

Implementation of Acoustic Sensor Network for Relative Positioning System

C. De Marziani, J. Ureña, A. Hernández, M. Mazo,
J. J. García, A. Jimenez, J. M. Villadangos,
M. C. Pérez; A. Ochoa, Javier Baliñas
Electronic Department, Polytechnics School
University of Alcalá
28805 Alcalá de Henares, Spain
Email: marziani@depeca.uah.es

F. Álvarez

Electronics and Electromechanics Department
University of Extremadura
Polytechnic School
10071 Cáceres -SPAIN

Abstract— This work presents the development and implementation of an acoustic sensor network mainly proposed for relative positioning of mobile robots and autonomous modules. The system consists of several objects to be located, each one of them with an acoustic sensor node. Every node has the required technology in order to compute its position, by using only acoustic emissions as ranging mechanism; this reduces the complexity in the hardware to be implemented. Direct Sequence Code Division Multiple Access (DS-CDMA) techniques are used to allow simultaneous emission from several objects, so spatial relations among objects can be measured in a shorter time. Using the data collected by the proposed ranging mechanism, a relative positioning algorithm is computed with the aim of obtaining the positions among objects.

I. INTRODUCTION

There is a wide range of works developed with the aim of solving the location problem of objects and its application in indoor and outdoor spaces. In some cases, due to the mobility requirements and “peer to peer” interaction of these objects, it is necessary to develop location systems able to work in non-prepared environments, using the smallest infrastructure. Therefore, relative positioning techniques should be used [2]. In this case, objects must have the technology required to execute all the location operations.

Examples of these types of systems are: Milibots project [3] and DOLPHIN system [4] in the case of robot teams. New fields of applications for relative localization systems are mobile computing systems [5] [6].

Different topics should be analyzed in this type of systems, most of them in the field of hardware architecture: design of low-complex ranging mechanisms; use of only one type of emissions with low power level; encoding of emissions for multi-user detection with different conditions; real-time signal processing; communication protocols; smaller infrastructure; and low complex organization of the system.

In this work, first results obtained in the implementation of a sensor network for a relative positioning system are described. A complete description of the proposed system could be found in [7], where a suitable encoding scheme, by Complementary Set of Sequences is used in order to simultaneously detect the emissions carried out by every node under similar conditions.

Also, a novel ranging mechanism has been designed in order to compute the spatial relations among objects using only acoustic emissions. Finally, the adaptation of a relative positioning algorithm [6], according to the proposed ranging mechanism, has been proposed.

Due to features of relative positioning systems, the designed signal processing algorithms must be performed in real-time with a good accuracy and precision. In this way, the hardware implementation efforts have been focused on the implementation of these algorithms in a configurable architecture.

The paper is organized as follows: Section II presents the main features of the proposed sensor network. Section III shows a brief revision of the designed ranging mechanism. Section IV describes the complete hardware architecture of every sensor node. Then, in section V, a presentation of the hardware implementation carried out is described. In section V, results obtained in experimental tests are shown, as well as results obtained with the used positioning algorithms. Finally, most important conclusions are discussed in Section VI.

II. SENSOR NETWORK ARCHITECTURE

The basic architecture of the sensor network is shown in Fig. 1, where every object has a node with acoustic transducers as sensory technology. The main characteristics of this system are: 1) small external infrastructure is used; 2) local computing of relative positions with all the objects; 3) all nodes are equal about architecture and functionality; 4) no physical connection among them; 5) using only acoustics emissions, reason why RF or IR connections will not be required for synchronization.

Acoustic transducers are used due to their low cost, easy implementation and availability in several mobile systems. Additionally, a non-centralized system is obtained since all nodes have similar architecture and functionality, reason why every node can locally compute the object positions.

