LOCAL POSITIONING SYSTEM USING SIMPLE ULTRASONIC SENSORS

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Reza Taherkhani[1], Zhinus Marzi[2], Saeed Karimi[3], Dr.Alireza Mohammadshahri[4]
[1,2,3,4] *Iran University of Science & Technology, Electrical Engineering , Tehran, Tehran*

Abstract: This paper describes the design and experimental test of a beacon based Ultrasonic Local Positioning System (ULPS) for indoor mobile robots. The beacons have been designed with a low cost, low power piezoelectric transducer but, multiple beacons might be used, according to the environment situation. Synchronization between mobile robot and beacons is the problem that is solved in this paper. In order to solve the problem of beacon's recognition, caused by interference of simultaneous emissions from transmitters, a simple technique is applied. In the proposed approach, all beacons transmit ultrasonic signals individually by a fixed time delay with the same frequency but different burst signals as their ID. The local position calculation is based on the difference time of arrival between beacon's signals. Therefore no radio synchronizer signal or intelligent beacon controller is required. The Newton-Rawson's method is used for position calculation. According to the experimental results an accuracy of %3 is achieved.

Key words: Local Positioning System, Robot, Ultrasonic, Active Beacon, Time Difference of Arrival

I INTRODUCTION

Local positioning systems of mobile robots based on ordinary ultrasonic beacon systems are broadly well-known. They consist of using several beacons located at known positions in the environment, where the robot find's its position by measuring the Time-of-Arrival (TOA) of the ultrasonic signals since the emission instants. To synchronize the emission instant of every beacon, a radio-frequency or an encoded infrared signal is often used, by selecting also which beacons are going to transmit [1].

In this paper by using of Newton-Rawson's calculation method and eliminating the necessity of synchronization between beacons and mobile agents, beacons would become a simple single-trip broadcasters and ultrasonic localization would become easier and more low cost. In addition more than one robot can use a single set of beacon broadcasters for their positioning.

II BEACON DESIGN

The "Coverage Range" of ultrasonic transmitters is a known challenge in sonar beacon design. The MA40B8S transmitter used in this work has 120 decibel (dB) sound pressure and with its coupled MA40B8R receiver, by – 63 (dB) of sensitivity, only 6 (m) range can be achieved.

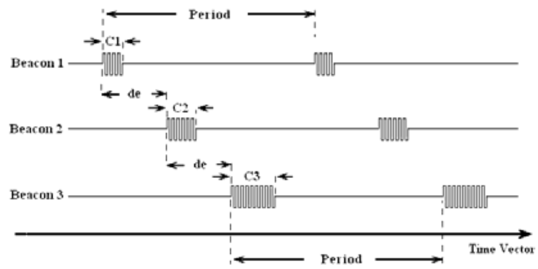

Figure 1. The timing diagram of a 3-beacon set, C1 to C3 are burst's lengths which determine beacon's codes.

This set is manufactured by ***muRata***. This sensor works at 40 KHz frequency and the receiver has a good built-in 40 KHz filter [2].

According to the range size, in bigger fields; needing more range, transmitters may be used as local indicators.

The position calculating algorithm generally should be able to give the position even in lose of one or more beacons data. To reduce complexity of receiver's signal detection, no simultaneous message is sent from beacons.

Each beacon sends a burst of 40 KHz signal as the message at each constant period of time. This period depends on the field's size and transmitters range to avoid interference of beacon's messages at any point of field. That means in any time just a single message should survey the field.

A unique code is assigned to each beacon, in order to detect the Difference-Time-of-Arrival (DTOA)

among at least 3 beacons. The length of burst, sent by each beacon, determines its unique code. The receiver can find the message's source-beacon using its preset database.
The moment of receiving is the base of positioning calculation. The message-sending periods in all beacons are same, but start point of each beacon's burst is at a fix time after the start-time of previous one, calling "de". "de" is fix an known by receiver and participates by a minus sign beside DTOAs and results "*td*". Fig. 1 shows the timing diagram of a 3-beacon set, C1 to C3 are burst's length which determines beacon's codes.

