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# HALO4: Horizontal Angle Localization and Orientation System with 4 receivers and based on Ultrasounds

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**Abstract** This paper presents a low cost ultrasonic localization and orientation system based on the DTOA (Differential Time Of Arrival) technique. The proposed system consists in deploying any number of autonomous nodes at the floor of a room and place some transmitters at the ceiling. Each node shall have four ultrasonic receivers to obtain the basic measures for the localization and orientation systems, and the coverage area of the system is defined by any region covered by at least three transmitters. The localization system is based on an estimation process of the horizontal angle of the node with respect to the transmitters. This implementation allows deploying the transmitters at different heights and ignores the error introduced by an incorrect estimation of the ultrasonic signal speed. The computational effort of the proposed system is greater than other ALO (Angle Localization and Orientation) systems, needing a minimization process to obtain the localization results, but it is smaller than in other typical techniques, like those based on the intersection of hyperboloids.

**Keywords** DTOA, location, ultrasonic, angle, DOA

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**1 Introduction**

Each year, new robots for indoor applications are developed, and one of the most characteristic differences that fix their market value is their navigation system, or in other words, the capacity of the robot to know its position and orientation, and its ability to map and navigate through the environment.

The mapping and navigation accuracy of the robot are limited by the precision of the localization and orientation system, and that is why these systems are being deeply studied.

There are a lot of technologies that allow knowing the position of a node in an indoor environment, as the systems based on radiofrequency [1] or the systems based on image processing [2, 3] or the system based on searching references points [4]. Each of them has advantages and disadvantages, and the selection is done in function of the computational capacity, the accuracy and the cost demanded by the application.

Among all localization systems, one that allows a relatively high precision with an associated low computational requirement and low cost is the one based on ultrasound technology [5].

Localization systems are based on estimating their position with respect to reference points whose positions are known. In function of the kind of the measure used, systems can be categorized as:

TOA (Time Of Arrival): These systems estimate the absolute distance between the node and the reference points [6, 7, 8]. These systems usually reach the higher precision on localization process and their associated computational cost is very small (they generate spheres at the reference points and intersect them). Their main problem is that they demand a high synchronization between the reference points and the node (system based on ultrasounds usually use a radiofrequency signal to reach this requirement, fact that increases the cost of the system)

DTOA (Difference Time Of Arrival): These systems estimate the difference in the distance between known points with respect to a signal generated at the reference points [9]. They usually reach less precision than TOA systems and their computational cost is also higher (they need to intersect hyperboloids [10, 11, 12, 13, 14, 15]). Their main advantage is that as known points are usually deployed at the same node, synchronization is easier (ultrasound systems do not need any auxiliary signal) making the systems more autonomous.

DOA (Direction Of Arrival): These systems base the localization process on the knowledge of the direction where the reference point is deployed [16, 17]. Knowing the direction among multiple reference points, trigonometric functions can be applied to know the position of the node. These systems present a high computational cost and, as DTOA systems, they don't need any synchronization process. These systems have been substituted by TOA and DTOA systems because they usually reach higher precision.

In this paper, an evolution of the ALO4 system [18] is presented. ALO systems implement a localization process based on TOA algorithms (intersection of spheres), but is based on using multiple receivers (as DTOA systems) to obtain the direction of arrival (as DOA systems) of the reference wave. The computational cost is similar to TOA systems but it does not require a high synchronization between transmitters and receivers.

HALO4 bases the localization on the estimated horizontal angle, fact that changes the localization process (making it more complex) but allowing deploying the transmitters at different heights and making the system immune to errors on the estimation of the ultrasonic speed, so it obtains a better precision on the localization and orientation processes.

The rest of the paper is organized in six main sections: "ALO4 System", where a summary of the previous ALO system is presented; "HALO4 System", where the new system is detailed; "HALO4 Minimization Process", in this section the minimization process is described and its computational cost analyzed; "HALO4 Errors", where some of the most typical errors that affect the precision of the system are analyzed; "Implementation", where the implementation of the system can be found; and "Results", where the experimental results are presented.

## 2 ALO4 System

ALO4 system (**Figure 1**) bases the estimation of the received angle in the measure of the propagation delay of a reference wave between 4 receivers deployed at the node in a square distribution. The node is located in the floor while the transmitters are in the ceiling.

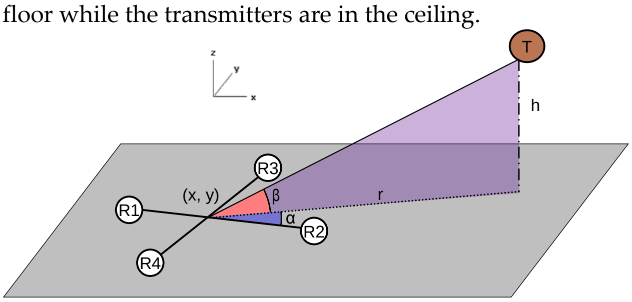



**Fig. 1** ALO4 system showing the node with 4 receivers and a transmitter

In this system, the height of the ceiling (*h*) is fixed, so the difference in the time of arrival to each receiver depends on both the horizontal distance to the transmitter (*r*) and the orientation of the node.

