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REAL-TIME ULTRASONIC LOCALIZATION USING AN ULTRASONIC SENSOR ARRAY

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Summary: This paper addresses localization using an ultrasonic receive array. The localization is realized in real-time. It is shown, that this method leads to good angle estimation accuracy in a low-cost indoor system.

Key words: localization, ultrasound, ultrasound sensor array

INTRODUCTION

The localization is an important problem in robotics. Although there are some globally accepted positioning systems (GPS, GLONASS, and etc.) for outdoor environments, there is not such a system for within buildings (1).

Typical indoor applications require better position accuracy than current outdoor systems provide. The outdoor location technologies have poor indoor performance due to the complex propagation environment inside buildings. Indoor environments often contain substantial amounts of metal and other reflective materials that affect the propagation of radio frequency signals in non-trivial ways, causing severe multi-path effects, dead-spots, noise and interference (2).

Many radio frequency systems include emitter positioning but suffer large errors due to multiple signal reflections from obstacles. Ultrasonic systems behave similarly due to the similar wavelengths and propagation mechanisms. The ultrasonic source localization methods can be characterized by the data used to calculated position i.e. Time of Arrival (TOA), Time Difference of Arrival (TDOA) and Interaural Time Difference (ITD) (essentially Angle of Arrival (AOA)) based methods. TDOA methods are used for outdoor localization. TDOA methods do not rely upon time synchronization between the receivers and the transmitter (3), (5). The differences in signal arrival times at multiple receivers can be evaluated using the cross-correlation of receive signal time-series. The purpose of this research is the development of an ultrasonic TDOA localization tool as part of an automatic navigation facility for an autonomous robot.

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1. GENERAL DESCRIPTION

In a 2D environment an ultrasonic localization system requires three or more ultrasonic receivers with known position. The receivers can be arranged in many ways including a line, a square or an equilateral triangle with a receiver at the geometric center of the triangle. Each receiver is connected through a linear analog amplifier to a central processor unit. The ultrasonic signal emitted by an individual ultrasonic source is received by the ultrasonic sensors and the central processor unit estimates the emitter position from these signals. Typically the received signals include multipath components due to reflections from walls, the ceiling and floor, furniture, people etc. These reflected signals differ from the direct signal in the amplitude and the delay. The direct (if present) and reflected signals combine to yield the total signal y_n at the n^{th} receiver:

$$y_n(k) = g_n * s(k) + v_n \qquad \text{for } n = 1, 2\ldots N \tag{1}$$

where

y_n	the total receive signal at the n^{th} receiver,
g_n	the impulse response of the channel between the source and n^{th} receiver,
$s(k)$	the transmitted signal, often a modulated pulse,
v_n	additive noise on the n^{th} channel.

2. TDOA

The ultrasonic sensors receive the signal from the transmitter. The time difference between the arrivals of the signal at pairs of receivers provides TDOA information. TDOA values indicate the difference in propagation path lengths along the two channels. Given sufficient TDOA information, the emitter location may be estimated. Where all the principal propagation paths are line-of-sight, this is straight-forward. For example, if there are the three ultrasonic receivers, then two independent TDOA measurements can be made. Each TDOA constraints the transmitter position to lie somewhere on a hyperbolic locus. The intersection of the two hyperbolic loci is the position of the transmitter. This method has typically two steps. The first step is the time delay estimation and the second one is the position estimation (3).

2.1 Time Delay Estimation

The Generalized Cross Correlation function (GCC) is used for the time difference estimation. The GCC function can be written as: (4)