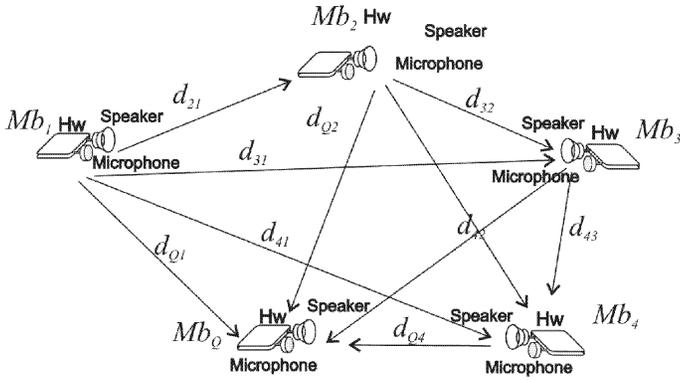


Fig. 1. General scheme of the proposed sensor network.

A Code Division Multiple Access scheme (CDMA) is used in order to simultaneously detect the emissions made by every object. The emissions are encoded by Complementary Sets of Sequences (CSS) that have suitable correlation properties and allow to obtain a high reduction in hardware complexity and computational load for real-time processing of acoustic emissions [8].

A. Acoustic Signal Processing

The signal processing of the emitted acoustic signals has been presented in [10]. With the proposed encoding scheme by CSS, more than one sequence encodes a user. In order to efficiently emit the encoding, a bit emission order has been used. In this way, a new sequence is generated, so-called "macro-sequence" M_s . Then, data can be transmitted by a digital phase modulation, such as *BPSK* (Binary Phase Shift Keying).

According to the described generation methods of M_s , the correlation function can be carried out with the efficient correlator of the M -CSS used for its generation [8]. Thus, the correlation function of $M_s[k]$ can be defined as:

$$\begin{aligned} \phi_{M_s} = & \phi_{M_s, S_{1,M}} [k - (D_{M-1})] + \phi_{M_s, S_{2,M}} [k - (D_{M-2})] + \dots \\ & \dots + \phi_{M_s, S_{M-1,M}} [k - D_1] + \phi_{M_s, S_{M,M}} [k] \end{aligned} \quad (1)$$

$$\phi_{M_s} = \sum_{i=1}^M \phi_{M_s, S_{i,M}} [k - (D_{M-i})]$$

Where D_{M-i} is a delay whose value depends on the method used to arrange the bits of the set; and $\phi_{M_s, S_{i,M}}$ is the correlation between M_s and the sequence $S_{i,M}^{(s)}[k]$ of a determined M -CSS, called the partial correlation of M_s .

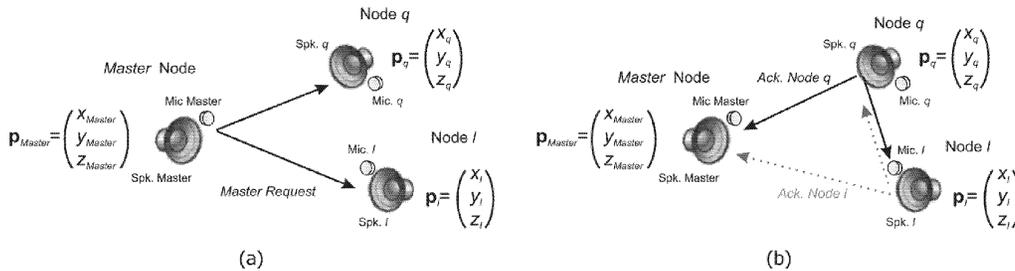


Fig. 3. Principle of Measurement using Simultaneous Round-Trip-Time-of-Flight

a) Emission of the request from the Master starting the location process. b) Acknowledgement from every node to compute distances.

In this way, it is possible to correctly add the correlation of the macro-sequence with the sequences used for its generation. The hardware implementation of this method is shown in Fig. 2. The input signal, captured by a transducer is demodulated and then, the obtained signal $e[k]$ drives the efficient correlator of the M -CSS used to generate the macro-sequence.

