# Coverage Analysis of an Ultrasonic Local Positioning System according to the Angle of Inclination of the Beacons Structure

David Gualda, Jesús Ureña, Juan Jesús García, Ana Jiménez, M. Carmen Pérez and Francisco Ciudad

Department of Electronics, University of Alcalá, Spain
david.gualda@uah.es

**Abstract.** This paper presents a coverage study related to position estimations by using an Ultrasonic Positioning System (ULPS), composed of a five beacons structure placed on the ceiling of an indoor environment, with the possibility of orienting it obliquely with different degrees of inclination. The objective when the ULPS is inclined is to focus the ultrasonic coverage on a specific area of interest, to obtain the maximum localization area as possible in that zone. This configuration can be very beneficial in certain situations such as when an ULPS is installed in the center of a limited-height ceiling and has to cover the whole area or when for certain considerations the ULPS must be installed on one side of the environment. This work is the first study in which the performance of the ultrasonic positioning system is evaluated when it is located inclined, since in previous works these systems are traditionally analyzed with the structures installed in a parallel plane to the ceiling or walls. Experimental tests have been carried out in a coverage area of 33m2 with the ULPS placed on one side of the localization space, evaluating several inclinations: 0º, 15º, 45º and 60º. The results show the possibility of estimating the position in practically all the area of interest when the ULPS is inclined up to 60º.

**Keywords:** ULPS, Positioning, Ultrasound.

## 1 Introduction

The development of indoor positioning systems is a topic that has been rising for more than a decade due to the large number of services and potential applications based on location that can be offered: mobile robot navigation, localization of products or places in large supermarkets such as shopping malls, airports, hospitals ..., augmented reality applications, rescue, location-related advertising, etc.

Each year a large number of research works are published related to position estimation in indoor environments, emphasizing this conference (Indoor Positioning and Indoor Navigation, IPIN) [1] as one of the most important in the area. Most of these works are based on radio frequency [2][3] taking advantage of the WiFi infrastructure that is installed in the majority of buildings. One of the limitations of these systems is that they required a periodic calibration stage due to possible variations of the WiFi nodes installed in the environment. This calibration stage is called fingerprinting [4] and requires capturing the signals of a grid of positions that includes the entire environment to be located. On the other hand, the errors reported by these types of works are few meters with a high dispersion in the estimates according to the propagation characteristics of the medium between the RF nodes and the receiving device, so its use may be limited in certain applications. Nevertheless, the ultra-wide band radio technology (UWB) provides indoor estimations with decametric errors thanks to the large bandwidth used by the system (higher than 500 MHz). The commercial Decawave system is the solution that provides the best performance, according to the work showed in [5]. The main disadvantage of this system is the high cost and the size of the receiver.

Another technology less used and low-cost is the ultrasonic one [6], which makes possible to estimate the position with centimeter errors in most cases when the coverage is adequate [7], being a suitable alternative to UWB systems.

In some works, the emitters are placed in a square structure, composed of 5 transducers. [8] shows one of the first versions of this system, which presents a large size. Currently, the structure of ultrasonic emitters has been improved in terms of portability and ease installation. In [9] and [10] the ULPS system called LOCATE-US is presented, developed by the Geintra group [11] of the University of Alcalá, which has been used in the development of the present study and it is described later.

All works that use this or similar systems place the structure of emitters on the ceiling or walls with the same orientation as the building, estimating the position when the receiver is located below the structure [12][13]. If the location area is large, several ULPSs are installed to cover the entire zone [14].

If the installation of these systems is carried out in long corridors, in areas where the ceiling height is low, or the location of the ULPSs has to be in a certain zone, it could be useful to install the structure with a specific inclination, in order to focus the ultrasonic coverage in the interest area (assuming that the range of this type of systems can reach tens of meters), optimizing the number of ULPSs to be installed, or using the installed ultrasonic system more efficiently.

Therefore, in this work we study the quality of position estimations with an ULPS placed on the ceiling over a tilting platform that can be inclined. It is installed at one side of a location area of 33m2 approximately. The objective is to evaluate the performance of the system with different inclination degrees to cover the largest area as possible. This study can be used for other future works to take the advantage of installing the ULPS with a specific inclination degree in order to get the highest coverage with minimum resources.

