Relative Positioning System Using Acoustic Sensors for Ubiquitous Computing Applications

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Abstract. Systems that characterize the state of an entity or object are very important in the “smart spaces” and “ubiquitous computing”; this information is usually known as the entity’s "context". Those applications, which describe or characterize these entities and interact with it, are often referred as "context-aware computing". One of the most important information is the position of an object with the purpose of offering the most suitable services to him. The mechanisms and techniques that determine these space relations are named “location"; and the computing applications, based on the position, are called “location-aware computing”. This article presents an indoor localization system in order to make a relative positioning among entities, fixed or mobile, without use an external infrastructure and only using acoustic transducers for their use in ubiquitous computing applications. Also, an analysis of the positioning algorithm, based on multidimensional scaling technique (MDS), is carried out in order to verify the errors in the position estimation when there are errors in the mechanism of ranging distances.

1 Introduction

Those applications, in ubiquitous computing and smart spaces, which describe or characterize an object and interact with this, are commonly called "context-aware computing" [1]. One of the most important dimensions of the context is the location, and the applications that are based on this context are known as "location-aware computing" [2]. It is useful in emergency services [3]; office applications, for example to find the nearest printer resources or "follow-me" services [4]; for supervision of surroundings; in hospitals to track the medical staff or monitoring patients.

Three kinds of location information can be distinguished: absolute, relative and symbolic [3]. The first one reports the position of an entity given their coordinates, in a two dimensions system (2D) o three dimensions system (3D), from a reference point whose position is known. The relative location determines the position among several objects, generally mobile, without any interest in its location in the surroundings, only given a geometric configuration that hold the space relations among them.

Therefore, all the entities in the system should have the necessary technology to compute their positions. Finally, a symbolic meaning of the position consists of determining if there is an entity in a specific zone without providing any other detail.

The new developments in hardware and in micro-electromechanical sensors (MEMS) allow to reduce sizes, costs, consumptions and to extend the functionality of the sensing technologies. Additionally, the improvements in wireless communications and the new capacities of COTS products (Commercial off-the-shelf), such as PDA's, make possible the development of new location applications. Many researches are centered in designing location mechanisms robust, safe, and easy to set up with very low cost and minimal infrastructure by taking advantage of these technologies advances.

This work presents a relative positioning system for fixed or mobile devices with no need to use of an external infrastructure and only using acoustic emissions as sensing technology. The following section gives a brief revision of the most popular works about location in indoor spaces for their application in ubiquitous computing. Section 3 presents the proposed location system, showing its mains characteristics and methods used to solve the location problem. Finally, Section 4 shows the simulations and results about positioning algorithm considering errors on the measurement of the distances according to the proposed ranging technology.

2 Location systems

There is a wide range of works developed by different researching groups with the aim of solving the location problem and its application in smart spaces and ubiquitous computing. The simplest and well-known solution would be to provide each object with a global positioning system (GPS). This solves the outdoor localization; nevertheless, in the field of mobile computing, size, costs, and, consumptions constraints exclude these systems. Additionally, in indoor environments or urban areas, GPS signals are not available for positioning, caused by their very weak signals. These facts bring to develop a lot of indoor positioning systems using different sensing techniques. In [3], a detailed description of the most important systems developed in the last years is made, in particular, for absolute positioning such as: Active Badge®, Active Bat, CRICKET, RADAR, etc.

The Milibots project [5] is focused on the design of a cooperative team of robots. In this case, the position of each object is very important; so, a method that combines aspects of positioning, recognition of marks and "dead-reckoning" is developed. The relative position among robots is determined through the "triangulation" technique, using ultrasonic signals (US). This system has the advantage of not using fixed beacons, which is an important requirement when unknown environments are explored, but it needs that some of them working as a reference to the others.

In [6], a location system for General-Purpose Computers (GPC, "General Purpose Computer"), such as PC´s, notebooks or PDA's is developed. The system takes the advantage of the acoustic transducers and radio frequency (RF) available in these devices, in order to range distances and make the necessary communications.

