Ultrasonic Sonar System for Target Localization with One Emitter and Four Receivers

Ultrasonic 3D Localization

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Abstract—**This paper presents an ultrasonic active sonar system in air constituting one emitter and four receivers. Target localization is achieved by means of intersection of four ellipsoids defined by the time of flight between emission and reception of the signal reflected by the target. This paper shows a proof of concept of the localization principle through some localization tasks conducted in a laboratory environment. The position of a spherical target is determined with an error between 1cm and 7cm depending on receiver configuration and target position. The purpose of the fully developed sonar system is to assist drones and robots in their autonomous navigation.**

Keywords—sonar system; ultrasonic localization; ellipsoids; triangulation

I. INTRODUCTION

Ultrasonic localization is used to avoid obstacles in robot autonomous navigation [1] and to locate reflecting targets [2, 3]. Sonar systems are typically equipped with one transmitter and two or more receivers. Parameters such as time of flight and attenuation, as a function of orientation, are processed to estimate the location of a reflector.

This paper describes an active sonar system for ultrasonic localization of a target in air. Sound is produced by one emitter and the reflected signal is recorded by four receivers. The localization procedure is based on the processing of the time of flight from emission to reception for each paired transmitter-receiver which allows the calculation of four ellipsoids whose interception point is the estimate of the reflecting target location. This proof of concept is tested through laboratory experiments. In the following, the intersection of ellipsoids method is described in Section II, the equipment and the experiment setting along with the experiment results are presented in Section III while results are discussed in Section IV with a plan for future work.

II. METHOD

A. Calculation of ellipsoids

The sonar system consists of one transmitter and four receivers. The ultrasonic signal is produced by the transmitter, reaches the target and is reflected back to the receivers. For each paired transmitter-receiver, the time of flight from emission to reception defines a set of points where the target could be. This set in 3D space is an ellipsoid whose focal points correspond to the location of the transmitter and of the receiver. From the time of flight value, parameters *a*, *b* and *c* in the ellipsoid equation can be calculated as

$$\begin{cases} \sqrt{\left(\frac{l}{2}\right)^2 - \left(\frac{d}{2}\right)^2} = b = c \\ \frac{l}{2} = a \end{cases} \tag{1}$$

where *l* is the length of the path corresponding to the measured time of flight. Parameter *a* is the length of the longest semi-axis of the ellipsoid while *b* is that of the shortest. In 3D, *c* is defined and in the case considered in this paper *b*=*c*.

B. Intersection of ellipsoids

As depicted in Fig. 1, the time of flight and the mutual positions of one transmitter and two receivers make it possible to define two ellipses through Eq. (1). Their intersections are two points of which one corresponds to the target location. In three dimensional space another ellipsoid is required to find 2 intersection points between the three ellipsoids of which only the one facing the transmitter is considered as a feasible target location. A fourth ellipsoid is included in the calculations to get a better estimate in case any of the previous three didn't return a good signal reading.

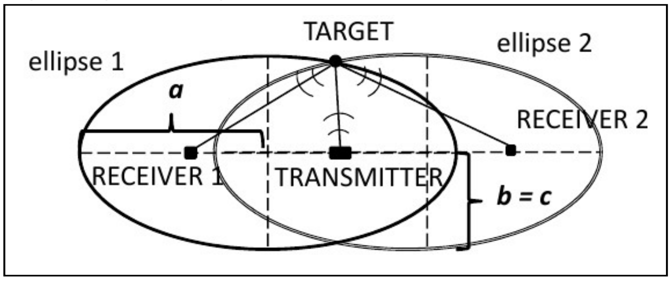

Fig. 1. Ellipses defined from transmitter and receiver locations as the focal points and the path of flight as half of the main axis *a*. Target location corresponds to one of the two intersection points of the ellipses.

III. EXPERIMENTS

A. *Experimental setting and equipment*

Experiments were performed in a sound-proof booth with dimensions 90x60x80cm (L-W-H), see Fig. 2. The walls, ceiling and floor of the booth were covered with acoustic foam to prevent reflections of the produced ultrasonic signals. The emitter is a Polaroid 7000 Series transducer [4] with resonant frequency around 50kHz. The four receivers are Bruel & Kjaer 4138 1/8-inch microphones capable of recording sounds up to 140kHz. The target is a brass sphere with a diameter of 2.5cm.

