Improvement of Cover Area in Ultrasonic Local Positioning System Using Cylindrical PVDF Transducer

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***Abstract*—This work describes the design of a reflector for a PVDF-based ultrasonic transducer (Piezofilm transducer) to carry out a ultrasonic beacon system, where the covered area be improved and a 3D indoor positioning be guaranteed. The proposed Local Positioning System (LPS) for Mobile Robots (MR) uses simultaneous emissions from ultrasonic beacons. In order to solve the problem of simultaneous emissions from ultrasonic beacons, the well-known technique Direct Sequence Code Multiple Division Access (DS-CDMA) is used. This technique encodes the ultrasonic signal with a 127-bit Gold code for every beacon. It implies the emitted signal by every beacon to have a wide bandwidth. PVDF-based transducers suitably guarantee this requirement. Their cylindrical or semi-cylindrical shape makes the emission pattern not suitable when using them as ultrasonic beacons, often located in the ceiling of an indoor room. To adapt the emission pattern and to increase the covered area in the ground, the design process of a conical reflector is described.**

I. Introduction

3D local positioning systems of mobile robots based on ultrasonic beacon systems are broadly well-known. They consist 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 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].

The narrowband transducers used in most existing ultrasonic location systems consider piezoelectric ceramics as active elements. These kinds of transducers are inexpensive, small, and they have a high sensitivity. However, they are highly resonant, and in most cases they provide a usable bandwidth below 5kHz. The way they are built allows their easy use, but it implies quite directive. Then it is necessary to place a significant number of them to have a wide covered area.

Many previous works have used this type of transducers when beacons emit ultrasonic pulses without encoding, not being necessary a large bandwidth in transducers. In the Bat system [2], users wear small badges which emit an ultrasonic pulse, radio-triggered by a central system. The system determines times-of-flight for pulses from badges to a network of receivers in the ceiling, and it computes the 3D positions of badges, by using a multilateration algorithm.

The Cricket location system [3] consists of independent and non-connected beacons distributed throughout a building. Beacons send an RF signal while simultaneously sending an ultrasonic pulse.

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, by using pseudo-random sequences [5] [6], Barker codes [7], or Golay codes [8].

Hazas [9] has been the first one using Gold sequences [10]. A novel polled location system employs transmitters, receivers and spread spectrum signalling to allow simultaneous multiple accesses and to provide excellent performance in the presence of noise. The location of mobile was estimated by measuring times-of-flight, correlating the received signals with the expected one (a 50kHz carrier modulated by Gold codes).

Emitting beacons can be based on Piezofilm transducers. These are small, inexpensive, more rugged than electrostatic transducers, and they have a wide frequency bandwidth. Nevertheless, they present low sensitivity. This means that they must be driven with high voltages as transmitters; and they are particularly sensitive to noise as receivers. A piezofilm ultrasonic transducer for air ranging has been designed by Fiorillo [11] [12], and further characterized by Wang and Toda [13]. It consists of a small, rectangular piece of piezofilm mounted along two edges to form a half-cylinder. The emission pattern is not omnidirectional enough when the beacon is placed in the ceiling.

The main goal of this work is to increase the area covered by a positioning system [14]. The main improvement of the described system involves not knowing the emission instant at the mobile robot. So, it is not necessary a synchronism trigger signal (RF, IR, etc.) between mobile robot and beacons. To solve the problem of simultaneous emissions from beacons, the DS-CDMA technique is used, by modulating a carrier (50kHz) 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 simultaneous correlations with codes assigned to each beacon, in order to detect the Time-Differences-of-Arrival (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. The used transducer is Murata Super Tweeter Driver (ESTD01), which has a wide bandwidth (100kHz). Although it presents an open emission pattern, it is not enough to have available a large covered area (see Fig. 1).

