Localization of networked mobile sensors and actuators in low-visibility conditions

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***Abstract*— Localization of networked mobile sensors and actuators is an active research field. One traditional approach in order to localize a mobile node has been the use of laser sensors. In some special circumstances, like a smoky environment, the use of this type of optical sensor is not a good solution. The use of radio and ultrasound signals can be used as a feasible alternative to node localization.**

Within the context of the EU GUARDIANS Project [1] (Group of Unmanned Assistant Robots Deployed In Aggregative Navigation supported by Scent detection) one essential aspect is having a simple localization method of a firefighter followed by a squad of robots, that allows tracking their instant position in the space related to the base station. The authors of this paper have been developing hardware devices capable of obtaining relative positions among them and the firefighter, and have studied several networking protocols that can be useful in those situations, using wireless links provided by Wi-Fi cards of the mobile nodes, as well as the sonar sensors and radio synchronization signals.

I. Introduction

THE mobility dynamics of swarm systems present additional challenges in network communications. Several network communication protocols have recently been developed for swarm-based sensor networks (directed diffusion, geographical routing protocol, flooding protocol, etc.) [2].

Many of those ad-hoc network protocols and applications assume the knowledge of geographic location of nodes. The absolute location of each networked node is an assumed fact by most sensor networks which can then present the sensed information on a geographical map [3].

Finding location without the aid of GPS in each node of an ad hoc network is important in cases where GPS is either not accessible, or not practical to use due to power, form factor or line of sight conditions [4,5]. Location information would also enable routing in sufficiently isotropic large networks, without the use of large routing tables.

Several methods have recently been proposed for determining the position of a mobile node by means of measuring radio signals —time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA), received signal strength (RSS) [6].

Mobile ad-hoc networks present a dynamic topology and routing overcomes another problem to take into account. The research community has produced several algorithmic methods for routing [7-10]. In the case of mobile nodes applied to rescue robotics, the speed of nodes and the urgency of the operations increase the need of designing routing protocols that work in a robust manner (real-time, high performance, etc.). As loosing of nodes may happen in those environments, fault-tolerance has to be taken into account in those special situations [11,12].

The design of special transport protocols has to be considered for these particular mobile sensor networks, trying to avoid congestion collapse and achieving a reasonable throughput level [13]. Those protocols need to be adapted to the field of telerobotics where the use of buffers is not feasible due to excessive time delays.

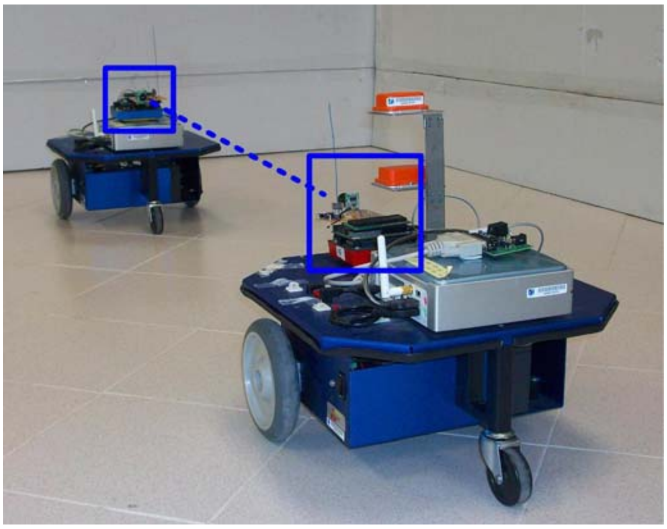

Fig. 1. Ultrasound-based distance estimation between two robots.

In this paper we focus on the localization of mobile nodes by means of ultrasound and radio signals, in order to combine this localization layer with higher level protocols. Previous successful experiments in the field of teleoperation control using wireless networks have already been done (i.e. BTP-Bilateral Transport Protocol) [14].

II. AVAILABLE HARDWARE

The system presented in this article uses ultrasound-based signals to make measurements between two points. It uses also radio signals for synchronization purposes. The setup for our experiments is based on the following hardware devices:

- Erratic-Videre mobile robot platform [15], equipped with an embedded PC computer. The PC computer runs an Ubuntu 6.10 distribution with 2.6.18 kernel version. The communication capabilities of the robot are provided by a PCI-integrated WLAN card with an external antenna attached to de robot's PC (Figure 2).

