Improvement of Ultrasonic Beacon-based Local Position System Using Multi-Access Techniques

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Abstract − **The present work shows a Local Positioning System (LPS) for Mobile Robots (MR) using simultaneous emissions in the ultrasonic beacons. In order to solve the problem of the simultaneous emission of the ultrasonic beacons, the well-known technique called Direct Sequence Code Division Multiple Access (DS-CDMA) is used. This technique modulates the ultrasonic signal (50 kHz) with a 127-bit Gold code for every beacon. In this way, it is possible to detect the arrival time of the code, by carrying out the simultaneous correlations with the assigned codes to each beacon. For determining the absolute position, the triangulation technique uses the Time Difference-of-Arrival (TDOA) obtained between a reference beacon and the others. Using this method, certain errors, derived from the delay in the firing of the beacons and the response times of the ultrasonic transducers, are avoided. The existence of a synchronism in the emission of the beacons, that guarantees a periodic and simultaneous emission in all of them, is required, not being necessary to know the emission instant in the mobile robot. This is particularly useful in environments where several robots can coexist.**

Keywords – **Local position system, ultrasonic beacon, Gold code, Direct Sequence CDMA.**

I. INTRODUCTION

The 3D local positioning system of mobile robots based on an ultrasonic beacon system is broadly well-known. It consists of using several beacons located at known positions in the environment, where the robot is moving, and of measuring the Time-of-Arrival (TOA) of the ultrasonic signal, starting from the emission instant. To synchronize the emission instant of every beacon, a radio-frequency or a coded infrared signal is often used, by selecting also which beacons are going to transmit [1]. This method implies that the robot should remain static until all the measurements have been captured. Also, it assumes that the maximum sampling frequency of the position is reduced in a factor similar to the number of used beacons.

If the beacons work as receivers and the MR as an ultrasonic emitter, it is only necessary to transmit an ultrasonic pulse to obtain the TOA for every beacon. This method requires a centralized communication and processing system, which, starting from the obtained TOAs, computes the robot's position and communicates it to the robot.

In the Bat system [2], users wear small badges which emit an ultrasonic pulse radio-triggered by a central system. The system determines the times-of-flight of the pulses from the badges to a network of receivers on the ceiling, and it calculates the 3D positions of the badges using a multilateration algorithm. The system, as reported in 1999, can locate badges to within 9 cm of their true position for 95% of the measurements.

The Cricket location system [3] consists of independent, unconnected beacons distributed throughout a building. The beacons send an RF signal while simultaneously sending an ultrasonic pulse. Small devices called listeners, carried by users, infer their locations using time-of-flight methods, with accuracies in the order of 6 cm in the best cases. The beacons broadcast at random times in order to minimize signal collisions. The listeners can independently locate themselves, avoiding the commitment of the user privacy involved with centralized systems.

A similar approach [4] uses four ultrasonic transducers placed at the corners of a square on the ceiling, and wired to a controller. The controller sends a RF trigger, and then issues a pulse from each one of the four transmitters in succession. A mobile receiver unit connected to a handheld computer receives the pulses, and estimates its location with accuracies between 10 and 25 cm.

There exist several previous works that have used the encoding of the ultrasonic signal to implement advanced sensors for the detection of obstacles in robotics, using pseudo-random sequences [5, 6], Barker codes [7], or Golay codes [8].

In absolute positioning with ultrasounds, Hazas [9] has been the first one in using Gold sequences. A novel polled location system employs transmitters and receivers and spread spectrum

signaling to allow simultaneous multiple accesses and to provide excellent performance in the presence of noise. The location of the mobile was estimated using times-of-flight for the T_{mobile}, ranging messages by correlating the receiver's signals with the expected signal (a 50 kHz carrier modulated by $T_{mobile's}$ Gold code). The time-of-flight was defined between the triggering of T_{mobile} and the arrival of a large peak in the correlated data. 95% of the returned location estimations have accuracy just over two centimeters.

The proposal of this work is the determination of the absolute position of a mobile robot by using the measurement of the TDOA between a reference beacon and the others, considering that all of them emit simultaneously and in a continuous way. The main improvement of this work involves not knowing the emission instant at the mobile robot. That is to say, it is not necessary a synchronism trigger signal (RF, IR, etc) between MR and beacons. To solve the problem of the simultaneous emissions of the beacons, the DS-CDMA technique is used, by modulating the ultrasonic signal (50 kHz) with a 127-bit Gold code, different for every beacon, and by transmitting it in a periodic way. A receiver on-board the robot carries out the simultaneous correlations with the codes assigned to each beacon, in order to detect the TDOAs among a reference beacon (the nearest) and the others. This method also avoids the robot to know the emission instant, because it is only necessary a common synchronism among all the beacons.