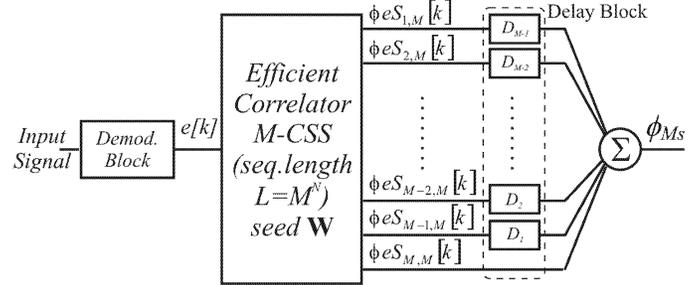


Fig. 2. Correlation architecture of macro-sequences using efficient correlators.

B. Ranging Mechanism

The proposed ranging mechanism used in the system has been discussed in detail in [7] and also in [8]. The main feature of this mechanism is the measurement in a shorter time, under similar conditions, of all the distances among objects by using only acoustic emissions. This avoids the use of high precision clocks or additional synchronization connections, as RF [4] or IR, reducing hardware complexity and power consumptions. Also a communication protocol should be designed to distribute data collected at every node.

The proposed ranging method is based on measuring the Round-Trip-Time-of-Flight (RTOF) of the emitted signals [11]. Taking advantage of the encoding used in emissions, the method is simultaneously implemented among all the nodes; it is called S-RTOF [7] (Simultaneous Round-Trip-Time-of-Flight). In this way, additional temporal relations among the acoustic emissions are obtained for the positioning algorithm.

III. S-RTOF MECHANISM

Since all nodes have similar architecture and functionality, anyone can start the location process. In order to determine which one starts the ranging process, called the *Master* node, a multiple access technique such as *Carrier Sense Multiple Access* (CSMA) is used.

Let assume that the *Master* node has a position with coordinates (x, y, z) , described by vector $\mathbf{p}_{\text{Master}}$; and also that the positions of two slave nodes q and l are given by vectors \mathbf{p}_q and \mathbf{p}_l . At a given instant, the *Master* node emits its acoustic signal with a particular encoding (see Fig. 3.a) and the measurement of RTOF starts in this node. This emission, called *Master Request*, is detected at every slave node by their microphones Mic. q and Mic. l at different times, according to their location in the environment. In response to *Master Request*, every node emits its characteristic code denoted as *Ack. Node*, which travels towards the *Master* node and also to the other slave nodes (see Fig. 3.b). In this way, in the *Master* node, the time from the *Master Request* emission to the reception of every *Ack. Node* can be computed.

$$\hat{t}_{\text{Master}-i} = \frac{\|\mathbf{p}_{\text{Master}} - \mathbf{p}_i\|}{c} + T_{\text{CODE}} + \frac{\|\mathbf{p}_i - \mathbf{p}_{\text{Master}}\|}{c} \quad (2)$$

Where $\hat{t}_{\text{Master}-i}$ is the emission time between the *Master* and the slave node i with $i \in \{1, 2, \dots, Q\}$; and Q is the maximum number of objects in the system. Additionally, c describes the propagation speed of acoustics signals; and T_{CODE} is the time of the emitted encoding. Finally, the operator $\|\cdot\|$ is the Euclidean norm between the considered position vectors.

Also, taking advantage of the slave node emissions, it is possible to compute temporal relations among them. For that, the interval from the *Master Request* detection until the detection of every *Ack. Node* is measured, obtaining a temporal relation in every slave node with the others.

$$\hat{t}_{q-l} = \frac{\|\mathbf{p}_{\text{Master}} - \mathbf{p}_l\|}{c} + \frac{\|\mathbf{p}_l - \mathbf{p}_q\|}{c} - \frac{\|\mathbf{p}_{\text{Master}} - \mathbf{p}_q\|}{c} + T_{\text{CODE}} \quad (3)$$

Where \hat{t}_{q-l} is the temporal relation measured in the slave node q , from the detection of the *Master Request* with the slave node l .

Using (2) and (3) it is possible to determine the distance among the master and the slaves nodes and to determine the position among objects.

IV. HARDWARE NODE ARCHITECTURE

The basic hardware architecture of every node 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 different acoustic sources, in the receiver block, a set of macro-sequence correlators are implemented. Finally a control unit has been designed to coordinate the S-RTOF ranging method, compute the pTOF among nodes and manage the sensor network communications.

