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Acoustic Self-Localization for Mobile Robots

Itamar Eliakim
Tel Aviv University
Tel Aviv, Israel
Itamare@gmail.com

Yossi Yovel
Tel Aviv University
Tel Aviv, Israel
yossiyovel@hotmail.com

Gabor Kosa
Tel Aviv University
Tel Aviv, Israel
gkosa@post.tau.ac.il

Abstract -

The problem of robot localization in an environment with no GPS reception is highly challenging. We suggest an acoustic positioning system, which only requires placing sound emitters around the environment of interest and a receiver on the robot. In agricultural robotics for instance, the environment of the greenhouse disables GPS positioning and makes it difficult to use optical or magnetic tracking due to the density of plants. The acoustic signals can overcome these difficulties being robust to lighting conditions, obscuring plants, and metal objects. We examine several passive localization algorithms using a set of four fixed loudspeakers and a single microphone on the mobile system. This study presents the algorithms and initial prove of concept experiments for the suggested positioning system.

Keywords — Acoustic, Autonomous Robot, Localization, Agriculture.

I. INTRODUCTION

The worldwide growing use of autonomous robots and smart systems emphasizes the need of finding new methods that can be implemented in these systems to improve the comprehension of our surroundings, including object recognition, classification, obstacle avoidance, path planning.

The goal of this research is to examine the different uses of acoustic signals for localization, mapping and obstacle avoidance. The current paper examines the use of external acoustic signals for localization.

Localization of mobile robots is commonly done by odometry [1], the use of data from the motion sensors of the robot to estimate its position. Relying on odometry is problematic because of the error that is quickly accumulated due the slip of the wheels. Several methods have been suggested to deal with this problem. The simplest one is the use of GPS. In a greenhouse, where agricultural robots must operate GPS is not a valid solution due the metal parts of the structure and the static charges accumulated in the polymer cover. Replacing GPS by acoustic signals enables navigation and correction of the robot's odometry similarly to the GPS. The acoustic signals can pass through and around plants and they are thus robust in contrary to other method such as optical tracking, magnetic tracking and RFID.

The suggested methods was used previously [2] with accuracy of the order several millimeters. *B*y using similar approach, the Cricket v2 passive localization system [3] combined with Extended Kalman Filter (EKF) estimation was able to locate an object moving at 0.7 m/s with an error of 20cm and a stationary object with an error of 3cm. Later, by adding a signal from the object coordinating the transmitters these results were improved to an error of 10 cm at 0.8 m/s the 3cm in 1.43 m/s using the active mode. Another acoustic localization system is the Hexamite HX19 [4], [5], which uses RF active synchronization and reported for an accuracy of 9 mm within a workspace of 3.5 m^2.

Unlike these two approaches, we use fully passive localization i.e. the sound signals transmitted do not require any time base synchronization (i.e., there is not communication between the robot and the ground stations). We locate the robot using numerical and analytical TDOA (Time Difference of Arrival) methods [6] for signal processing.

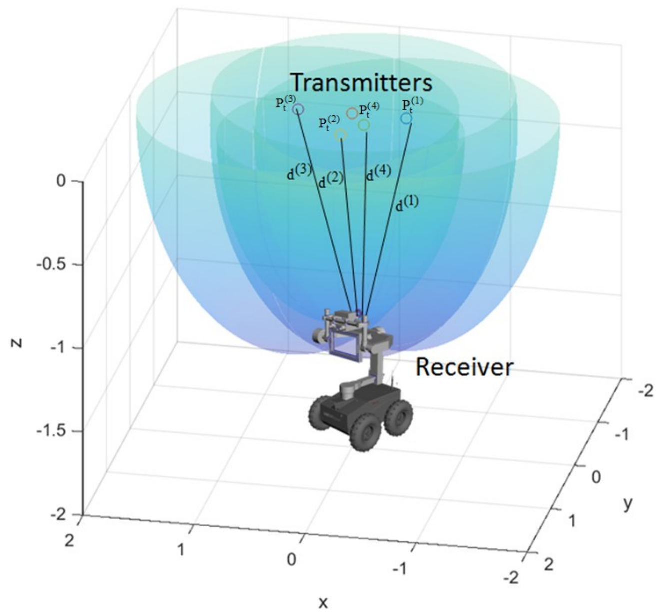


Fig. 1 – Illustration of the Acoustic Positioning System. The scale is in meters. $d^{(i)}$ **is the distance from the robot.**