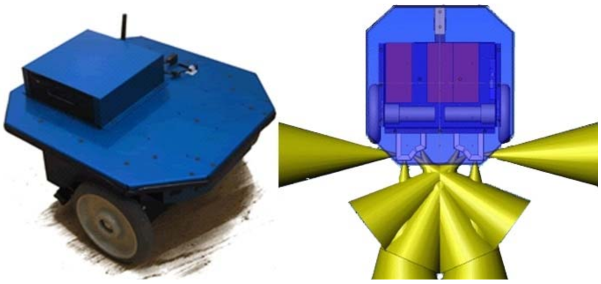

Fig. 2. Erratic-Videre mobile robot platform.

- Integrated WLAN cards to allow the communication between robots and the interchange of information.

- Hagisonic sonars (transmitters/receivers) [16]. Two different models of ultrasonic sonar (see Figure 3) have been studied and used for implementing Time Difference of Arrival (TDoA) in order to derive position information.

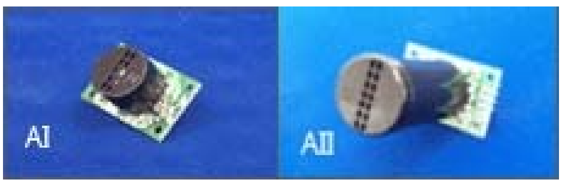

Fig. 3. Hagisonic ultrasound sensors.

- Radio modules: standard radio transmitter/receiver working at 433MHz [17] (see Figure 4). Those modules allow the modulation of digital signals up to 1KHz at maximum distances of about 20-30m. Those wireless modules are intended to provide a synchronization mechanism, by sending real-time signals between the different nodes of the scenario. As we will describe in detail below, some prototypes of measurement units have been integrated in the robot platforms, using these radio modules (see Fig. 7).

- Handy Board: general purpose board based on the 68HC11 microcontroller. It is widely used in the field of mobile robots for educational, hobbyist, and industrial purposes.

Fig. 4. Radio Tx/Rx modules. (a) Transmitter. (b) Receiver.

III. SYSTEM DESCRIPTION

The system presented implements TDoA for measurement of distances. For this purpose, we use ultrasound-based signals to measure the distance between two points, and radio signals for synchronization. For localization estimation, we use three measurement devices and the trilateration technique described below.

A. *TDoA with RF and ultrasound*

With this approximation, we try to determine the 2D position of a physical object (i.e. a robot or a firefighter) w.r.t. a mobile robot by using the time difference of arrival of two different signals each one with a known propagation speed (i.e. radio and ultrasound, see Fig. 5).

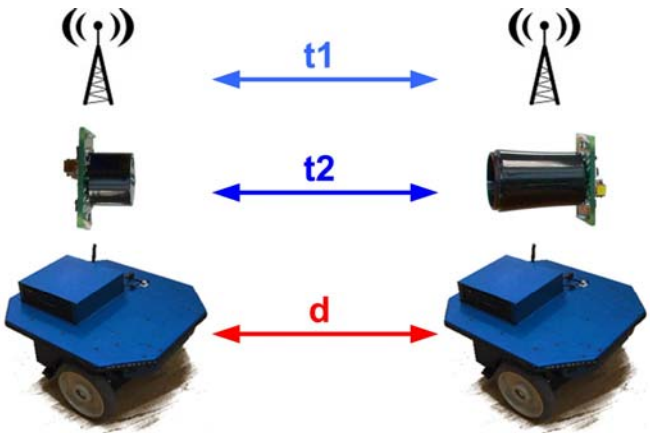

Fig. 5. TDoA principle for measuring distances between robots.

The first step was to determine the feasibility of the use of ultrasound signals to obtain distances. In order to do that, several laboratory experiments have been done to evaluate some available ultrasound transmitters/receivers using wires to connect both transmitter and receiver. Those sensors (HG-M40DAI and HG-M40DAII) are ultrasonic object detectors and range finders that offer very-short-to-medium-range detection. The AII model offers a special narrow directional response, 25-30 degrees in vertical direction to minimize the reflection of unwanted sound waves (see Fig. 3). We obtain larger transmission distances by removing the frontal cover of the sensors that acts as an anisotropic filter.