With the measured delays, ALO4 system obtains the direction of arrival of the ultrasound signal applying the following formulas (distances in (1) are the result of multiply the measured delays by the propagation speed of the reference signal). The details on how to obtain these formulas can be found in [9] and [18], but the general idea is that if the signal arrives in all the transmitters almost at the same time it is because node is below the transmitter, so all the receivers have a similar distance to the transmitter, and therefore the vertical angle β approaches 90°. On the contrary, if the horizontal distance *r* increases, the difference in the time of arrival to each receiver will increase.

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

- $d_1$ = measured distance between R1 and R2
- $d_2$ = measured distance between R3 and R4
- $a$ = distance between receivers

With a single distance to a transmitter it is impossible to know the location of the node. However, knowing the distance to two transmitters the location can be deduced as the intersection of two circumferences. In fact, there would be two possible solutions, but using the orientation of the node (which nodes receive the signal first), the exact location can be deduced. Therefore, merging the measured vertical angle with respect to two transmitters, the system is able to obtain the localization of the node as:

$$r_1 = \frac{h}{\tan(\beta_1)} \qquad r_2 = \frac{h}{\tan(\beta_2)} \tag{2}$$

$$x = \frac{{r_1}^2 - {r_2}^2 + b^2}{2 \cdot b} \qquad y = \pm\sqrt{{r_1}^2 - x^2} \tag{2}$$

- $r_x$ = distance from the projection of transmitter X on the flour to the node.
- $h$ = height of the ceiling
- $b$ = distance between transmitters
- $\beta x$= vertical angle measured to transmitter X

And with the horizontal angle with respect to one transmitter and the position of the node, it obtains its absolute orientation.

## 3 HALO4 System

The HALO4 system uses the same receivers and measures to obtain the same angles as ALO4 (**Figure 1**), but instead of using the vertical angle for the localization process it only uses the horizontal angle. Once the node location is obtained, the node obtains its orientation in the same way as in ALO4 implementations.

This new approximation makes the system immune to errors on the estimation of the reference wave speed: Equations described in (1) are expressed in distances, but the node does not measure distances, it measures propagation delays, transforming these formulas in:

$$\sin(\beta) = \sqrt{1 - \frac{(t_2 \cdot v_s)^2 + (t_1 \cdot v_s)^2}{a^2}} \tag{3}$$

$$\cos(\alpha) = \sqrt{\frac{(t_1 \cdot v_s)^2}{(t_2 \cdot v_s)^2 + (t_1 \cdot v_s)^2}} = \sqrt{\frac{{t_1}^2}{{t_2}^2 + {t_1}^2}} \tag{4}$$

- $t_1$ = time measured between R1 and R2
- $t_2$ = time measured between R3 and R4
- $v_s$ = estimated propagation speed of reference wave.

To calculate the vertical angle β (3), the system converts the time that the reference signal need to travel the distance between receivers ($t_2$ and $t_1$) to a distance using the estimated propagation speed of the ultrasonic signal. As the system cannot obtain the propagation speed of the reference wave at each instant, it considers a propagation speed established by a calibration process and considers that this propagation speed as a constant. Ultrasound propagation speed depends on multiple factors, as the temperature or the humidity of the environment, so it usually changes frequently, demanding a constant calibration process or an error will be introduced in the estimation of the vertical angle.

The horizontal angle *α* (4) only depends on the time measure by the system, so the propagation speed can be removed from the formula without introducing any error on the estimation. Besides, if the localization process only needs the horizontal angle, the transmitters can be deployed at different heights, and the localization error introduced by the incorrect parallelization between the floor and the ceiling of the room is reduced too.

To obtain the position of a node only requesting the horizontal angle, the node must obtain the angle with respect to two transmitters (ϕ at **Figure 2**).

Knowing the angle ϕ with respect to three transmitters, the node position is constrained to only one point, as shown in **Figure 3**:

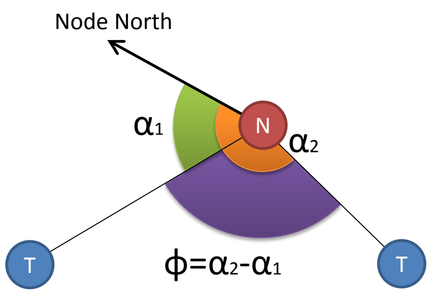



**Fig. 2** HALO4 ϕ angle in function of the horizontal angle of the node with respect to two transmitters

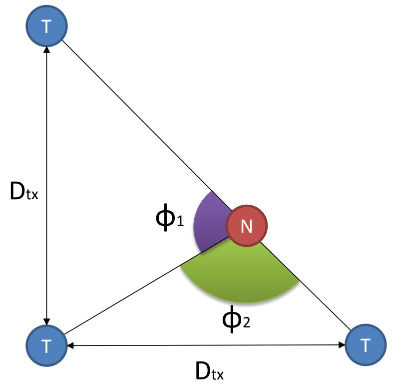



**Fig. 3** HALO4 necessary angles to implement the localization algorithm

If we analyze the possible points that are defined by a pair of transmitters [at (0,0,*h*) and (250,0,*h*)] and a measured angle ϕ, the **Figure 4** is obtained.