II. SYSTEM OVERVIEW

Localization problem of a mobile robot is defined by an unknown position of the receiver unit, $\mathbf{P}_r(t)$, (See Fig 1) given the transmitters position in the room $\mathbf{P}_t^{(i)} = [X_1^{(i)} \quad X_2^{(i)} \quad X_3^{(i)}]^{\mathrm{T}} \,\forall\; i = 1:4$ and time of arrival from each speaker $\boldsymbol{\delta} = [\delta_1, \delta_2, \delta_3, \delta_4]^{\mathrm{T}}$. using TDOA (Time difference of arrival), we estimate the robot's position within the workspace.

Solving the localization problem has been done by many methods and techniques. Here, we present the acoustic positioning system (APS) which is based on at least four transmitters and one receiver on the mobile system as illustrated in Fig. 1.

A. Acoustic sensing

The system works asynchrony, the robot continuously acquires recordings from the environment while the transmitter unit located at the cross frame continuously emits chirp signals at known frequencies.

Four speakers are connected to speaker amplifiers custom built for these experiments. Linear chirp signal (Swept-frequency cosine), 2.5KHz bandwidth, starting at 5KHz, the first speaker emits chirp signals from 5KHz – 7.5KHz, second 7.5KHz – 10KHz, etc. Chirp length – 1ms to prevent echoes interference with direct signals from speakers.

Main advantage of this method is that the 'passive' positioning system works at low frequencies, and narrow bandwidth, meaning we can use 20KHz – 120KHz for classification purposes planned as a future research. The robot continuously acquires data from the environment via MCC DAQ, sampling at 250KHz under Nyquist theorem, even though we are working at frequencies less than 20KHz.

Each data set consists 6144 samples to prevent buffer overflow, first the data set is checked by a dynamic threshold to determine whatever signal (one or more speakers) was being 'heard' by the acquisition process. At the second step to prevent estimation of position on echoes and false signals the data set is passed through 'Silent-Filter' ensure that 250 samples before and 500 after the signal the recording is under a predefined threshold (Noise cancellation), by using this method we were able to absolutely eliminate 80% of false readings and improve cross correlation process. the data set is passed through FFT windows filter, similar to FM radar processing, window is running on the frequency domain of FFT looking for specific frequencies (as transmitted by the 'passive' speakers) obtaining the results by a dynamic threshold examine peaks at multiple frequencies. After three step verification of the signal it passes through LPF to eliminate frequencies higher than transmitted ones, cut off frequency at 25KHz.

The filtered data passes through cross correlation in compare to the theoretical swept chirp transmitted by the transmitter side, the data from each speaker is separated by transmitted frequency, 2.5KHz bandwidth. Four time differences, also known as TDOA (Time Difference of Arrival) are generated from each valid recording, by the cross correlation process.

This TOF vector transfers to ROS service custom written for this purpose to estimate the robots position by three different methods, Iterative - Newton Gauss, analytic method, Chan's algorithm.

The transmitter unit includes National Instruments (NI) DAQ USB-6343, includes 4 analogs out channels, 4 x Apex PA-12 speaker amplifiers, 4x Avisoft Vifa Speakers located on a crossed frame above the Denso robot and Power supply set to ±31.8V (see Fig. 2.d)

The receiver module includes1 x Avisoft CMPA ,connected through measurement computing data acquisition board (see Fig 2.b.)

Fig. 2 – Acoustic Positioning System Transmitter Module (a) Avisoft CMPA40 Amplifier (b) MCC DAQ -1608G (c) CMP16 Microphone (d) 4 Vifa Speaker 3D printed box

The transmitters are four speakers capable of transmitting high frequency signals located in the four corners of the room not in the same height. Each transmitter emits chirp signals in different ranges in order to distinguish between the different sources. The signal emission is triggered at constant time intervals without synchronization with the receiver.

The transmitters are separated using cross correlation between the theoretical and measured signals. Assuming the transmitter's emission is spherical the receiver is found by trilateration [7].

B. Acoustic Localization

The position of the robot was estimated using two methods: an analytic solution suggested by [6], and iterative optimization of sphere intersection using Newton-Gauss [8].

