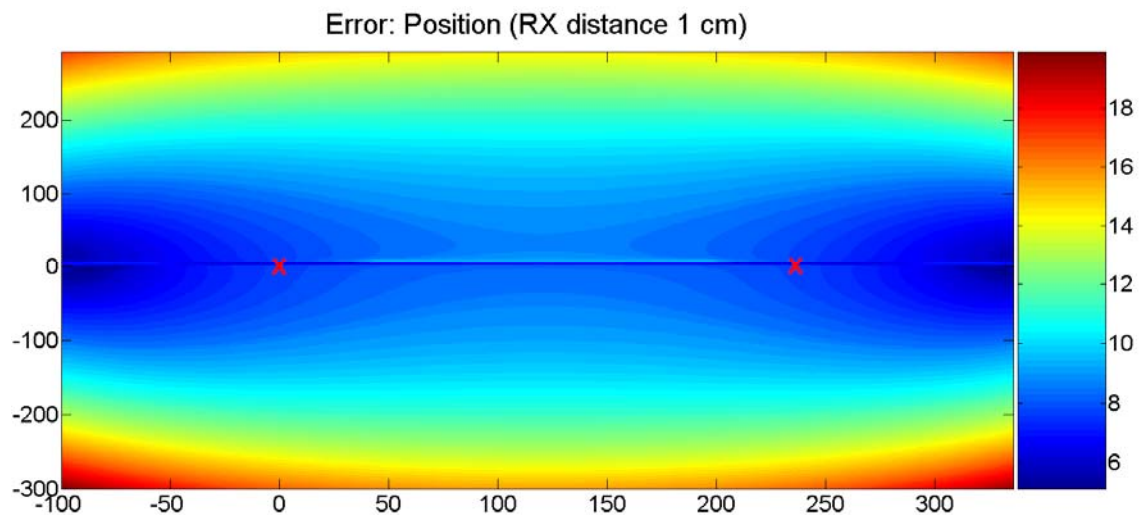

Fig. 15 - Position error due to non ideal amplification phase (receivers distance 1 cm)

As it can be observed, the error distribution shown in Fig. 14 and Fig. 15 is similar, but error scale of Fig. 15 is three times greater than in Fig. 14.

So the error due to plane wave approximation increases with the distance between receivers, but the error due to non ideal amplification decreases. Therefore, there is an optimum in the distance between the receivers in order to minimize the global error.

The third error to be analyzed is the error due to the incorrect parallelization of the ceiling with respect to the floor. Given that the transmitters are in the ceiling of the room but the receivers are on the floor, if the building has different inclinations in the floor and ceiling, this error will affect the localization precision of the system. To simulate this error, we consider that one of the transmitters is at the correct height while the other is 4.2 cm nearer to the floor (given that the distance between transmitters is 240 cm, the parallelization error is ~1°). This error in the deployment of the transmitters generates the localization error show in Fig. 16 when the distance between receivers is 10 cm:
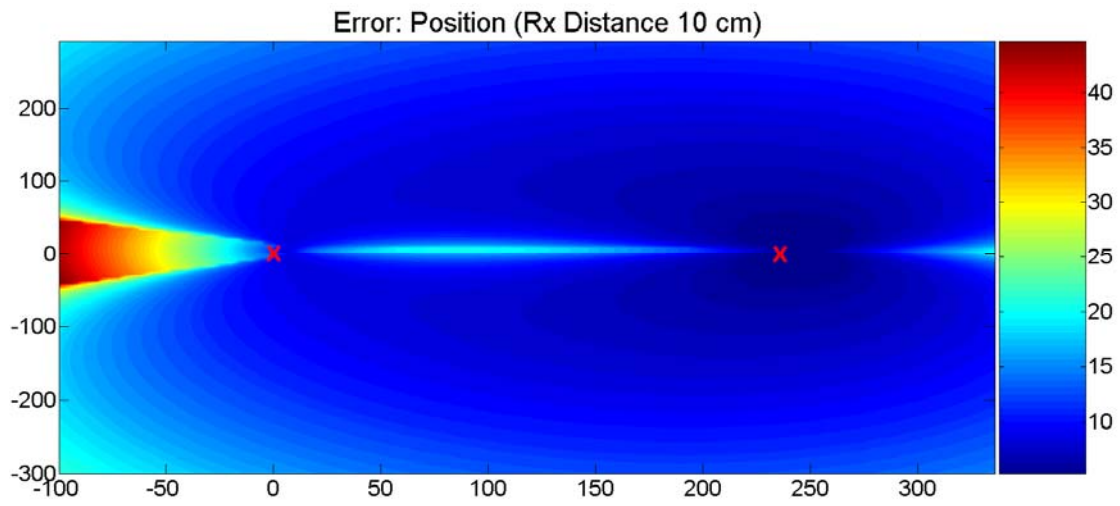