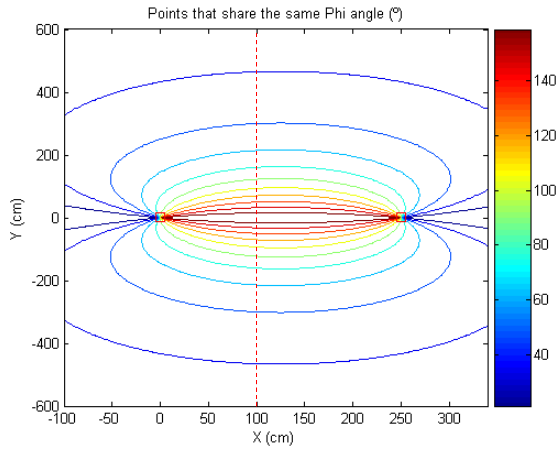



**Fig. 4** Points that share the same ϕ angle. ϕ angle at the vertical red line in the figure is detailed in **Figure 7**.

Combining two of these curves, the position of the node is defined.

Mathematically, the solution of the problem is very complex (has an associated high computational cost).

To show an example of this complexity, if we define three transmitters at (0, 0), (300, 0) and (0, 300) and the node is at (200, 50), the points that share the two measured horizontal angles with respect to the three transmitters are the ones that exist in the two curves, (5) and (6), of **Figure 5**.

$$2 \cdot 300^2 = x^2 + y^2 + 1.8159xy \quad (5)$$

$$300^2 = \left( \frac{x^2 - y^2}{-1.5185x - 0.8333y} \right)^2 + x^2 + 1.5185 \frac{x^2 - y^2}{-1.5185x - 0.8333y} y \quad (6)$$

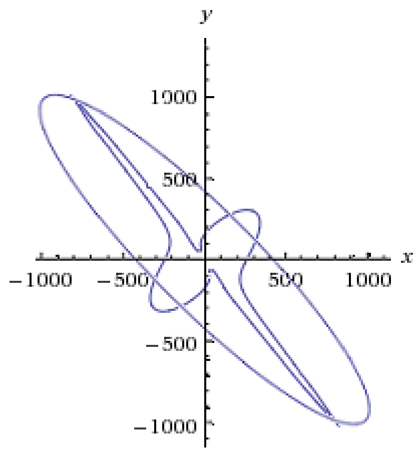



**Fig. 5** Graphical representation of the mathematical solution (positions expressed in cm)

With this process, the node obtains 8 points: 6 of them are discarded as the node can know its region in function of the horizontal angles measured (**Figure 6**), and as the node knows the angle associated to each pair of transmitters, only one solution is obtained.

In order to discern between regions 2 and 3, the following reasoning can be used. In region 2, the ϕ angle with respect to the transmitters deployed at the X axis is found counter clockwise with respect to the ϕ angle obtained with respect to the transmitters deployed at the Y axis, while at region 3 this order is inverted (clockwise). A similar reasoning can be used to discern between regions 1 and 4, where one ϕ angle is smaller and included in the other ϕ angle.

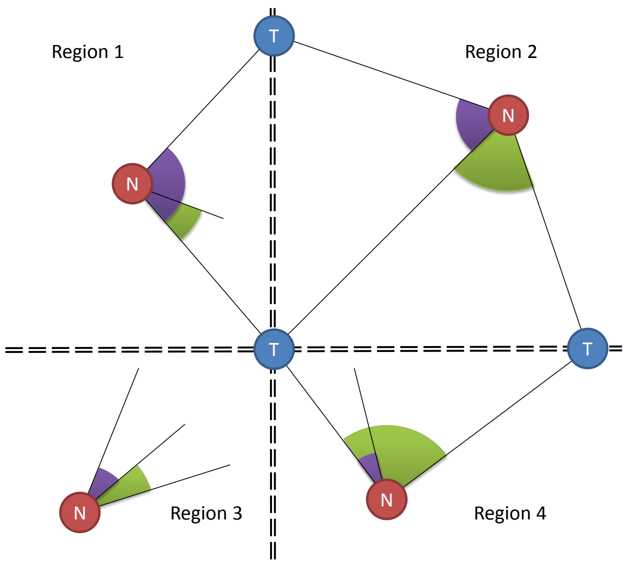



**Fig. 6** ϕ angles in function of the node position and region

**4 HALO4 Minimization Process**

Instead of using a complex algorithm that solves the localization system, a minimization process has been implemented.