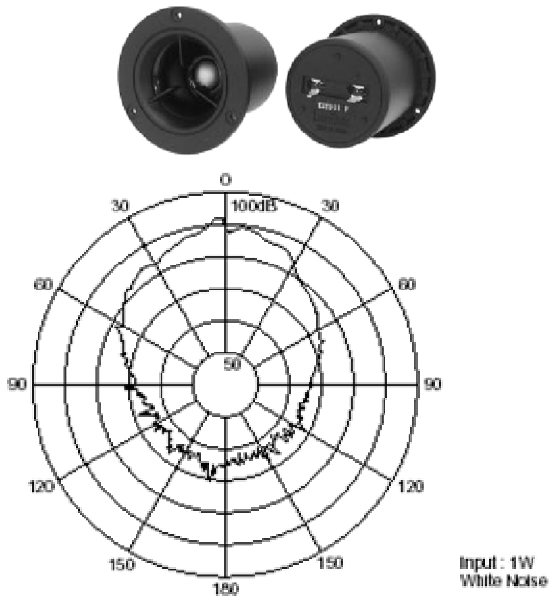

Fig.1. Directivity of Super Tweeter Driver (Murata ESTD01) [15].

The new transducer is manufactured by MSI and it is PVDF type. It has been already used in [15], where a new ultrasonic sensor for 3D coordinate estimation has been especially designed to localize and sketch findings after they are extracted by archaeologists. The system contains two ultrasonic emitters and measures times-of-flight (TOF): the ultrasonic signal reaches several fixed receivers, and a robust trilateration algorithm to determine the position of a rod tip with 10mm accuracy. The MSI transducer (see Fig. 2) presents an emission pattern completely omnidirectional in the horizontal plane. This feature makes the transducer optimal for this application, since all the beacons are placed at the same height.

In order to use the transducer as an ultrasonic beacon in a LPS, it is possible to couple a conical reflector to obtain a maximum radiation reflected over the floor. The work describes the design process of the reflector, characterizing it at physical level, and analysing the most remarkable features contributions to the loss of signal intensity with the distance (assuming movements on the surface of the floor). It is organised as follows: Section II proposes the design of a conic reflector, whereas Section III analyses effects and losses in the proposed setup; Section IV show the experimental results, and finally, conclusions are discussed in Section V.

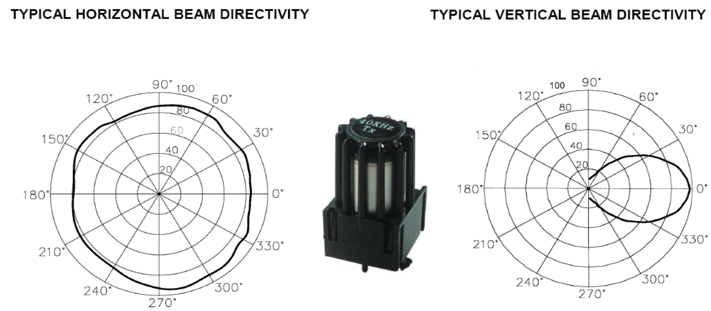

Fig.2. Horizontal and vertical beam pattern of PVDF transducer (MSI corporation).

II. Design of a Conic Reflector

A disposition of the transducer as shown in Fig. 3 has been considered for the design of the conic reflector. Furthermore, the vertical emission pattern given by the manufacturer has been taken into account.

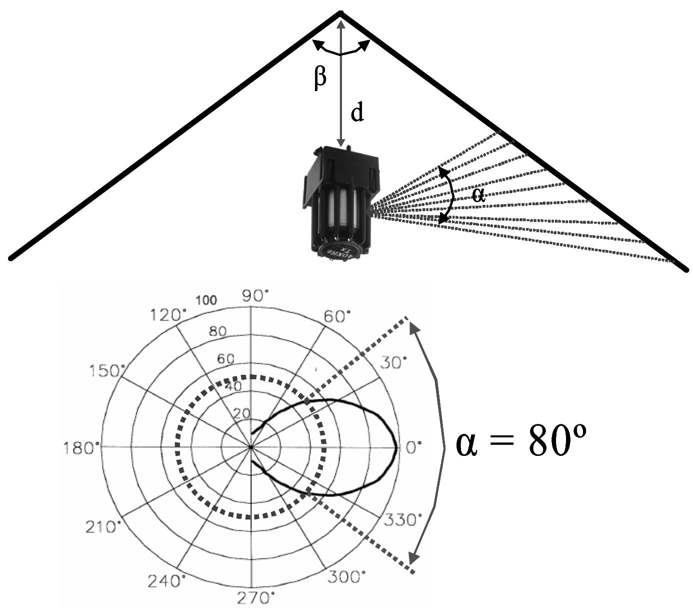

Fig. 3. Position of the transducer inside the conic reflector and vertical beam directivity of the transducer.