Fig. 16 - Position error due to non ideal parallelization (receivers distance 10 cm)

This error doesn't depend on the relative distance between the transmitters and the receivers so strongly. To show this effect, if we reduce the distance between receivers to 3 cm, the error is similar as shown in Fig. 17:
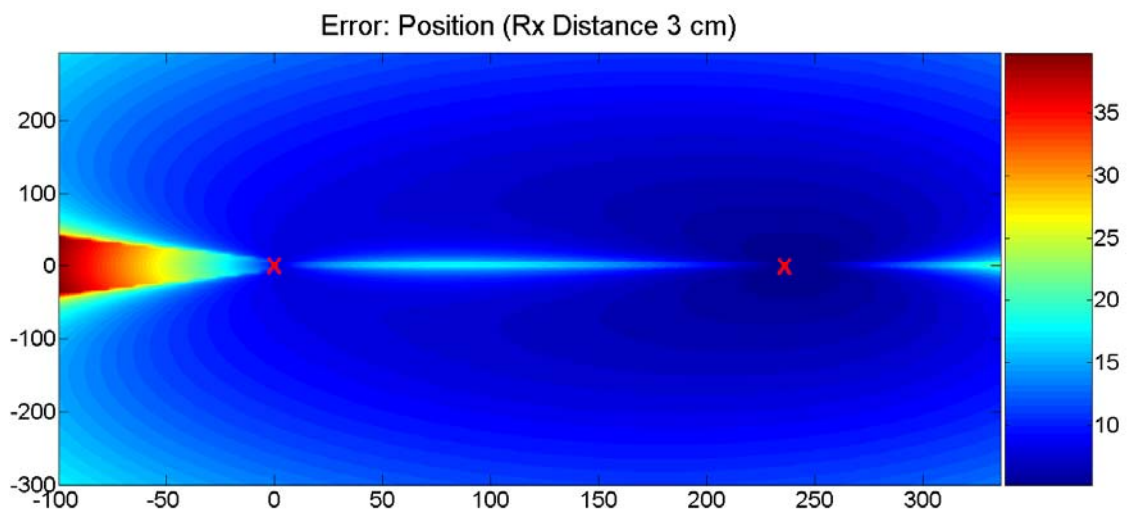

Fig. 17 - Position error due to non ideal parallelization (receivers distance 3 cm)

