Ultrasonic Localization Methods for Accurate Positioning

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Abstract

This paper gives a general overview of projects developed in our labs to localize objects using ultrasonic waves in air. All the developed solutions use active trilateration techniques, i.e. they rely on measuring the Time-of-Flight (ToF) an ultrasound signal needs to go from one (or several) emitter(s) to one (or several) receiver(s). These localization systems were applied in different sectors, such as robotics, intelligent warehouses, greenhouses, hospitals or archaeological sites, among others. A short historical introduction is given, including the trilateration concept, and then the most interesting details for each project are described. The main approaches are presented and the most difficult challenges, that had to be overcome to meet the project specifications, are highlighted.

1. Introduction

As it is known, there are some very good solutions, such as GPS, which are appropriated for many navigation applications. GPS uses the so called spherical positioning or trilateration methodology where the absolute Time-of-Flights (ToF) between a RF emitter on -board several satellites and one receiver had to be estimated. The trilateration principle can be explained as follows. Assuming that emitters and receivers are synchronized, i.e. their clocks have exactly the same time without significant delays, if at the receiver of unknown position (x, y, z) we measure the TOF, t_k, to each satellite k, then multiplying them by the speed of the propagating wave, c, we obtain a set of ranges from the receiver to each individual satellite, r_k. Writing down the equation of a sphere of radius r_k centered at each satellite at position (x_k, y_k, z_k) (eq. 1), we obtain a system of N equations ($N \geq 3$), whose solution tell us the receiver or user position (x, y, z).

$$\sqrt{(x_k - x)^2 + (y_k - y)^2 + (z_k - z)^2} = r_k \tag{1}$$

On the other hand, the robotics community has been conducting very active research in the area of “intelligent robotics”, starting more than two decades ago. Most of the required artificial intelligence are focused on providing a mobile robot the ability to navigate autonomously. Many research for robot navigation has been inspired by the way humans navigate when we do not have any man-made instrument, that is, using visual natural or artificial landmarks, and using a map of references, where we match our visually identified references to draw our location. The literature about map localization is vast enough

Figure 1: Ultrasonic mobile 'Bat' device to be carried on the person's chest, as part of the AT&T 'Active Bat' location system

to deserve some special dedicated books and a high percentage of total papers in prestigious robotics conferences such as ICRA (International Conference on Robotics and Automation).

An alternative to the map-based localization approaches for mobile robot navigation, would be to use GPS receivers. The problem come for robots that have to navigate indoors (offices, hospitals, warehouses, and so on), where GPS signals are not available because their intensity is too low. The absence of GPS-like navigation aids valid for indoors, motivated the development of new Local Positioning Systems (LPS) that require the installation of active beacons acting as satellites on the walls or ceilings of rooms in buildings. During the last ten years, we can see several LPS proposals using different types of energies: infrared, ultrasound or radio, and employing different principles for position estimation: spherical, hyperbolic and trilateration by signal strength.

As we will realize, most of the LPS systems developed were not focused toward the navigation of mobile robots, but devoted to create intelligent environments where the building senses and updates a dynamic model made of persons or objects in motion that continuously change their positions. This concept is also known as *ubiquitous computing* (also termed as calm, pervasive or proactive computing) [1], where one of the important services a building can facilitate to their moving inhabitants, are those depending on their physical position. The services that are offered depending on the current positioning model of the building are called location-aware services, and rely on the existence of a LPS system to know exactly where each person or mobile device is located [2]. For example, some location-aware services are the urgent location of a doctor in a hospital [3], the continuous monitoring of valuable equipment in a hospital for emergencies, the guidance of people with disabilities (blind persons) along rooms in a big building, the monitoring and automatization of a warehouse having a model of where each good is located, or for example the automatic configuration of electronic equipment (printer, PC, PDA, camera, and so on) depending on the identity of the closest person who is supposed to be using it.

One of the first LPS systems proposed in the literature at the beginning of the nineties for the above-explained ubiquitous computing concept, is the *Active Badge* system, developed by the AT&T research team [4]. It uses sparse infrared detectors at room scale (i.e. one or a few sensors per room) and a diffusive infrared emitting badge which is carried by a person on his waist. Each badge has its own identification code to permit the multiple localization of persons; wherever a person goes, the building detects the badge's presence and its identity. The localization is not physical, does not provide cartesian coordinates, but it provides a symbolic location, i.e. determines in what room the person is located. The same AT&T research group developed a few years later the Active Bat [5] ultrasonic location system, which uses radio signals for synchronization. The Times-of-arrival (TOA) of ultrasound are measured from the Bat emitting device to each transducer setting-up a grid of ultrasonic receivers on ceilings. The location accuracy is below 10 cm for 95% of the time.

Another relevant ultrasound LPS system for ubiquitous computation is called Cricket [6, 7], which also uses radio signals for synchronization and ultrasonic TOA for trilateration. In this case, instead of using a mobile emitter with several fixed receivers and a central station for computing the location, the Cricket system has fixed emitters with an ultrasonic receiver on the mobile device. Therefore the TOA's and the device position is estimated on-board. This feature implies privacy since the location is only known by the device and the intelligent building does not know positioning information unless the mobile device provides it voluntarily. Similar systems oriented to keep privacy using CDMA (Gold codes) and broad-band ultrasonic emitters (PVDF films) mounted on the ceiling are proposed by Hazas [8, 9]. A quite similar concept but using transmitters emitting *Silent Acoustical Signals* (upper audible frequency range, instead of ultrasound), and utilizing as receivers PDAs with on-board microphone and powerful processing capabilities, is presented at Roke Manor Research [10], for multi-lateration position estimation.