This process is based on the next principle: as it can be observed in **Figure 4**, in the region limited by two transmitters, if we trace a line perpendicular to the line that joins the transmitters (as the red line in the figure), the points nearest to the transmitters have a greater angle associated, while the points at a greater distance have an associated smaller angle. For example, if we only draw in a figure the ϕ angle evolution for the points of **Figure 4** that share X=100 cm, **Figure 7** is obtained.

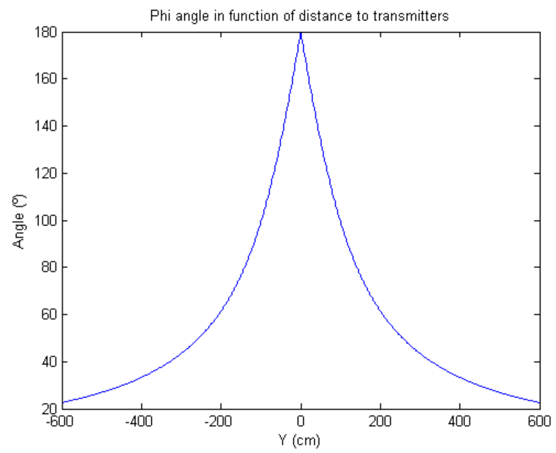



**Fig. 7** ϕ angle evolution as a function of the distance to the line joining the transmitters for X=100 (see **Figure 4**)

Based on this fact, the minimization algorithm consists in:

1. Capturing the two angles that are generated between the node and the transmitters ($\phi_1$ and $\phi_2$)
2. Place an imaginary node in the center of the map and calculate the theoretical angles with respect to all transmitters ($\phi_{1i}$ and $\phi_{2i}$)
3. Compare $\phi_1$ and $\phi_2$ with $\phi_{1i}$ and $\phi_{2i}$.
4. Select the angle that diverges more.
5. Move the imaginary node in the direction perpendicular to the transmitters that involves this angle. *
6. Recalculate $\phi_{1i}$ and $\phi_{2i}$ for the new position.
7. If imaginary and captured angles are "identical" stop the process, else iterate from step 3.

* The node starts moving 50 cm every iteration (the distance between transmitters divide by 5), but each time that the direction associated to any angle switches, this movement is divided by 2 up to a minimum of 0.1 cm. Starting with a higher step (more than 50 cm) would be better for positions near the corners of the map, but worse for positions near the center. This is a good trade-off between the necessary number of iterations and accuracy.

When the imaginary node position goes outside the region between transmitters, the direction of minimization must be changed by the line that joins the imaginary node position with the mid-point of the transmitters.

This minimization process requires a higher computational cost than other ALO systems. To illustrate the computational cost of HALO4 system, a MATLAB simulation has been done. In this simulation, transmitters were placed at the ceiling of a room at (0,0,280), (0,250,280) and (250,0,280) and the node was placed in the floor between (0.5,0.5) and (249.5,249.5) in all points of a grid of 0.5x0.5 centimeters (generating a total of 249000 measures). The minimization process stops when the difference between imaginary and calculated angles is less than 0.001 rad. For these conditions, the minimization algorithm needs the number of iterations shown in **Figure 8**.

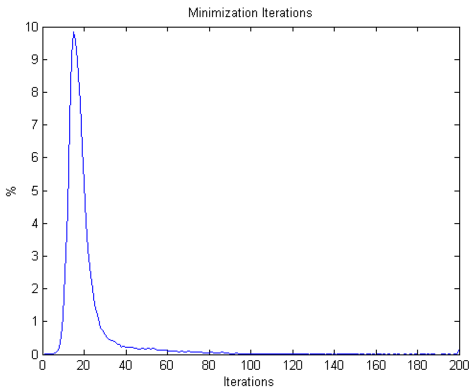



**Fig. 8** Number of iterations for the minimization process

The mean number of iterations needed to localize a node via this minimization algorithm for the detailed environment is 20.54.

The time requested by Matlab to execute this localization process has been measured with different computers and operating systems (no parallelization techniques have been implemented to solve the algorithms). The results are summarized in Table 1:

**Table 1.** Computational Cost - Localization Algorithms

| System | Num. Measures | Execution Time (min) | Mean Time per Measure (ms) |
|---|---|---|---|
| HALO4 (CPU1) | 249000 | 0.2863 | 0.0690 |
| ALO4 (CPU1) | 249000 | 0.0237 | 0.0057 |
| HALO4 (CPU2) | 249000 | 0.6057 | 0.1460 |
| ALO4 (CPU2) | 249000 | 0.0318 | 0.0077 |
| DTOA with Gauss-Newton minimization algorithm [19] (CPU3) | 160000 | 3.7333 | 1.3999 |
| DTOA with Cayley-Menger minimization algorithm [19] (CPU3) | 160000 | 43.1833 | 16.1937 |

** CPU1: Intel Core i5-2500K processor (working at 3.30 GHz with 8GB of RAM) with Windows 7 (64 bits)*
** CPU2: Intel Core 2 Duo E8200 processor (working at 2.66 GHz with 2GB of RAM) with Windows XP (32 bits)*
** CPU3: Intel Core 2 Duo 2.00 GHz [19]*

It can be deduced that HALO4 has a computational cost between 10-20 times higher than ALO4 systems, but comparing it with other DTOA minimization systems, its cost has been significantly reduced.