To find the optimum distance between receivers, a characterization process of these errors must be performed. Fig. 18 shows the mean error (calculated in all the target area, -100 < x < 340 and -300 < y < 300) depending on the distance between receivers. The error due to plane wave approximation increases with the distance between receivers, as expected. However, the error due to non-ideal amplification decreases with the distance between receivers, while the error due to parallelization is almost independent of this parameter. As a consequence, the total error has a minimum around 3 cm of distance between receivers. This value would change depending on the amplification time error, which has been taken as 500 ns according to our experimental results. This time can change depending on the electronic implementation of the amplification phase, and the optimum distance between receivers would change accordingly: higher distance for higher time errors.
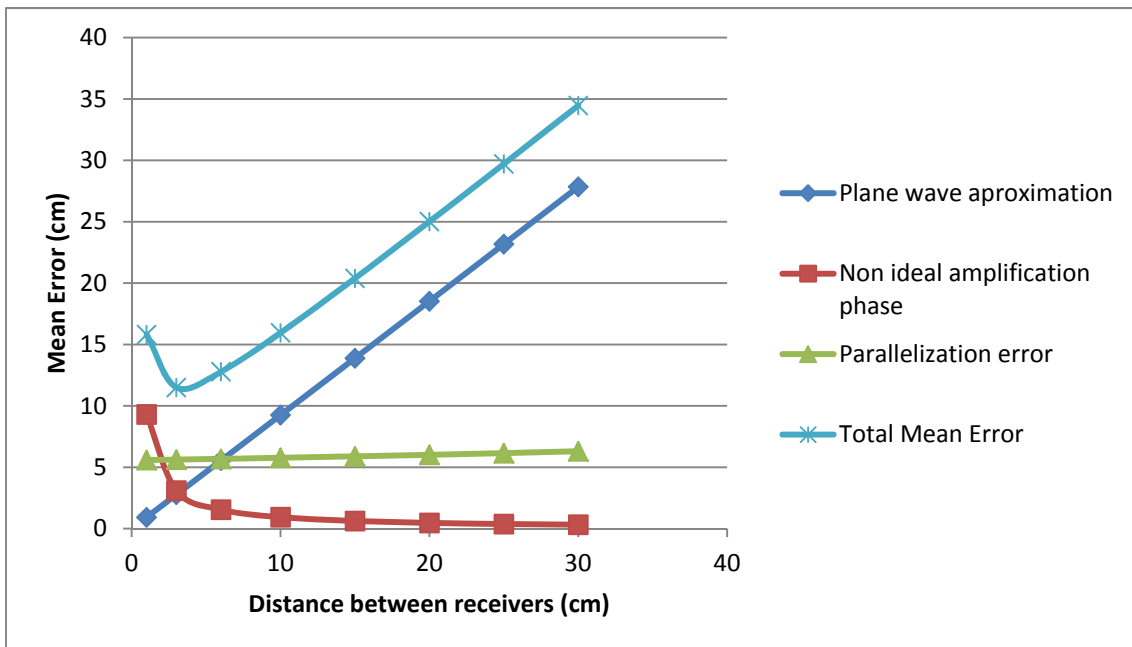

Fig. 18: Mean error versus distance between receivers

The last error that will be analyzed is the error of synchronization between receivers. As the robot has three receivers and each receiver is connected to a different amplification path, the reference signal at each receiver can arrive at the comparator with different intensity. This fact can cause that the comparator sends a valid signal of one receiver with an integer number of ultrasonic pulses of error. This error source can be observed in Fig. 19.
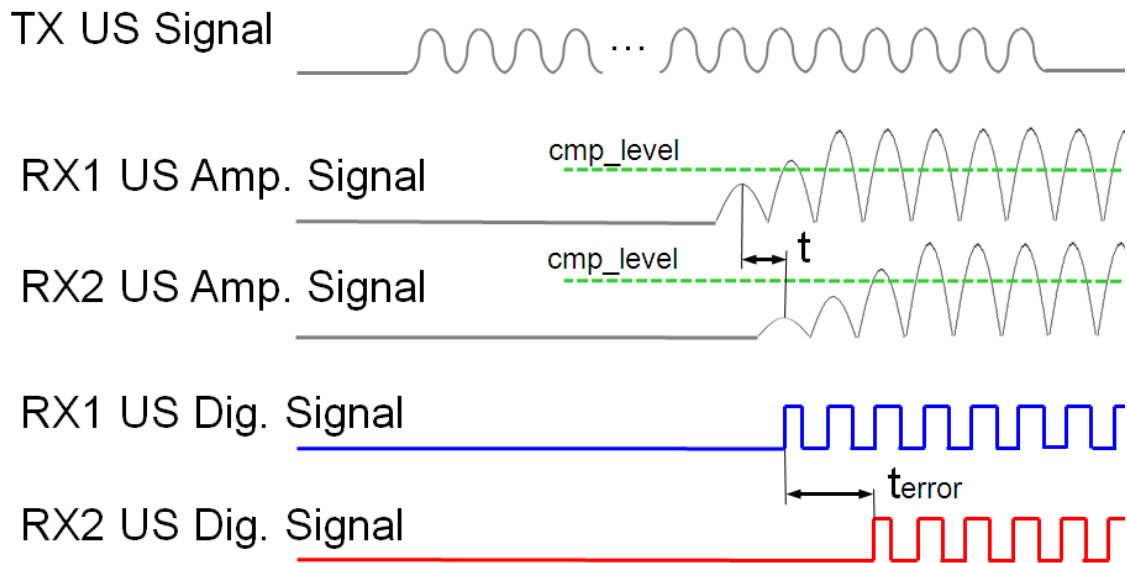
Fig. 19 - Synchronization error