Both of these estimation techniques work without the need of time synchronization. Fig. 3 shows data recorded by the robot, we can notice the recorded signal, spectrogram is checked to ensure that the signal includes a valid data that can be passed to the position estimation algorithm, further information is described at experiment section

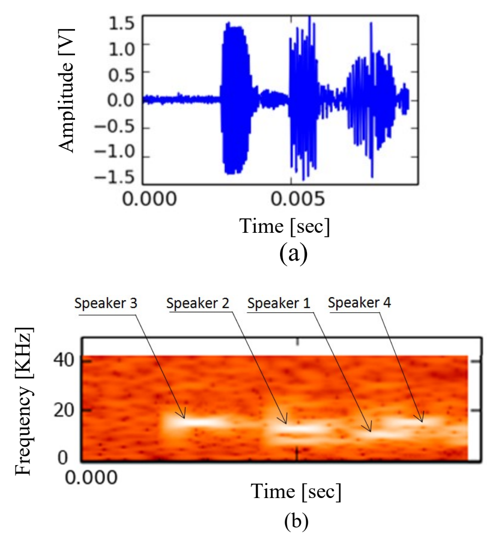


Fig. 3 - 2 Axis Experiment Signal description as received by ROS service, (a) signal, (b) spectrogram

1) Iterative Method

Here, the location of the robot, $\mathbf{P}_r$,is found by iterations. A single location $\mathbf{P}_r(t) = [X_1(t) \quad X_2(t) \quad X_3(t)]^T$ is identified after 10 iterations without using an iteration convergence criterion.

The iteration method we chose is Newton-Gauss [8]. The position calculation evolves by the equation.

$$\mathbf{P}_r(n+1) = \mathbf{P}_r(n) + \boldsymbol{\varepsilon}(n; \mathbf{P}_t, \boldsymbol{\delta}). \qquad (1)$$

$\boldsymbol{P_r(i)}$ Is the i-th iteration of the location calculation.

The evolution variables $\boldsymbol{\varepsilon}(n; \mathbf{P}_t, \boldsymbol{\delta})$ is

$$\boldsymbol{\varepsilon}(n) = -(\mathbf{J}(n)^T \mathbf{J}(n))^{-1} \mathbf{J}(n)\mathbf{e}(n) \qquad (2)$$

$\mathbf{J}(n) = [\mathbf{J}_1(n), \mathbf{J}_2(n), \mathbf{J}_3(n)]$ is the Jacobian of the distance between $\mathbf{P}_r(n)$ to $\mathbf{P}_t^{(i)}$

$$d^{(i)}(n) = \left\| \mathbf{X}(n) - \mathbf{X}^{(i)} \right\|_2 . \quad (3)$$

The Jacobian $\mathbf{J}(n)$ is approximated by numerical derivation. The $\{k,j\}$ element of the approximation is defined as

$$\mathbf{J}_{kj}(n) = \frac{P_{t,k}^{(4)} - X_k(n)}{d^{(4)}(n)} - \frac{\mathbf{P}_{tm,kj} - X_k(n)}{d^{(j)}(n)} \; \forall j = 1:3. \quad (4)$$

The transmitter position matrix is defined as:

$$\mathbf{P}_{tm} = [\mathbf{P}_t^{(1)} \quad \mathbf{P}_t^{(2)} \quad \mathbf{P}_t^{(3)}]^T . \quad (5)$$

One of the transmitters is chosen as a reference and designated as i=4 without loose of generality. The error by the calculated and measured value:

$$\mathbf{e}(n) = \mathbf{T} - \begin{bmatrix} d^{(1)}(n) - d^{(4)}(n) \\ d^{(2)}(n) - d^{(4)}(n) \\ d^{(3)}(n) - d^{(4)}(n) \end{bmatrix} . \quad (6)$$

$\mathbf{T} = c[\delta_1 - \delta_4 \quad \delta_2 - \delta_4 \quad \delta_3 - \delta_4]^T$ is the relative TDOA, (c=343.2 m/s is the speed of sound in air).