III CALCULATION OF POSITION

By a given DTOA, the difference of distance between the robot and two fix transmitters is known and the only possible locus of robot's location is a one half of a two-sheeted hyperboloid and by assuming of a two dimensional filed, it is a hyperboloid curve.

In simple terms, with two transmitters at known locations, a receiver can be located onto a hyperboloid. Note that the receivers do not need to know the absolute time at which the pulse was transmitted, only the difference time is enough.

Now consider the third transmitter at a third location. (the three transmitters should not be placed on a line.) This would provide a second DTOA measurement; hence locate the receiver on a second hyperboloid. The intersection of these two hyperboloids determines the point which the receiver lies.

Consider a robot which is at an unknown position (X, Y), and receives two DTOAs, which are called td_1 and td_2, from three transmitters, located at (x_1,y_1), (x_2,y_2) and (x_3,y_3). The relations are:

$$\begin{cases} td_1 = \sqrt{(X-x_1)^2+(Y-y_1)^2} - \sqrt{(X-x_2)^2+(Y-y_2)^2} \\ td_2 = \sqrt{(X-x_2)^2+(Y-y_2)^2} - \sqrt{(X-x_3)^2+(Y-y_3)^2} \end{cases}$$

Lo The DTOA problem involves solving a highly nonlinear system of coupled equations given imperfect information. Nonlinear estimation problems are notoriously difficult, and exact solution is generally intractable. Because of that, using of numeric methods for solving of equations is inevitable, and Newton-Rawson's method could be a good choice.
The "Newton-Rawson" algorithm is a numerical method for finding the roots of an equation. It does so by computing the Jacobean linearization of the function around an initial guess point, and using this linearization to move closer to the nearest zero.

The equation below gives from initial guess X^i, a better and better approximation of X^{i+1} *vector*. The algorithm terminates, when once a value of *x* is reached, such that the function we search for its zeros, H(x) is sufficiently close to zero.

$$x^{i+1} = x_i - J_H(x^i)^{-1} H(x^i)$$

J_H is the Jacobean matrix of function H(X). Assuming H(X, Y):

$$J_H\,(X,Y) = \begin{bmatrix} \dfrac{\partial H_1}{\partial X} & \dfrac{\partial H_2}{\partial Y} \\ \dfrac{\partial H_1}{\partial X} & \dfrac{\partial H_2}{\partial Y} \end{bmatrix}$$

In our problem, functions H and J are as fallow:

$$H(X,Y) = \begin{bmatrix} \sqrt{(X-x_1)^2+(Y-y_1)^2} - \sqrt{(X-x_2)^2+(Y-y_2)^2} - td1 \\ \sqrt{(X-x_2)^2+(Y-y_2)^2} - \sqrt{(X-x_3)^2+(Y-y_3)^2} - td2 \end{bmatrix}$$

$$J_H(X,Y) = \begin{bmatrix} \dfrac{(X-x_1)}{\sqrt{(X-x_1)^2+(Y-y_1)^2}} - \dfrac{(X-x_2)}{\sqrt{(X-x_2)^2+(Y-y_2)^2}} & \dfrac{(Y-y_1)}{\sqrt{(X-x_1)^2+(Y-y_1)^2}} - \dfrac{(Y-y_2)}{\sqrt{(X-x_2)^2+(Y-y_2)^2}} \\ \dfrac{(X-x_2)}{\sqrt{(X-x_2)^2+(Y-y_2)^2}} - \dfrac{(X-x_3)}{\sqrt{(X-x_3)^2+(Y-y_3)^2}} & \dfrac{(Y-y_2)}{\sqrt{(X-x_2)^2+(Y-y_2)^2}} - \dfrac{(Y-y_3)}{\sqrt{(X-x_3)^2+(Y-y_3)^2}} \end{bmatrix}$$

These equations are shown for 3-beacons and two DTOAs. Positioning could be done by any three beacons. If more than two DTOAs be available, the calculation could be done two by two and the "Least Squares" method can be applied to find a more precision answer.