Regarding the parameters remarked in Fig. 3, α is the vertical beam angle of the transducer and β is the aperture angle of the conic reflector, where $\beta \geq \alpha$ to avoid reflections. If the distance d to the vertex of the cone should be reduced to consider punctual the transducer with the reflector, the structure can be transformed as shown in Fig. 4. Here, the conical surface behaves as a specular surface for the transducer located inside.

Taking into account that the new transducer model is placed at a determined height from the floor, the overlapping area appearing in the floor should be avoided. For that, it is necessary to rotate the vertical emission pattern by an aperture angle α, so the extreme axes become parallel.

The new transformation of the structure is shown in Fig. 5, where it can be obtained (1) and (2):

$$\frac{\beta}{2}+\beta+\frac{\beta}{2}=180+\frac{\alpha}{2}+\frac{\alpha}{2} \qquad (1)$$

$$\beta=\frac{180+\alpha}{2}=130^{\circ} \qquad (2)$$

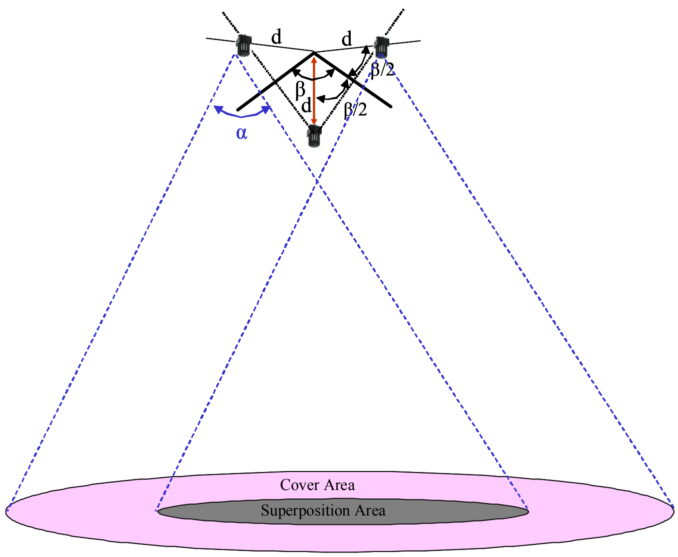

Fig. 4. Transformation of the transducer considering the conic reflector as a specular surface.

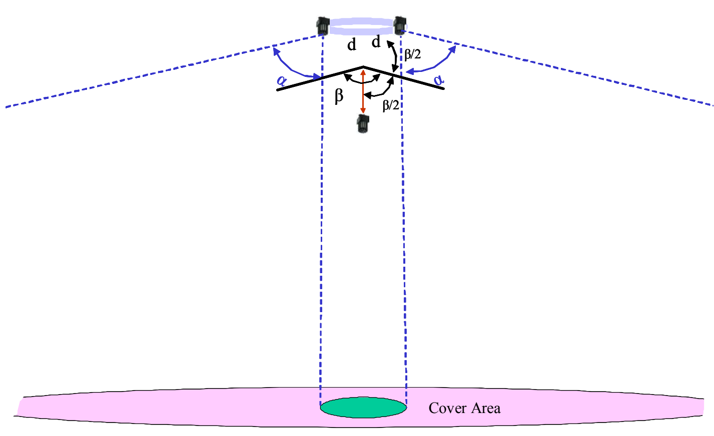

Fig. 5. Final result after eliminating the overlapping area.