The rest of this work has been organized as follows:

Section 2 describes the system and position estimation method; Section 3 shows the experimental results obtained by studying various inclinations of the positioning system; and finally, Section 4 presents the conclusions of this work.

## 2 Description of the System and Position Estimation Method

The ultrasonic positioning system used is called LOCATE-US, developed by the GEINTRA research group at the Electronics Department of the University of Alcalá. This infrastructure is composed of five ultrasonic transducers [15] that are controlled by an FPGA based on a Xilinx Zynq 7000 device [16]. Each transducer emits Kasami [17] sequences of 255 bits of length, phase modulated (BPSK, Binary Phase Shift Keying) with two carrier periods of a sinusoidal waveform centered at 41.67 kHz, according to the emission characteristics of the transducers.

Fig. 1 shows an image of the ULPS located on the ceiling and installed on a support [18] that allows the structure to be inclined.

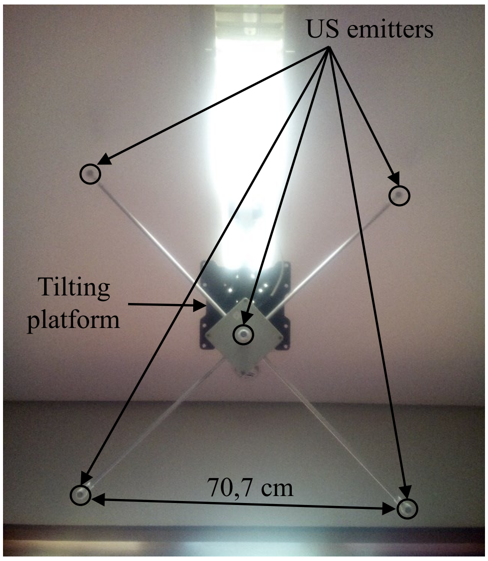


**Fig. 1.** LOCATE-US system placed on the ceiling and installed on a tilting platform [18].

The emission frequency of the ULPS is generated by a clock at 500 kHz, whilst the acquisition in the receiver microphone is at 100 kHz. This receiver module can be connected to a portable device (Tablet, PC, ...) by using an USB port as shown in Fig. 2.


**Fig. 2.** Microphone-based receiver connected to a laptop that processes the ultrasonic information.

When a packet of 10000 samples (size of the receiving buffer) every 0.1 seconds (according to the receiver frequency of 100 kHz) is received through the USB connection, the arrival instants of each emission are identified by using a correlation process with each one of the Kasami codes assigned to the transmitters. Since there is no synchronization between the emitters and the receiver, difference of distances are obtained, using as a reference the emitter whose correlation shows the highest peak amplitude.

From the set of difference of distances, a non-linear system of equations is obtained that allows to estimate the position of the receiver. The number of equations will depend on the number of valid receptions, with a maximum of four equations in the ULPS with five emitters. As a minimum, the position will be solved when the number of equations is three, so it is possible to estimate the position of the receiver when one of the emissions is not properly received or its correlation quality is not enough.

The generic nonlinear equation system is shown in (1) where $r_{n,ref}$ represents the difference in Euclidean distance, d(), between the $n^{th}$ emitter and the transducer chosen as a reference; $\boldsymbol{\hat{p}}$ is the unknown position to be solved, i.e. the estimated 2D position of the receiver (2); $\boldsymbol{b_n}$ represents the coordinates of the $n^{th}$ emitter (3) and $\boldsymbol{b_{ref}}$ represents the coordinates of the emitter used as a reference.

$$\begin{cases} r_{1,ref} = \mathrm{d}(\boldsymbol{\hat{p}}, \boldsymbol{b_1}) - \mathrm{d}(\boldsymbol{\hat{p}}, \boldsymbol{b_{ref}}) \\ \quad\vdots \\ r_{n,ref} = \mathrm{d}(\boldsymbol{\hat{p}}, \boldsymbol{b_n}) - \mathrm{d}(\boldsymbol{\hat{p}}, \boldsymbol{b_{ref}}) \\ \quad\vdots \\ r_{N-1,ref} = \mathrm{d}(\boldsymbol{\hat{p}}, \boldsymbol{b_{N-1}}) - \mathrm{d}(\boldsymbol{\hat{p}}, \boldsymbol{b_{ref}}) \end{cases} \tag{1}$$