A Microsoft research group developed the RADAR location and tracking system [11] using signal strength lateration within IEEE 802.11 wireless networks. It can compute the 2D position at every location in one single floor with a 4 meter accuracy using the signal strength received at two access-points. It is complex to extend this system to 3D (localization in several floors) due to the strong radio reflections and attenuation when getting through walls and floors from room to room; some attempts to increase accuracy and scale are based on using databases of experimental signal strength values collected for a mesh of pre-visited locations in the particular building of interest. Other LPS system using RF signals is the so-called PinPoint 3D-iD [12], which uses specially-designed radio transmitters as beacons that are activated sequentially. The mobile object to be located carries a light tag that act as a transponder (change frequency, add codes by phase modulation, and re-emit RF signal). This way of operation, measuring round-trip propagation, circumvents the problem of time synchronization between tag and emitting beacon since the beacon's internal clock is the only time reference.

Some other local positioning systems (LPS), that were not specially designed under the influence and objectives of pervasive environments, are those prototypes designed particulary for autonomous robot navigation. Some prototypes and basic research activities using ultrasonic multi-lateration concepts were conducted by several authors, such as Figueroa (Tunale University) [13, 14], Mahajan and Ray (Southern Illinois University) [15, 16], Lamancusa (Pennylvania State University) [17] or Belanger (McGil University, Toronto) [18], during the last decade. Some commercial available systems exists nowadays such as the "Constelation 3D-i" device [19] that was designed for precise airplane metrology making use of indoor GPS technology, but with significant differences with the GPS concept (for example, triangulation is used instead of multi-lateration). Indoor accurate localization is not a solved problem as it is demonstrated by the intensive research in this field. Commercial solutions that start to appear are customized designs for special applications and do not provide a versatile solution for a large range of applications, as would be desired.

The authors of this paper, working at the SAM group (Sensors, Actuators and Microsystems) belonging to the System Department in the Industrial Automation Institute (CSIC) in Madrid (http://www.iai.csic.es/sam), have carried intensive research on the localization topic using ultrasound technology. Next section gives an overview of some challenging aspect we coped with for the successful development of past and on-going projects where ultrasound localization played an essential research role.

2. Ultrasonic LPS realizations at IAI-CSIC

The first ultrasound localization system developed at IAI-CSIC was devoted to study the locomotion problems of a experimental legged robot called 'Rimho' [20]. The purpose to be covered by this spatial measurement system was three-fold: 1) Analyze the fidelity of following predefined trajectories during locomotion, 2) Monitoring the up-and-down body movement caused by rising legs during locomotion, and 3) Study the control strategies to minimize the consumed energy by avoiding unnecessary vertical body movements against the gravity force. The adopted solution (fig. 2) was to use an omnidirectional ultrasound emitter utilizing a spark generator, that not only generates ultrasound pulses but a radio signal that is used for synchronization. Three ultrasound receivers are fixed on a wall and a central unit based

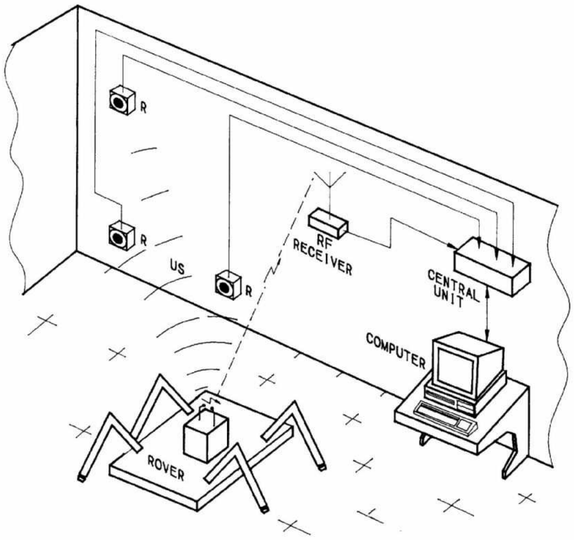

Figure 2: Localization system for Rimho walking robot

on a personal computer (PC) triggers a three channel acquisition using the radio signal as an event. The received ultrasonic signals, are band-pass filtered around 40 kHz, then rectified and low-pass filtered to get the envelope of the signal. A method for time of arrival determination is based on fitting a straight line on the central ascending portion of the envelope, which is the envelope section with maximum slope and therefore having the lowest time uncertainty. As this method has a bias error which depends on the shape of the ultrasonic signal, the algorithms are previously calibrated for a predefined signal. The 3D accuracy was below 1.5 mm for ranges up to 6 meters distance from the wall where receivers are placed, and the update frequency was about 40 Hz.

2.1. Ultrasonic lobe shaping

Other research projects were focused towards the definition of the 'Intelligent Warehouse' where autonomous pallet trucks are smart vehicles in charge of transporting the new incoming goods piled on pallets to the location designated by a central station at the warehouse; and they were also responsible of taking out the needed goods from the known position in the warehouse to the delivery platform for distribution. For this purpose it was needed to automate a conventional pallet truck (fig. 3) to navigate autonomously based on absolute positioning information provided by a 2D LPS. This local positioning system should have an accuracy of 1-2 cm in a wide indoor space (above 20$\times$20 m), as well as, the capability to estimate the absolute robot orientation with a precision of at least one degree.

The designed locating system, for the 'Intelligent Warehouse' concept, used two active beacons placed on one warehouse wall at 2.5 meters height and separated horizontally about 15 meters. These beacons were activated sequentially (only one beacon emitting at a time) using a coded radio signal emitted from the control unit on board of the pallet truck. This control unit was based on a micro-controller (Intel 87196KC) performing most of the required tasks and a PC platform for better interface and high-level configuration labors. Apart from the general design concepts of the system, the location requirements above-stated were achieved paying special attention to the following challenging topics:

- *Ultrasonic wavefront shaping to obtain a uniform hemispherical emission.* It is a non-trivial problem since conventional ultrasound transducers using piezoelectricity (Murata [21]) or capacitive effects (Polaroid [22]) have ultrasonic lobes narrower than 100 and 50 degrees respectively. Just using a reflective curved surface to spread out the ultrasonic beam to cover a 180 degrees angular range has the strong disadvantage of dropping the sound intensity and therefore reducing the measuring range. The solution adopted was the arrangement of several piezoelectric transducers

Figure 3: Automated pallet truck for 'Intelligent Warehouses'. Omnidirectional ultrasonic receiver on the upper tip of the vertical post

(Murata) on a cylindrical holding, forming an array made of an upper row of four transmitters and a lower line with five (see fig. 4 left). This configuration was selected, after some far-field simulations, for being capable of providing an almost constant radial sound pressure level (see fig. 4 right) and enough intensity to perform measurements above the 20 m range.