II. SYSTEM DESCRIPTION

Gold codes are a particular set of pseudo-random sequences (PN), which have high auto-correlation and low cross-correlation values[10]. If different Gold codes are assigned to emitters in a Direct-Sequence Spread Spectrum (DSSS) system, their signals can be sent simultaneously and can be still separated at the receiver. The wide bandwidth provided by the PN code allows the signal power to drop below the noise threshold without loss of information.

A. Beacons system

In the proposed system, every beacon has assigned a 127-bit Gold sequence that identifies it. The symbol, formed in this case by a 50kHz carrier cycle (Tc=20us), is BPSK modulated by the Gold sequence, providing a signal whose duration is 127•20us=2.54ms. Every beacon emits this signal in a periodic and continuous way (Fig. 1).

All the beacons are synchronized by a common clock (fclk=500kHz) and they emit periodically every 40ms (see figure 1), avoiding in this way the necessity of carrying out a synchronism from the mobile robot by means of some wireless system (RF, infrareds, etc.).

Let us consider a beacon system formed by 5 beacons placed over the floor, with an approximated height of 3m, and into a 6x6m surface (Fig. 2). The nearest beacon to the robot is considered as the reference beacon (beacon 3). The robot was located at the coordinates (x=3m, y=3.1m, z=1m). Let us consider acquisition signal corresponding to the simultaneous emission of the 5 beacons, having a signal-to-noise ratio of 0dB.
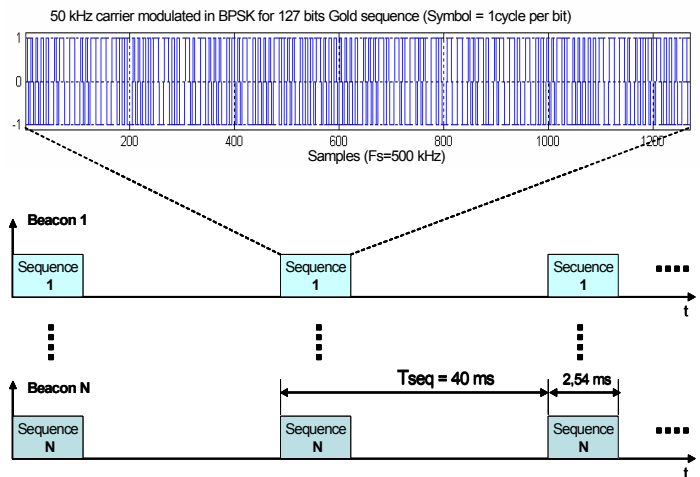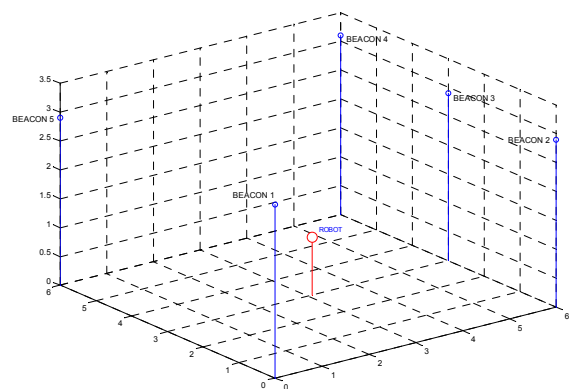

Fig.1. Periodical signal emitted for every beacon.

Fig.2. Example of a beacon system.

B. Received signal

Once the signal is captured, the correlations between the received signal and the Gold sequences from every beacon are carried out. The maximum values in the correlation function determine the arrival instant of the corresponding sequences (Fig. 3).