After performing those experimentations, we concluded that the measurement of the time of flight of ultrasound waves could be a feasible way of estimating distances. The estimation of distances by measuring the time of propagation of ultrasonic waves can be useful for several localization methods based on the knowledge of some distances. Further experimentation demonstrated that this technique offered a good performance of the sensors for distances up to 7-8 meters.

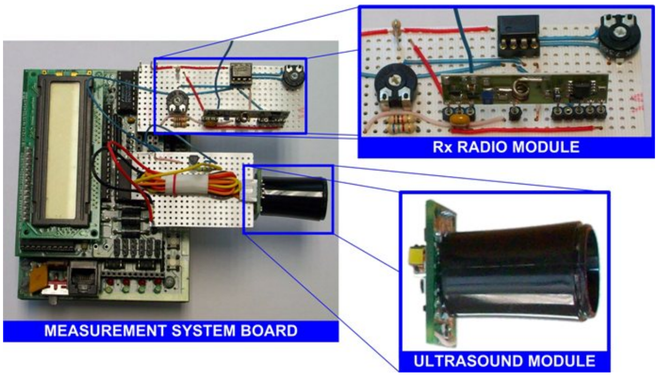

Fig. 6. Radio/Ultrasound measurement system module implemented with a HandyBoard.

The next step was to introduce synchronization radio signals in order to estimate distances between two independent nodes (i.e. a fire-fighter and a robot). To achieve this purpose, the theoretical idea of the time difference of arrival (TDoA) has been implemented (see Fig. 5).

The idea is to measure the time of flight of the ultrasound signals using the radio signal as synchronization method. The time of flight of the radio signal is considered constant for the range of distances that we are going to measure (from 0 to a maximum of 8 meters).

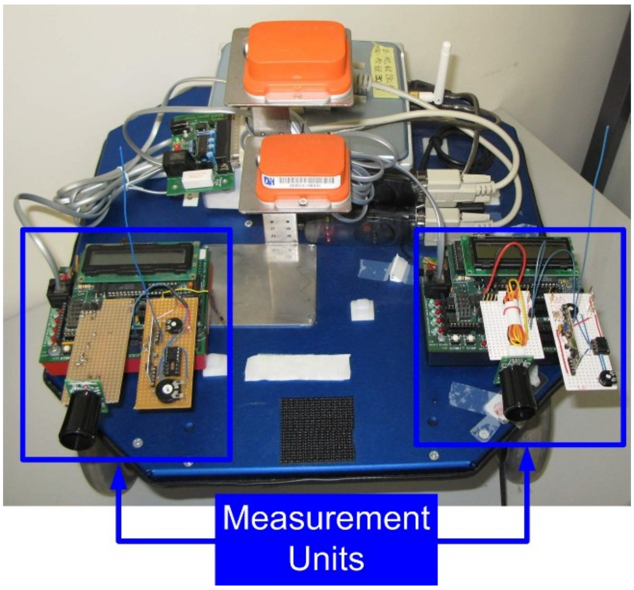

Fig. 7. Erratic robot prototype with a couple of Radio/Ultrasound measurement systems.

The most challenging task in order to implement the TDoA has been to find a hardware platform that could realize those measurements, being able to control both, radio and ultrasound sensors. After an exhaustive research about its capabilities, the Handy Board [18], widely used for teaching purposes in Jaume I university has been used. Some additional electronics were necessary for coupling those components to the board (see Fig. 6). The programming of the board has been done with a mixture of C programming language for the global routine and assembly language for the real time reading and writing of signals.

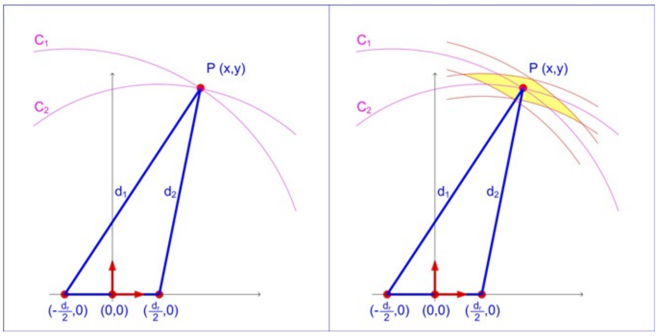

Fig. 8. Trilateration principle. (a) The *P* point in the intersection of C_1 and C_2. (b) Uncertainty area due to measurements errors of d_1 and d_2.