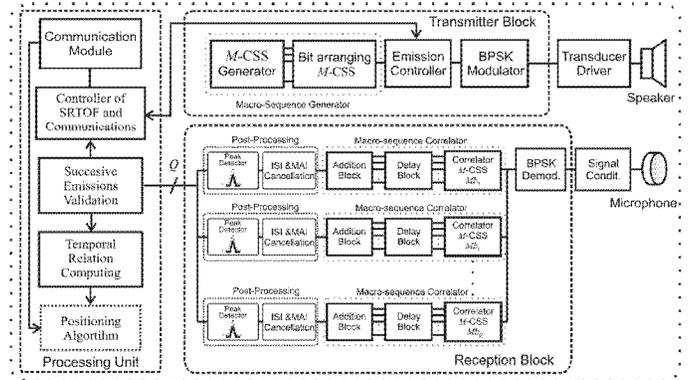


Fig. 4. Hardware node architecture.

C. Emitter Block

The transducers used in the proposed system should have small size, low cost and a suitable frequency response. The last characteristic has been analyzed in detail with the aim of emitting the encoding with frequencies that are negligible to the human ear. Different transducers have been analyzed [12]; the search was focused on sonic transducers by evaluating its response at frequencies higher than the audible band. In this way the REGAL RE-16 acoustic transducer has been selected [13].

The emission process consists of generating the macro-sequence and transmitting it by a BPSK modulation, with a digital symbol with a period of 30 μ s.

D. Receiver Block

On the reception stage, a Panasonic microphone WM-61 [14] is used to detect the acoustic signals emitted from every node taking advantage of its small size and suitable frequency response. The characteristic response allows to detect the acoustic signals emitted with frequencies higher than 20kHz. The received signal is adapted before processing it with the algorithms described in previous sections.

The first step in the digital signal processing is the demodulation of the captured signal. Since no temporal reference is available, the demodulation is carried out asynchronously by sampling the received signal at a high enough rate and then correlating it with the symbol used in the modulation [12]. The signal coming out from the demodulator is correlated with the macro-sequence correlator described in previous sections. A generic implementation of the algorithms proposed in [8] has been developed in a Field-Programmable Gate Arrays (FPGA) [15].

According to the macro-sequence emission process, an adaptation of the efficient correlator structure is required. The correlation of the input signal should be performed with an interpolation version of the sequences of the M -CSS. The interpolation factor depends on the number of sequences M , the number of symbols used in the modulation and the oversampling factor used to capture the input data. Also, it is necessary to consider the interpolation when the interleaving method is used to emit the encoding.

This modified correlator carries out simultaneously the correlation between the input sequence and every sequence of the searched M -CCS. These autocorrelations are not in phase, the phase shift depends on the used arranging method, the number of symbols in the modulation, and the oversampling factor. Thus, it is necessary to insert delays at every output of the correlator, in order to perform the in-phase addition of the autocorrelation functions (see Fig. 2). Finally, a post-processing algorithm [10] and a peak detector based on a dynamic threshold are included in order to validate the arrival time of every encoded acoustic emission. The peak detector emits a digital pulse in those cases where the correlation result exceeds a certain threshold.

E. Processing Unit

The processing unit control the emissions made by the node. Also, this unit performs the computation of the temporal relations among the emissions made by every node, using the results obtained at the output of every correlator implemented in the node. In order to determine this temporal relations, or pseudo-time of flight, it is necessary to implement a block that validates the successive emissions transmitted from every node. Finally, the processing unit manages communications of collected data and computes positioning algorithms.

V. HARDWARE IMPLEMENTATION AND EXPERIMENTAL RESULTS

Experimental tests have been carried out in order to verify the accuracy and precision obtained in the position estimation with the proposed sensory network architecture and signal processing algorithms.

A. Implemented Hardware

According to the description in the previous section of the node hardware architecture, the proposed signal processing algorithms have been implemented in a board based on a Xilinx XC2S200E FPGA [16]. The architecture implemented for every node consists of a transmitter block, a receiver block, and finally a block required to compute temporal relations among emissions. Afterwards, the obtained results are communicated to a central unit to compute the positioning algorithms.