- *Omnidirectional reception and estimation of absolute orientation.* To solve the reception problem we used an approach similar to the one used for emission, that is, a cylinder holding surrounded by a single row of 8 receiving transducers. This configuration was better than other special single-element cylindrical transducers made of PVDF films from MSI [23], because its greater sensitivity. Additionally, the multi-element array configuration, due to the specially-designed ratio between wavelength (about 8 mm for 40 kHz signals) and the radius of the supporting cylinder, has the ability to sense the direction of arrival (DOA) of ultrasound by measuring the phase differences at adjacent transducers. Therefore, this receiving sensor array was used for the 2D position estimation of the robot from times of arrival (TOA), and additionally for the estimation of robot's orientation with good accuracy (below 1 degrees).

- *Compensation of position errors caused by the motion of robot.* As we already mentioned, the firing of each beacon is sequential, this causes that the two times of arrival (TOA) needed to fix a location by multi-lateration are taken at different times. If the robot is static there is no problem, but if the robot moves it causes an error in the determination of its position (fig.5). This error depends on the robot speed and on the well-studied effect called Geometric Dilution of Precision (GDOP), which basically is a factor that measures the propagation of errors from TOA estimates to the final 3D estimation. Depending on the relative robot-to-beacons configuration, GDOP changes and so the error amplification, it means that there are some region where position estimation is worse than in others. In our case, when the robot moves in region with poor GDOP (values above 4, typical when the robot is too far from, or too close to, the wall containing the beacons) then the error caused by non-simultaneous TOA measuring is even much more significant. The solution we applied (eq. 2) was based on a interpolation between current position estimation $ps(n) = \{xs(n), y(n)\}$ and the previous one $ps(n-1) = \{xs(n-1), ys(n-1)\}$.

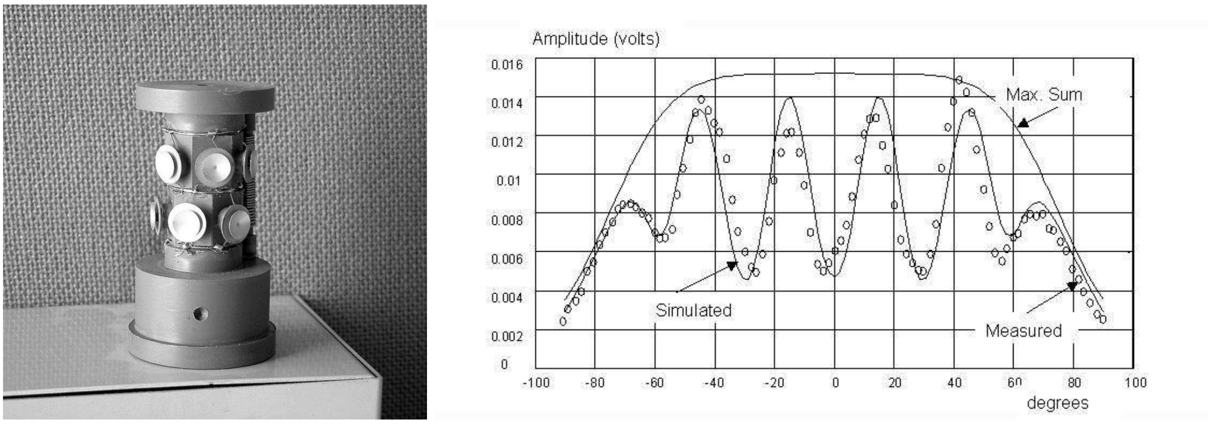

Figure 4: Ultrasonic piezoelectric transducer arrangement for hemispherical emission (left); Resulting emission wavefront for a horizontal angular interval from -90 to 90 degrees (right)

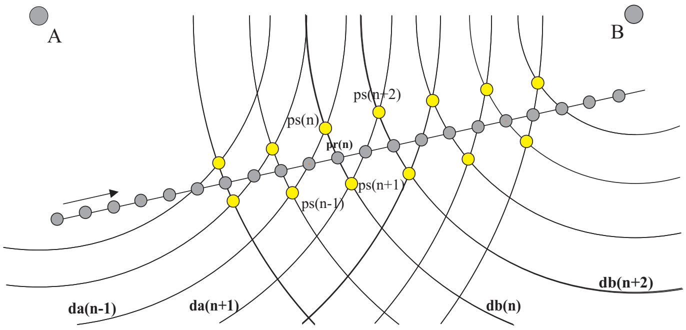

Figure 5: Error caused by non-simultaneous measurement of TOA from beacon A and B. Gray spots indicate the real straight trajectory followed by the robot; Yellow spots are the erroneous estimations, before applying the proposed correction, that zig-zag at both sides of the real trajectory.

$$\begin{cases} x_i(n) = (xs(n-1) + xs(n))/2 \\ y_i(n) = (ys(n-1) + ys(n))/2 \end{cases} \tag{2}$$

The interpolated estimation $\{x_i(n), y_i(n)\}$ in equation (2) was able to remove most of the zig-zag effect, but it causes a one sampling interval delay. To solve that inconvenience an extrapolation process is performed (eq.3) predicting current position based on two last interpolation estimates.