The measurement capabilities of the boards were tested, and it seems that the obtained measurements are quite accurate, being able to measure up to 8 meters with a maximum error about 3cm.

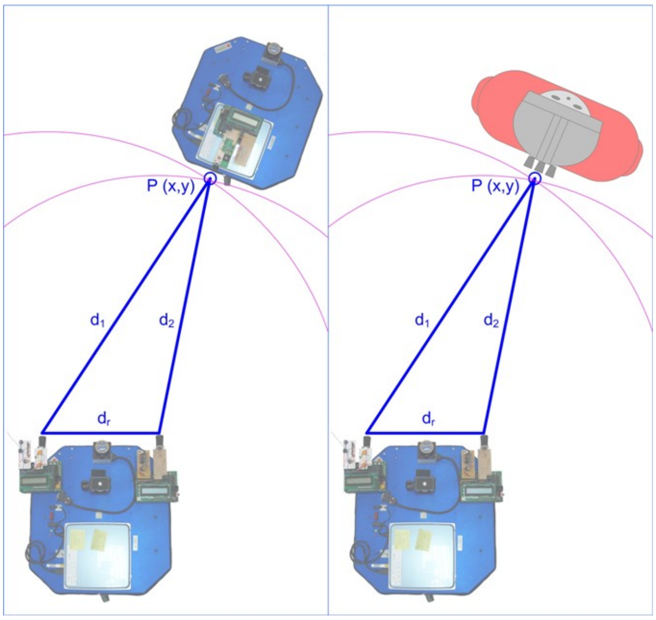

Fig. 9. Position determination by trilateration.

The first test configuration included an ultrasound/radio transmitter and a receiver, mounted each one on a different node (see Fig. 1). The first one is emitting pulses that the receiver will detect at different distances from the emitter. The time delay that appears between transmission and reception will be used to estimate the distance from the transmitter to the receiver. From this first evaluation, we concluded that the estimated distances closely approach the real measurements, so that we should continue developing this technique.

B. *Trilateration for position determination*

The second step of this development was using these boards to determine the 2D position of a physical object (robot, fire-fighter, etc). In this case, the robot platform has been equipped with two Radio/Ultrasound measurement systems (see Fig. 7), separated by a known distance d_r.

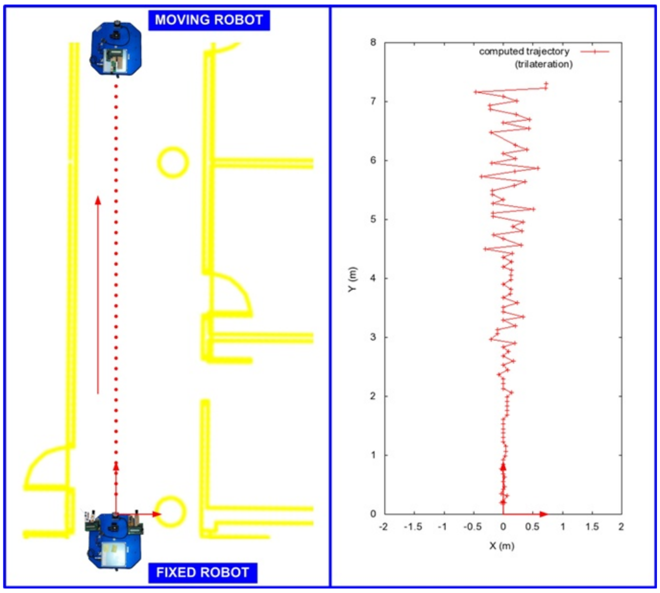

Fig. 10. First experiment of localization estimation. (a) Real trajectory of the robot along a corridor with constant velocity. (b) Estimated trajectory calculated by the first robot with the aid of his two measurement units and a trilateration operation.

With this configuration we can measure the distances from an emitter located at point *P* (see Fig. 8). The point *P* is the position of the object that we want to locate (i.e. a robot or a fire-fighter, see Fig. 9).