The maximum value nearest to time origin determines which the reference beacon is. It will be enough to compute the difference in samples among the other maximum values in the different correlation functions, and to multiply them by the sampling frequency, in order to obtain the differences in times-of-arrival between the reference beacon and the others. These values will be used in the positioning algorithm to determine the robot's absolute position.
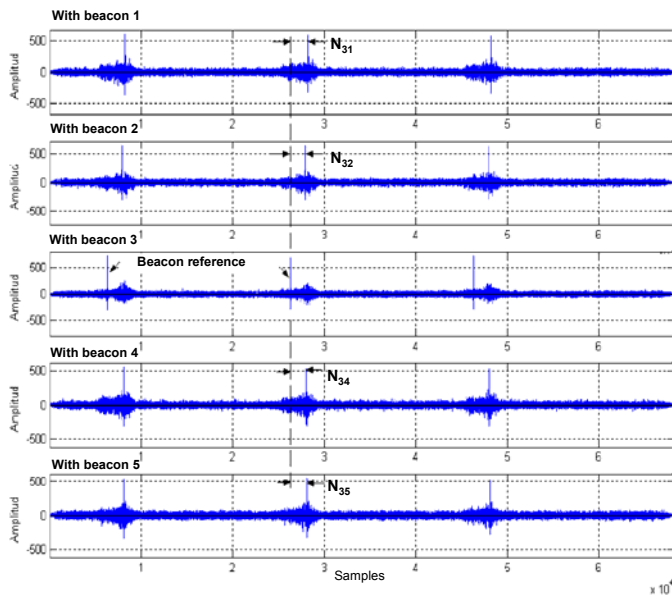
353

Fig.3. Cross-correlations between the received signal and 127-bit Gold sequences for every beacon.

C. Determination of the absolute position

The triangulation technique is used in order to obtain the absolute position of the MR, using the time differences of arrival [11]. Considering a group of N beacons (N=5, minimum for 3D positioning), a equation system (1) can be proposed to obtain the absolute position of the MR in 3D (x, y, z), by using the positions where the beacons are located (x_i, y_i, z_i) and the differences in times-of-arrival between a reference beacon (for example, beacon 1) and the others.

$$
\begin{aligned}
(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 &= d_1^2 \\
(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 &= (d_1 + c \cdot \Delta T_{12})^2 \\
(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 &= (d_1 + c \cdot \Delta T_{13})^2 \\
\cdots \quad \cdots \quad \cdots \quad &= \quad \cdots \\
(x - x_N)^2 + (y - y_N)^2 + (z - z_N)^2 &= (d_1 + c \cdot \Delta T_{1N})^2
\end{aligned}
\tag{1}
$$

Where d_1 is the distance to beacon 1 (reference one), considered as a variable; and ΔT_{12}, ΔT_{13}... ΔT_{1N} are the differences in times-of-arrival measurements, between the reference beacon and the others. We assume the propagation speed of ultrasounds c=342m/s. Developing the squared values, subtracting the first equation to the others, and regrouping terms, a lineal equation system is achieved, which can be solved in a simple way, by the lineal minimum square method, as shown in (2):

$$
\mathbf{A}\vec{\mathbf{x}} = \vec{\mathbf{b}}
\tag{2}
$$

Where,

$$
\mathbf{A} =
\begin{bmatrix}
2x_1 - 2x_2 & 2y_1 - 2y_2 & 2z_1 - 2z_2 & -2c\Delta T_{12} \\
2x_1 - 2x_3 & 2y_1 - 2y_3 & 2z_1 - 2z_3 & -2c\Delta T_{13} \\
\cdots & \cdots & \cdots & \cdots \\
2x_1 - 2x_N & 2y_1 - 2y_N & 2z_1 - 2z_N & -2c\Delta T_{1N}
\end{bmatrix}
\tag{3}
$$

$$
\vec{\mathbf{x}} =
\begin{bmatrix}
x \\
y \\
z \\
d_1
\end{bmatrix}
\tag{4}
$$

$$
\vec{\mathbf{b}} =
\begin{bmatrix}
c^2 \Delta T_{12} + x_1^2 + y_1^2 + z_1^2 - x_2^2 - y_2^2 - z_2^2 \\
c^2 \Delta T_{13} + x_1^2 + y_1^2 + z_1^2 - x_3^2 - y_3^2 - z_3^2 \\
\cdots \\
c^2 \Delta T_{1N} + x_1^2 + y_1^2 + z_1^2 - x_N^2 - y_N^2 - z_N^2
\end{bmatrix}
\tag{5}
$$

The solution is equal to (6):

$$
\vec{\mathbf{x}} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \vec{\mathbf{b}}
\tag{6}
$$