$$\boldsymbol{\hat{p}} = [\hat{x} \quad \hat{y} \quad z] \tag{2}$$

$$\boldsymbol{b_n} = [x_{b,n} \quad y_{b,n} \quad z_{b,n}] \tag{3}$$

The nonlinear equation system is solved by the Gauss Newton method, which is iterative and allows to solve nonlinear equation systems in which there are more equations than variables to be solved. In this case, we assume as known the receiver height. Thus, we are estimating the 2D position, since when there is no synchronism between the emitters and the receiver the 3D estimation presents a high uncertainty in the perpendicular coordinate with respect to the ULPS (height value of the receiver in this case).

## 3 Experimental Results

The experimental tests have been carried out in a hall where an ULPS has been installed with the inclination platform in one side of the space, as can be seen in Fig. 3.

The approximate height of the ceiling is 3 m and the size of the localization area is around 33 m$^2$. A total of 34 positions have been considered for the study, taking 100 measurements for each one at three different heights of the receiver: 0 m, 0.5 m and 1 m. We also have evaluated four different inclination degrees of the ULSP structure: 0º, 15º, 30º, 45º and 60º, with respect to the ceiling orientation.

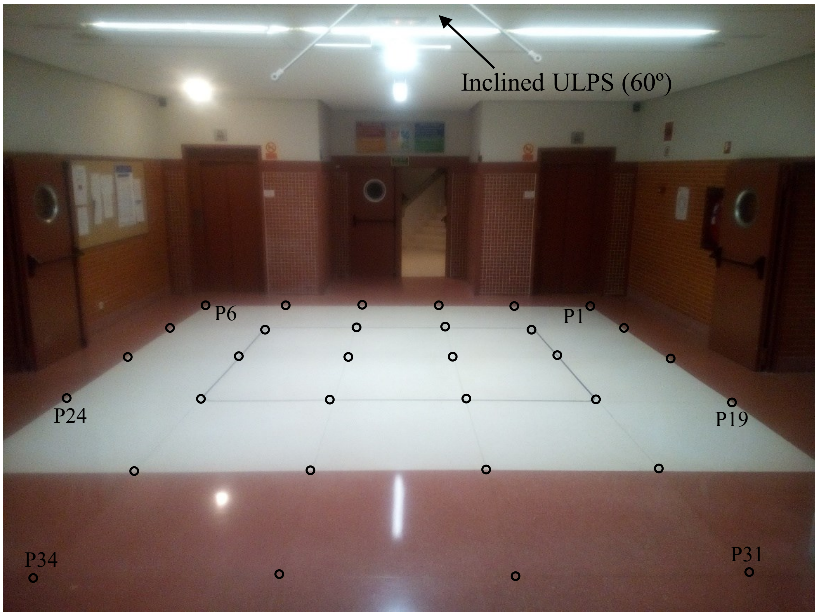


**Fig. 3.** Experimental test scenario consisting of a grid of 34 positions and an inclined ULPS installed on one side of the ceiling.

Fig. 4 shows the visual results of the position estimations related to the 3 height planes in the most unfavorable case (when the ULPS is not inclined), representing the position when more than 50% valid measurements (there are, at least, three difference of distances available) are obtained (100 measures are captured for each position of the grid).