Due to the available resources in the mentioned board, only the hardware related to pre-processing of transducers signals has been implemented in additional boards in order to simulate every node (see Fig. 5).

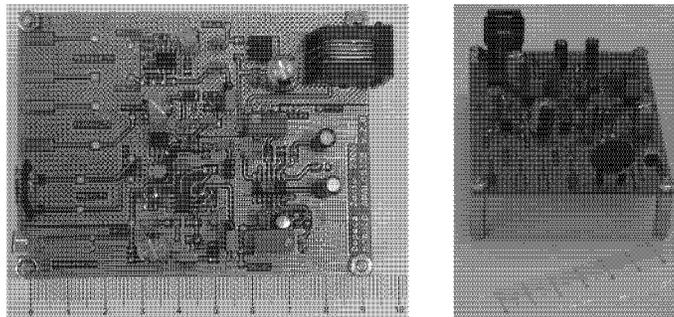


Fig. 5. Hardware implemented for every node.

B. Ranging Mechanism Characterization

According to the features of the proposed ranging mechanism S-RTOF, two different experimental tests have been carried out in order to verify its performance. The first one consists of obtaining the distance between objects by using a direct measurement of the propagation time of the emitted acoustic signals. In the second test, the distance between nodes is determined by measuring the propagation time of the emitted signals with the round trip time of flight method.

Fig. 6.a shows the high accuracy obtained in the measurement of the propagation time of acoustic emissions. Also a low variability is obtained in the measurements, where the standard deviations is $\sigma = \pm 1$ sample or $\sigma = \pm 3 \mu s$.

In the second case, when measuring the distance among nodes by the RTOF method, also a high accuracy is obtained. In this case, due to the uncertainty on the detection of two acoustic emissions, the variability or precision is degraded to a standard deviation $\sigma = \pm 2$ sample or $\sigma = \pm 6 \mu s$, whereas the distance is up to 2,5m. When the distance among objects is higher than 2,5m, the variability is increased obtaining $\sigma = \pm 9 \mu s$ (see Fig. 6.b).

C. Positioning Algorithm results

Using the characterization of the ranging mechanism and signal processing algorithms described in Fig. 6, the final step has been the simulation of the positioning algorithm with the aim of obtaining the positions of the objects. The positions are computed by the MDS technique and then, considering the different error sources, a close solution is obtained by performing a Levenberg-Marquardt (LVM) algorithm. A complete description of the used positioning algorithms has been presented in [8].

