Ultrasonic Based Outdoor Localization Using Threshold Crossing

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***Abstract*—This paper presents an outdoor localization approach utilizing ultrasonic technology for the estimation of an object's 3D coordinates. The methodology integrates Time of Arrival (TOA) and Angle of Arrival (AOA) techniques. Specifically focusing on the periodicity of ultrasonic signals, it introduces an AOA estimation method based on threshold crossing. Furthermore, the paper includes simulation results illustrating the distance error in position coordinate estimations derived from the AOA technique.**

***Index Terms*—Ultrasonic, Threshold Crossing, Outdoor Localization,Time of Arrival,Angle of Arrival**

I. Introduction

Research into short-distance positioning-based systems, which provide services based on the location of users or objects, has been actively progressing. These systems encompass various applications such as autonomous vehicles, robotics, and user positioning systems. Within the realm of short-distance localization, ongoing investigations focus on wireless positioning systems utilizing ultrasonic signals. Unlike UWB, ultrasound exhibits periodicity and strong directivity. Despite its advantages in portability and cost due to smaller sensor sizes, its drawback lies in lower transmission speeds. This limitation proves to be a critical flaw in real-world system implementations. This paper proposes a novel AOA estimation method aimed at mitigating these issues within ultrasound-based wireless positioning systems. The proposed method reduces computational complexity compared to existing methods by employing a probabilistic approach to AOA estimation through ultrasound periodicity and threshold crossing.

II. Related works

Various techniques, including Received Signal Strength (RSS), TOA, and AOA, are employed to estimate the location of an object [1]. As illustrated in reference [1], object positioning relies on signal information, and this section details the measurement techniques applied within this paper. Specifically, this paper utilizes TOA and AOA techniques for location estimation, which are elaborated upon in subsections A and B.

A. TOA(Time of Arrival)

The TOA represents the measurement time of the signal's initial arrival at the receiver. In Active Localization, the difference between the measured TOA and the time when the signal was transmitted signifies the estimated signal's time of flight. This time of flight multiplied by the speed of the signal allows for estimation of the signal's flight distance. Therefore, to estimate the distance between the sensor and the object, it is imperative to employ TOA estimation techniques, with the signal's flight distance represented as shown in Equation (1).

$$RTT_i \times v_{sig} = d_t + d_r \quad (1)$$

Here, RTT_i represents the time of flight of the signal received by the i^{th} receiver, v_{sig} is the speed of the signal, d_t stands for the distance between the transmitter and the object, and d_i signifies the distance between the i^{th} receiver and the object.

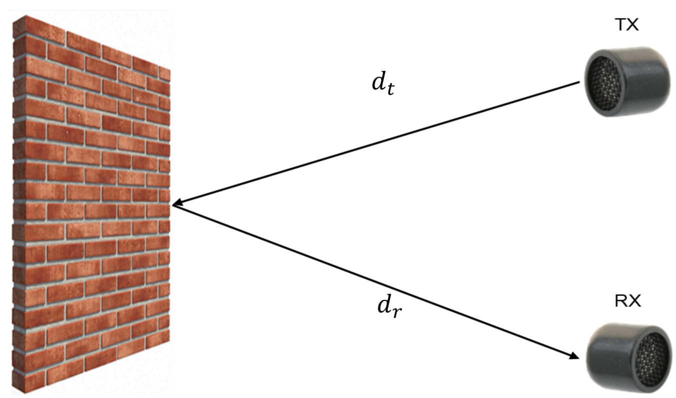

Fig. 1. Example of distance estimation using TOA

In this study, TOA estimation was performed using the rising edge of the Envelope passing through the Threshold after transforming the received signal into an Low Pass Filter(LPF) Envelope. The relationship between the signal's flight time and flight distance is as follows. Given that the utilized signal is an ultrasonic signal, the speed of sound in air approximates 340 m/s.

B. AOA(Angle of Arrival)

The AOA represents the angle at which the received signal impinges upon the receiver. Estimating the AOA of the signal reflected by an object allows for the estimation of the object's position. Within this paper, AOA estimation is conducted by analyzing the phase difference between received signals. For the estimation of the object's 3D coordinates, the receivers were positioned as depicted in Figure 2. Information regarding azimuth and elevation can be derived through the phase difference between receivers situated along the same axis. Moreover, given the extremely narrow spacing between receivers and assuming a far-field scenario, the AOA estimation relies on the difference in flight distance of the received signal, as illustrated in Figure 3.