In Fig. 19, the same ultrasonic signal arrives to both receivers with a differential reception time 't', but as the ultrasonic signal from the first receiver is captured with higher intensity, the signal is digitalized in the second cycle, while the signal from second receiver is captured in the third one, so the localization system will consider that the difference of arrival time will be 't_{error}' instead of 't'. This error would affect the system with a similar distribution as the one shown in Fig 14, but instead of considering 500 ns as the variation, the error in this case is 25 us (50 times greater).

This error is not acceptable, but can be discarded by software methods. The solution is to consider the previous position of the robot when obtaining its new localization. Given that the error is due to the fact that the robot misses the first cycles of one of the signals, the error is always a multiple of 25 us (the period of the ultrasonic signal), so if the new calculated position represents that the robot has moved more than a threshold (e.g. 1 meter), a check process is started that consists in applying a ±25 us factor until the calculated position differs less than that threshold.

6   Experimental results

In order to test the proposed system, a prototype robot (Fig. 9) has been implemented. For this experiment, two transmitters were deployed at the ceiling of a room at positions (0, 0, 280) and (240, 0, 280) cm. The robot has three receivers at a distance of 3 cm between them and was deployed at the floor in three different positions:

- (100, 100, 0)

- (160, 100, 0)

- (160, 200, 0)

In each position, the robot was oriented with four different orientations (0º, 90º, 180º and 270º) and, for each orientation, 45 measures were taken with respect to both transmitters.

The first preprocess of the measures was to adjust them to the estimated position of the robot, adding or subtracting multiples of the ultrasonic period (T), 25 us, as explained in the previous section. Fig. 20 shows the correction factor that has been applied to the measures in function of the position of the robot.
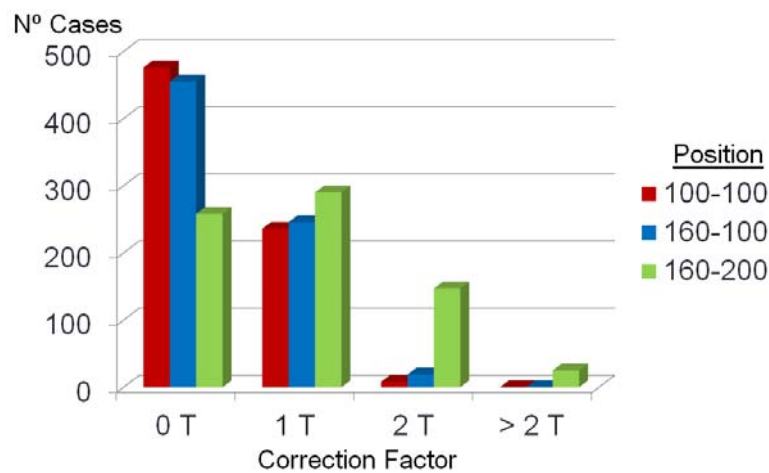

Fig. 20 - US period correction factor

After removing this error from the measures, a median filter is applied to the estimated positions. The angle estimation error obtained for each resulting position and orientation is shown in Table 1, being Tx1 the first transmitter and Tx2 the second transmitter.