III. SIGNAL ANALYSIS

Every beacon j has assigned an identifying N-bits Gold sequence. The symbol, formed in this case by a 50 kHz carrier cycle (Tc=20us), is BPSK modulated by the Gold sequence. Every beacon emits this signal in a periodic and continuous way (Tsq). The modulation process is described in (7), in order to obtain the signal $e_j[n]$ to be emitted by the beacon j:

$$
e_j[n] = A_j[n] * S[n] = \sum_{k=0}^{N \cdot M \cdot m - 1} A_j\left[\frac{k}{M \cdot m}\right] \cdot S[n - k]
\tag{7}
$$

where M is the number of samples per period of the symbol $S[n]$ (related to the sampling frequency f_S of the received signal); m is the number of periods per symbol; and N is the bits number or length of the sequence. The signal $A_j[n]$ constitutes the sequence Gold assigned to each beacon j. On the other hand, the signal $S[n]$ is the symbol formed by $m \cdot M$ samples of a 50 kHz carrier period.
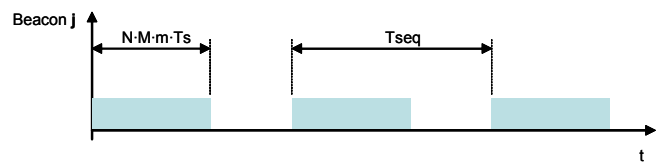

Fig.4. Periodical signal emitted for each beacon

The carrier $p[n]$ is a digital signal with a frequency of 50kHz, as is shown in Fig 5. Taking into account that the sign received $r_i(t)$ will be digitised at a frequency Fs=500kHz, the parameter M becomes equal to 10. In order to increase the emitted power, and to make possible to reach longer distances, the symbol $S[n]$

354

can be formed by several carrier periods p[n], according to the parameter m. This symbol S[n] can be represented as a sequence (for m=1), according to (8).
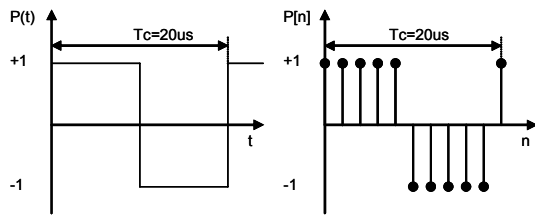
$$S[n] = [1\,1\,1\,1\,-1\,-1\,-1\,-1\,-1] \qquad (8)$$

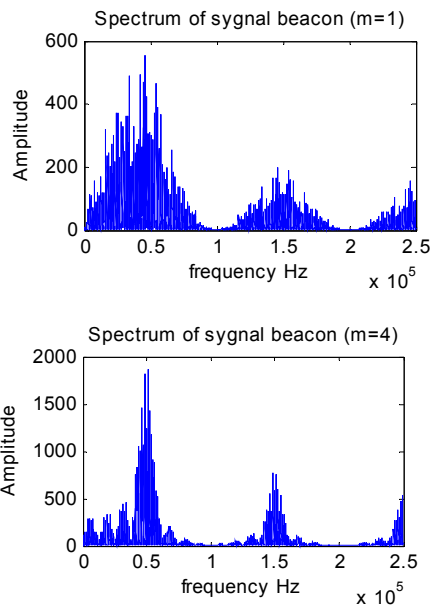Fig.5. Symbol for BPSK modulation (M=10, m=1, Fs=500kHz)

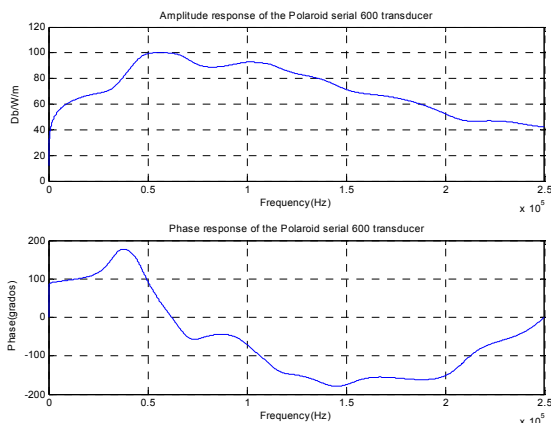Fig.6. Spectrum of BPSK modulation of signal beacons for a different *m* parameter (m=1 and m=4)

Fig.7. Frequency and phase response of Polaroid transducer (serial 600).