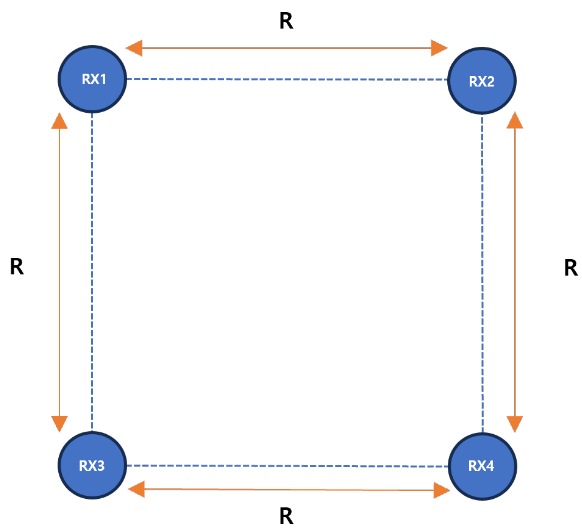

Fig. 2. Receiver Array used for simulation

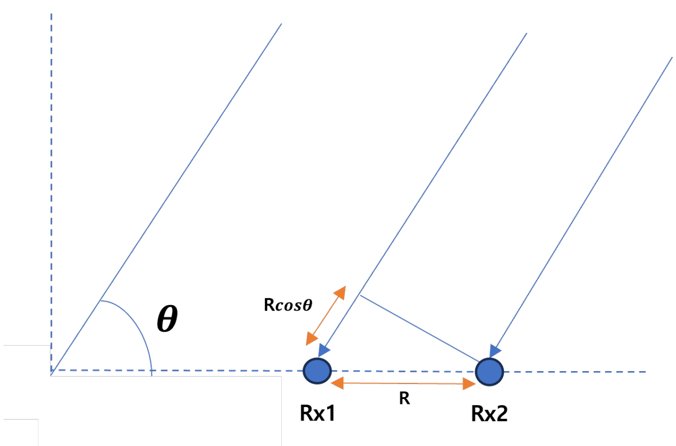

Fig. 3. Time Difference of Arrival in Far-Field Situation

C. Localization System

This section furnishes an intricate delineation of the location estimation system employed in the paper. Initially, the system configuration for estimating TOA and AOA is illustrated in Figure 4. Following the TOA estimation method depicted in the figure, the AOA is estimated based on the acquired information. Additionally, the accuracy of TOA estimation is presented below in a multipath-free channel [2].

$$var(TOA) \geq \frac{1}{8\pi^2 B T_s F_c^2 SNR} \tag{2}$$

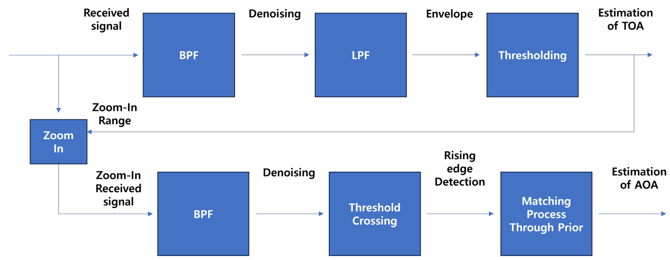

Fig. 4. BlockDiagram of Localization System

In the given context, F_c denotes the center frequency, B represents the bandwidth, and T_s signifies the signal duration.The lower bound of the variance for TOA estimation was reduced by enhancing the Signal-to-Noise Ratio (SNR) using Bandpass Filtering (BPF). TOA estimation was performed based on the rising edge that surpasses the threshold post-envelope conversion. The distance between the receiver and the object was estimated utilizing the obtained TOA. Subsequently, the threshold-crossing technique was utilized to estimate AOA.

III. Method

In a scenario devoid of multipath interference, it can be assumed, under the far-field assumption, that the AOA remains consistent across each receiver. Under ideal conditions, the phase could be estimated through the time difference of arrival for each received signal. However, in practical environments, determining the initial receiver for signal input becomes challenging due to noise influence. Additionally, discrepancies in the number of threshold crossings among receivers pose difficulties in estimation. As a result, the estimated AOA is as follows.

$$\theta^{'} = arccos(\frac{v(\tau + n_\tau)}{R}) \tag{3}$$

In this context, $\theta^{'}$ represents the estimated AOA, v signifies the signal velocity, τ stands for the arrival time difference between receivers,n_τ denotes the arrival time difference error attributed to noise, and R denotes the interval distance between receivers. Subsequently, by estimating the arrival time difference between receivers, accounting for the error due to noise, through averaging, it becomes feasible to correct errors, which is represented as follows.