The distances among objects are calculated using times-of-flight (TOF) or differences of time-of-flight (DTOF) of the acoustic signals emitted by every object. Since this system does not use external beacons, some of them work as reference for the rest.

According to the above description, there are a large development of absolute location systems, some of them commercial. Basically they consist of an external infrastructure, which acts as a reference of the object to be located, and measures distances between the entity and the infrastructure. After that, the computation of the position can be made through a central system or in the same object to be located. Nevertheless, due to the requirements of mobility and "peer to peer" interaction of entities with a computing application, it is necessary to develop location systems that can work in non-prepared environments, with the minimum possible infrastructure. As a result, a relative positioning between devices is more suitable. The objects should have the necessary technology to execute all the operations of the location process. This trend carries to develop non-centralized applications, which do not depend on one object for the positioning and they are able to compute its location respect to others in a local way.

The more used location technique, because of its low computing requirements, is triangulation. This can be divided into two methods: measuring distances or angles, among objects or to a reference system. The first one is more usual and it consists of determining the range of an object from several reference points, minimum three, or among them, and then solving a nonlinear equations system by any method, such as: minimums square, SVD, etc. The techniques for ranging distances in indoor spaces are usually based on the determination of the propagation time of an emitted signal. Three versions of this method are known: the calculation of TOF in direct way, by the method of double way (RTOF), or differences of TOF (DTOF) of emitted signals by every objects [7]. The sensing technologies frequently used to compute the TOF can be acoustic transducers, RF or infrared (IR). The US signals are more used due to its easy synchronization with RF or IR connections, and also their high precision. The acoustic transducers of the audible band (20 Hz-20 kHz) are starting to use, because of the good bandwidth characteristics and their availability in many mobile computing devices compared with US.

3 Proposed Location System

Once discussed the advantages, difficulties and trends in the positioning systems, this section presents a proposed of a location system for indoor spaces that considers the facts mentioned before.

3.1 System Characteristics

Figure 1 shows the basic architecture that uses acoustic transducers in order to carry out a relative positioning of entities or objects, usually mobile, denoted as Mb_p, with $p \in \{1,2,\cdots,P\}$ and P is the maximum number of objects.

The more important characteristics of this system are: 1) without need of using an external infrastructure; 2) local computing of the relative position with all the objects; 3) all entities are equal in their architecture and functionality; 4) no physical connection among them; 5) only using acoustics emissions, reason why RF or IR connections will not be required for the synchronization.

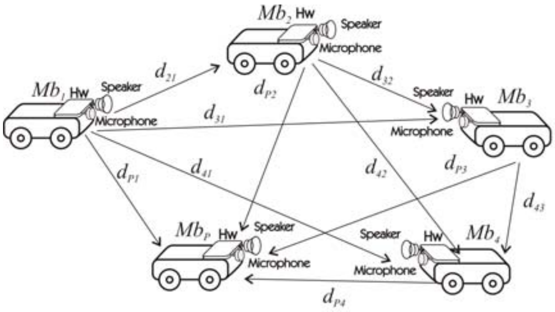

Fig 1. General scheme of the proposed system. Every object of the system is denoted as Mb_p, with $p \in \{1,2,\cdots,P\}$, P is the maximum number of objects

The Multidimensional Scaling technique (MDS) [8] will be used to determine the positions, reason why the system should determine all the ranges as a previous step to execute the positioning algorithm. In Fig.1, d_{ij} means the distance from object *i* to object *j*; that will be determined measures the propagation time of emitted acoustic signals by every object. These emissions can be masked in a conventional acoustic emission, as a “watermark” technique, in order to be negligible for the human hear.

Acoustic signals, in audible band are used taking advantage of their low cost, easy implementation and availability in mobile computer systems. About drawbacks, environmental aspects affect their performance in outdoors, but in indoor spaces, these are minimized. Also, the acoustic signals are sensitive to the solid objects, but these errors can be eliminated through algorithms of geometric consistency.

Additionally, a non-centralized system is obtained because all nodes are equal in their architecture and functionality reason why every node can compute locally the object positions.