These calculations may look complicated but by recent processors it's easy to do, and is preferred to hardware complications.

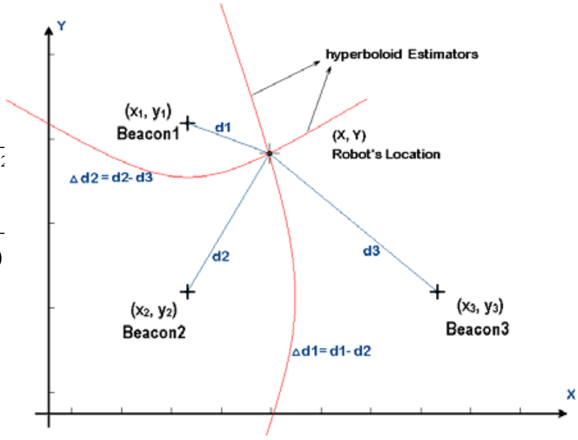

Figure 2. Calculation of position using a couple of difference of distance between the robot and two fix beacon.

IV Error Propagation in Calculation

It is clear that the measurement of DTOAs, which are the base of position calculation, contains an amount of error, thus some error appears in positioning results. According to the calculation formula the dependence of positioning error to the DTOA error is a function of position. It means the error in DTOA measurement, may have greater effect in positioning on some parts of field than the other parts. The arrangement of beacons in, or around the field can affect this error propagation in calculation. The less error propagation, the more measurement error elimination and more accuracy in positioning.

A simple method for estimation the distribution of the formula accuracy is to calculate the position of a set of DTOA which has a uniform distribution. By tracing the results of this set on the field, the effect of DTOA variation on the positioning could be established. This task which is carried out using MATLAB is shown Fig. 3.

Let have three beacons A, B and C at positions (1,0), (0,1) and (0,0). Two DTOAs are achieved, one for A&C, the other for B&C. Consider each of them have 29 value between -0.7 to +0.7 by 0.05 step size. Totally 841 couples of "DTOA", thus 841 "Position" achieved. By plotting them as some points on the field's map, the density of points shows the amount of accuracy of calculation.

Fig. 2 shows the accuracy of position calculation is more on the field's center (as there is more point density) and while the robot goes through the top-right corner, as the point's density reduce, the accuracy is loosed.

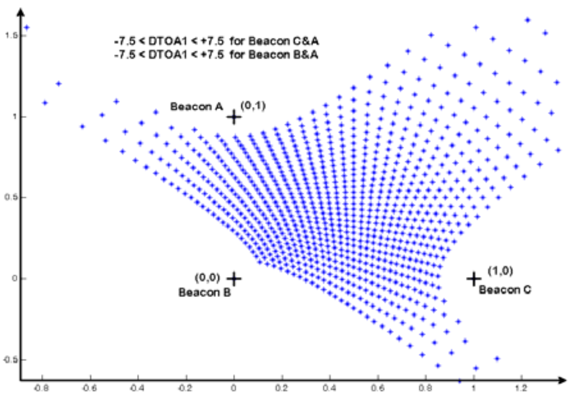

Figure 3. Estimation of distribution of the formula accuracy

V System Transmitter

For increasing stability and accuracy a fully digital circuit used, instead of a software or microcontroller based one. The transmitter circuit is clocked by a 2MHz crystal oscillator. A frequency divider creates a 40 KHz square wave that is base of beacon's message signals.

As explained, a unique code is modulated on each beacon message which determines its source. This code is modulated on the length of the burst. It means messages are a burst of 40 KHz square wave with a unique number of pulses or bursts length, that determines its code. The period, timings and even the code modulation is done by a set of counters and flip-flops. The circuit's diagram is depicted in Fig. 4.