The increase of *m* has two important effects on the resulting signal. An increase of the transmitted energy, and therefore a larger covering or reaching for the beacons, since the length of

the resulting sequence increases proportionally to this parameter. On the other hand, in the spectrum of the signal, *m-1* side-lobes appear, concentrating the spectrum around the carrier and decreasing the energy in the audio band. This implies an advantage from the point of view of the reduced bandwidth of the ultrasonic transducers existing in the market.

Figure 6 shows this effect for *m=1* and *m=4*, considering a 127-bit Gold sequence modulated with 50kHz carried, and sampled at Fs=500kHz (*M=10*), with repetition period Tseq=20ms. The duration of the sequence for *m=1* is 127·10·20us=2,54ms and 10,16ms for *m=4*.

Figure 7 shows the frequency and phase response of a commercial transducer (Polaroid series 600). The signal provided by the transducer is distorted due to its reduced bandwidth, what implies more difficulty in its detection (Fig. 8).
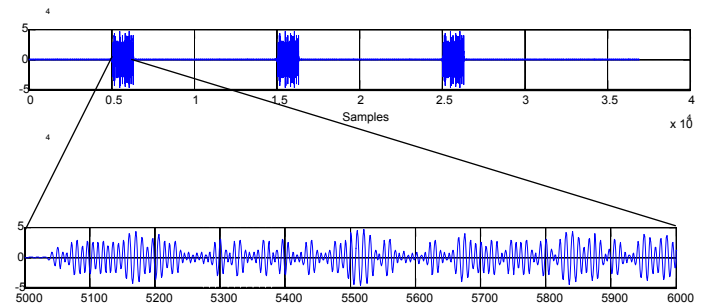

Fig.8. Signal output of Polaroid transducer in the time domain

The detection process is based on applying to the received signal the mathed-filter or correlation function with each one of the sequences assigned to beacons (Fig. 9). This allows to obtain the maximum values corresponding with arrival of the sequence emitted by the beacon. A peak is considered as valid peak if its value is greater than a determined threshold, and if it is the maximum value in an analysis window of *m·M*=10 samples. This analysis window eliminates the modulation sidelobes. The threshold can be configured to adapt the system to certain environmental conditions, and to guarantee a correct detection of peaks. The size of memory buffer should be equal o higher than the sequence period in order to guarantee a maximum in the correlation function. As long as the reception is asynchronous, every acquisition will provide peak of correlation at different times. The first peak is associated to the nearest beacon. The time of this peak is the reference to compute TDOAs with respect to the other beacons.
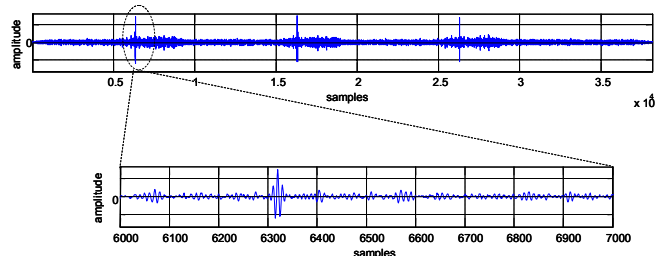

Fig.9. Cross-correlation between signal received and 127 bit Gold code assigned to beacon j

355

IV.   SYSTEM HARDWARE

A. Beacon system

Every beacon generates a Gold code using an EEPROM serial memory, at which the samples of the ultrasonic signal modulated in BPSK are directly stored and transmitted periodically every *Tseq* (Fig. 10). The output of the memory is connected to the power driver amplifier that excites the ultrasonic transducer. A high pass filter remove the audio components for have no audible system. The used transducer is *Murata* Super Tweeter Driver (ESTD01), which has a wide bandwidth (100kHz) and a long emission pattern (Fig. 11).
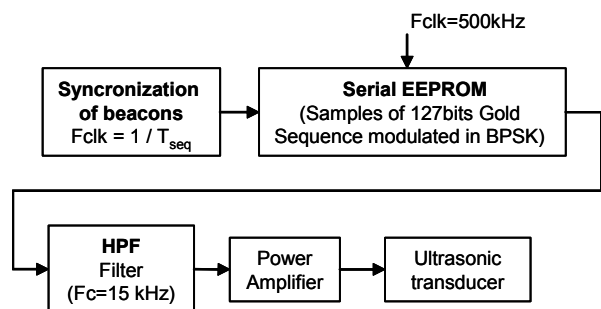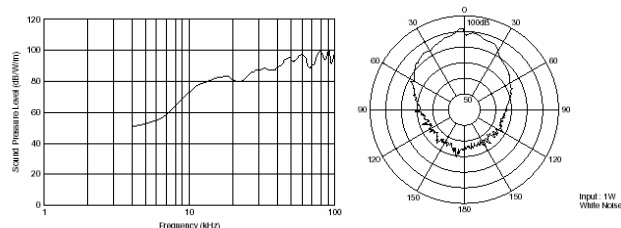
Fig.10. Diagram of the beacon