3.2 Metric Multidimensional Scaling Technique.

These technique, also known as classic MDS, provides a geometric configuration of the objects, in the smallest possible number of dimensions, when the only thing know is a relation among them; in this case their distances.

Figure 2 summarizes the process to carry out. First of all, in each node, all distances are necessary to know before starting the computations of the position and they are described in a matrix of distances denoted as **D** (step 1).

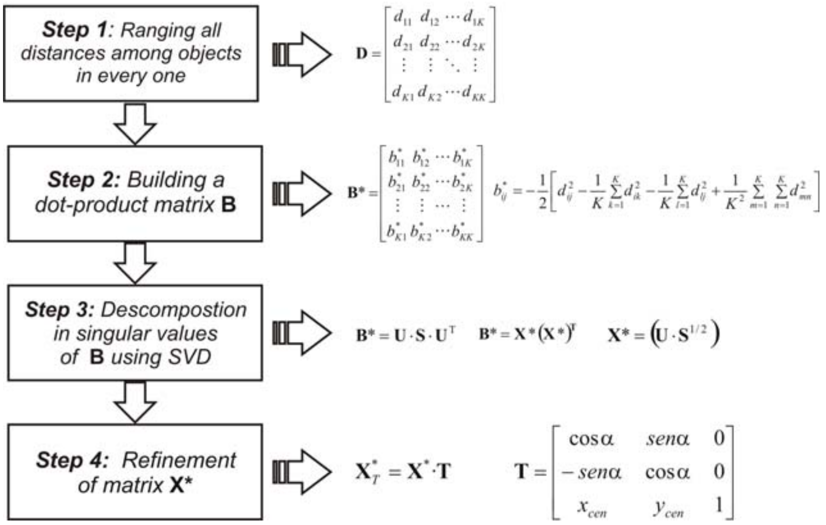

Fig 2. Steps of the MDS positioning algorithm. Each step shows the operations with the aim of obtaining, in every node, the estimated coordinates in a matrix $\mathbf{X^*_T}$, in 2D or 3D, of all the objects

Once known all distance the second step is build a matrix **B***, called dot-product, that considers the distances among objects from a reference point, being the most suitable the centroid of the figure that the objects form in a two or three dimensions system. The following step is the decomposition in singular values (SVD) of **B*** and considering the properties of the resulting matrixes of eigenvectors and eingenvalues, **U** and **S** respectively. The coordinates of the objects can be obtained selecting the first two or three columns of matrix **X*** according to the dimensions of the system (Step 3).

Finally, a refinement process is carried out, which considers a rotation and translation process of **X***, by means of matrix **T**, because the estimated coordinates are obtained for the centroid. Matrix **T** is defined using one object as origin of the coordinate systems and selecting another one, that forming a line with these one. The resulting matrix $\mathbf{X^*_T}$ gives the correct coordinates. In addition, in this step the ambiguities in the ranging can be eliminated as a previous step to compute the algorithm.

3.3 Mechanism of ranging distances.

The mechanism described in this section allows to measure, in a simultaneous way, all the distances among objects; calculating the propagation time of the emissions among the objects using only acoustic signals. This is with the purpose of eliminating all type of additional synchronization connections by RF or IR, reducing the hardware complexity. Also, in indoor spaces, the RF signals can be interfered by other systems such as 802.11 networks, or by spurious signals from the fluorescent illumination in the case of IR.

Based on this synchronization constraint, the distances are calculated with a method similar to RTOF technique [7]. In this case, taking advantage of the codification properties used on the emissions, the method will be simultaneous in all nodes (see Fig. 3) and will be called S-RTOF (Simultaneous Round-Trip-Time-of-Flight). Because all objects are equal in their architecture and functionality, anyone of them can start the location process, working as "Master". By means of multiple access technique (CSMA), it is possible to determine which object takes the control of the process. After that, the "Master" emits its acoustic signal with a particular encoding assigned to it (see Fig. 3.a). At this moment, the measures of TOF's starts.