This system is designed for 3 beacons but easily could expand for supporting more beacons. This method is tested, and a great stability and accuracy achieved.

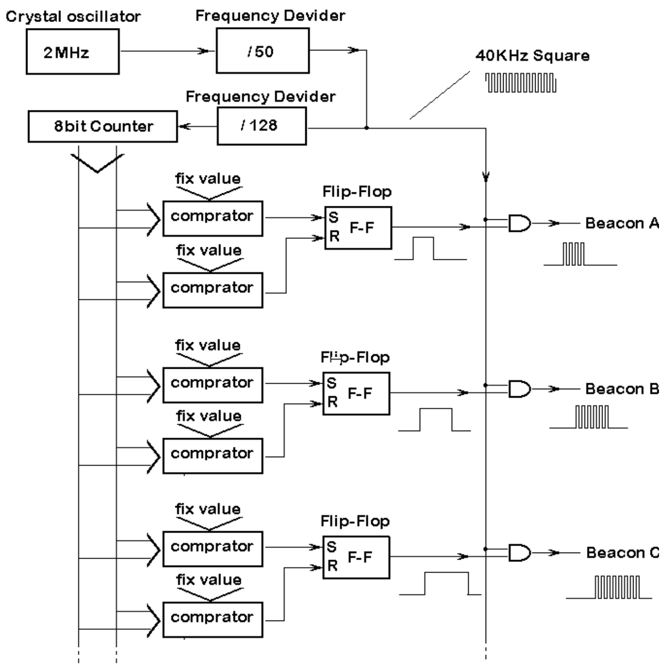

Figure 4. The transmitter's fully digital circuit diagram.

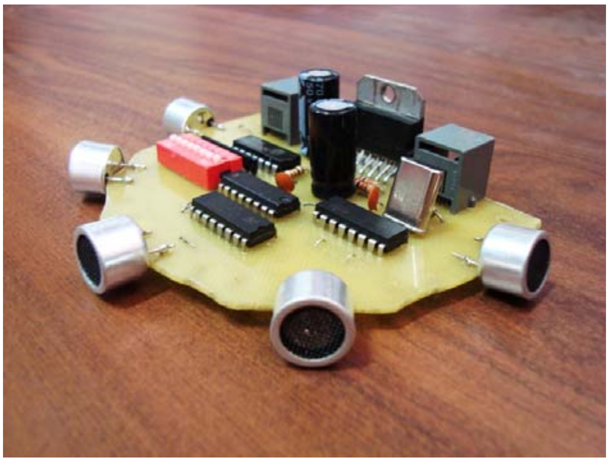

Figure 5. Setup of sonar transmitter's driver circuit

The transmitter circuit was performed by CMOS digital ICs. Amplitudes of Beacon's signal, (from 3 till 15 Volts) may be supplied directly by this CMOS ICs. Greater amplitudes should be performed by additional amplifiers. Fig. 5 depicts the setup of sonar transmitter's driver circuit.

VI SYSTEM RECEIVER

The receiver system is a combination of two parts, the analog and the digital. The main task of analog part is to amplify and digitize the weak and noisy received signal. The signal detection and code demodulation of the messages are done by digital part of the system. An operation amplifier is the core of analog part whereas an AVR Microcontroller is the base of the digital part.

The TL084, a high frequency Op-Amp, with 4MHz gain-bandwidth and 16 Volt per micro second slew rate, produced by ST-Microelectronic™, is used in receiver's analog part. At first, the received signal amplified for 40 db, after that the digitizing done by a comparator. A frequency filtering is needed for each part to reject the interference signals and offset of Op-Amp outputs.

The digitized signal fed into an interrupt port of the ATMega16™ microcontroller. The software measures the input signal's period and detects 40 KHz signals. Then the lengths of signal bursts are measured thus the receive-start time and unique code of each message is approached.

In further processes and numeric calculations, DTOAs and finally the position could be derived. The receiver's diagram is depicted in Fig. 6.