Table 1: Angle error after median filter

	Horizontal Angle Error Tx1	Horizontal Angle Error Tx2	Vertical Angle Error Tx1	Vertical Angle Error Tx2
100-100 0º	2.06º	0.13º	0.23º	2.74º
100-100 90º	0.45º	7.93º	1.07º	0.66º
100-100 180º	3.44º	0.03º	0.36º	1.22º
100-100 270º	0.14º	3.60º	0.60º	2.05º

160-100 0º	0.61º	2.32º	0.81º	0.03º
160-100 90º	1.68º	6.41º	1.76º	0.10º
160-100 180º	1.94º	1.12º	0.33º	0.04º
160-100 270º	0.47º	4.30º	2.96º	0.77º
160-200 0º	2.88º	0.78º	3.20º	1.25º
160-200 90º	0.47º	4.98º	0.62º	0.27º
160-200 180º	1.83º	2.15º	3.04º	2.07º
160-200 270º	0.11º	5.22º	1.08º	0.86º

This table shows directly the orientation error of the system, which goes from 0.13º up to 7.93º, but it doesn't represent the error in the localization system. The localization results obtained after applying the algorithm are shown in Fig. 21, Fig. 22 and Fig. 23, including each particular value and the median of the values for each orientation. The calculated positions are expressed in cm, and the ideal position (reference) is also represented for comparison purposes.
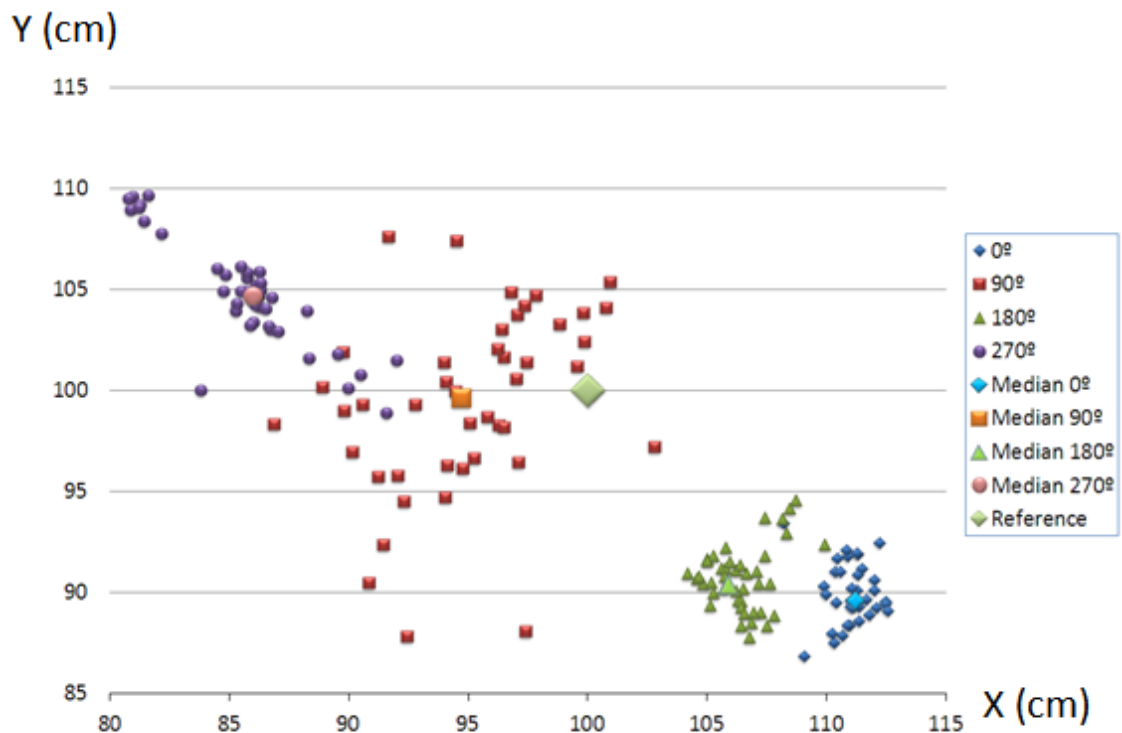