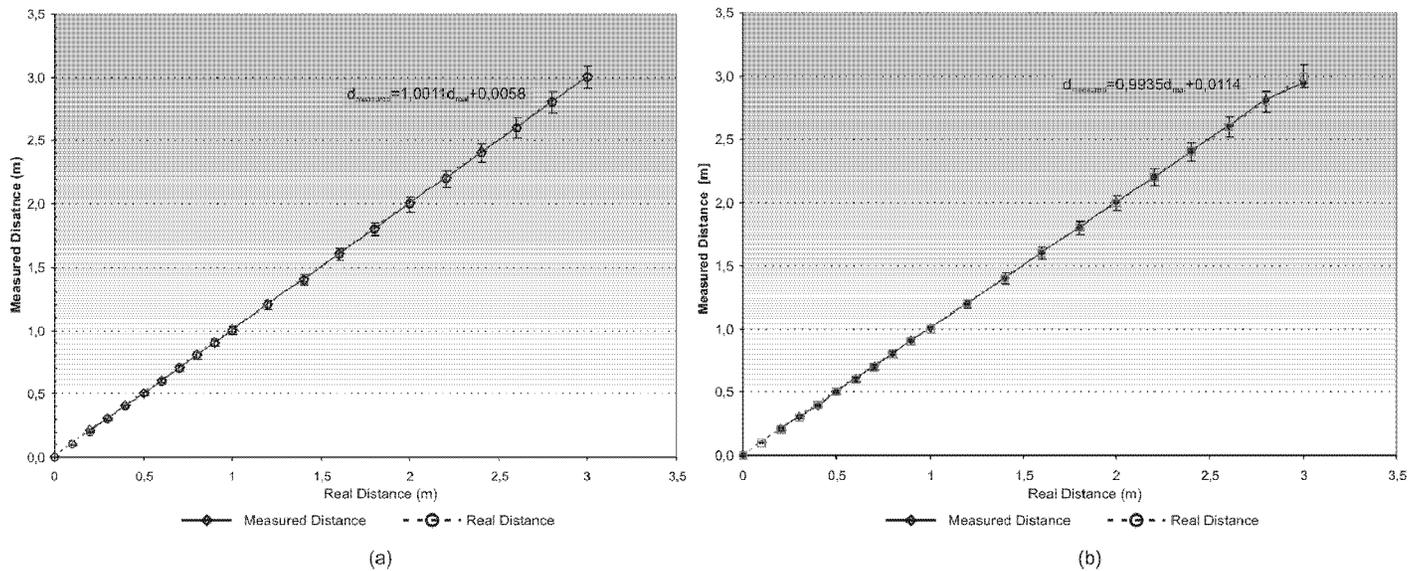


Fig. 6. Results obtained in the characterization of the hardware architecture and ranging mechanism. a) Results obtained in the measuring of distance using TOF method. b) Results obtained in the measuring of distance using RTOF method.

In order to compare performances of the positioning algorithms, a Monte-Carlo simulation has been performed. A topology of sixteen nodes, 2D distributed as shown in Fig. 7, is used. On the proposed topology, the *Master Node* condition is assigned to the object Mb_1 with coordinates $(0, 0)$, whereas the node Mb_2 forms a line with coordinates $(0, y_2)$, obtaining the reference system.

The S-RTOF ranging method has been simulated using the experimental results obtained in Fig. 6. The distance between the *Master* node and every slave nodes has been simulated using the results obtained in Fig. 6.a. On the other hand, the spatial relations among slave nodes has been simulated combining the results obtained in Fig. 6.a and Fig. 6.b, according to the features described in Section III. In this way, every node has a matrix whose elements are the distances measured using the experimental results.

The Monte-Carlo simulation has been performed for one thousand tests. The LVM optimization was performed with the Matlab® function `lsqnonlin`. Fig. 8 shows the 95% uncertainty ellipses (2D) obtained from the coordinate estimation in the case of Node Mb_4 when different numbers of nodes are used in the system: 8 nodes (see Fig. 8.a) and 16 nodes (see Fig. 8.a) respectively. The obtained results show a good performance of the positioning algorithms according to the characterization carried out, verifying a millimetric precision on the position estimation. The obtained results show that the LVM has a better performance in the estimation compared to the MDS algorithm. Although, when the number of nodes in the system increases, a high precision in the positioning algorithms is obtained.

Finally, a bias in the position estimation is obtained due to the bias error obtained in the characterization; nevertheless, these errors have a millimetric magnitude, verifying a good performance in the proposed relative localization system.

VI. CONCLUSIONS

In this work, the hardware implementation of an acoustic sensor network has been presented, in order to use it for relative positioning of a robot team. The developed signal-processing algorithms have been implemented in a configurable architecture, verifying a suitable real-time operation. Furthermore, some properties related to the proposed ranging method have been experimentally verified. In this case a good precision and accuracy can be obtained in the measurement of distance among objects. The obtained accuracy and precision allow to achieve a millimetric precision in position estimations with the used positioning algorithms.