$$\tau^{'} = \frac{1}{NM} \sum_{k=0}^{N-1} \sum_{j=0}^{M-1} (\tau + n_{\tau j,k}) \tag{4}$$

Certainly, the provided equations describe the process of estimating flight time differences $\tau^{'}$ between each receiver after threshold crossing averaging. Here, N signifies the standard count of the receiver's threshold rising edge among the two receivers, M represents the rising edge index within the maximum range based on the rising edge index of the reference receiver. This method is employed to correct the errors in flight time difference estimation caused by noise, ultimately enabling the estimation of AOA. Notably, compared to the existing correlator-based estimation method, this approach involves reduced computational complexity, potentially leading to an improved update rate.

IV. Result

A. Simulation environment

The transmitted signal utilized in the experiment is an ultrasonic signal with a center frequency of 40 kHz, employing direct sequence spread spectrum (DSSS) modulation to enhance self-recognition capabilities. [3]

Various objects were randomly positioned within a three-dimensional space relative to the sensor, which acted as the origin point. The horizontal and vertical angles were configured at 60 degrees. All objects were assumed to be metallic in nature, with a reflectance value set to 0.99. Moreover, considering the objects' shapes, they were assumed to be arranged randomly as either plane-like or pillar-like structures with equal probabilities.

To emulate the channel characteristics, factors such as path loss and noise were incorporated. An assumption was made regarding the attenuation rate of reflected signals, wherein the reflection coefficient was set as a uniformly distributed random variable ranging between 0.1 and 0.8. Additionally, it was assumed that the reflection coefficient increases when the object takes the form of a pillar.

B. Simulation Result

The simulation involved incremental distance variations from 30 cm to 3 meters at intervals of 5.4 cm, with objects placed randomly at various angles. Each distance point underwent 1,000 repetitions in the simulation.

As depicted in Figure 5, the difference between estimated position coordinates and the accurate coordinates was represented as 'Error'. Notably, it's observed that errors in the x and y axes were larger compared to the z-axis. This discrepancy is attributable to the z-axis estimation relying solely on elevation information. In contrast, both azimuth and elevation information contribute to x and y axes estimation, hence resulting in relatively larger errors.

V. Conclusion

In this paper, we introduce a 3D localization algorithm for outdoor areas using ultrasonic. To estimate AOA, we minimized AOA errors caused by noise by utilizing the threshold crossing technique, which involves signal periodicity and thresholds. Furthermore, by applying the threshold crossing technique for AOA calculation in position estimation, we were able to estimate the 3D coordinates of an object using only three receivers. This method reduced system complexity in comparison to correlator-based localization.

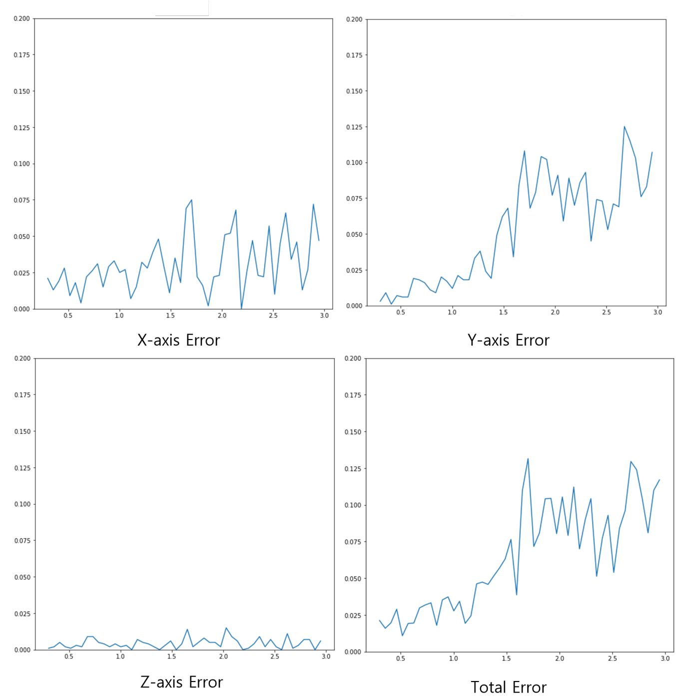

Fig. 5. Graph of error trends according to distance

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