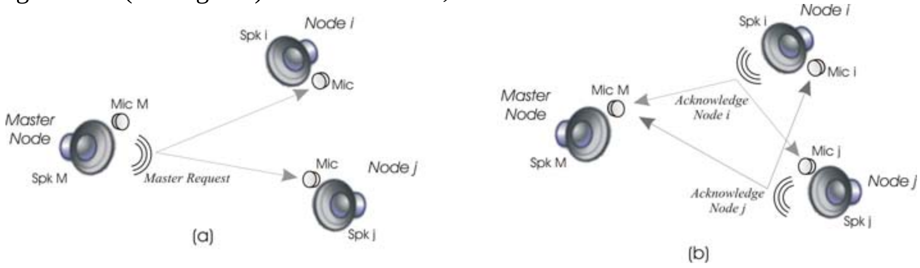

Fig 3. a) Emission of the request from the "Master" starting the location process. b) Acknowledgement of each node for calculating the distances

This code, called "Master Request ", is received in every slave object at different moments. In answer to this request, each entity emits its characteristic code denoted as "Ack. Node *i*" which propagates towards the "Master" and also to the other objects (see Fig 3.b). In this way, in the "Master", the time since the "Master Request" was emitted until the "Ack. Node *i*" was detected, can be computed and consequently the distances among the "Master" and the slave Node *i*. Also, taking advantage of the emission of every one, it is possible to compute the distances among them by means of similar temporal relations.

3.4 Acoustic signals encoding and hardware architecture

Every object emits an acoustic signal codified by means of complementary sets of eight sequences (*8*-CSS) [9], where the sequence length is a power of the number of sequences of the set, that is $L = 8^N$.

These sets allow obtaining auto-correlation (AC) maximum values of $8 \cdot L \cdot \delta[k]$ for non-time shifted versions, where $\delta[k]$ is a Krönecker function. Also, null AC side-lobes in ideal conditions for shifted versions of them can be obtained. Additionally, eight mutually orthogonal (MO) sets can be easily obtained, which allow to make simultaneous emissions, up to eight, without no-interference among them. In this way, the number of objects to locate simultaneously is based on the number of codes MO that can be obtained, being M in the case of M-CSS, with $M = 2^m$ and $m \in \mathbb{N} - \{0\}$. The use of the *8*-CSS by means of the algorithm proposed in [9] allows an efficient implementation of their generator and correlador, so, a high reduction on to the hardware complexity and the computational load is obtained compared to the straightforward implementation.

The basic hardware architecture of each object is described in Fig.4. There are a transmission block and another one for the reception of acoustic signals. In order to simultaneously detect the codes emitted by the eight different sources, in the receiver block, a set of efficient correlators is implemented in order to detect each code assigned to every entity. Finally a processing unit, that coordinates the communications and computes the algorithm, is implemented.

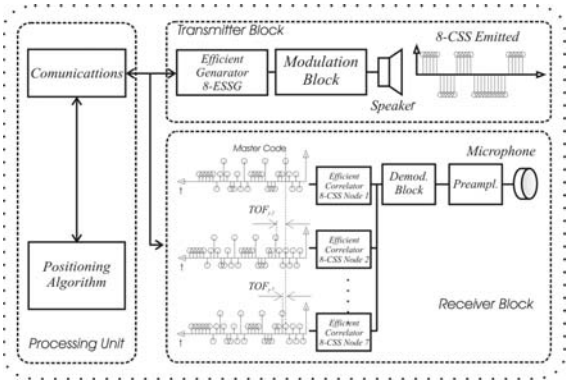

Fig 4. Hardware Architecture of every object, constituted by an emitting block. The receiving blocks contain a set of correlators in order to detect the different codes of the system in a simultaneous way.

4 Simulations and results

This section provides simulations that show the results obtained when there are errors in the mechanism of ranging distances due to Gaussian noise and other sources, such as non-correct synchronization among nodes because they do not use the same clock. Two situations were simulated, one considering errors in the ranging, assuming a metric space, this is $d_{ij} = d_{ji}$; and another one where the space is non-metric, i.e. $d_{ij} \neq d_{ji}$,so all the distances have different errors in their measurement.