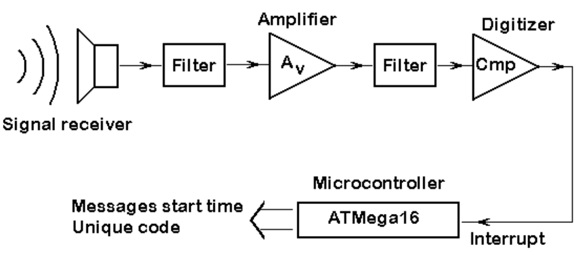

Figure 6 . System receiver's diagram

VII RESULTS

For The system including three beacons has been placed in three corner of a flat square surface (with 1.6 m length), where some experimental tests have been carried out to get the real result of positioning.

In this test, the three sonar transmitters have been excited with a voltage of 10Vpp. Greater amount of voltage, till 24Vpp might be used in bigger fields. Fig.7 depicts the setup of sonar transmitters on test arena.

The receiver set placed in different points of the field at known positions. For each test, a couple of DTOA measured by the receiver set and also difference-distances measured manually which are presented in second and third column. Geometric mean used to calculate the DTOA's measurement errors that are presented in fourth. Receiver's position which is carried out using presented numeric method is presented in 6^{th} column and manually measurement of position presented in 5^{th}. And again geometric mean used to calculate the accuracy of receiver's position, presented in final column. As predicted the calculation formula can converge or diverge errors. In other word, position of receiver may affect on error propagation, for example in first test (presented in table 1) position's error is even less than DTOA's measurement error.

	Difference distance (cm)			Position (X,Y) (cm)		
Test No.	Measured	Calculated	Er(%)	Measured	Calculated	Er %
1	(-43,-58)	(-41.2, -54.3)	5.7	(56,44)	(56,46.2)	3.1
2	(-65,-63.5)	(-68.8, -60.7)	5.2	(42.2,43.4)	(39.3,45.7)	6.1
3	(-3,-82.5)	(-3.1,-89.1)	8	(80,18.5)	(78.4,11.1)	9.2

TABLE 1. Results of some experimental localization tests and its errors.

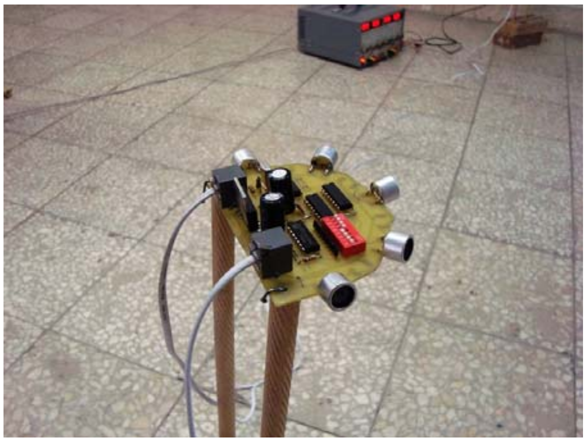

Figure 7. Transmitters set.

VIII CONCLUSION AND FUTURE RESEARCH

A new method for positioning of indoor mobile robots is proposed. The proposed positioning method provides an accurate position by measuring the difference time of arrival of ultrasonic signals. The proposed method is easy to setup and it can also avoid the demand of radio frequency or infrared synchronization between beacons and robot.

No extraordinary or expensive components are used in any part of the systems hardware.

This system might be also used in an arena with multiple robots. Measurement results are presented for a 160cm square field. The real measured results fairly verify the simulated results. An error estimation analysis is given for a square field. The results illustrates that a measurement error of less than 5cm in 1.6 meters field (≈%3) is achieved. As it is clear from the simulation (Fig. 2) and experimental results, depending on the robot position and beacons involved in the position estimation, the accuracy of positioning could be different. As our next research approach we are examining an intelligent algorithm to select those beacons in range to have more accurate position estimation.

Figure 8 . Experimental test set.

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