Fig.11. Frequency characteristics and directivity of Super Tweeter Driver (Murata ESTD01)

B. Receiver system

The receiver is based on an acquisition system formed by an 8-bit ADC (f_s=500kHz) connected to a 32 Kbytes FIFO memory, enough to achieve the repetition period of the ultrasonic signal in the beacons. The FIFO memory is read by a FPGA device, that carries out the correlation between the acquired signal and the corresponding Gold code. The maximum value of the correlation is stored and, afterwards, and the positioning algorithm is performed (Fig. 12).

V. RESULTS

In order to show the feasibility of the system, some simulation tests have been carried out. Assuming a beacons distribution as the one shown in Fig. 2, the mobile robot was placed in the coordinate (x=4m, y=5m and z=0m). In this

situation, 50 measurements were done, a Gaussian noise, with a null averaged value and a typical deviation of 30μs, was added to TOA's. The estimation of the position is shown in Fig. 13, where it is possible to achieve maximum position errors of 2cm, by applying the LMSE method explained in a previous section, whereas the averaged value is smaller than 1cm. Currently, the real physical system is being validated, trying to obtain similar results to those achieved in simulations.
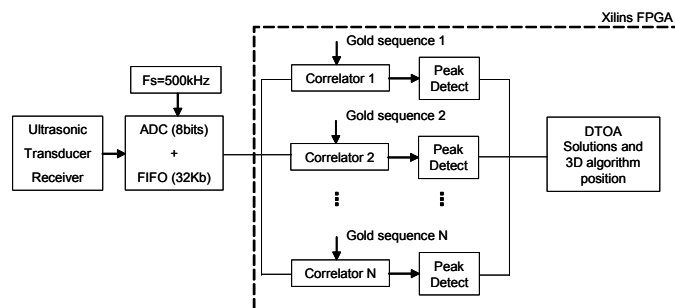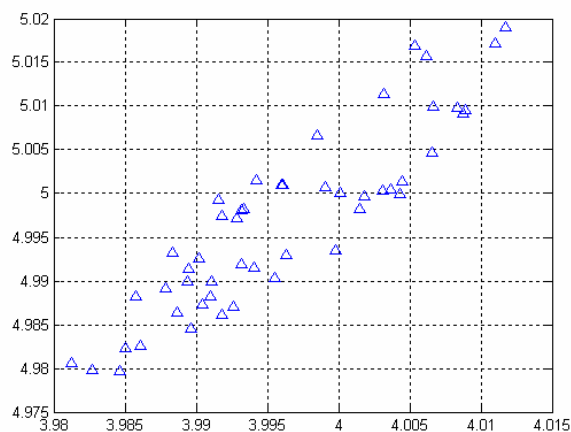
Fig.12. Diagram of receiver

Fig. 13.   Example of a 2D position error estimation with the robots placed at coordinate (x=4m, y=5m).

Figure 14 shows the appearance of the developed beacon system. The emitters are mounted in 2x2 meters metallic structure.

VI.   CONCLUSIONS

A Local Positioning System (LPS) for mobile robots using simultaneous emissions from multiple ultrasonic beacons has been presented. To solve the problem of the simultaneous emission of the ultrasonic beacons, the DS-CDMA technique has been used, by modulating the ultrasonic signal (50kHz) with a 127-bit Gold code in every beacon. The resulting signal is transmitted periodically and continuously, not knowing the emission instant at the mobile robot, and therefore, it is not necessary a synchronism trigger signal (RF, IR, etc) between MR and beacons.

To detect the arrival time of codes, carrying out the simultaneous correlations with the assigned codes to each beacon. The determination of the absolute position is performed using the triangulation technique with the TDOAs obtained between one reference beacon and the others.

Fig.14. Aspect of the beacon system

ACKNOWLEDGMENTS

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