4.1 Analysis in 2D with errors on the distances ranging in a metric space

Considering eight objects distributed, in an indoor space, at a distance non-longer than three meters; according to the map observed in Fig. 5. Let assumes that the Mb_1 is the reference of the system with coordinates ($x = 0; y = 0$) and that Mb_2 forms a line with Mb_1 ($x = 0; y = y_2$). A simulation of the positioning algorithm was made assuming errors in the measurements of TOF non greater than $150\mu s$, which implies that errors in the distances are less than $5cm$. The matrix of distances **D** affected by this random error is called $\mathbf{D_{noise}}$ (1), where every element is denoted as d_{ij}, which is the distance between node *i* and node *j*.

$$\mathbf{D_{noise}} = \begin{pmatrix} 0 & 134.92 & 275.76 & 277.33 & 204.82 & 240.35 & 137.12 & 295.51 \\ 134.92 & 0 & 166.88 & 194.05 & 176.94 & 106.94 & 147.23 & 242.53 \\ 275.76 & 166.88 & 0 & 64.547 & 165.73 & 89.556 & 177.46 & 134.14 \\ 277.33 & 194.05 & 64.547 & 0 & 124.19 & 144.24 & 158.75 & 72.064 \\ 204.82 & 176.94 & 165.73 & 124.19 & 0 & 198.97 & 51.197 & 102.38 \\ 240.35 & 106.94 & 89.556 & 144.24 & 198.97 & 0 & 189.13 & 214.62 \\ 137.12 & 147.23 & 177.46 & 158.75 & 51.197 & 189.13 & 0 & 161.85 \\ 295.51 & 242.53 & 134.14 & 72.064 & 102.38 & 214.62 & 161.85 & 0 \end{pmatrix} \qquad \mathbf{(1)}$$

Figure 5 shows the obtained results of the estimated positions after executing the positioning algorithm described in Section 3. The real positions and also the estimated positions after selecting the two first columns in matrix $\mathbf{X^*_T}$ can be observed in Fig. 5. The errors in the estimations of the coordinates, in centimeters, are described in (2).

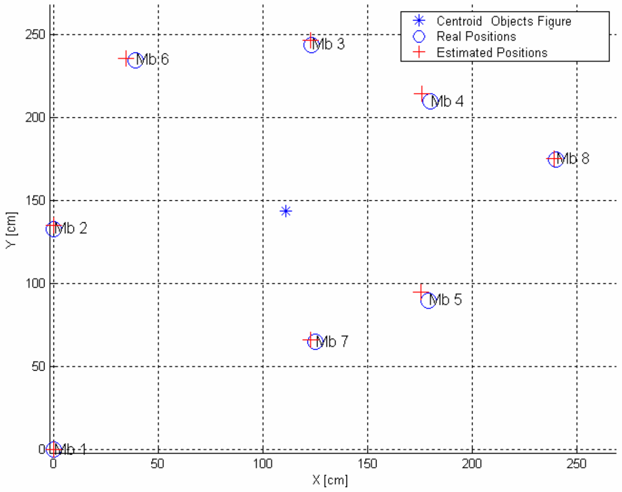

Fig. 5. Map of real positions and estimated coordinates considering a 2D system and a Gaussian noise in the measures of the distances assuming a metric space.

$$\mathbf{E} = \mathbf{X}_{\mathbf{T}}^{*} - \mathbf{X} = \begin{pmatrix} 0 & 0 \\ 0 & 2{,}3575 \\ -0.040142 & 2.6935 \\ -3.96 & 4.7608 \\ -3.3512 & 4.8573 \\ -4.195 & 0.98277 \\ -2.0574 & 1.2974 \\ -0.92993 & 0.40706 \end{pmatrix} \qquad (2)$$