$$R_{ij}(\tau) = F^{-1}\{\Psi(f)X_i(f)X_j^*(f)\} \tag{2}$$

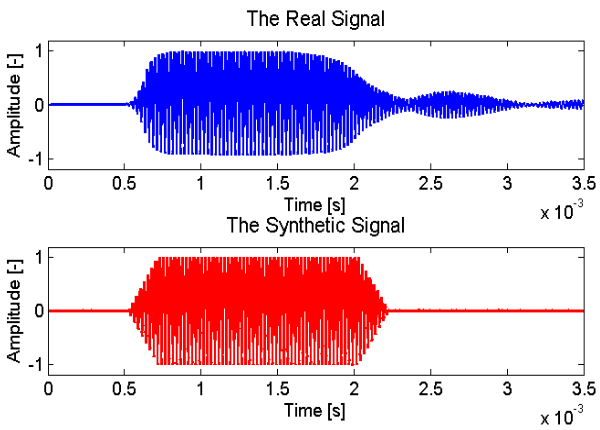
where

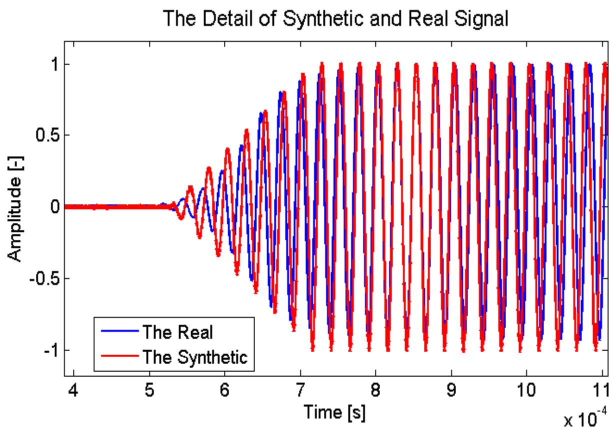
$R_{ij}(\tau)$	is the Generalized Cross Correlation Function,
$X_i(f)$, $X_j^*(f)$	are the Fourier transform of the signals at receivers i and j,
$\Psi(f)$	is the Fourier transform of the general filter.

of the TDOA is assumed to be the maximum this function. The GCC is robust to noise due to the averaging over signal times but is computationally demanding and may require specialist hardware.

This paper explores an alternative approach to delay estimation based on observation of the time when a rising edge of the signal crosses a trigger threshold.

Received signals are band pass filtered and the noise estimation is computed. The standard deviation is computed and the trigger threshold is set to a multiple, usually fifty times, of the maximum signal standard deviation. When the amplitude of received signal exceeds the level of the trigger, then the time of arrival is noted. Figure 1 compares this process for a synthetic and a real measured signal. The synthetic signal was created in MATLAB. Figure 2 shows the detail of rising edges both signals. The all of these signals are normalized.





Source: Authors

Fig. 1– The Real and the synthetic signal

Fig. 2 – The Rising Edge of the signal

Due to limits in the slew rate of ultrasonic transducers, rectangular pulse envelopes are not used. This paper uses a trapezoidal synthetic impulse with a maximum slew rate of 3 V/ms. The real impulse is similar to the synthetic pattern.

Zero mean Gaussian noise with a standard deviation of 0.005 V was added to the synthetic signal. The measured signal has propagated through a low-multipath environment and is contaminated by both acoustic and electronic noise. The received signal can by expressed by:

$$x_i(n) = g_i * s(n - \tau_i) + v(n), \tag{3}$$

where

τ_i is propagation time,

g_i is an impulse response between transmitter and an i^{th} receiver,

v_n is an additive noise.

The falling edge of the measured signal is not as steep or distinct as the synthetic signal due to delayed multipath components due to reflections from room surfaces. The other parameters as the frequency, the length of the impulse are the similar to the synthetic signal.

2.2 Position Estimation

Once TDOA has been measured from several pairs of receivers, localization requires the solution of a set of non-linear equations given by the constraining hyperbolic loci. Many methods could be used; for example the Least Squares, Levenberg–Marquard and Simplex methods. The brute force approach was used in (5) where the results of estimation of position were the good. This paper uses the same solution.

A general model for the three dimensional estimations of is expressed:

$$ct_i = \sqrt{(x_i - x_0) + (y_i - y_0) + (z_i - z_0)} \quad \text{for } i = 1 \text{ to } N \tag{4}$$

Where

$[x_n,\ y_n, z_n]$ are the coordinates of the i^{th} ultrasonic receiver,

$[x_o,\ y_o, z_o]$ are the coordinates of the ultrasonic transmitter,

c is the velocity of the ultrasound,

t_i is the propagation time between the transmitter and i^{th} receiver.

It is possible to rewrite the equation the matrix format:

$$c(t_j - t_i) = |R_i - T| - |R_j - T| \tag{5}$$

Where

R_i are the coordinates of the i^{th} receiving sensor,

T are the coordinates of the transmitters.

3. SIMULATION AND REAL SITUATION

3.1 Simulation

The goal of following simulation is to evaluate the feasibility of localization of an ultrasonic transmitter in an indoor environmental using the methods described above. The simulation is realized in MATLAB. The simulator was used to determine influence of the array configuration on the position estimation error (6). Simulation was used to optimize the signal processing. For example, it was found that squaring the receive signal yielded better localization and this was implemented in the experimental system.