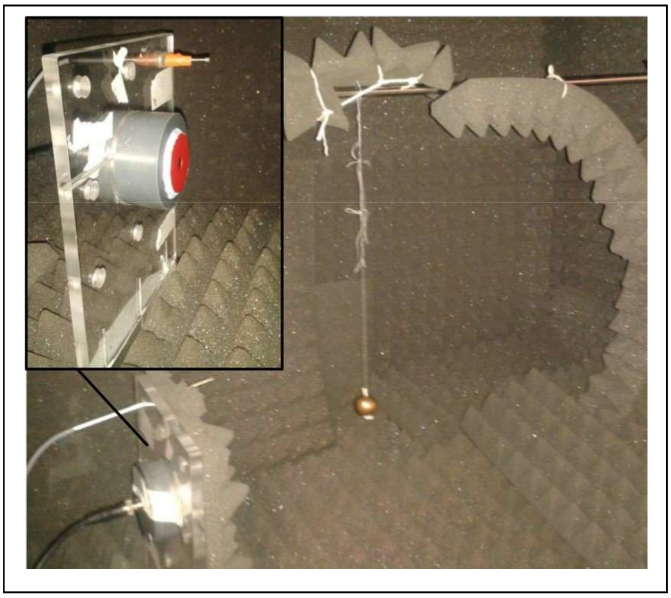

Fig. 2. Experimental setting. The frame holds in place the transmitter with a mask (in red) to enlarge its beam pattern. The microphone is mounted on the frame. The target is held in front of the transmitter with a rod. Acoustic foam covers the walls of the booth.

In the experiments the sphere was fixed with a rod in front of a frame holding together the emitter and the receivers. The frame has a central hole to accommodate the transducer and holes with smaller diameter for the microphone positions. There are 8 holes for the receivers so the microphone configuration in the experimental tasks can be changed. The front of the Polaroid transducer was covered with a cylindrical mask in order to reduce the active vibrating surface conveying the acoustic signal into the environment, see Fig. 2. This way, a wider area can in principle be ensonified in one emission only as it makes it possible to enlarge the width of the beam pattern [5]. Fig. 3 shows the schematics of the experimental setup with the microphone configurations A, B and C used in determining target location. The target is in front of the support for the transducer and the receivers. The reference frame has its origin in the bottom-right corner of the support, thus the position of the target can also be defined with respect to it.

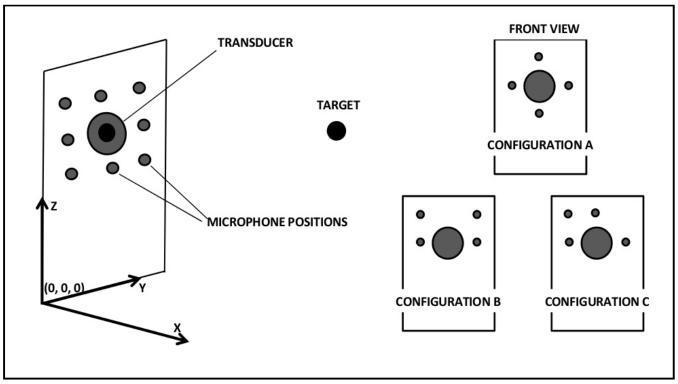

Fig. 3. Reference frame with positions of target, transducer and microphones (left in the figure). Microphone positions according to configurations A, B and C for the experiments (right in the figure).

B. *Time of flight detection*

The transducer produced tone bursts at 55kHz consisting of 5-cycle sinewaves with 10Vpp amplitude: 10Vpp were necessary in order to get a clear reflection from the target at all the locations chosen in the experiments. The bias voltage supplied to the transducer was 100V. The ultrasonic signal in the booth reached the target and was reflected back to each of the receiver positions. The reflected signals were then analysed to estimate the location of the brass sphere. Namely, an envelope detection method was used where the analytic signal of each recording was calculated using its Hilbert transform. The analytic signal $a_s(t)$ of the recording $s(t)$ is defined as

$$a_s(t)=s(t)+h_s(t) \qquad (2)$$

while the envelope of $s(t)$ is calculated according to

$$e(t)= |a_s(t)|=\sqrt{s(t)^2+h_s(t)^2} \qquad (3)$$

In (3) $h_s(t)$ is the Hilbert transform of $s(t)$ and $a_s(t)$ is the analytic signal from which the envelope $e(t)$ is recovered. The envelope of the analytic signal was downsampled by a factor of 9 and filtered. A threshold was then applied to the result signal to detect the time of flight corresponding to the detection of the target in the recording $s(t)$.