Assuming d=2cm and a height from the floor h=3m, an optimal cover is practically assured up to the central axis from the vertical emission pattern central axis. This cover area, considered on the surface of the floor, corresponds to a circle with a radius of 2.5m whose centre is at the vertical of the sensor. Notice that the radiation on the floor has become a beam coming from a circular ring cut by the angle α from the vertical emission pattern. The aspect of a first prototype is depicted in Fig. 6.

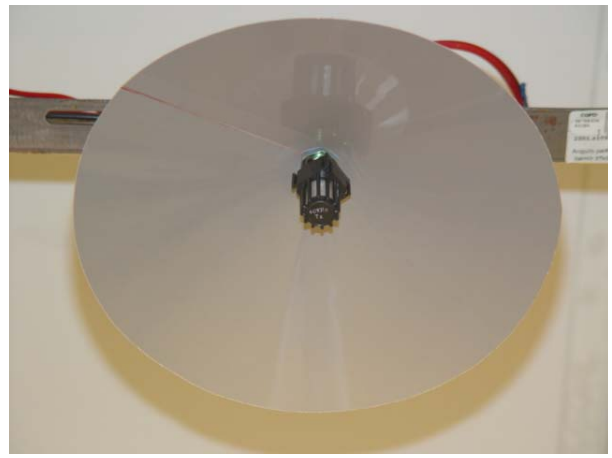

Fig. 6. Aspect of the prototype: cylindrical PVDF transducer with conic reflector.

III. Loss in the Transducer with Conic Reflector

Different loss effects have been analyzed when moving away from the vertical of the sensor on the floor, in order to evaluate global loss and to determine how the received energy decreases moving away from the sensor.

The first effect to be considered is the absorption loss related to the distance D from the beacon, as shown in Fig. 7. Considering a typical value of 2dB/m at ambient temperature, the distance attenuation because of absorption is given by (3):

$$A=2h\sqrt{1+tg^2\delta}\quad [dB] \qquad 0\le\delta\le 80^{\circ} \qquad (3)$$

Another effect is divergence, whose loss is produced by two effects: attenuation from the emission pattern $H(\delta)$, and the effect of spherical divergence $A(r)$ due to the distance D from the surface points of the floor to the sensor transducer:

$$H(\delta)=\frac{6}{1600}\delta(80-\delta)-6\quad [dB] \qquad (4)$$

$$\frac{dr}{d\delta}=\frac{h}{\cos^2\delta} \qquad A(r)=10\log\left(\cos^2\delta\right)\quad [dB] \qquad (5)$$

Where δ=40º is the axial axis; and $H(\delta)$ is parabolically approximated and referred to this axis. The losses $A(r)$ considers the incidence angle of the beam with the floor (see Fig. 8).

