

Detection of Gunshot Direction on Gunshot Locator Using TDOA (Time Difference of Arrival)

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Abstract – In order to avoid shots being fired in undesirable areas, a device is required that can detect the origin of the shot so that the source of the bullet can be identified. This research was conducted to maintain the security and stability of a region. The objective of this study is to develop a device that utilizes the time difference of arrival (TDoA) method to determine the direction of gunshot on a gunshot location device. Prior to the implementation of TDoA, the received sound undergoes a filtration process utilizing an FIR filter. The filtered sound is then subjected to the time-of-arrival (TDoA) method. This method involves the comparison of the direction of sound arrival, followed by calculation and conversion to determine the origin of the gunshot sound. The TDoA coordinates are subsequently determined through the utilization of the multilateration method. In the experiments conducted using a speaker as the sound source and four microphones as receiving sensors, changing the speaker's location demonstrated that the signal-to-noise ratio (SNR) of the sound signal increased as the distance between the sensor and the sound source decreased. Furthermore, the implementation of an FIR filter during post-processing can enhance the SNR of the sound received at the sensor by 27% to 32%. In this research, the TDoA method demonstrated a high degree of efficacy, attaining a detection accuracy of 99.78%.

Keywords – TDOA; Gunshot Locator; FIR; SNR; Multilateration.

I. INTRODUCTION

RECENTLY, there has been an alarming increase in random shootings, which have occurred not only in conflict-prone regions but also in densely populated areas. This phenomenon has emerged as a matter of considerable concern within the domain of civil security. To address this issue, it is imperative to implement a system capable of identifying the origin of gunfire by analyzing the direction of the sound, called a gunshot locator.

The system utilizes the Time Difference of Arrival (TDoA) method, a positioning technique that relies on the arrival time of signals received by multiple sensors (i.e., microphones) that employ absolute time measurements at a designated microphone. This measurement is performed during the cross-correlation synchronization of two signals received by the receiver to determine the time difference at the receiver. The calculation of each time difference is predicated on the assumption of

a linear relationship between the sound source and the receiver. It is anticipated that this approach will yield enhanced precision.

A substantial body of research has previously employed an LMS filter to attenuate extraneous components from gunshot sounds [1]. In this study, in addition to applying an FIR filter for gunshot detection, the time-domain-based method is also implemented. In previous research, the direction of the gunshot source was also detected using the Frequency Difference of Arrival (FDoA) method in a gunshot locator, focusing on the frequency difference obtained from the detection process [2]. Other approaches, such as NLMS for denoising [3], MVDR beamforming for noise variance minimization with 96.29% accuracy [4], and the MUSIC algorithm with reported accuracies up to 99.21% [5], have also been investigated.

Research Gap and Novelty: Despite these advancements, each method has limitations. The FDoA method is highly dependent on the relative velocity between the sound source and the sensor, making it error-prone under varying propagation conditions. NLMS can reduce noise effectively but struggles in environments with very low signal-to-noise ratios. MVDR

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achieves improved clarity but demands high computational resources and is sensitive to modeling inaccuracies in acoustic environments. MUSIC, while accurate, requires covariance estimation and a large number of samples, limiting its suitability for portable real-time systems.

Addressing these gaps, the integration of **FIR filtering** with the **TDoA** method offers a balanced solution in terms of accuracy, stability, and computational efficiency. FIR filters enhance input signal quality by suppressing noise without introducing phase distortion, thereby improving the accuracy of arrival time estimation across sensors. As a result, multilateration based on TDoA achieves higher precision.

The novelty of this research lies in the implementation of a gunshot direction detection system that combines FIR filtering with the TDoA method using a simple linear microphone configuration. This approach not only demonstrates significant improvement in SNR (27–32%) but also achieves a detection accuracy of up to **99.78%**, surpassing MVDR performance reported in previous studies. Moreover, the proposed system is lightweight, portable, and has strong potential for real-time applications, making it a practical subsystem for random shooting mitigation and civil security enhancement.