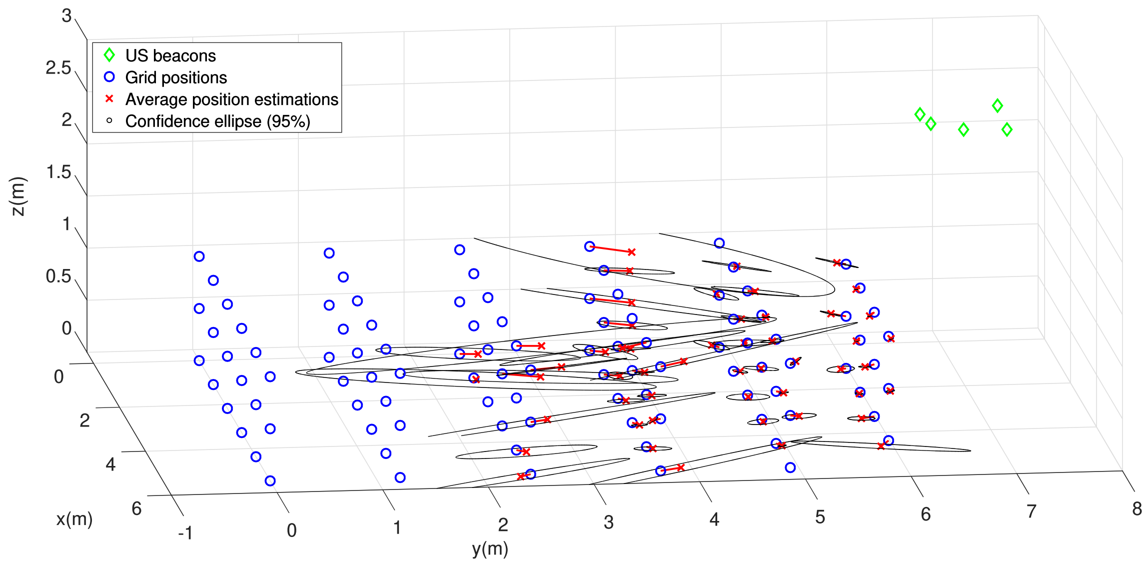


**Fig. 4.** Visual results of the position estimations related to the ULPS without inclination.

It can be seen that the best estimations are located in the positions corresponding to the two rows closest to the ULPS (for y≈5 m and y≈6 m). In the third and fourth rows furthest from the ULPS, it is possible to estimate some positions, especially in the z=0 m plane. It is also important the high uncertainty, represented by the confidence ellipse in the farthest position estimates, as well as in the x-axis limit.

On the other hand, Fig. 5 shows the results for the most favorable case (when the inclination angle is 45º).

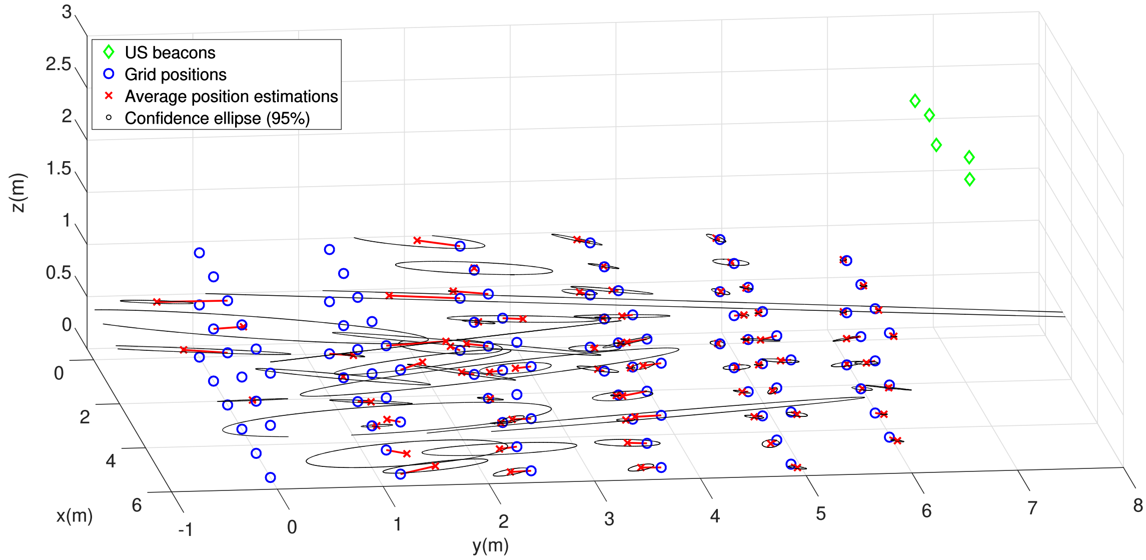


**Fig. 5.** Visual results of the position estimations related to the ULPS inclined 45º with respect the orientation of the ceiling.

There are estimations up to row y≈1 m, at an approximate distance of 6m from the ULPS position, showing a high uncertainty as in the previous case in the farthest positions of the x-axis limits.