2) Analytic Method

An analytic solution for spherical intersection was suggested by [6]:

$$\mathbf{P}_r = \mathbf{P}_{tmr} \times (d^{(4)}\mathbf{T} + (\widetilde{\mathbf{T}} - \mathbf{K})/2) . \quad (7)$$

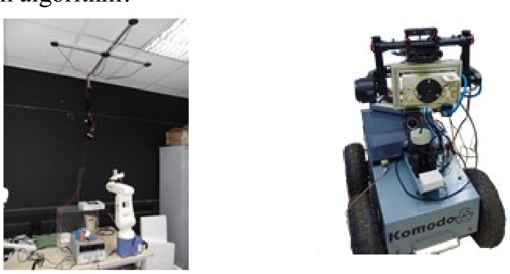
In (7), $\mathbf{P}_{tmr} = [\mathbf{P}_t^{(1)} - \mathbf{P}_t^{(4)} \quad \mathbf{P}_t^{(2)} - \mathbf{P}_t^{(4)} \quad \mathbf{P}_t^{(3)} - \mathbf{P}_t^{(4)}]^T$ is the relative position matrix of the transmitters

$\widetilde{\mathbf{T}} = [T_1^2 \quad T_2^2 \quad T_3^2]^T$ is a vector of the squares of the elements of $\mathbf{T}$ and $\mathbf{K} = [K^{(1)} \quad K^{(2)} \quad K^{(3)}]^T$ is the squared distance between reference transmitter and the other transmitters;

$$K^{(i)} = (X_1^{(i)} - X_1^{(4)})^2 + (X_2^{(i)} - X_2^{(4)})^2 + (X_3^{(i)} - X_3^{(4)})^2 .$$

III. Experimental Results

Our experiment is divided into two separate questions, which algorithm is more efficient and what is the accuracy of the chosen algorithm?



(a) (b)

Fig. 4 (a) Denso VP-6242 6DoF Robotic Arm (b) 'Komodo' Robot Platform

A. Comparative Experiment

First experiments goal to the determine the most efficient algorithm to use in future positioning process of the robot, comparison between two different approaches, Iterative optimization by Newton Gauss as presented at equations (1-5) or analytic solution using [6] presented at equation (8).

For the first set of experiments the Denso VP-6242 6DOF Robotic arm was used (see Fig. 2. b) as the receiver module.
Denso robot was chosen for these set of experiment as it has accuracy of ±0.02 mm and 0.5 m working area. A sensing unit mounted on the end of the robotic arm and it can be moved in 6 DoF.
The sensing unit is connected to Single Board Computer (SBC) BeagleBone Black Linux embedded system based on 1GHz ARM Cortex-A8 run Ubuntu 14.04 ARMHF .The system is based on ROS(Robot Operating System) developed in Stanford University The platform is running the core and nodes for sensing, nodes were written by us for sonar applications for our localization purpose.
The Denso arm was placed in a starting position, 3 experiments each includes 12 measurements of 20 mm displacement between each location, comparing the two methods as seen on Fig. 5,6. Results show the received signal by BeagleBone system, as seen on Fig. 5. Calibration of speaker's location was solved by equations (1-4).

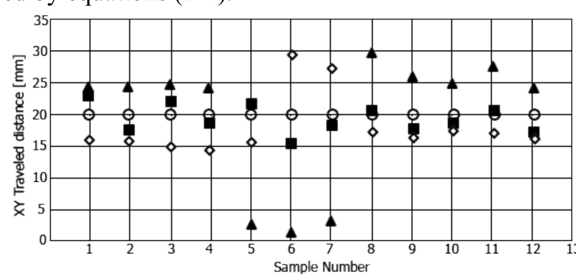


Fig. 5 - XY APS Estimated displacement using our acoustic positioning system, ▲ Exp 1, ■ Exp 2, ◇ Exp 3, ○ Real Displacement

Results processed by Newton Gauss algorithm converge to the same results as the analytic method of iterative optimization, Chan's algorithm, to decide between these two methods the same experiment was performed with ROS service solving the problem in two different approaches, results prove that Chan's algorithm work 8 times faster than solving by 10 iterations of Newton Gauss.

B. Accuracy Experiment

Second set of experiments includes two axis movement as seen in Fig. 6 was executed to determine the precision of position estimation in a bigger room to simulate the greenhouse environment.
Estimated point for each physical point is given by calculation using Chan's algorithm solving for X,Y position. The estimated position is transferred to the point cloud on map, using RVIZ simulation of ROS platform real-time visualization of the mobile robot as seen on Fig. 8.
For this experiment, we used the same set of sensors equipment connected to the Intel NUC computer trough USB port MCC DAQ USB-1608G-2AO board, sampling at 250KHz which is located on 'Komodo' , robot platform as seen on Fig 4.b manufactured by Robotican located in Beer Sheva, Israel.