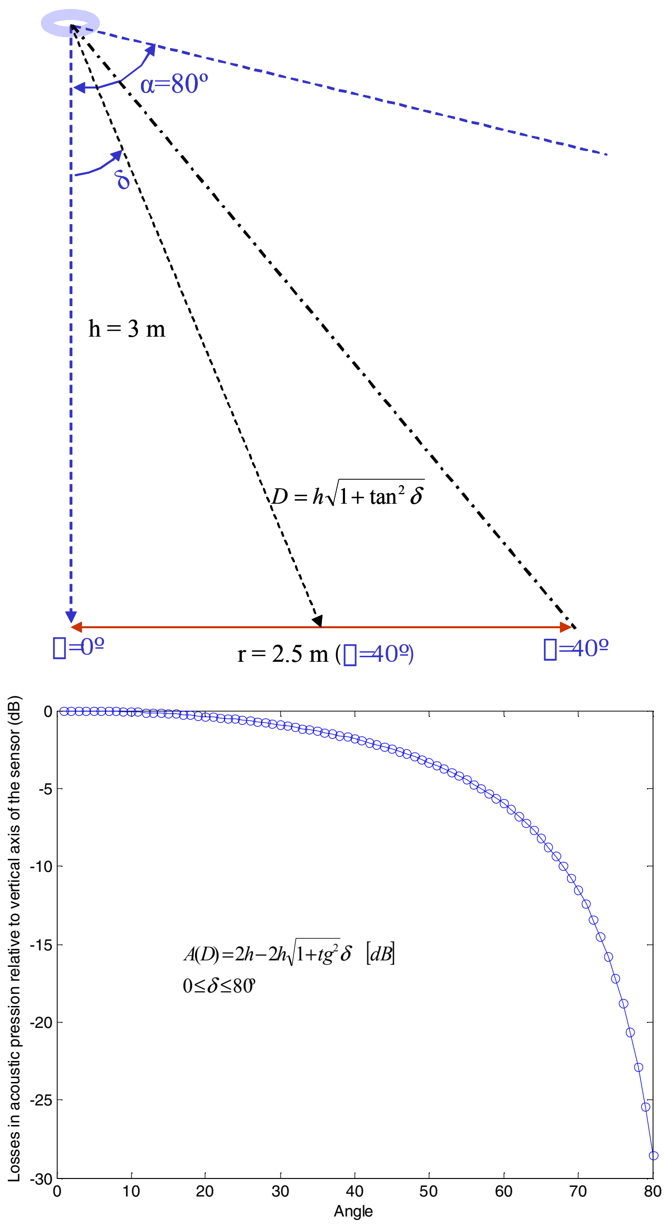

Fig. 7. Loss effect by absorption.

The addition of both effects (Fig. 9) provides that, up to δ=60º, a covered area around a circle of 5m radius can be guaranteed on the surface of the floor with attenuation levels below 8dB, for a height of the transducer of h=3m from the floor. Taking into account the correlation techniques and the encoding of the beacon signal, an acceptable dynamic range is available in the receiver to assure a wide covered area with the designed reflector.

IV. Results

The prototype of the reflector transducer has been placed at the ceiling of wide enough room (with a height of 3m), where some experimental tests have been carried out to measure the real covered area by the assembly. The PVDF transducer has been excited with a voltage of $24V_{pp}$. The used receiver is a condenser microphone capsule CM16 by Avisoft Bioacoustics. Fig. 10 shows the losses obtained, referred to vertical axis of the sensor. The shape of this experimental attenuation is similar to the theoretical one, existing some differences in magnitude due to defects in the manufacturing of the reflector (aperture angle and size) and losses from the material used. It is important to note that it has been possible to detect the emission up to 5m far away from the vertical axis, remarkably increasing the cover area compared to the isolated PVDF transducer.