$$\begin{cases} x_e(n) = 2x_i(n) - x_i(n-1) \\ y_e(n) = 2y_i(n) - y_i(n-1) \end{cases} \tag{3}$$

Merging both interpolation and extrapolation methods (eq. 4) it is obtained a very precise estimation of current robot position $\{\hat{X}(n), \hat{Y}(n)\}$ based on only two previous sampling fixes .

$$\begin{cases} \hat{X}(n) = xs(n) + xs(n-1)/2 - xs(n-2)/2 \\ \hat{Y}(n) = ys(n) + ys(n-1)/2 - ys(n-2)/2 \end{cases} \tag{4}$$

In the Mino project we worked in the development of a LPS to assist the autonomous navigation of a fertilizer/fumigation system operating in a greenhouse, in order to reduce the exposure of human beings to the toxic products used in soil treatments. As the vehicle already incorporated a collision avoidance system to keep it on track along a row, the challenge was to design a positioning system able to cover great areas (up to 50×50 m or higher) with a minimum number of beacons. We implemented a solution based on PVDF hemispherical emitters placed on the walls and two piezoelectric receivers on board of the vehicle, in an omnidirectional (panoramic) configuration (see figure 6). Robust estimation of position

Figure 6: Emitter and receiver transducers in the Mino system.

and orientation of the vehicle was achieved with LS minimization techniques performed by a computer on board. In the trial version, the Mino vehicle was able to navigate in a 20×20 m area with a 5 cm precision (figure 7) using only four beacons.

2.2. Robust estimation

A totally different application area, under the European project Kaylite (BRITE/EURAM, OL-962875), was the development of a system to construct hulls and decks of boats or other engineering shell structures, by means of precisely depositing small drops of composite material using a huge gantry robot. The accuracy needed for the robot to position the injection head was about 1 mm, but due to the long flexion and slack at links and joints, at the end-effector that requirements were not fulfilled. Therefore, it was needed a 3D localization system to feedback the actual position to the robot controller.

The LPS system utilized for Kaylite application had a similar design to the one used in the Rimho solution, i.e. an omnidirectional emitter on board the object to be located, but instead of using three receivers we used a redundant configuration with eight receivers (fig.8). This redundant configuration was needed to be able to provide good position estimates under circumstances of occlusions, which are normally caused by the presence of the robot arm or the structure under-construction along the ultrasonic transmission path connecting emitter and receivers. The redundant network of sensors was also used to obtain estimates with lower standard deviation, and to get rid of false TOA measurements due to multi-path or other degrading effects [24]; in this way the estimations can be guaranteed to be more reliable than in the non-redundant case.

Given a set of three ultrasonic receivers, we can find an algebraic solution to the trilateration problem (eq. 1), under the assumption that receivers are placed at these particular locations ($R1 = \{0,0,0\}$, $R2 = \{x_2,0,0\}$, $R3 = \{x_3,y_3,0\}$), by means of this equation:

$$\begin{cases} x = (r_1^2 - r_2^2 + x_2^2)/2x_2 \\ y = (r_1^2 - r_3^2 + y_3^2 + x_3^2 - 2x_3x)/2y_3 \\ z = \pm\sqrt{r_1^2 - x^2 - y^2} \end{cases} \tag{5}$$

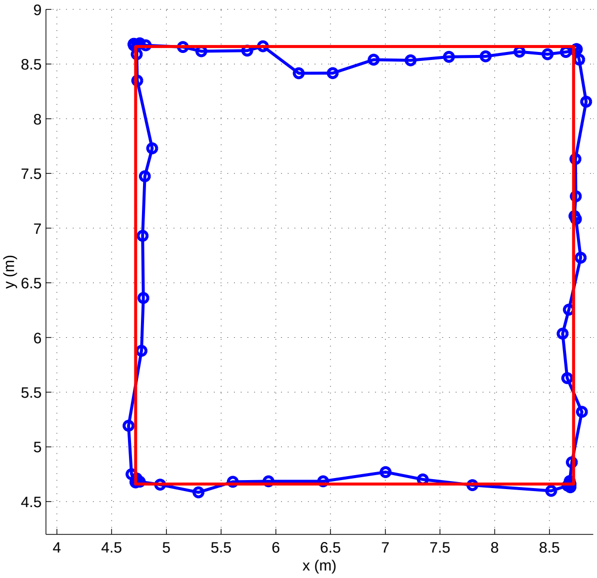

Figure 7: Following a square trajectory by the Mino system.