## 5 Implementation

HALO4 system has been implemented using an FPGA platform. We have used four transmitters in order to cover a wider area. They are placed on the ceiling of a room, and they take turns to transmit. The distance between the transmitters is 237 cm. The possible points where the object can be placed are defined in the floor of the room. The ceiling height is 284 cm. This distribution allows the implementation of ALO4 and HALO4 systems (**Figure 9**).

For the transmitter system, a state machine has been implemented in a Xilinx Spartan3 FPGA. The transmitter module consists in the generation, each 200 us, of a train of 20 pulses at 40 kHz. This signal is sent to a driver that increases the voltage of the signal from 3.3 V to 20 V, and this amplified signal is the input of the ultrasonic transmitters (model 400ST120-PROWAVE).

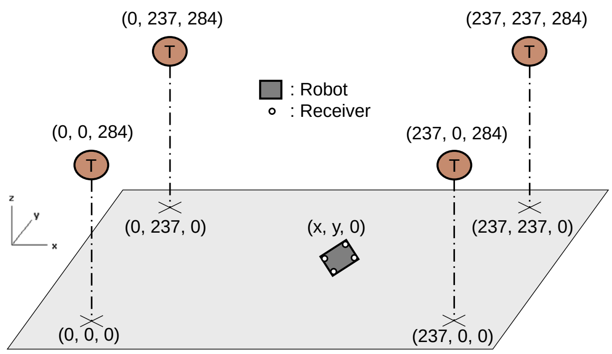



**Fig. 9** System deployment (positions are expressed in cm)

The receiver module (**Figure 10**) consists of four ultrasonic receivers (model 400SR120-PROWAVE) in a square distribution. The diagonal of this square is 10.15

cm.

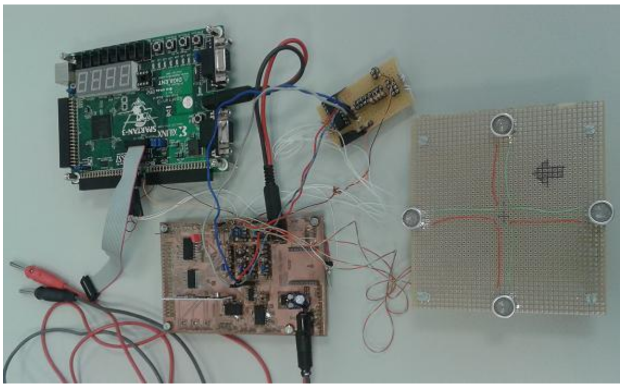


Fig. 10 Receiver implementation

The analog conditioning circuit and the digital processing system of the receiver are explained in detail in [9].

## 6 HALO4 Errors

The main error sources that affect HALO4 localization algorithm are the errors introduced in the minimization algorithm and the errors generated by an incorrect estimation of the horizontal angle (mainly, the error introduced by the non-ideal amplification phase).

To show the effect of these errors, the same environment as in the previous sections has been used. Different simulations have been executed and in each one only one of the previous errors listed has been analyzed.

HALO4 system precision is also affected by other error sources, as the incorrect parallelization between the receivers and the ceiling. This section only includes the error sources whose effect is very different in HALO4 and ALO4 systems.

### *6.1 Minimization error*

The implemented minimization algorithm has two main error sources: The first limitation is the maximum error defined between the measured angles and the estimated angles. The second error is that the algorithm limits the number of iterations to 200. This represents the maximum time between measures that the algorithm has to obtain its position. Although this number is ten times greater than the mean number of iterations show in Figure 8, the 0.053% of the analyzed points need more iterations to reach the requested precision. The effect of these errors is shown in **Figure 11**.

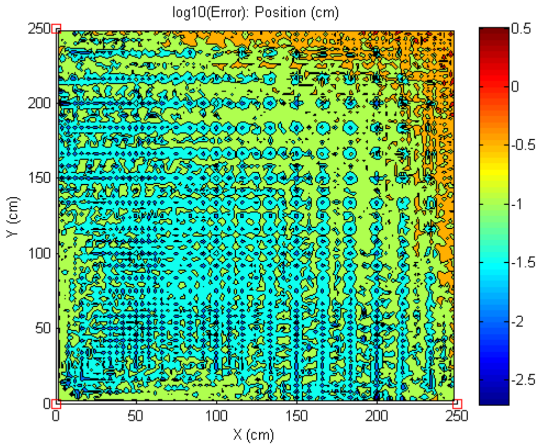



**Fig. 11** HALO4 minimization error (represented in a logarithmic scale)

In the zone at a greater distance from transmitters, the error is higher. This effect is due to that in this zone, the measured angles are smaller than in the rest of regions, so the maximum error between imaginary and measured angles represents a higher percentage error than in the rest of zones. For this simulation, the maximum localization error obtained is 6.72 cm while the mean error is 0.16 cm.