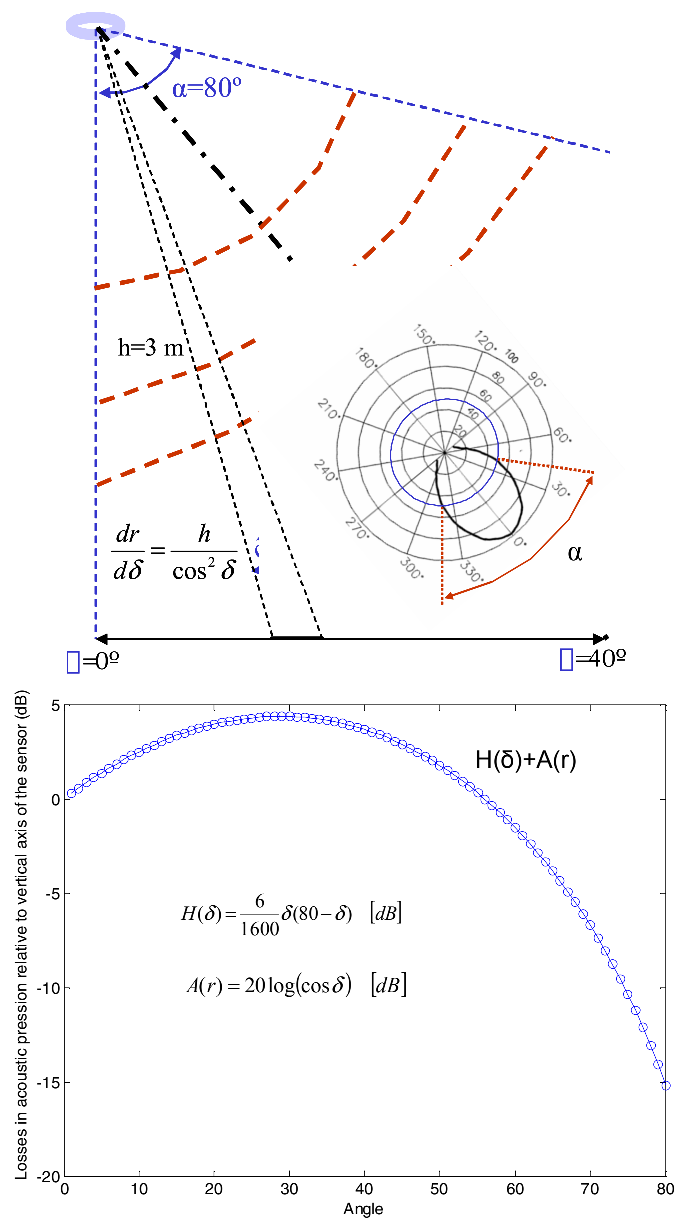

Fig. 8. Loss effect by divergence.

V. CONCLUSIONS

A conic reflector has been designed for a cylindrical PVDF-based transducer that allows to use this type of transducers for beacons in ultrasonic LPS. Absorption and divergence effects have been studied for the new resulting transducer model to obtain the attenuation of the ultrasonic signal on the surface of the floor, around the vertical of the transducer. The reflector provides an increase in the covered area, assuming beacons located in the ceiling. In this way, for attenuation below 8dB obtained with a beam inclination of 60º and a height of 3m, the covered area is 85m^2 on the surface of the floor, given by only one transducer.

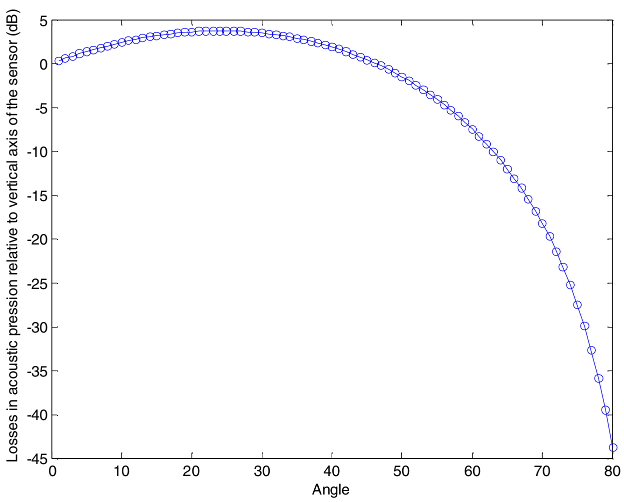

Fig. 9. Loss effect by sum of absorption and divergence influence.

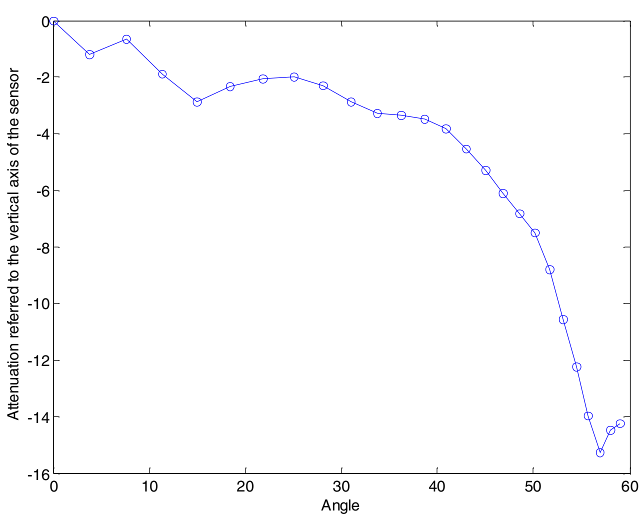

Fig. 10. Attenuation referred to the vertical axis of the sensor, determined by experimental measurements.

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