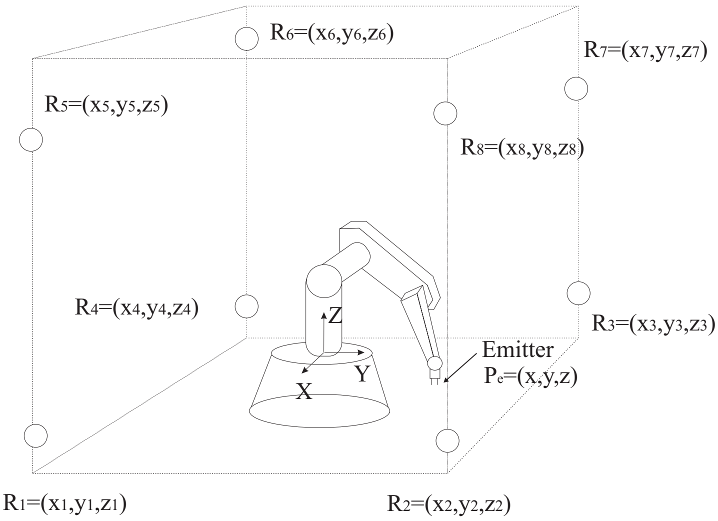

Figure 8: Redundant 8 receiver configuration for Kaylite project

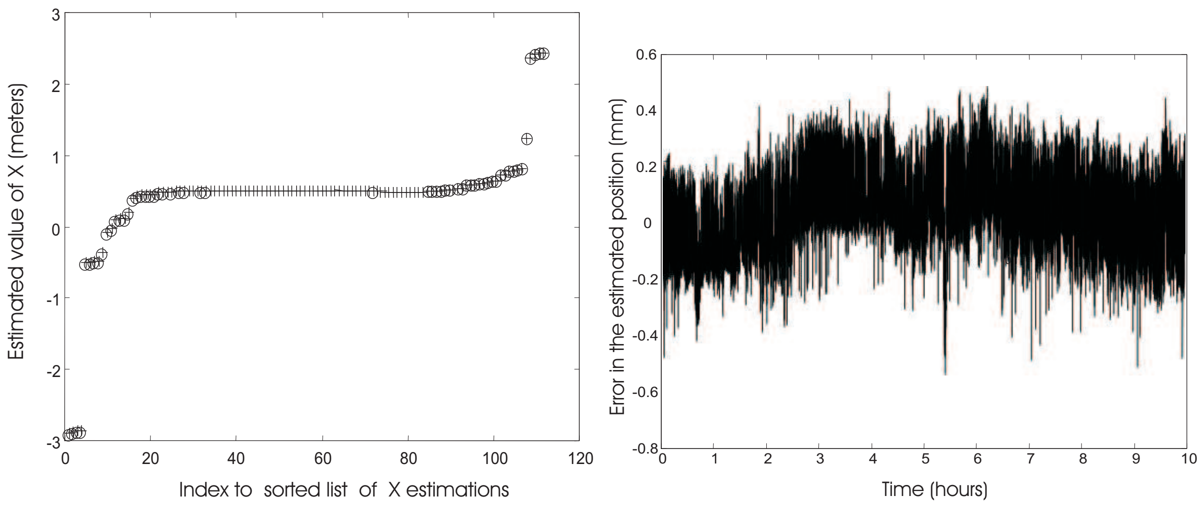

Figure 9: (left) Selection of best X estimate by averaging around median value; (right) Variance tests in Kaylite redundant and robust localization system

The above expression can be used to find a double solution (note $\pm$ sign at z solution), one below the plane $z = 0$, and the mirror-like solution above the $z = 0$ plane. The valid solution can be chosen, for example, using prior information about the approximate emitter location. An ill-conditioning problem appears only when two receivers are at the same physical point ($x_2 = 0$), or in a more realistic case, when the three receivers are aligned ($y_3 = 0$). So, there is a need to place receivers in such a way that are never aligned, then we can assure that the expression above stated (eq. 5) is always applicable. The assumption of receiver's locations at points $R1 = \{0, 0, 0\}$, $R2 = \{x_2, 0, 0\}$, $R3 = \{x_3, y_3, 0\}$ is not restrictive at all, because given an arbitrary positioning of receivers, there is always a possible coordinate transformation (1 translation and three rotations) to place receivers at the assumed positions.

This basic formulation, that is able to find a solution from a given set of three receivers (or triplets), is what we used to obtained a robust estimation for Kaylite project. Given an N set of receivers ($N = 8$ in our case), it is possible to obtain a set of $M = \frac{N!}{3!(n-3)!}$ different triplets ($M = 56$ for $N = 8$). So in the case of an emission sensed by the eight receivers, we find a double solution using eq. 5 for each of the 56 possible triplets. The robust estimation method we used to get rid of outliers (false TOA's) and to reject non-valid-specular solutions without using prior knowledge, consist in making a separate list of 112 solutions for each component X,Y and Z. Then we sort each of these three lists (see fig. 9 left) and select as robust estimate an average around the median value (0.5 m for the case of figure 9 left). Note that non-valid solutions are filtered out because of being at the upper and lower tails of the sorted list of estimations. The averaging around the median causes a variance reduction, as can be seen on fig. 9 right, along an estimation test that lasted more than 10 hours.

2.3. Wind compensation

Another new contribution of our group in the localization field was the development of an ultrasonic LPS working outdoors, specially designed for automatic localization and outline sketching of archaeological findings [25, 26]. The motivation of these development was to increase efficiency and accuracy during the archaeological documentation process, consisting in measuring fossil position, shape, orientation, and other data relative to fossil properties; tasks that are performed just after the fossil discovery or extraction. This documentation labor takes much time, lowering the pace at which sediments and fossils are extracted by archeologists, and so, dilating the time in-years needed to finish the excavation of the whole archaeological site. Additionally, the positioning method still in use today is based on the partitioning of

Figure 10: 'Gran Dolina' archaeological site during the excavation campaign (Atapuerca, Burgos, Spain)

the working area using cords, creating reticles of several $1{\times}1$ cells. The positioning is made relatively to this reticle using a metric tape. It is clear for archeologists that the traditional positioning method is prone to errors that can cause misinterpretations during the global analysis of data in the laboratory.

Therefore due to the above-mentioned reasons, it was required a technical aid, such as our proposed ultrasonic LPS solution, designed to maximize efficiency and accuracy in the measured data for documentation. The requirements settled by archaeologist were stringent: 5 mm positioning estimation error, capability to adapt the system to excavations between 10 and 200 meters square, and enough resolution to sketch precisely objects larger than 1 centimeter square. But the great challenge came from using ultrasound waves outdoors, so methods for attenuating wind influence on accuracy were developed. Attending to these and several other considerations such as minimum interference with archaeological setups, easiness of operation, cost, robustness, etcetera, the location system was conceived.

The positioning system we designed allows simultaneous characterization of several findings (absolute position, shape, size and orientation) using a mobile measuring device consisting in a wireless 2-meter-long thin rod, which is placed on the object under study and kept more or less in the upright position (strict verticality is not required). The system contains two ultrasonic emitters on-board the mobile rod and employs trilateration TOA estimation to a set of eight receivers for estimating the position of each emitter. Then, once the position of each emitter is known, by extrapolation the lower tip of the mobile rod on the fossil is computed. Figure 10 is a snapshot showing the traditional excavation and documentation processes in a real archaeological site ("Gran Dolina´´, Atapuerca, Spain), and figure 11 gives a conceptual sketch of the designed ultrasonic localization system for archaeological applications.