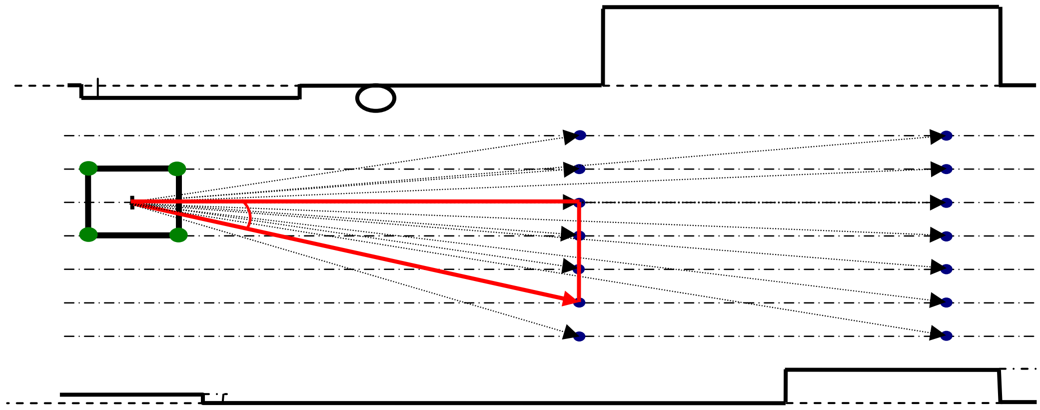
3.2 Experimental System

The system consists of the ultrasonic transmitter, the four receivers, and the amplifier for each receiver and the central processor unit.

The system uses low-cost, commercial ultrasonic transducers and circuit. The ultrasonic transmitter transmits a trapezoidal impulse 1 ms long and the impulse is repeated every 60 ms. The impulse is modulated at 40 kHz ± 1 kHz, and the slew rate is limited by the maximum bandwidth between 2 and 2.5 kHz. The receiver array has the four ultrasonic sensors at the corners of a 50 cm square. The central processor unit is the low-cost kit STM32F4 with an ARM processor. The central processor unit has four analog-to-digital convertors (ADC). All the ADC convertors are synchronized with one clock. The ADCs provide 500 kilo-samples per second. The output from the kit is via a serial line.

3.3 Measurement

The measurements were performed in a corridor of width and length 2.3 x 50 m. The ultrasonic square array was situated close to one wall, as illustrated in figure 3. The green points are the position of the ultrasonic receivers. The blue points are the position of the transmitter.



Source: Tomaš Vaňkát

Fig. 3 – The Testing Bed

The transmitter positions were situated close to the each other. The difference of the angle between neighbor positions was approximately 4 degrees. Two sets of experiments were performed where the distance from the receiver array was chosen to be three and five meters. The square receiver array has sides of 50 cm.

RESULTS

Table 1 contains the results of the two experiments. The measurements were performed ten times for each transmitter position. The first column for each experiment shows the actual angle of arrival from the array to the transmitter.

Tab. 1 – The Result of the Two Experiments

The square array 3 m away from the source				The square array 5 m away from the source			
actual angle [°]	mean	median	diff.of median	**actual angle [°]**	mean	median	diff.of median
351,47	348,73	349,00	2,47	**354,86**	352,67	352,90	1,96
355,24	355,13	355,30	-0,06	**357,14**	356,30	356,70	0,44
360,00	359,77	359,80	0,20	**360,00**	358,77	358,80	1,20
4,76	5,07	5,20	-0,44	**2,86**	5,23	5,91	-3,05
8,53	9,13	8,80	-0,27	**5,14**	5,67	5,20	-0,06
14,04	12,83	13,00	1,04	**8,53**	6,60	6,30	2,23
19,29	17,40	17,80	1,49	**11,85**	8,70	9,50	2,35
		RMS	**1.17**			**RMS**	**1.90**

Source: Author

The second and third columns are the mean and median values from ten repetitions. The last columns are the difference between the actual angle and the median values. The cell labeled “RMS” provides Root Mean Square value of all differences between the actual and the measured angle.

CONCLUSION

The paper describes the method of ultrasonic localization using TDOA, threshold time-different estimation and Brute-Force solution of the resulting system of non-linear equations. The method was implemented in MATLAB and run on a kit with an ARM processor. Experiments in a corridor yielded good azimuth estimation accuracy. Consequently the square microphone array should be used for this purpose.

The azimuth estimation error was always smaller than three degrees. This angle error is adequate for the target application in the navigation of an autonomous robot. The future work will focus on geometry of the array, the properties of rising edge. The system will be tested in difference environments.

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