In order to obtain the *(x; y)* coordinates of the point *P*, we proceed as follows: the *P* point is in the intersection of the two circumferences *C1* and *C2*. Let be the equation of the circumference, $(x - a)^2 + (y - b)^2 = r^2$, where *(a, b)* is the center, *r* the radius and *(x, y)* are the coordinate center points of the circumference.

Knowing both center points $(-d_r=2.0)$ and $(d_r=2.0)$, and the distances d_1, d_2 from the object located at *P(x, y)*, we can write the following system of equations:

$$\begin{cases} \left(x+\frac{d_r}{2}\right)^2 + y^2 = d_1^2 \\ \left(x+\frac{d_r}{2}\right)^2 + y^2 = d_2^2 \end{cases}$$

Solving this system of equations, we obtain the point *P(x; y)* where the emitter is located:

$$x = \frac{d_1^2 - d_2^2}{2d_r}$$

$$y = \frac{\sqrt{-d_1^4 + 2d_1^2\left(d_2^2 - d_r^2\right) - d_2^4 + d_r^2\left(2d_2^2 - d_r^2\right)}}{2d_r}$$

In Fig. 8b we represent in yellow the uncertainty area due to measurement errors of d_1 and d_2.

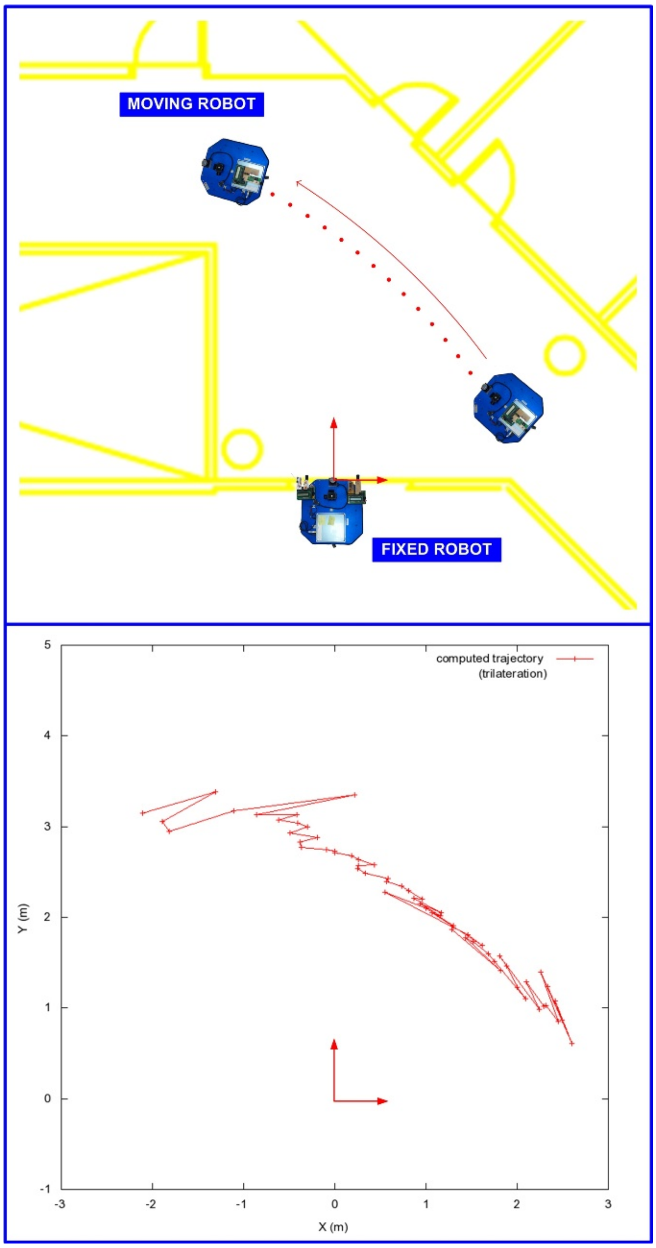

Fig. 11. Second experiment of localization estimation. (a) Real trajectory of the robot. (b) Estimated trajectory calculated by the first robot with the aid of his two measurement units and a trilateration operation.