Switching the maximum number of iterations and the threshold of the maximum angle divergence, a higher precision can be reached, but the computational cost of the algorithm is increased. Anyhow, the minimization process is subject to future optimizations using other minimization algorithms, but the basic idea is that the minimization process necessary in HALO4 is not a high computational demanding one, which can be solved using a simple minimization process with less computational resources than other state of the art localization algorithms, as shown in section 4.

### *6.2 Non-ideal amplification phase error*

This error consists in that as there are four analog paths from the different receivers to the input of the processing system, there is a difference in the propagation delays of the generated signals. In our experiments, the error of this type measured was up to 2.1us. To show the effect of this error in the HALO4 system, a simulation where only one of the measures captured contains this error has been executed. The simulation results are shown in **Figure 12.**

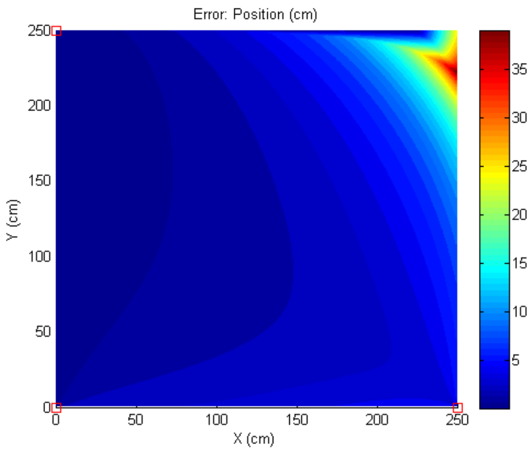



**Fig. 12** Non-ideal amplification error

This error has a great repercussion on the localization performance of the system, with a maximum error of 39.06 cm and a mean error of 3.15 cm. To minimize this effect, it is recommend that the paths from receivers to FPGA pins should be almost identical and the robot should execute the calibration process detailed at [18] before start the localization algorithm.

## 7 Results

In order to test the proposed system, a prototype robot has been used, the same as the one detailed in [18]. The experiment consists on placing the robot on different points in the environment defined in section 5. The robot was calibrated following the algorithm described in [18], before the localization process starts.

After this calibration process, the system parameters for the experiment are the ones defined in section 5, except the following: sound propagation speed was 346.6 m/s, and the offset applied was up to 2.1 us between two different receivers.

A total of 9 points have been analyzed and at each point, 10 different measures have been taken for each node orientation (0°, 90°, 180° and 270°) and for each transmitter, generating a total of 360 localization measures.

The same measures are used to obtain the node position and orientation applying the ALO4 and HALO4 algorithms.

As our implementation uses resonant devices, an offset error (Δ' in **Figure 13**) is sometimes added to the ideal time (Δ) between the captured signals. This error is caused because the reference signal does not arrive with the same strength and angle to all receivers, so the comparator will not always detect the signal after the same number of cycles. This error is always a multiple of the ultrasonic wave period (Δ=Δ' ± n·T), and it causes a great error on the localization results. It can be easily removed by a simple algorithm: the node only needs to add or subtract the ultrasonic period to the captured measures until the resultant position is nearer to the previous one.

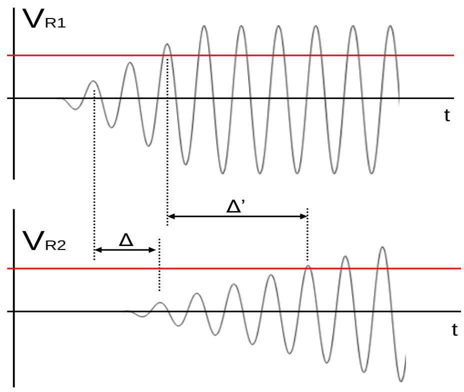



**Fig. 13** Ultrasonic resonant devices offset error

The correction factor applied to the experimental measures is summarized in **Figure 14.**

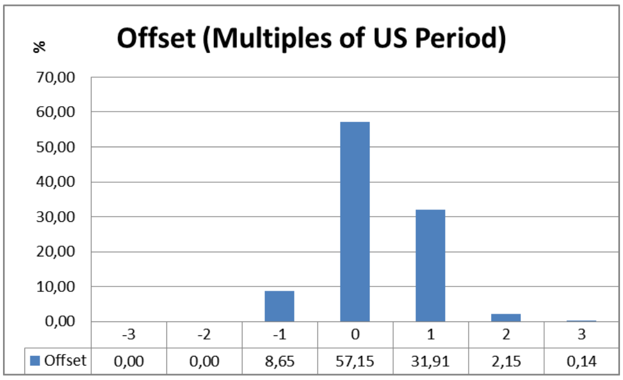



**Fig. 14** Offset generated by resonant receivers

As the environment has four transmitters and the ALO4 system can calculate its position with respect to only two of them, the systems applies the localization algorithm with respect to each pair of transmitters that form a side of the square where the transmitters are deployed. The HALO4 system needs three transmitters, so it uses the four possible combinations that involve the three transmitters in a right triangle distribution.