II. RESEARCH METHODS

This section describes the research scheme used in the TDoA method analysis to detect differences in the arrival time of gunshot sounds on a gunshot locator. This scheme provides guidance on how this research was conducted, starting from data collection, data processing, adding FIR filters, applying TDoA, and converting the coordinates of the source of the gunshot and the coordinates of the microphone sensor. MATLAB software was used to design the simulation for this research.



Figure 1: Block diagram of gunshot direction detection system

Figure 1 shows a block diagram of the sound direction detection system. The research began with data collection, namely by recording the sound of gunshots in the form of impulses. The sensors used are four microphones arranged in a linear configuration, each spaced 30 cm apart. Sound data acquisition is performed using Simulink software in MATLAB to record the sound signals received by each microphone, with

the recorded sound output saved in Waveform Audio File Format (WAV) files.

Then, the recorded sound is filtered using an FIR filter to remove noise contained in the recording. The data acquisition configuration is shown in Figure 2.

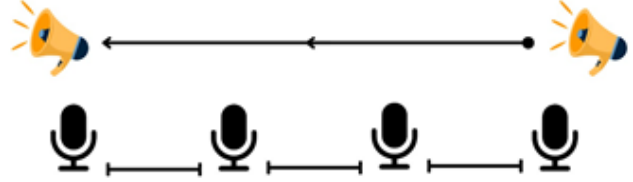


Figure 2: Configuration of gunshot source (transmitter) and microphone (receiver)

Figure 2 shows four microphones as receivers with a sound source or speaker used in this test, namely a laptop and Simulink software to record incoming sounds for post-processing. Post-processing is performed using MATLAB software to apply the Time Difference of Arrival (TDoA) method. Subsequently, the TDoA method is converted using multilateration calculations to obtain the coordinates of the detected sound source.

The microphones used are USB 9.7 devices that can capture sound from all directions. These microphones have a frequency response of 50–20,000 Hz with a sensitivity of -38 dBV/Pa. Real-time data acquisition is performed and illustrated in Figure 3.



Figure 3: Data collection with microphones arranged linearly

i. TDoA (Time Difference of Arrival)

TDoA is a method that implements a one-way transmission ranging algorithm to measure the time differences of arrival [6]. In principle, it is based on the difference in the arrival time of signals at a microphone array. This microphone array will receive signals at different times from the same signal source. For example, sounds that reach the closer microphone will arrive earlier than those reaching the farther microphone [7]. Time Difference of Arrival (TDOA) is a widely used acoustic source localization method that measures the time differences between signals arriving at spatially separated microphones in an array [8, 9]. The technique exploits the fact that sound waves reach

closer microphones earlier than farther ones, creating hyperboloid surfaces where TDOA values remain constant [9, 10]. Key challenges include accurate time delay estimation, typically addressed through generalized cross-correlation (GCC) methods [11, 12]. Various algorithmic approaches have been developed, including parameter identification methods [8], Taylor algorithms [11], and closed-form solutions requiring a minimum of five microphones [10]. Applications range from video conferencing to military signal intelligence [8, 13]. Performance varies with environmental conditions, achieving positioning errors within 3–7 cm in controlled settings [11, 14], though real-world performance may be degraded by noise and reverberation [13, 15].

It works by detecting the sound emitted by a sound source or gunshot, which transmits a signal, and then several sensors or receivers (microphones) record the arrival time of the sound signal. Since each sound signal arrives at the receivers at different times, the time difference in signal arrival can be calculated to determine the relative position of the signal source [16]. With this data and the known positions of the microphones, the location of the sound source can be mathematically calculated, typically using the multilateration method. The equations used are given in Eq. (1) and Eq. (2):

$$t_1 = s(n) \quad (1)$$

$$t_2 = s(n - y) \quad (2)$$

where t_1 and t_2 are the times to microphone 1 and microphone 2, $s(n)$ is the reference signal, n is the distance from the sound source to microphone 1, and y is the time difference between t_1 and t_2 .

ii. FIR Filter

FIR (Finite Impulse Response) is a type of digital filter with limited impulse response. That is, the filter's response to an impulse input signal only lasts for a limited duration, after which the response value returns to zero. This is a characteristic of FIR filters, where the length of the impulse response corresponds to the number of filter coefficients used [17].