As already mentioned, the speed of air influences strongly the speed for ultrasound to propagate in air. Therefore, the apparent speed of sound when a sound propagates between an emitter and a receiver is different when air is still or in motion. If we decompose the speed of air in two components: 1) v_{al}, that we call *longitudinal speed of air* or the speed of air projected onto the straight line joining emitter to receiver; and 2) v_{at}, called *transversal speed of air* or air orthogonal to the emitter-receiver line; then the apparent speed of sound, v_{sa}, which can be higher or lower to the speed of sound in still air, v_s, is [25]:

$$v_{sa} = v_{al} + v_s\sqrt{1-(v_{at}/v_s)^2} \tag{6}$$

The above expression (eq. 6) can be approximated in some cases where the speed of air, v_a, is not too high when compared to the speed of sound v_s (for example $v_a < 10$ m/s or equivalently $v_a < 36$ km/s),

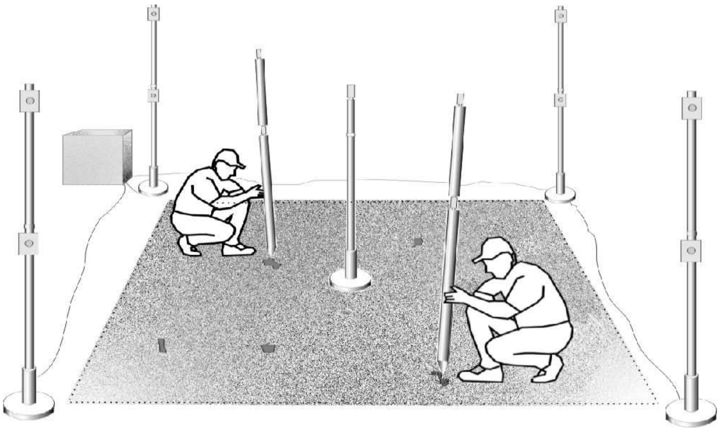

Figure 11: Designed ultrasound localization system for archaeological applications

neglecting the transversal component by this expression:

$$v_{sa} \simeq v_{al} + v_s \tag{7}$$

The influence of air on estimations is important. When using the trilateration equation (eq. 1) that assumes that v_s is known and that there is no airflow, then the estimated position fixes $\{x, y, z\}$ are biased by a distance δr (eq. 8) proportional to the actual wind speed v_{al} along the emitter-receiver$_k$ axis:

$$\delta r = r_k (v_{al}/v_s) \tag{8}$$

In a practical case, for ranges around 3-4 m, a magnitude of 1 m/s in the wind speed causes an error about 1 cm. This is the reason why a moderate wind (above 0.5 m/s) causes errors greater than our specifications (5 mm positioning accuracy), so the challenge in this project was the attenuation of these disturbing wind effects.

The more intuitive method for wind compensation can be based on the extension of equation 1 to the following complex trilateration equations (eq. 9 and 10) that contain as unknowns the components of air speed $\{v_{ax}, v_{ay}, v_{az}\}$.

$$t_k = \frac{r_k}{v_s + v_{al}} \tag{9}$$

$$t_k = \frac{r_k^2}{v_s r_k - v_{ax}(x - x_k) - v_{ay}(y - y_k) - v_{az}(z - z_k)} \tag{10}$$

where r_k is the unknown real distance between emitter and receiver$_k$, i.e. $\sqrt{(x_k - x)^2 + (y_k - y)^2 + (z_k - z)^2}$, and t_k is the TOA measured value.

The air compensation method based on equations (9) and (10) would need a minimum of 7 TOA's measures to be made in order to deduce the unknowns: $\{x, y, z, v_s, v_{ax}, v_{ay}, v_{az}\}$. In principle, this method is feasible and works well in simulations using homogeneous wind and ideal TOA values without noise, but it does not provide good results when the TOA values have a certain quantity of any kind of noise (for example gaussian noise with 2 microseconds of standard deviation as is common in any real implementation).

As already mentioned, the solutions using the above-described compensation method (eq. 9 and 10) regarding position and air speed estimations are quite inaccurate (high standard deviation) whenever TOA's are slightly corrupted with noise. The reason of this phenomenon is that the cost function minimized during the resolution of the trilateration problem (over-determined system of equations) has a

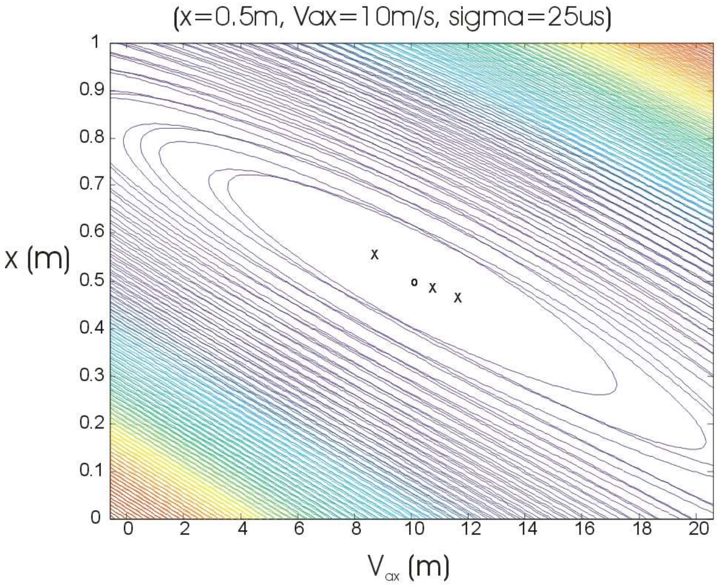

Figure 12: Multilateration cost-function contour graph for two dimensions (x and V_{ax}). Central circle indicates real values ($x = 5$ m and $V_{ax} = 10$ m/s); Crosses indicates several noisy estimates both in position and air speed.

almost-flat concave surface around the right solution. In fact, it is an hyper-surface of 7 dimensions corresponding to parameters $\{x, y, z, v_s, v_{ax}, v_{ay}, v_{az}\}$). This cost-function surface changes its orientation slightly due to TOA errors, then the optimum parameters for the cost-function minimum, change abruptly from current estimation to the next one (see crossed marks on fig. 12). Another interpretation of the same phenomenon, is that the hyper-surfaces, defined by each of the equations, intersect each other quite tangentially causing an amplification of initial noise present on measured times of arrival (TOA's).