This implies that four different positions are calculated for each measure (obtaining a total of 1440 localization points).

The results of the localization process are summarized in **Figure 15** (ALO4 system) and **Figure 16** (HALO4 system):

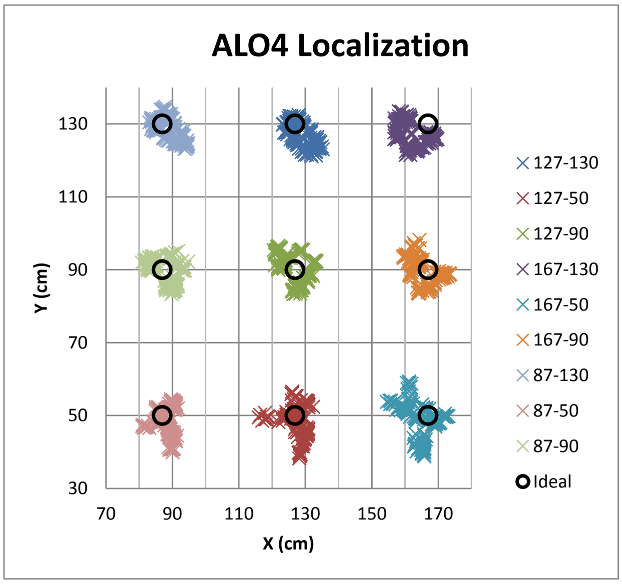



**Fig. 15** ALO4 localization results

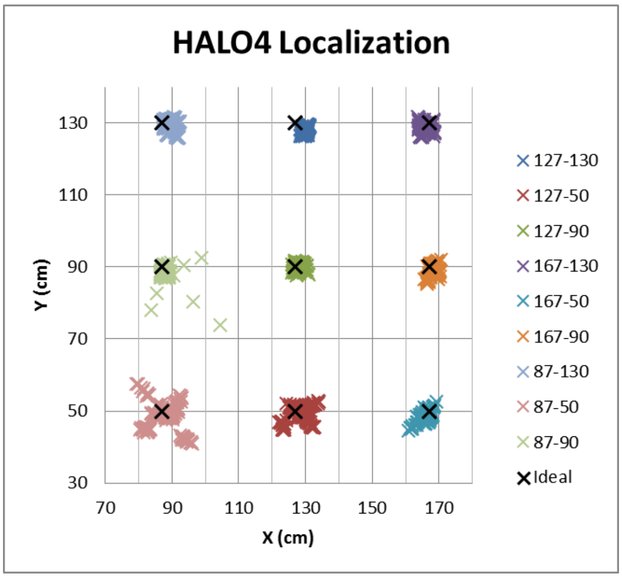
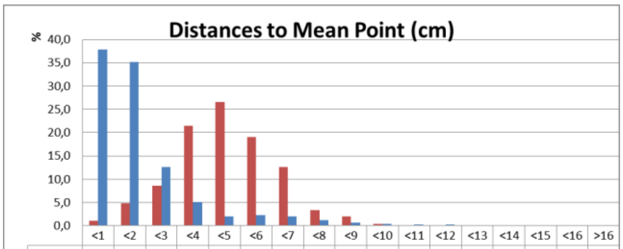



**Fig. 16** HALO4 localization results

The first conclusion is that the HALO4 system obtains localization results with less dispersion than ALO4 system with one consideration. If one of the measures captured has an amplification error different than the value obtained by calibration (resonant receiver responds a bit faster/slower because a previous noise has charged the receiver, for example), the error introduced with HALO4 algorithm is bigger than the effect of the same error source on ALO4.