FIR filters are known for their stability, as they do not have feedback elements that can cause system instability. Additionally, this type of filter allows for linear phase design, meaning all frequencies in the signal are treated uniformly in terms of time delay, thereby avoiding phase distortion.

In previous research, the performance comparison of FIR filter design using Rectangular, Hanning, and Hamming window methods analyzed the simulation of

filters in a low-pass configuration using MATLAB software, with the results being a performance comparison of each window [18].

FIR filters are widely applied in various fields, including audio signal processing, digital communication, image processing, and control systems, where accuracy and stability are critical. The FIR filter is illustrated in Figure 4.

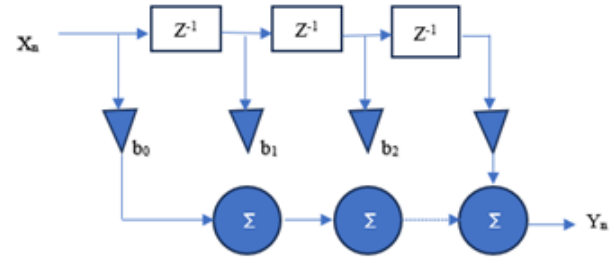


Figure 4: Finite Impulse Response filter illustration

The equation for FIR filters is expressed as:

$$y(n) = \sum_{k=0}^M b_k x(n-k) \quad (3)$$

where b_k is the filter coefficient, $x(n)$ is the input, and k is the filter order notation.

iii. Multilateration

Multilateration is a method for determining the position of a point (usually in 2D or 3D) based on the difference in distance from that point to several reference stations whose positions are known [19]. A range-based multilateration technique is presented to improve localization accuracy.

Multilateration calculates a position based on the range measurements of three or more anchors, with each anchor acting as the center of a sphere. The system of equations matrix used in multilateration is derived from the geometric principle of Euclidean distance [20]. The multilateration equation can be expressed as:

$$(x - x_i)^2 + (y - y_i)^2 - (x - x_1)^2 - (y - y_1)^2 = R_i^2 \quad (4)$$

where x, y are the target positions, x_1, y_1 are the reference or sensor positions, and R_i is the distance in the i -th notation.

iv. Signal to Noise Ratio (SNR)

Signal to Noise Ratio (SNR) is a measure used to compare the strength of the desired signal to the level of interference or noise accompanying it [21]. SNR is an important parameter in assessing the quality of communication systems, signal processing, and measurement accuracy in various electronic devices.

A high SNR indicates that the signal is much stronger than the noise, resulting in better quality of the received or processed information [22, 23]. A low SNR indicates that noise dominates the signal, which can cause distortion, transmission errors, or a decrease in communication quality. SNR is formulated as the ratio of signal strength to noise, as shown in Eq. (5):

$$\text{SNR} = 10 \log_{10} \left(\frac{S}{N} \right) \text{ dB} \quad (5)$$

where S is the average signal power (Watts) and N is the noise power (Watts).

III. RESULTS AND DISCUSSION

From the previous research it has been shown that gunshot sound detection using the FDoA method can obtain information on the distance of the shot sound from the Doppler frequency generated by the moving sound source [2]. However, in this study, the direction from which the gunshot sound source originated was unknown. There is also research that obtains information on the Direction of Arrival (DoA) of gunshot sound location, which can detect the direction of sound arrival using MVDR with a detection accuracy of 96.29% [4]. Both of these studies are closely related to this study, which obtains information on the origin of the gunshot sound converted into coordinate points with accuracy in the analysis. From the research conducted, the four microphones used as sensors each display the sound of gunshots in the time domain, as shown in Figure 5.