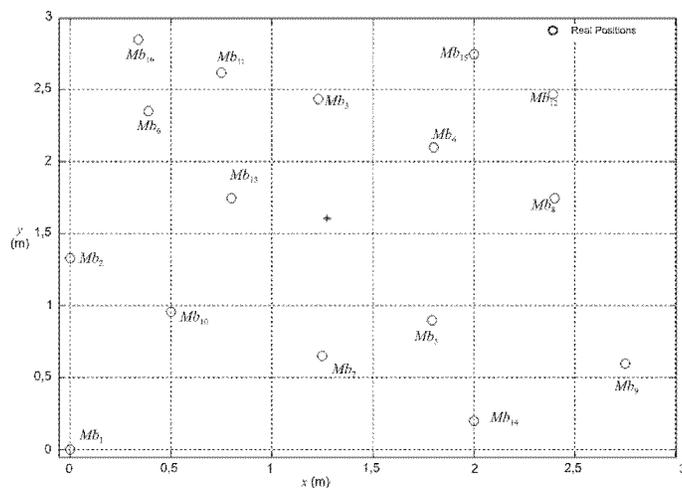


Fig. 7. Topology of nodes used to test the positioning algorithms with the proposed characterization.

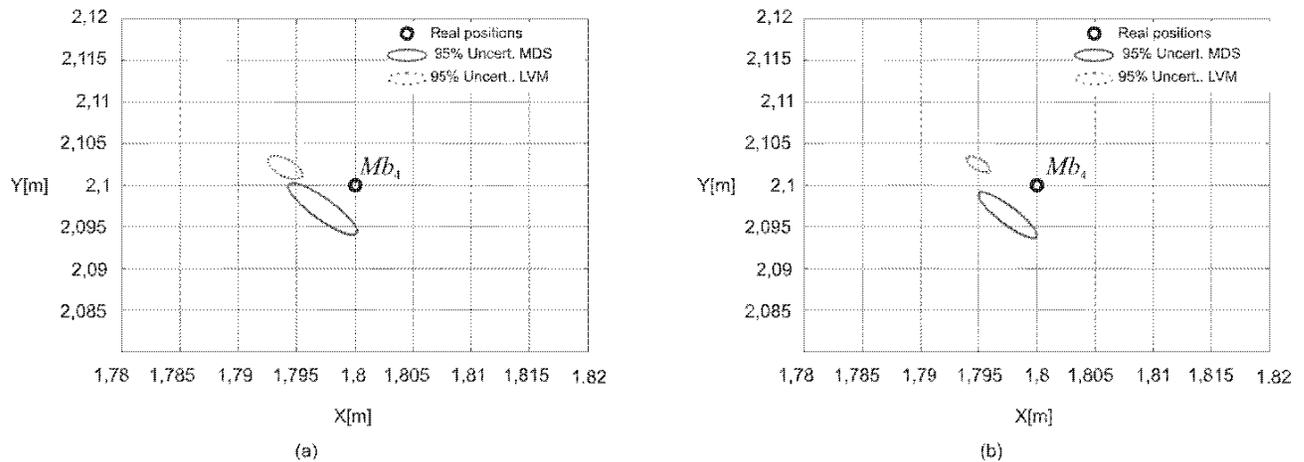


Fig. 8. Positioning estimation results obtained in Node Mb_4 using experimental measurements and different number of nodes.
a) Positioning results obtained in Node Mb_4 using 8 nodes in the system. b) Positioning results obtained in Node Mb_4 using 16 nodes in the system

ACKNOWLEDGMENT

This work has been possible by funding from IMSERSO (ARIADNA project -ref. 212/05- and DEDALO project ref. 81/06) the Community of Madrid (INCUBUS project, CAM-UAH2006).and the Spanish Ministry of Education and Science (RESELAI project TIN2006-14896-C02-01).