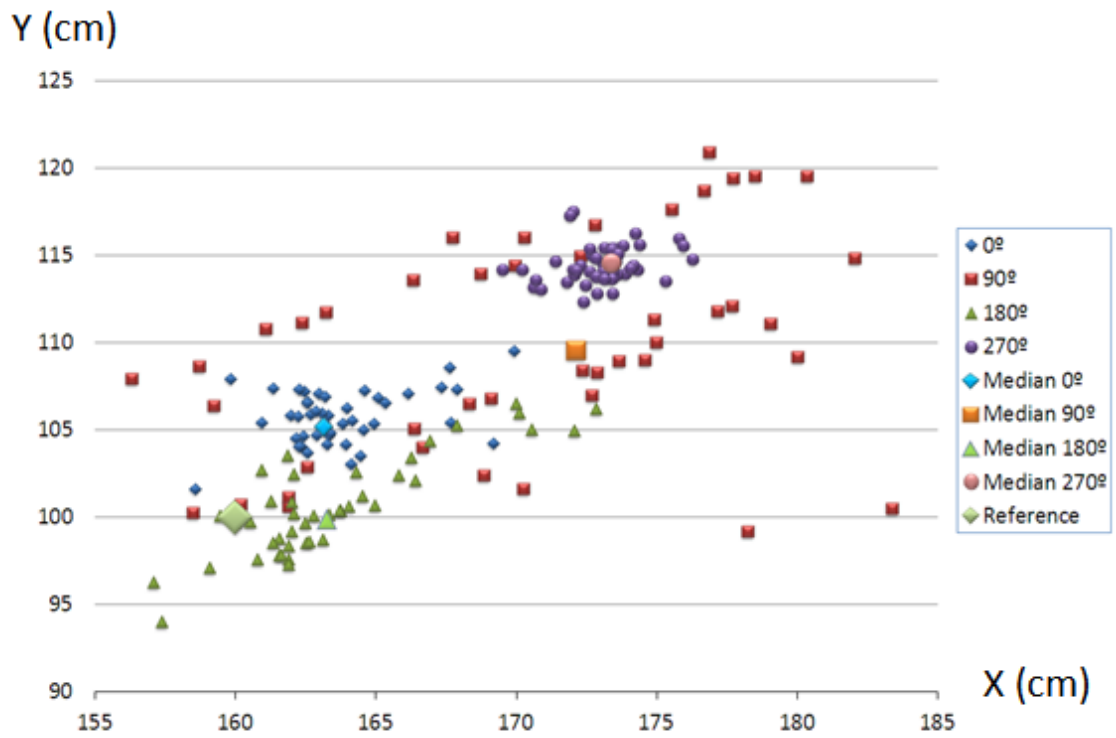Fig. 21 - Localization results at (100, 100, 0)
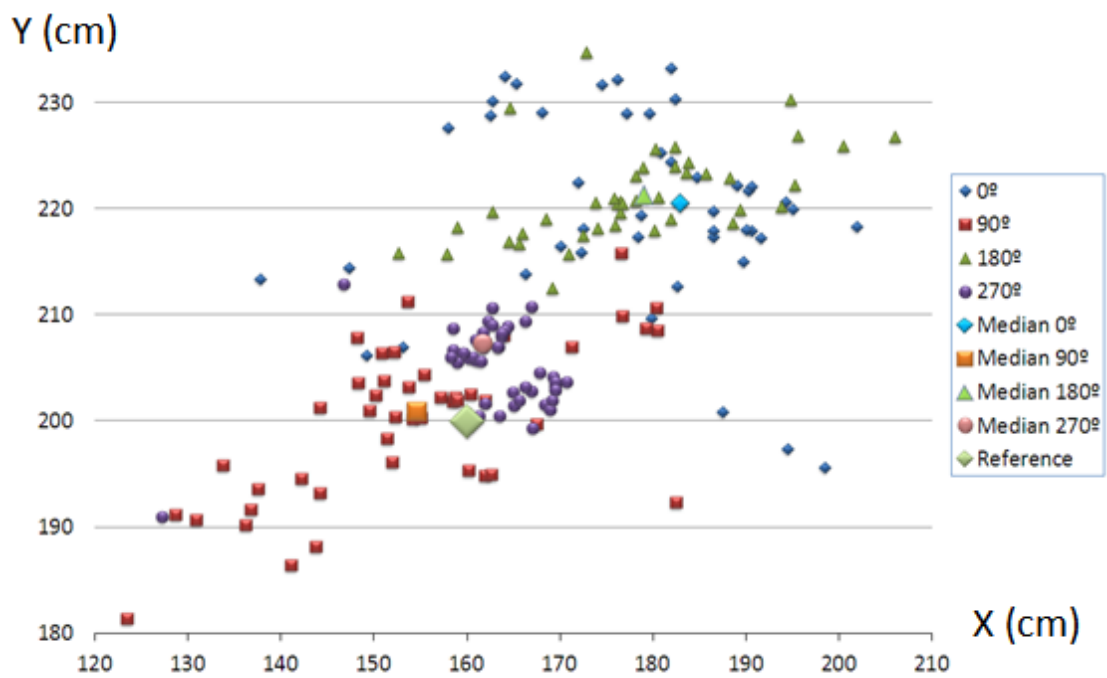
Fig. 22 - Localization results at (160, 100, 0)