4.2 Analysis in 2D with errors in all distances ranging

In this case, an estimation of the positions when matrix **D** is affected with Gaussian noise and, $d_{ij} \neq d_{ji}$ is simulated. This fact does not fulfill one of the axioms of the metric space. Adding random error at all distances in **D** with the same magnitudes as in the previous case, the matrix $\mathbf{D}_{\mathbf{noise}}$ (3) obtained is:

$$\mathbf{D}_{noise} = \begin{pmatrix} 0 & 134.03 & 270.47 & 274.92 & 203.3 & 239.44 & 140.62 & 299.57 \\ 126.91 & 0 & 169.81 & 195.57 & 182.76 & 111.27 & 144.49 & 247.11 \\ 276.43 & 169.86 & 0 & 65.522 & 161.46 & 82.462 & 178.12 & 140.06 \\ 271.32 & 194.46 & 67.306 & 0 & 122.81 & 139.87 & 154.73 & 69.897 \\ 200.56 & 185.36 & 163.51 & 117.64 & 0 & 200.24 & 59.561 & 109.28 \\ 239.63 & 109.44 & 85.481 & 144.81 & 207.62 & 0 & 191.4 & 214.9 \\ 141.97 & 145.03 & 180.99 & 161.13 & 56.317 & 187.4 & 0 & 160.42 \\ 300.12 & 244.17 & 135.14 & 74.524 & 102.51 & 212.52 & 165.7 & 0 \end{pmatrix} \qquad (3)$$

Applying the MDS algorithm to $\mathbf{D}_{\mathbf{noise}}$, selecting the first two columns of **X*** and making the transformation, the results obtained can be observed in Fig.6.The errors in the estimation coordinates are higher than the previous analyzed case, according to the errors described in matrix **E**.

$$\mathbf{E} = \mathbf{X}_{\mathbf{T}}^{*} - \mathbf{X} = \begin{pmatrix} 0 & 0 \\ 0 & -6.4841 \\ -0.17179 & -2.1843 \\ 1.8035 & -4.2345 \\ 2.2102 & -4.6011 \\ 2.9138 & -2.9105 \\ 6.0309 & -2.3029 \\ -0.94535 & -0.086448 \end{pmatrix} \qquad (4)$$

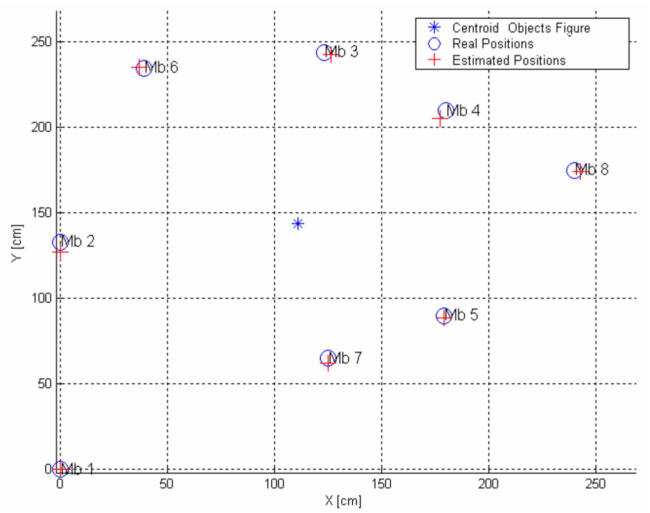

Fig.6. Map of real and estimated positions of the system in 2D in a non-metric conditions

5 Conclusions

An architecture of a location system using acoustic transducers for the relative positioning among different objects is presented. This system is attractive for its use in ubiquitous computing applications that imply mobile units have available acoustic transducers. The use encoding allows to detect up to eight different codes and consequently it is possible to locate eight objects in simultaneous way. The positioning algorithm requires to know all the space relations among objects before computing the process, so a communication protocol using acoustic emissions should be developed. In addition, it is necessary to implement a refinement stage with two objectives: to transform the results obtained and also to eliminate incompatibilities in the matrix of distances, generated by errors in the determination of times-of-flight, in order to reduce the errors on the position estimation.

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