IV. Experimental Setup and Results

A. *Position estimation using a two-receiver configuration*

To evaluate the feasibility and the accuracy of the developed system, a simple experiment has been carried out, consisting of a static robot equipped with two measurement boards and a second robot equipped with a third one. The second robot emits pulses toward the first one, and moves away with a constant velocity along a corridor (see Fig. 10a).

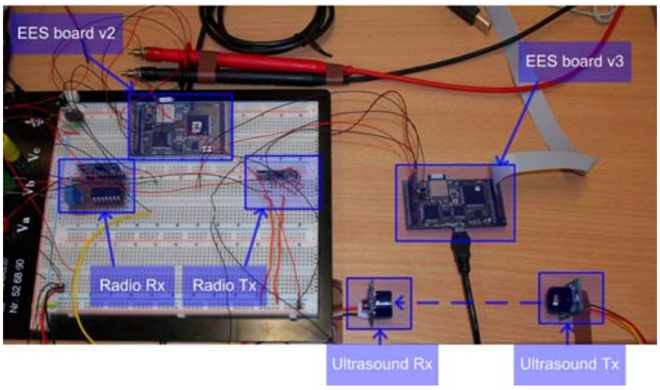

Fig. 12. Prototype device for measurement based on NXP LPC2136 microcontroller.

Fig. 10b represents the estimated trajectory calculated by the first robot with the aid of his two measurement units and a trilateration operation. As can be seen in Fig. 10b, the error in *x* coordinate increases with the distance. This is due to individual measurement errors from boards, and can be understood by seeing Fig. 8b, where the yellow area represents the uncertainty area due to measurement errors of *d1* and *d2*. The error region increases with the distance from one robot to the other, but it can be reduced by increasing the distance of the two reception sensors mounted in the first robot.

In the current setup, the two sensors have been mounted on the robot at a distance of 30cm. Increasing this distance would improve the results but it would also enlarge the perimeter of the robot. This distance, in fact, could be easily increased in bigger robots. Moreover, it would be possible to improve the system by including statistical filtering.

TABLE I
COMPARISON BETWEEN HANDY BOARD AND NXP MICROCONTROLLER BASED BOARD

real dist (cm)	Handy Board	NXP micro
0	0,00	0,00
20	20,25	19,50
50	49,75	49,50
100	100,00	101,00
150	149,75	149,50
200	200,00	199,25
250	250,00	250,00
300	300,25	300,75
350	350,00	350,25
400	399,75	400,25
450	450,00	450,25
500	500,25	500,50
550	550,00	549,75
600	599,75	600,00
650	650,25	650,25
700	700,00	700,75

The results of a second experiment can be seen in Fig. 11. In this case, the moving robot follows a diagonal trajectory w.r.t the fixed robot. The ultrasound transmitter has been oriented towards the fixed robot to ensure that the signal is properly received. As in the first experiment, it appears an error caused by individual measurement errors from boards.

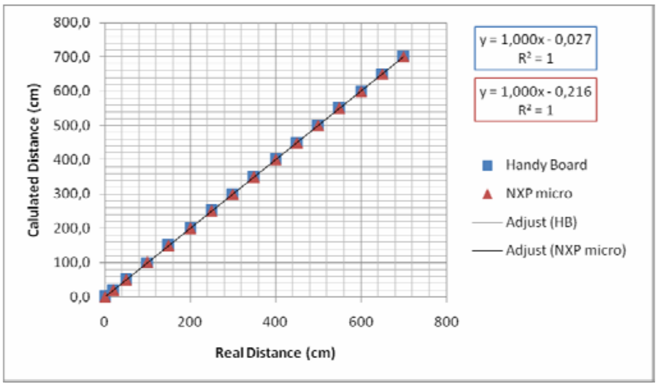

Fig. 13. Comparative results between Handy Board and NXP microprocessor-based board.

B. Hardware improvements using FPGA and Microcontroller-based board

It is desirable to reduce the size of the transmitting and receiving measurement boards while increasing the precision and versatility. To achieve these purposes, we have also been working in the development of an improved version of the system based on dual microcontroller-FPGA boards. The first proposed prototype (Figure 12) is based on a NXP LPC2136 microcontroller.