C. *Results*

For a particular microphone configuration, the time of flight values associated to each recording, along with the coordinates of the transducer and the receiver itself, define an ellipsoid. The intersection of the four ellipsoids returns a location that is taken as the estimate of the true target location, see Fig. 4.

This research is funded by the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. [615030].

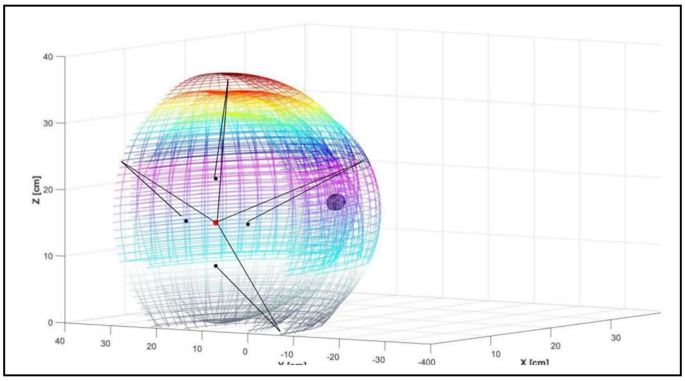

Fig. 4. The four ellipsoids associated with each pair microphone-transmitter and intersecting in a location defining the estimate of the target one.

Three target positions are considered in this paper and they are detailed in Table 1 for the reference frame shown in Fig. 3. The localization method depends on the configuration of the receivers also. In Table 2 the error, as the Euclidean distance between the estimated and the true target location, is shown for each target position and microphone configuration.

TABLE I. TARGET POSITIONS

TARGET POSITION	X coordinate	Y coordinate	Z coordinate
0	20cm	7cm	17cm
1	19.25cm	7cm	25.25cm
2	20cm	-1cm	17cm

TABLE II. LOCALIZATION ERROR

MICROPHONE CONFIGURATION	**TARGET POSITION**	**ERROR [cm]**
A	0	2.2
A	1	4.7
A	2	7.6
B	0	3.25
B	1	4.7
B	2	6.3
C	0	2.1
C	1	1.6
C	2	3.7

IV. DISCUSSION

The purpose of this paper is the design of an ultrasonic sonar system and the proof of concept of a localization method implemented in it. The localization is based on the definition of 4 ellipsoids calculated from the time of flight values and the mutual positions of the transmitter and each receiver. The intersection of the ellipsoids returns a 3D location which estimates that of the target reflecting the acoustic signal back to the receivers. Three microphone configurations were considered for three target positions, as described in the previous section. The measurement of the time of flight is based on the calculation of the envelope of each received signal defined as the absolute value of the analytic signal where the imaginary part is the Hilbert transform of the recorded signal and the real part is the recorded signal itself.

The error values in Table 2 show a dependence of the localization method implemented in the sonar system on microphone configuration and, as expected, on target position. Microphone configuration C is shown to guarantee the most accurate estimates. This can be explained because configuration C is asymmetric thus returning ellipsoids with different sizes more than in the case where the microphones were displaced like in configuration A or B. Error values range from a minimum of 1.6cm to a maximum of 7.6cm. Those beyond 5cm are due to the weakness of the acoustic signal returning to the receivers, and to the merging of the signal with background noise. Further improvements will be to increase the separation between the receivers and the transducer and increase the power of the transmitted signal including power amplifiers in the design of the sonar system. In addition, more signal processing techniques, such as cross-correlation, and waveforms as the transmitted signal will be investigated.

The final aim is to mount this sonar system on robots engaged in non-destructive evaluation, thus supporting their autonomous navigation, and on drones performing area patrolling and surveillance in military operations.

ACKNOWLEDGMENT

The authors would like to thank the staff and researchers at the Centre for Ultrasonic Engineering of the University of Strathclyde for their support throughout this research work.

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