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ALO: An ultrasound system for localization and orientation based on angles

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A B S T R A C T

This paper presents a low cost system based on ultrasound transducers to obtain the localization and orientation information of a mobile node, such as a robot, in a 2D indoor space. The system applies a new differential time of arrival (DTOA) technique with reduced computational cost, which is called ALO (angle localization and orientation). Instead of directly calculating its position, the system calculates the direction of arrival of the received ultrasonic signal and, through it, its position and orientation. A prototype of a robot has been built in order to show the validity of the method through experimental results.

1. Introduction

In the last years, localization systems for indoor spaces have been deeply studied. The advantages obtained by outdoor localization systems, like GPS, and the problems to adapt these systems to indoor environments have been the base for the research of alternative localization methods suitable for indoor environments.

For indoor localization, there are many systems already developed and tested. From RFID [1] localization systems, based on measuring the strength of the received signal and the knowledge of the position of the transmitters, to systems based on image recognition [2,3], where the system must identify patrons on the floor, ceiling or walls, there are a lot of techniques that can be used. The selection is done in function of the computational capacity of the system and the accuracy requested by the application. Some of the most extended localization systems for indoor applications are the ones based on ultrasonic technology. This is because this technology allows high accuracy with low cost and low computational effort.

The main advantage of ultrasonic signals is their low propagation velocity, at least when compared to electronic circuits processing speed. This characteristic allows capturing the propagation delay between known points with high precision and using relatively low frequency counters.

Two main approaches are used when using ultrasonic technology: "time of arrival" (TOA) localization techniques, in which the system estimates the propagation delay between transmitter and receiver; and "differential time of arrival" (DTOA) techniques, in which the system estimates the propagation delay between multiple receivers but not between transmitter and receiver. TOA systems based on ultrasonic transceivers need an auxiliary radio-frequency signal in order to know both the time of transmission and reception, while DTOA systems can use only ultrasounds because they only need reception times.

TOA localization systems usually calculate the position of the mobile node with the intersection of spheres, whose radii are the measured distances and whose centers are the positions of some known points, called anchor points. These anchor points can be either the transmitters (passive architecture) or the receivers (active architecture). Examples of systems that use this technology are the BAT Ultrasonic Location System [4], The MIT Cricket Indoor System [5,6], the system developed at the UAM [7,8] or the Single Compact Base Station system [9]. In all these proposals, the anchor points are deployed in the ceiling, except in [9], where the three transmitters are included in a compact platform. This simplifies deployment, but at the cost of obtaining less precision.

DTOA localization systems are divided in two main groups. The systems of the first group, called multilateration systems,

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calculate the position of the mobile nodes with the intersection of hyperboloids where the focuses are the anchor points, while the systems of the second group estimate the direction of arrival (DOA) of the reference signal.

The multilateration systems have been implemented in multiple proposals, like the one developed in the Univ. of Bristol [10,11], Decca Navigator System [12] or LORAN-C [13]. Their main disadvantage is their high computational cost, so when they are implemented in low cost robots they are usually implemented using linearized equations [14] or with minimization functions [15].

The DOA algorithms allow obtaining both the position and orientation of the mobile node. The main problem of these systems is their high complexity because they use complex trigonometric equations. An example of DOA based on DTOA techniques is the MUSIC algorithm [16] that allows estimating, simultaneously, the reception angle of different signals from multiple transmitters, checking the correlation of the received signal in the array of receivers. Other example, but using audible signals instead of ultrasounds, is presented in [17]. Although the algorithm is simplified, it still uses FFT (Fast Fourier Transform) apart from other calculations.

In this paper, a new localization and orientation DTOA system, ALO (angle localization and orientation), is presented, which is based on the angle of reception of an ultrasonic signal in a mobile node moving in a 2D space (i.e., the floor). This allows obtaining the position of the node and its orientation. The main novelty of the proposed system is that it uses low complexity calculations, so it can be implemented in low cost devices. The rest of the paper is organized in five main sections: "Angle Estimation", where the base of the system and the mathematical equations are described; "Localization and Orientation", where the localization and orientation technique based on angles is presented; "Implementation", where the implementation of the system can be found; "Error Analysis", section that describes the main error sources and their effect on the precision of the localization system; and "Results", where the experimental results are presented.