In order to test this new design, we have performed a comparison of distance measurements between this new NXP microcontroller-based prototype and the previous one based on the Handy Board. The obtained results are quite good in both cases and can be seen in Table I and Figure 13.

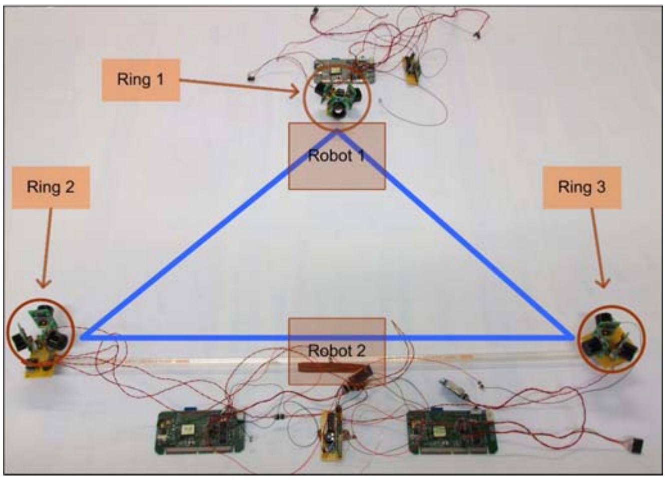

Fig. 14. Prototype of the proposed structure.

In this experiment we are showing a mean of four measures for each of the real distances. Measured distances range from 0 to 7 meters, the maximum distance for getting a good ultrasound signal reception. Results are very similar and accurate in both cases, as can be seen in the linear regression lines plotted in Figure 13.

The second proposed prototype is intended to increase the angular range of ultrasound signal detection. A prototype of the proposed system can be seen in Figure 14. Robot 1 is equipped with a transmitter ring. Robot 2 is equipped with two independent receiver rings separated with a known distance of about 50cm. With the aid of a FPGA-based board, we intend to get as much information as possible from sensors, like obtaining the angle of arrival of the signal. This configuration is intended to be used in robot following applications. In Figure 15, a prototype of the proposed receiver has been installed on an Erratic-Videre mobile robot platform. The two ultrasound rings have been installed in both front sides of the robot. The processed information is then sent to the on-board computer.

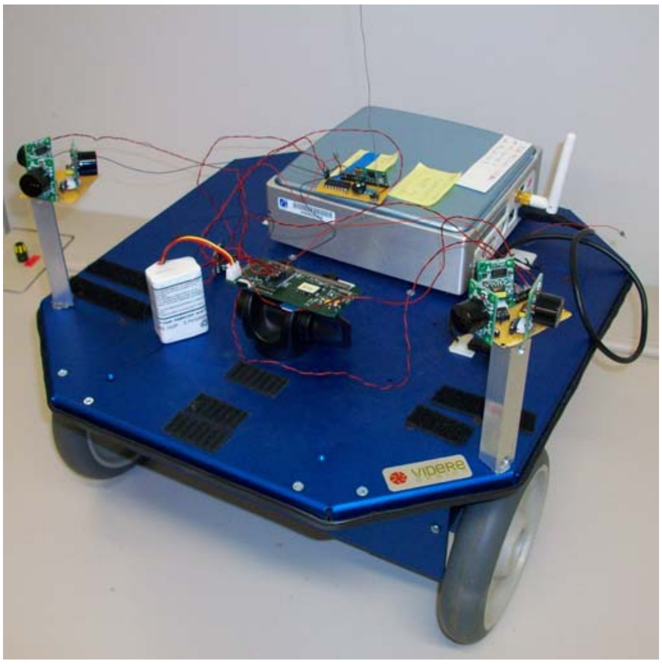

Fig. 15. Prototype of the proposed receiver installed on an Erratic-Videre mobile robot platform.

V. Conclusion

In this paper, a real localization technique for networked mobile sensors and actuators using ultrasound and radio signals has been presented. Localization of networked mobile sensors and actuators is an active research field, but most of the approaches for indoors are focused in laser rangefinder sensors. The use of ultrasound sensors is a good solution in some special circumstances, like smoky environments, being a feasible alternative to node localization. Authors of this paper aim to carry on in the improvement of the presented system and the development of a cross-layer architecture in order to increase the network efficiency in this particular scenario.

VI. Acknowledgements

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