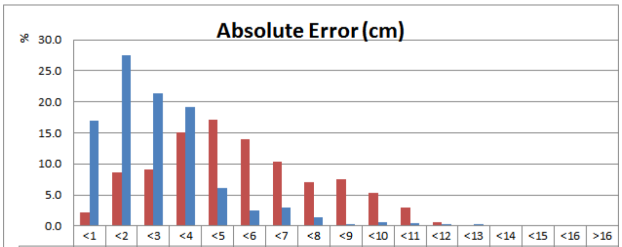
The mean point of each localization area has been calculated and the distances of each point to this reference point have been measured. These distances have been summarized in a histogram (**Figure 17**). ALO4 has a mean distance of 4.55 cm with a maximum distance of 10.06 cm (the standard deviation is 1.57 cm) while HALO4 reaches a mean distance of 1.85 cm, but its maximum distance is 21.94 cm (its standard deviation is 1.89 cm).




| | <1 | <2 | <3 | <4 | <5 | <6 | <7 | <8 | <9 | <10 | <11 | <12 | <13 | <14 | <15 | <16 | >16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ALO4 | 1,0 | 4,9 | 8,6 | 21,5 | 26,5 | 19,1 | 12,6 | 3,3 | 1,9 | 0,3 | 0,1 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| HALO4 | 37,8 | 35,1 | 12,6 | 5,1 | 1,9 | 2,2 | 1,9 | 1,3 | 0,7 | 0,4 | 0,3 | 0,3 | 0,1 | 0,0 | 0,0 | 0,0 | 0,1 |

**Fig. 17** Histogram of the distances to the mean point, reflecting the dispersion of each method

HALO4 system has also more precision in the localization results. To measure this effect, the error between the ideal point (where the node was deployed) and the result of the localization process has been calculated for both systems, and these results are shown in **Figure 18**.

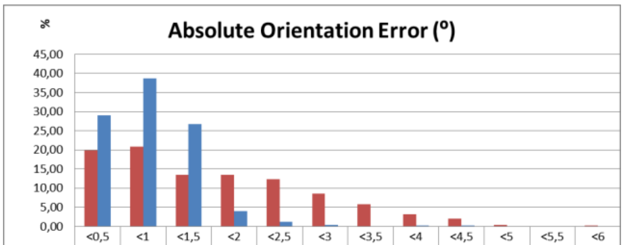



| | <1 | <2 | <3 | <4 | <5 | <6 | <7 | <8 | <9 | <10 | <11 | <12 | <13 | <14 | <15 | <16 | >16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ALO4 | 2.2 | 8.7 | 9.1 | 15.1 | 17.1 | 14.0 | 10.3 | 7.0 | 7.5 | 5.3 | 2.9 | 0.6 | 0.1 | 0.1 | 0.0 | 0.0 | 0 |
| HALO4 | 16.9 | 27.4 | 21.3 | 19.2 | 6.1 | 2.5 | 2.9 | 1.5 | 0.3 | 0.6 | 0.5 | 0.3 | 0.3 | 0.1 | 0.0 | 0.0 | 0.1 |

**Fig. 18** Histogram of the localization absolute error (distance between the localization result and the node real position)

As with the distance to the mean point, ALO4 obtains a smaller maximum error (20.06 cm with respect to 23.77 cm of HALO4 system) but HALO4 reaches a better mean error (2.65 cm with respect to 5.18 cm obtained by ALO4).

Both ALO4 and HALO4 also give the orientation apart from the localization. The errors in the absolute orientation, in degrees, are shown in (**Figure 19**).




| | <0,5 | <1 | <1,5 | <2 | <2,5 | <3 | <3,5 | <4 | <4,5 | <5 | <5,5 | <6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ALO4 | 19,86 | 20,90 | 13,47 | 13,54 | 12,29 | 8,54 | 5,83 | 3,19 | 1,94 | 0,35 | 0,00 | 0,07 |
| HALO4 | 28,96 | 38,61 | 26,74 | 3,96 | 1,25 | 0,35 | 0,00 | 0,07 | 0,07 | 0,00 | 0,00 | 0,00 |

**Fig. 19** Histogram of the absolute orientation error

The HALO4 system improves the precision of localization system due to the higher localization precision reached, obtaining a mean orientation error of 0.80º (its maximum error is 4.02º and its standard deviation 0.48º) while ALO4 obtains a mean error of 1.53º (with a maximum of

5.88º and a standard deviation of 1.09º).

## 8 Conclusions

This paper presents a new algorithm to obtain the position and orientation of a robot, HALO4. It is based on the direction of arrival of signals generated by three transmitters. The estimation of the direction of arrival is the same as in the ALO4 system, but the localization algorithm differs from this one, using the horizontal angles instead of the vertical angles to obtain the position of the robot.

Using the horizontal angles allows deploying the transmitters at different heights and making the system immune to errors generated by an incorrect estimation of the ultrasonic signal speed. The disadvantage of HALO4 with respect to ALO4 is that the localization algorithm has a greater complexity, needing a minimization process to obtain the position of the node, representing a computational cost that is up to 20 times higher, but it is less than other DTOA minimization algorithms based on hyperboloid intersections.

Experimental results that share the same measures to obtain the orientation and position of the node have been carried out. HALO4 can estimate more precisely the position and orientation of the node than ALO4, reaching a mean error of 2.65 cm with respect to the ideal point (while ALO4 obtains 5.18 cm) and a mean orientation error of 0.80º (ALO4 obtains 1.53º), therefore showing the advantage of using the horizontal angles instead of the vertical ones at a cost of more computational effort.

## 9 Acknowledgments

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