At the end we concluded that there is no way to estimate simultaneously localization and air speed using an approach such as the previously described based on equations eq. 9 and 10. On the contrary, we studied that it is possible to estimate speed of sound and speed of wind simultaneously with high precision using a reference consisting of an emitter placed at a known position. Therefore, the final compensation of wind effects could be done in two stages:

- 1) Estimate speed of air v_a and speed of sound v_s using a reference station at a known location
- 2) Estimate x, y, z using the now known values of v_a and v_s using equations 9 and 10

This compensation method works perfectly, whereas the wind flow along the working volume is uniform; in cases of turbulence the compensation can be moderate or even poor. See figure 13 for some compensation trials made using this method. Other solutions inspired on GPS differential technology, that estimate positioning errors at the base station, and then subtract this error values directly from the estimation made at the point of interest, gives a lower performance in the homogeneous ideal case, performs worst when turbulence appear, but works quite well when distance between unknown emitter and base station is short. As none of the above-mentioned compensation methods cancel out the wind effect then a solution based on bi-directional propagation of ultrasound is being developed which eliminates the longitudinal air effect v_{al} although the transversal component v_{at} will still remain active, causing an acceptable wind influence (5 mm error for wind about 20 m/s or 72 km/h) that could be further attenuated using techniques based on reference stations.

2.4. Singularities and optimum beacon placement

Nowadays we are involved in another project called PARMEI (ref. DPI2003-08715-C02-02, funded by Spanish Ministry of Science, and in collaboration with Univesity of Alcalá de Henares, Spain) devoted

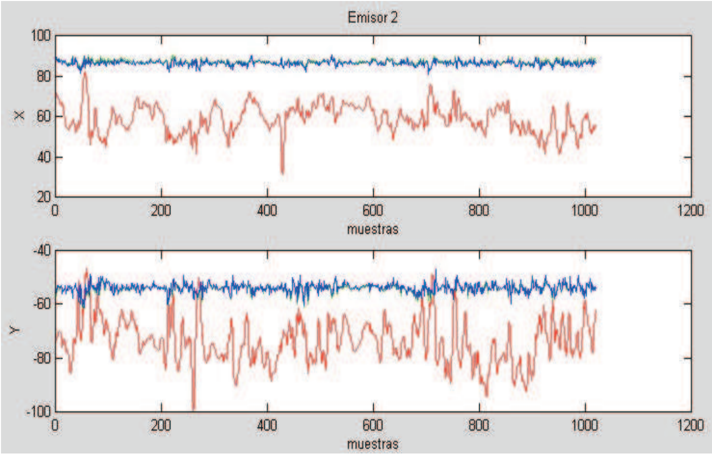

Figure 13: (Red) X and Y estimations under a wind-flow varying between calm condition to 5 m/s speed, which suffer from errors up to 5 cm ; (Blue) Same case but using the compensation method, a moderate to good compensation (1 cm error still remains) is obtained for this case where reference station is 1 m apart from point of interest

to the design and implementation of an indoor building-scale localization system using ultrasound and infrared technology. This general-purpose indoors localization system has many potential applications; the authors believe that the most interesting are those related to provide added-value location-aware services in hospitals, elderly residences, psychiatric centers, big offices and even warehouses. Some of the large amount of potential location-aware services could be (as already mentioned in first section): the monitoring of patient's location or routines; the urgent location of people, doctors or valuable equipment; the detection of falls; controlling the access to restricted areas for some kind of people; to help or guide people to find a desired destination in a building; automatic guidance of wheelchairs; study of staff activity, for example nurses in a hospital, to try to optimize their base location or daily routines; and many others.

After an initial design phase, the localization systems are conceived to use difference time of arrival DTOA, that is, hyperbolic positioning, in order to avoid a precise synchronization between mobile unit and fixed beacons. These beacons will be fixed on the ceiling of rooms forming a grid with enough density for having at sight at least four beacons anywhere the mobile unit is. In order to have good coverage, or to minimize areas where is not possible to find a fix, the transducer used at the beacons should have a hemispherical emission/reception lobe. On the contrary to previous developments made at IAI-CSIC, the PARMEI localization system will make use of coded signals using spread-spectrum techniques. In particular we will use Gold codes, which are special pseudo-random PRN maximum length codes with good auto- and cross-correlation properties. These properties are essential to be able to emit simultaneously from several beacons, and then at the receiver perform separate correlation in order to estimate de TDOA's. Working with long codes (32, 64 or 128 chips) permit the signal to be detected even with very low Signal-to-Noise Ratio (SNR). In the particular case of using Golay PRN codes [27] correct detections are obtained with SNR of -12, -15 and -18 dB, respectively while increasing the number of chips in the sequence [28].