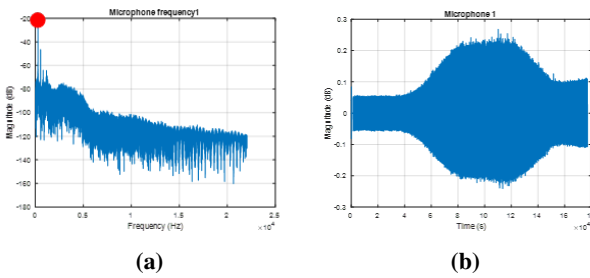


Figure 5: Display of gunshots in time domain

i. Filter Results of Each Microphone

From the application of the FIR filter to the sound of gunshots captured by microphone 1, the results are displayed in the Matlab simulation in Figure 6.

Figure 6 shows the FIR filter results of the gunshot sound received by microphone 1. The highest magnitude value is 0.0282. The SNR value after filtering is 33.36 dB. The SNR increased by 27.39% after filtering. Compared to the SNR of other microphones, the SNR of microphone 1 is the lowest, due to the considerable

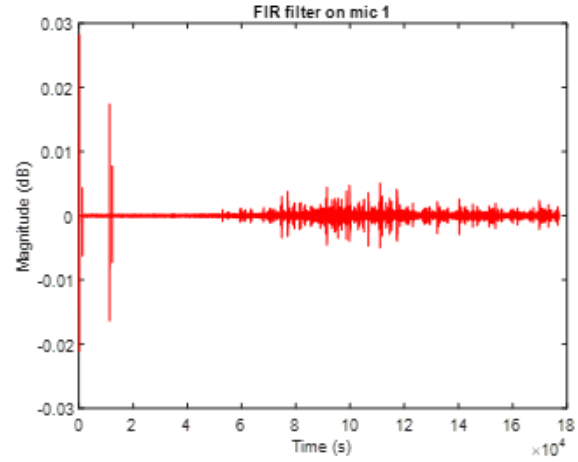


Figure 6: FIR filter results on mic 1

distance between the microphone and the source of the gunshot.

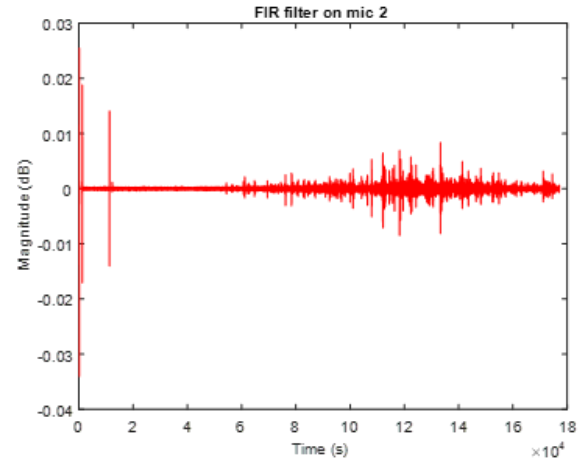


Figure 7: FIR filter results on mic 2

Figure 7 shows the FIR filter results of the gunshot sound received by microphone 2. The magnitude value is quite high at 0.0255. The SNR value after filtering is 33.94 dB. The SNR increased by 30.34% after filtering. The SNR on microphone 2 is quite high, which is due to the close proximity of the sound source to the gunshot source.

Figure 8 shows the FIR filter results of the gunshot sound received by microphone 3. The highest magnitude value is 0.0834. The SNR value after filtering is 41.61 dB. The SNR increased by 33.71% after filtering. Microphone 3 produced the highest SNR because the sound source was closest to microphone 3.