2. Angle estimation

To estimate the reception angle to any transmitter, it is only necessary to measure the time elapsed between the receptions of the same ultrasonic signal in different points. The only assumption of our proposal is that all the receivers see the transmitter under approximately the same angle. This is true if the distance between the transmitter and the receivers is much greater than the distance between receivers. With this condition, the approximation error on the angle of the proposed method is negligible.

First, an object must be defined as a group of receivers located in a plane. This object will have a reference receiver (R1 in Fig. 1) and one or two auxiliary receivers (R2 and R3 in Fig. 1). All the angle estimation process will make reference to this reference receiver, using the auxiliary receivers to measure the propagation delay and direction of the reference wave.

This object, which moves in a plain (which will be the floor in the real world), has two main orientations with respect to any point in the space: The first orientation, that will be called horizontal orientation (α in Fig. 1), makes reference to the angle that forms the north of the object (R1 to R2 direction) with the projection of the vector that joins the reference receiver and the transmitter on the receiver's plane. The other orientation, called vertical orientation (β in Fig. 1), makes reference to the angle between the plane that contains the receivers and the vector that joins the transmitter and the reference receiver.

To calculate the localization of the object, the vertical angle must be always obtained, while the horizontal angle has only two possible values (0° or 180°) when the object moves in a 1D space (a line), but can have any value when the object has 2 or 3 degrees of freedom.

2.1. Estimating the reception angle in a 1D space

If the object can only move in a line, a plane that contains that line and the transmitter can be defined. In this plane, the axis X will be the same as the movement line, and the axis Y will be a line perpendicular to the movement line and that contains the transmitter (see Fig. 2). In this case, if the system north reference is $+X$, the horizontal angle can only be 0° (if R2 is nearer to $X=0$ than R1) or 180° (if R1 is nearer to $X=0$ than R2), and given that the object cannot rotate, once the object is deployed it can be deduced in function of the receiving order of the reference wave. This allows calculating the sign of the X position of the receiver R1 (positive for 0°, negative for 180°). To estimate the vertical angle, the system must measure the difference in the time of arrival between the two receivers.

For this example, the transmitter will be in the position $(0, h)$, the reference receiver (R1 in Fig. 2) in $(x, 0)$ and the auxiliary receiver (R2 in Fig. 2) in $(x-a, 0)$. If the transmitter is omnidirectional and there are not obstacles in the space, the propagation delay from the transmitter to the receivers will be proportional to the distance between the transmitter and each receiver (D and D' in Fig. 2). As both receivers are in different positions, the difference in the time of arrival (d_m in Fig. 2) can be measured counting the number of clock cycles between the arrivals of the ultrasonic signal in each receiver (N_{clk}).

If the distance between the transmitter and the receivers is much greater than the distance between the receivers ('a' in Fig. 2):

$$D \ggg a \quad D' \ggg a \Rightarrow \beta_1 \approx \beta_2 \quad d_m \approx d \tag{1}$$

This difference can be considered as a cathetus of a right triangle (d in Fig. 2). In this right triangle, the hypotenuse is the distance between the receivers (a), that is known, so the reception

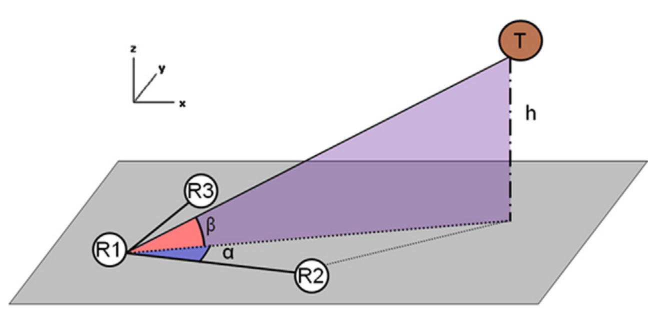

Fig. 1. Angles in the receiver.

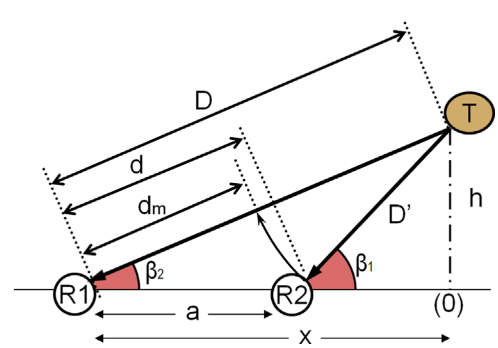

Fig. 2. Angle estimation for 1D space system.