The more challenging activities to be done by our IAI group in this project are:

- Strategies to perform a robust XYZ estimation using redundant sensors, avoiding singularities and filtering out bad TDOA readings due to multi-path effects
- Study of transducers (ultrasonic or even acoustic) with good bandwidth, to allow the use of spread-spectrum coded signals, and having hemispherical emission/reception lobe to achieve good coverage and reduce the number of beacons needed
- Algorithms optimizing a cost function to fix beacons at the right place to achieve maximum coverage, accuracy, and using the minimum number of beacons

Regarding the first objective, one important aspect is the formulation of the trilateration system of equations, and the analysis of singularities in the matrices to solve the problem [29]. In our hyperbolic positioning problem we can use beacon number 1 as the reference for the other beacons, since we do not measure absolute TOA (t_k) but DTOA (t_{k1}). Then the reference range equation is

$$r_1^2 = (x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2 \tag{11}$$

and the other equations for beacon k ($k = 2 \ldots N$) are

$$(r_k + \Delta r_{k1})^2 = (x_k - x)^2 + (y_k - y)^2 + (z_k - z)^2 \tag{12}$$

Substituting equation (11) into equation (12) we obtain, if N beacons are used, $N-1$ expressions of this type:

$$\begin{aligned} &2x(x_k - x_1) + 2y(y_k - y_1) + 2z(z_k - z_1) + 2r_1(\Delta r_{k1}) = \\ &x_k^2 + y_k^2 + z_k^2 - x_1^2 - y_1^2 - z_1^2 - \Delta r_{k1}^2 \end{aligned} \tag{13}$$

Arranging above set of equations in matrix form, we obtain this simple relationship

$$A \cdot X = B \tag{14}$$

where X is a column vector containing all unknowns

$$X = \begin{pmatrix} x \\ y \\ z \\ r_1 \end{pmatrix} \tag{15}$$

and where A (eq. 16) is a $(N-1) \times 4$ matrix and B (eq. 17) is a column vector of length $N-1$. In both cases this matrices depends on beacon positioning coordinates x_k, y_k, z_k and measured differences of range Δr_{k1}

$$A = \begin{pmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) & 2(z_2 - z_1) & 2\Delta r_{21} \\ 2(x_3 - x_1) & 2(y_3 - y_1) & 2(z_3 - z_1) & 2\Delta r_{31} \\ \vdots & \vdots & \vdots & \vdots \\ 2(x_N - x_1) & 2(y_N - y_1) & 2(z_N - z_1) & 2\Delta r_{N1} \end{pmatrix} \tag{16}$$

$$B = \begin{pmatrix} x_2^2 + y_2^2 + z_2^2 - x_1^2 + y_1^2 + z_1^2 - \Delta r_{21}^2 \\ x_3^2 + y_3^2 + z_3^2 - x_1^2 + y_1^2 + z_1^2 - \Delta r_{31}^2 \\ \vdots \\ x_N^2 + y_N^2 + z_N^2 - x_1^2 + y_1^2 + z_1^2 - \Delta r_{N1}^2 \end{pmatrix} \tag{17}$$

According to equation (14) the solution to this hyperbolic trilateration problem can be solved inverting matrix A, in the following form when $N = 5$ (minimum number of visible beacons required to solve this problem)

$$X = A^{-1} \cdot B \tag{18}$$

or using the Least Square (LS) formulation when there are more than 5 beacons

$$X = (A^T \cdot A)^{-1} \cdot A^T \cdot B \tag{19}$$

The remarkable fact is that matrix A is not always invertible, in fact, if we place the beacons on the ceiling, that is, all laying on the $Z = 0$ plane or parallel to it, then the third column of matrix A (16) is zero. So, from the mathematical point of view is not a good idea to place beacons on the ceiling as it is our intention. Other conflicting situations occurs when the mobile terminal is at the same distance from every beacon, then the fourth column of A becomes a zero vector, and matrix A is singular. We have identified some cases where matrix A is not invertible, so different methods to find a solution must be applied, such as, SVD decomposition [30], forcing beacons to be at different heights, or by means of iterative solutions such as those based on Taylor decompositions. The root of this mathematical problem comes from the inability to select a single solution when there are more than two (for example, in the beacons-on-the-same-plane case there are two solutions, one below the plane and the specular solution above Z plane). The solution to this problem can always be found providing 'a priori' information to algorithms about where our mobile device is more probable to be located.

Once the singularities are overcome, and we can provide a free-of-singularities estimation, then it is very important not only to provide the estimated location value alone, but an index indicating the quality or accuracy of the positioning estimation. This important task can be done using classical GPS-inherited *Remote Autonomous Monitoring* (RAIM) techniques, that basically detect incongruities between TOA measured and re-estimated TOA from computed location [31].

3. Conclusions

Along this paper we have presented an overview of localization methods using active beacons. We gave, for some specific problems, our ultrasonic-based solutions, paying special attention to some challenging aspect that we had to face when developing them. Some of these important topics include ultrasonic lobe shaping, robust estimation, wind compensation, singularity analysis and optimum beacon placement.

The localization prototypes described in this paper were applied to different sectors, such as robotics, intelligent warehouses, greenhouses, hospitals and archaeological sites; but there are many other application fields where accurate location systems are very useful, specially those where a person is the *object* to be located . Especially-tailored services could be offered to people depending on their current position in the world, city or street. Some of these location-aware services could be achieved using ultrasonic technology (for limited coverage and high precision), and of course radio-frequency (RF) technology making use of trilateration concepts, such as, GPS, Telephony or TV networks, WLAN, Bluetooth, RFID or UWB. In most of these RF approaches the positioning accuracy will be lower than using Ultrasound, but the coverage will be much larger (at a level of a whole building, campus, city or even world-wide).

Next generation of mobile phones (SmartPhones) will include, apart from the capabilities of a 3G phone, a DGPS receiver, a integrated PDA, probably WiFi connectivity, and localization services based on mobile 2D-3D positioning. The position accuracy will be good (close to 1 m) and the coverage quite satisfactory both indoors and outdoors. Despite this revolution, we still think there are reasons to continue research on fine-grain localization (mainly ultrasonic and UWB), which are funded on the existence of applications (for example, ubiquitous computing, industrial applications, services at hospitals, psychiatric centers, elderly residences, among others) all requiring accurate indoor localization.

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