Figure 9 shows the FIR filter results of the gunshot sound received by microphone 4. The magnitude value is quite high at 0.0352. The SNR value after filtering is 41.23 dB. The SNR increased by 32.67% after filtering.

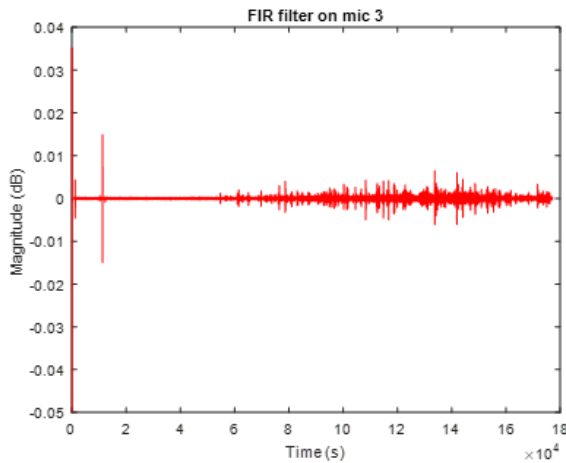


Figure 8: FIR filter results on mic 3

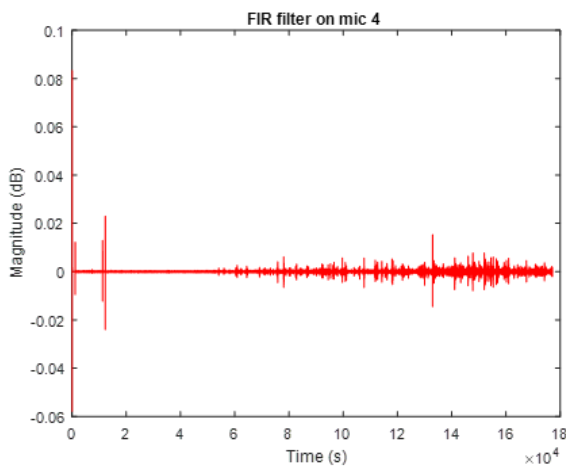


Figure 9: FIR filter results on mic 4

ii. Gunshot Detection

In this study, data was collected several times using four microphone sensors placed at intervals of 30 cm in a linear fashion. The sound source was moved around. The average accuracy of the shot coordinates and detected points is shown in Figure 10.

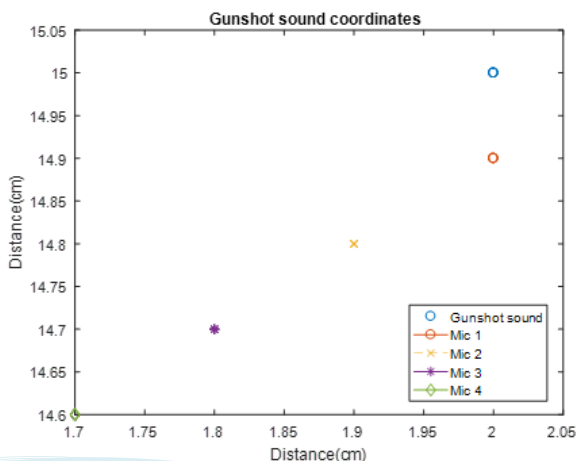


Figure 10: Gunshot coordinates at point (2,15)

Figure 10 shows a comparison of the shot coordinates with the detection point coordinates from 10 tests. Starting with the closest distance to the receiving sensor (microphone) located at point (2,15), which means the microphone is at coordinates 2 cm on the X-axis and 15 cm on the Y-axis. From the four microphones as sensors, the detection coordinates closest to the sound source of the second microphone is 98.67%, the detection accuracy of the third microphone is 98%, and the furthest sensor detected is the fourth microphone with a detection accuracy of 97.34%.