REFERENCES

- [1] Hightower, J.; Borriello, G.; "Location systems for ubiquitous computing", IEEE Computer, Vol. 34, Issue 8, August 2001, pp.: 57-66.
- [2] J Patwari, N.; Hero, A.; Perkins, M.; Correal, N; O'dea, R.; "Relative Location Estimation in Wireless Sensor Networks"; IEEE Transactions on Signal Processing, Vol. 51, N° 8, August 2003, pp.: 2137-2148.
- [3] Navarro-Serment, L.; Grabowski, R.; Paredis, C.; Kohsla, P.; "Milibots", IEEE Robotics & Automation Magazine, December 2002, Vol. 9, N° 4, pp.: 31-40.
- [4] Fukuju, Y.; Minami, M.; Morikawa, H.; Aoyama, T.; "Dolphin: an autonomous indoor positioning system in ubiquitous computing environment", IEEE Workshop on Software Technologies for Future Embedded Systems, May 2003, pp.:53-56.
- [5] Hazas, M.; Kray, C.; Gellersen, H.; Agbota, H.; Kortuem, G. And Krohn, A.; "A Relative Positioning System for Co-Located Mobile Devices", Proceedings of the 3rd international conference on Mobile systems, applications, and services (Mobisys'05), Seattle, Washington, June 2005, pp.:177-190.
- [6] Raykar, V.C.; Kozintsev, I.V.; Lienhart, R.; "Position calibration of microphones and loudspeakers in distributed computing platforms", IEEE Transactions on Speech and Audio Processing, Vol. 13, Issue 2, January 2005, pp.: 70-83.
- [7] De Marziani, C.; Ureña, J.; Mazo, M.; Hernández, A.; Alvarez, F.; Garcia, J.J.; Villadangos, J. M.; Jimenez, A.; "Simultaneous Measurement of Times-of-Flight and Communications in Acoustic Sensor Networks", Proceedings of IEEE International Symposium on Intelligent Signal Processing (WISP'05), edition on CD (ISBN:0-7803-9031-8), Faro, Portugal, September 2005.
- [8] De Marziani, C.; Ureña, J.; Mazo, M.; Hernández, A.; Garcia, J.J.; Jimenez, A.; Perez, M.C.; Ochoa, A.; Villadangos, J.M.; "Relative Positioning System Using Simultaneous Round Trip Time of Flight Measurements", *Proceedings of 11th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2006)*
- [9] De Marziani, C.; Ureña, J.; Hernández, A.; Mazo, M.; Alvarez, F.; Garcia, J.J.; Donato, P. "Modular Architecture for Efficient Generation and Correlation of Complementary Set of Sequences", IEEE Transactions on Signal Processing, Accepted for publication June 2006 (Paper Submitted on May 2005).
- [10] De Marziani, C.; Ureña, J.; Mazo, M.; Hernández, A.; Garcia, J.J.; Jimenez, A.; Villadangos, J.M.; Alvarez, F.; Perez, M.C.; "Inter-Symbol Interference Reduction on Macro-Sequences Generated from Complementary Set of Sequences, *Proceedings of The 32nd Annual Conference of the IEEE Industrial Electronics Society (IECON 2006)*,
- [11] Vossiek, M.; Wiebking, L.; Gulden, P.; Wieghardt, J.; Hoffmann, C.; Heide, P.; "Wireless Local Positioning", IEEE Microwave Magazine, Vol. 4, Issue 4, December 2003, pp. 77-86.
- [12] Ureña, J.; Hernandez, A.; Jimenez, A.; Villadangos, J.M.; Mazo, M.; Garcia, J.J.; Alvarez, F.; De Marziani, C.; Perez, M.C.; Jimenez J.A.; Jimenez, A.R.; Seco, F.; "Advanced Sensorial System for an Acoustic LPS", Accepted on Journal of Microprocessors and Microsystems, Special Issue on Sensor Systems.
- [13] Regal Electronic; "Regal Electronic Speakers", available online, URL: <http://www.regalusa.com/speakers.html> (07 February 2006).
- [14] Panasonic; "Panasonic Industrial Components | Audio Component | Electret Condenser Microphone", available on line, URL: http://www.panasonic.com/industrial/components/audio/aud_mic.htm (07 February 2006).
- [15] Perez, M.C.; Ureña, J.; Hernandez, A.; Marnmane, W.; De Marziani, C.; Ochoa, A.; "FPGA Implementation of an Efficient Correlator for Complementary Sets of Sequences", Proceedings of IEEE International Conference on Field-Programmable Logic and its Applications (FPL'06), Madrid, Spain, August 2006.
- [16] Xilinx, Inc.; "Spartan-III 1.8V FPGA family: complete data sheet", Product Specification, 2006.