Fig. 23 - Localization results at (160, 200, 0)

The localization error is summarized at Table 2:

Table 2: Localization Error Summary

	Error at Median Position	Mean Error	Standard Deviation
100-100 0⁰	15.33 cm	18.15 cm	8.17 cm
100-100 90⁰	5.27 cm	7.32 cm	4.48 cm
100-100 180⁰	11.28 cm	11.65 cm	1.56 cm
100-100 270⁰	14.73 cm	15.69 cm	4.16 cm
160-100 0⁰	6.07 cm	7.31 cm	2.56 cm
160-100 90⁰	15.46 cm	16.00 cm	8.44 cm
160-100 180⁰	3.27 cm	5.53 cm	4.46 cm
160-100 270⁰	19.77 cm	19.47 cm	1.40 cm
160-200 0⁰	30.84 cm	31.10 cm	8.52 cm
160-200 90⁰	5.36 cm	14.05 cm	9.42 cm
160-200 180⁰	28.62 cm	30.42 cm	12.08 cm
160-200 270⁰	7.45 cm	8.63 cm	4.76 cm

7 Conclusions

The results show that the proposed algorithm, ALO (Angle Localization and Orientation), is valid for indoor localization and orientation systems, allowing it to be implemented in low cost systems: less than 10 € for the electronic components of the reception system, and also for the transmission system, and any low cost processing element can be used as the formula have been simplified as much as possible.

The localization error is greater than the one obtained with other localization systems based on ultrasonic technology using TOA algorithms. For example, in [8], for a system that uses similar ultrasonic transducers, the mean error is about 3.5 cm, while the position error of the proposed system ranges between 5 and 30 cm.

The inferior obtained precision is due to the fact that an error in the estimation of the ultrasonic reception instant is less significant if the measured time is the time of arrival instead of the differential time of arrival. In TOA techniques, the time to be measured is in the order of 15 ms (a distance of 5 meters at 340 m/s), while in DTOA techniques the time to be measured is about 90 us (for a distance between receivers of 3 cm). Therefore, a fixed error (for example, 500 ns) is relatively much more important in DTOA than in TOA techniques. However, analyzing the ALO system with respect to other ultrasonic TOA systems, we conclude that the ALO system has three main advantages:

1. Apart from the localization information, ALO also obtains the orientation of the receiver.
2. Like other DTOA systems, the system doesn't need a synchronization signal between transmitters and receivers (i.e. no RF is needed).

3. The robot only needs to be in line of sight of two transmitters to obtain its localization, while TOA systems need at least three transmitters.

Comparing the ALO system with others DTOA systems, the main advantages are:

1. The computational cost has been drastically reduced, making it comparable to TOA localization systems.
2. The number of receivers is only three, while other DTOA systems are usually implemented with more receivers.
3. It doesn't need a minimization method to solve the localization of the robot, simplifying its implementation.

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