Table 1 shows the numerical results for a comparison with respect to the coverage of the positioning system in the different inclination degrees of the ULPS. It can be observed two coverage percentages for each inclination case according to each receiver height. The first column of coverage percentages shows the proportion of position estimations that have been obtained when at least one valid measurement is detected; while the second column of percentages shows the proportion of position estimations when the number of valid measurements is higher than 50%.

**Table 1.** Coverage analysis results for all cases.

| Inclination degrees (º) | Height (*m*) | Coverage (%) Valid measurements> 0% | Coverage (%) Valid measurements >50% |
|---|---|---|---|
| 0 | 0 | 55.89 | 55.89 |
| | 0.5 | 52.94 | 35.29 |
| | 1 | 44.12 | 32.35 |
| 15 | 0 | 64.71 | 61.77 |
| | 0.5 | 55.89 | 44.12 |
| | 1 | 50.00 | 41.12 |
| 30 | 0 | 73.53 | 73.53 |
| | 0.5 | 58.82 | 50 |
| | 1 | 55.89 | 47.06 |
| 45 | 0 | 82.35 | 76.47 |
| | 0.5 | 73.52 | 58.82 |
| | 1 | 70.58 | 52.94 |
| 60 | 0 | 64.71 | 64.71 |
| | 0.5 | 58.82 | 58.82 |
| | 1 | 44.12 | 41.17 |

The worst case appears when the ULPS is not inclined and the height of the receiver is the maximum (1 m). In this case, the coverage obtained is slightly less than the half of the grid points (44.12%), being approximately one third (32.35%) if the percentage is estimated when the number of valid measurements is higher than 50%.

On the contrary, the best case is when the ULPS is inclined at 45º with respect to the ceiling orientation. In this case, a total of 82.35% of the grid points are covered when the receiver is placed on the floor and there is at least one valid measurement. The value of this percentage decreases to 76.47% when the number of valid measures is higher than 50.

If the ULPS is inclined more than 45º, the coverage area is worse, as shown in the table, achieving position estimations that cover 64.71% of the grid points when the receiver is at z=0 m, showing a similar performance when the ULPS is inclined 15º.

Finally, Table 2 shows the mean errors and deviations related to the Euclidean distance between the position estimations and the real coordinates of each grid position for all cases of ULPS inclinations and receiver heights, showing distance errors up to 28 cm.

**Table 2.** Average distance errors and standard deviations for all cases.

| Inclination degrees (º) | Height (*m*) | Mean distance error (*m*) | Mean standard deviation (*m*) of the grid points |
|---|---|---|---|
| 0 | 0 | 0.20 | 0.16 |
| | 0.5 | 0.16 | 0.10 |
| | 1 | 0.23 | 0.22 |
| 15 | 0 | 0.18 | 0.12 |
| | 0.5 | 0.14 | 0.09 |
| | 1 | 0.16 | 0.11 |
| 30 | 0 | 0.26 | 0.18 |
| | 0.5 | 0.13 | 0.04 |
| | 1 | 0.19 | 0.10 |
| 45 | 0 | 0.14 | 0.08 |
| | 0.5 | 0.16 | 0.10 |
| | 1 | 0.15 | 0.06 |
| 60 | 0 | 0.25 | 0.08 |
| | 0.5 | 0.21 | 0.09 |
| | 1 | 0.28 | 0.08 |

## 4 Conclusions

This work has analyzed the coverage of an Ultrasonic Positioning System (ULPS) evaluating different degrees of inclination with respect to the ceiling orientation, with the objective of maximizing the coverage area when the ULPS is placed on one side of the ceiling. The results show the possibility to estimate the position of the receiver with decimeters of error in a localization area of $33m^2$ and at a distance of up to 8 m from the receiver to the ULPS when the positioning system is inclined 45º with respect to the ceiling orientation.

This configuration can be suitable in providing ultrasonic coverage for estimating the position of a receiver in indoor scenarios with the minimum number of ULPSs installed in narrow environments such as corridors or in situations where the ceiling height is low. Compared to a traditional installation of non-inclined ULPSs, a larger number of ULPSs would be required to cover the same location area.

Future works will evaluate the inclined ULPS performance when the emitters and the receiver are synchronized. This configuration will provide more accurate position estimations of the receiver.

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