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The sensing unit as seen at figure 2a – 2c is balanced on DJI Ronin M gimbal controlled by custom board control circuit connected to the main NUC processor unit.

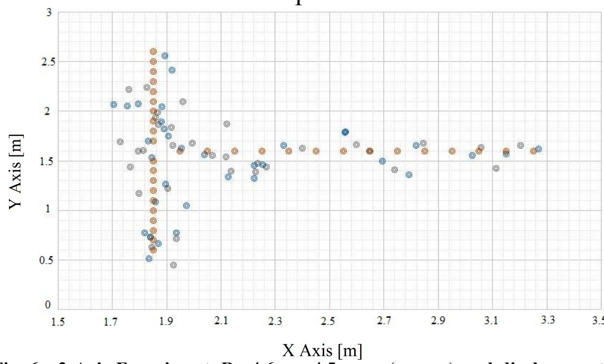

Fig. 6 - 2 Axis Experiment, Rm4.6m x 4.5oom , (orange) real displacement, (blue) EXP 1, (gray) EXP 2

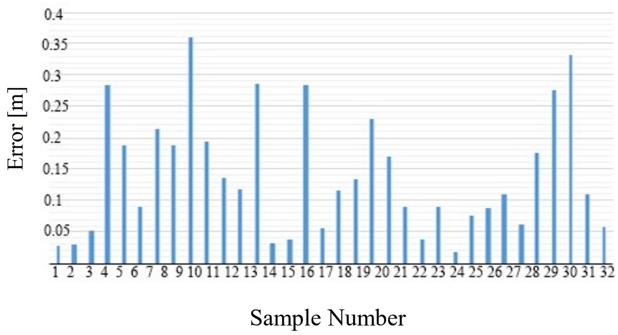

Fig. 7 – Experiment error bars

For each position, 10 data sets are taken to ensure the reliability of estimated point.

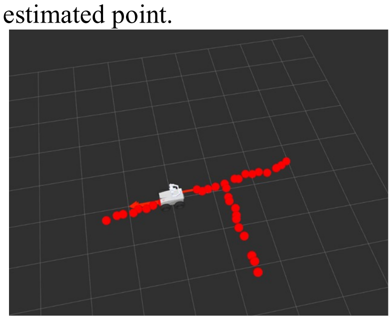

Fig. 8 - Real-time visualization of signal received by ROS Service

Results prove that the Chan's analytic method works as an indoor localization method were can clearly see a trend of samples that describes the actual robot movement meaning that these can used to as positioning system for our needs at the greenhouse. At Fig. 7 we can notice regions with error slightly larger than other, few reasons can cause to these issues as described at the discussion.

IV. Discussion and Conclusions

All the data gathered in this sets of experiments included sonar data only, images from front camera were used to verify the robots position on the ground. The results from the experiments show that Chan's algorithm proves to be the best approximation of location by using this system. Few assumption regarding to the error in position estimation in these experiments, all of the experiments above executed in a closed environment to resemble indoor environment e.g. greenhouse. The room included many solid objects that generate large amount of echoes, few filters described above to try eliminating these issues. To check our assumptions first outdoor experiments, we have notice different issues with our system the speakers were not powerful enough to emit chirp signals for above 3m range. Future research currently in progress trying to change the approach described in this paper of chirp, swept signals at low frequencies to near digital communication using ultrasonic signals, PWM or pulse transmitter. The results prove that this method of APS, passive localization can be implemented in robotics to improve the basic odometry or dead reckoning that is widely used in this market. This method has few major advantages over other positioning system currently in use in robotics: It can work in indoor environment, e.g. greenhouse. No error accumulation, the system does not work relatively to past positions. The system works at low frequencies (5KHz – 15KHz) and low bandwidth (2.5KHz), giving us the ability to actively navigate in higher frequencies (20KHz – 120KHz) used for future research of classification of objects using ultrasonic signals. As described above acoustic positioning system (APS) is part of ongoing research thesis including future research of object classification for 2D map generation SLAM (simultaneous localization and mapping) by using ultrasonic signals ranging from 20KHz – 120KHz, and path planning algorithms.

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