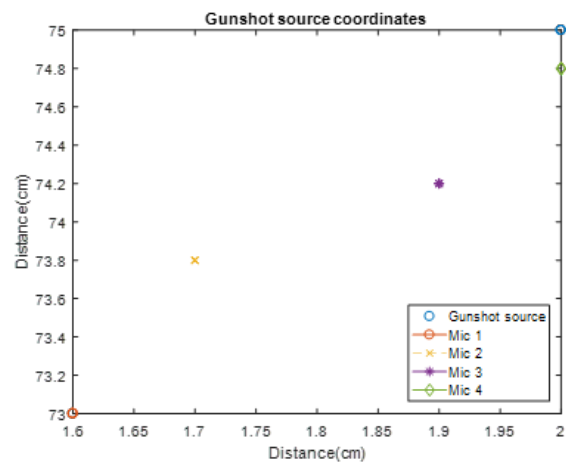


Figure 11: Gunshot coordinates at point (2,45)

Figure 11 shows a comparison of the sound coordinates of the shots with the detection point coordinates from 10 tests. Starting with the closest distance to the receiver sensor (microphone) located at point (2,45), which means the microphone is at coordinates 2 cm on the X-axis and 45 cm on the Y-axis. Among the four microphones used as sensors, the detection coordinates closest to the sound source of the gunshot are from the second microphone with a detection accuracy of 99.78%, the detection accuracy of the third microphone is 98.89%, the detection accuracy of the fourth microphone is 98.45%, and the farthest sensor to detect is the first microphone with a detection accuracy of 97.78%.

Figure 12 shows a comparison of the shot coordinates with the detection point coordinates from 10 tests. Starting with the closest distance to the receiving sensor (microphone) located at point (2,75), which means that the microphone is at coordinates 2 cm on the X axis and 75 cm on the Y-axis. Of the four microphones used as sensors, the detection coordinates closest to the source of the gunshot were obtained by the fourth microphone with a detection accuracy of 99.74%, the third microphone with a detection accuracy of 98.94%, the second microphone with a detection accuracy of 98.4%, and the farthest sensor detected was the first microphone with a detection accuracy of 97.4%.

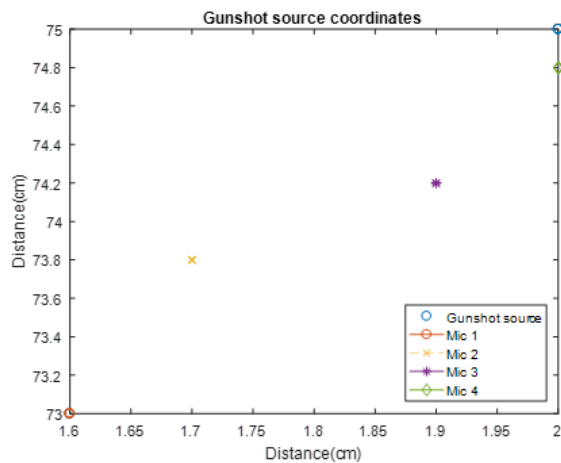


Figure 12: Gunshot coordinates at point (2,75)

From the three testing scenarios, namely testing with the sound source placed at points (2,15), (2,45), and (2,75), the highest accuracy was 99.78% and the lowest accuracy was 97.34%. This indicates that detecting the source of gunfire using the TDoA method is sufficiently accurate to determine the origin of the sound with high accuracy.

IV. CONCLUSION

From the research and testing that has been conducted, it can be concluded that the detection of the origin of gunshots will yield maximum results with the addition of an FIR filter, which shows an increase in SNR in the simulation results of 27% to 32% from the SNR before the FIR filter was added. Gunshot source detection using TDoA can effectively detect the source of the sound with the highest detection accuracy of 99.78%.

This accuracy value is higher than the detection accuracy using the MVDR algorithm. This accuracy is also influenced by the distance between the microphone sensor and the sound source. The closer the sound source is to the microphone sensor, the closer the accuracy will be to 100%. In the future, it may be possible to design a gunshot location detector consisting of a mobile and real-time microphone configuration.

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