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Abstract. In this paper, an acoustic threat detection system is investigated as preliminary study of one of the anti-terrorism systems. The proposed system is a prototype of acoustic threats detection, classification, and direction finding system. For this purpose, an experiment is performed to test the capability of a proposed warning system to perform the task accurately. The direction of the sound source is determined by means of two microphones. The angle to the acoustic threat is calculated based on time difference of arrival (TDOA). The limitations of the system are discussed and some possible solutions are introduced to improve the performance of the system.

1. Introduction

Sound localization is the science concerned with determining the distance and direction of a sound source with the knowledge of the sound signals emitted from it [1]. Knowing these two parameters allows obtaining an accurate localization of a sound source which is important in many applications, especially at the present time, in the field of force protection and anti-terrorism. Technology that detects gunfire has existed for nearly two decades. For this purpose, many approaches have been proposed [2-4]. In many applications, the distance to the sound source is not as important as the direction information and this enables to design cost effective and less-complex systems. Some applications that ignore the distance and depend on the direction for locating the sound source like gunfire location [4], and intrusion detection systems [5]. As many other inventions all along the history, one of the first purposes of sound location was for military applications. A method called sound ranging was developed. Its principle is obtaining the coordinates of a hostile by the sound of its gun firing [6]. This technique allows the detection of the enemy even without direct vision. Other studies regarding sound localization are performed for closed or open environments, some of them introduced some techniques to minimize the errors [7], and echo or noise cancellation [8]. The common factors that control the system performance are either the number of microphones used in the array[9-13] or the technique of the signal processing after detecting the sound [14-16].The physical characteristics and the spectral content of the impulse noise from common weapons such as pistol 9 mm, military rifle (7.62 mm), and other weapons are discussed in [17]. The microphone arrays should be designed to make sure these frequencies are detected.

Optical or acoustic methods are the common techniques for acoustic threats detection such as sniper detection systems. Optical systems can be based on one or a combination of a laser system and a thermal camera. Laser systems used for sniper detection, based on cat's eye effect, can detect the sniper before firing but false alarm rate in these systems is still a limiting factor and needs further investigation [18, 19]. Thermal camera system can be used to detect the sniper before firing and just after the firing by

detecting the muzzle flash[20]. Clear line of sight to the sniper's weapon is required to use the optical systems for sniper detection which is considered a limitation or a disadvantage of these systems. The acoustic systems used for sniper detection can't detect the sniper before shooting. So, using these systems alone can limit losses in troops and determine the direction of the threat to deal with the executor. The advantage of acoustic sniper detection systems is the unnecessity of the presence of a direct line of sight between the detector and the weapon if distributed sensor arrays are used. It is expected that best results can be obtained if the optical and acoustic systems are combined.

In this paper a simple technique to determine the direction of a sound source in real time by two microphones is proposed. The proposed warning system allows simultaneous acquisition, recording, processing and analysis of the incoming acoustic signals using two microphones for signal identification and determination of the direction of the acoustic source. Signal processing is performed using MATLAB.

2. Experimental setup

The proposed system is based on a single point sensor (SPS) which usually used to point a surveillance camera towards the gunfire. SPS has some disadvantages;

It generally requires a line-of-sight for accurate direction finding of the acoustic source.

It lacks the ability to correctly calculate range to the sound source instead it can just find the direction to the source. Even the correct direction can be misled by non-direct path propagation.

The advantage of using SPS is its speed of reaction. It can detect the acoustic threat within 1 second or less. For our purpose SPS is adopted. The system consists of two microphones, microcontroller, servo motor, LCD, cables, connectors and a computer for processing and display. At least two microphones are required to extract the time delay between the two measured signals and consequently to calculate the direction of arrival. The used microphones are omnidirectional, have frequency response range 50 Hz to 20 kHz, and sensitivity -46 ± 2.0 dB at 1 kHz.
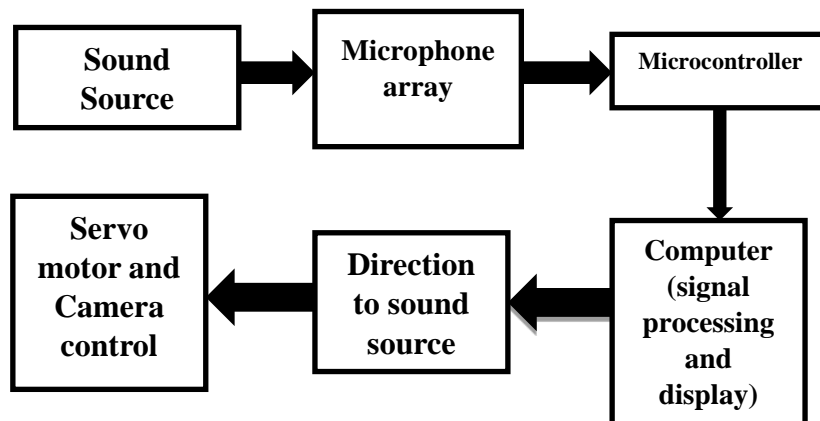

Figure 1. Block diagram of the proposed acoustic threat detection system

The Block diagram of the proposed acoustic threat detection system is shown in Figure 1. The sound source emits a signal that acquires some noise and reflections from the surrounding environment while traveling to the microphones. The output analog electrical signals from the two microphones are amplified and converted to digital signals using the microcontroller which is connected to the computer where the signals are acquired and processed in real time by MATLAB to determine the direction of the sound source. The signals are sampled at 44 kHz allowing analysis of the detected acoustic signals in the audible band. The angular information is sent back to the microcontroller that controls a servo motor

and a camera. The initial experimental setup of the proposed acoustic threat detection and direction finding system is shown in Figure 2. This set up was modified many times during the study.
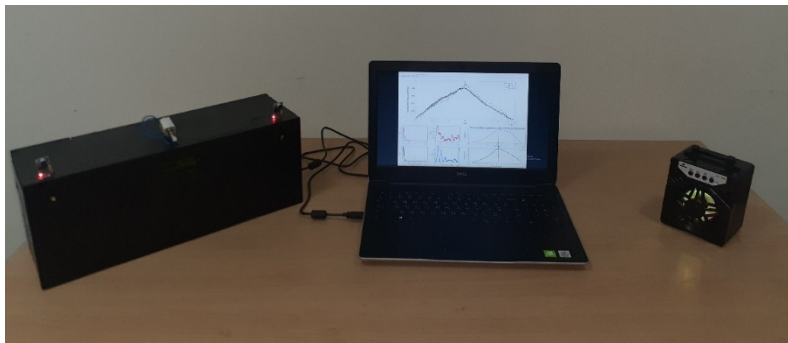

Figure 2. The initial experimental setup of the proposed acoustic threat detection and direction finding system.

3. Signal processing and direction finding

After detection of the incoming acoustic signals, cross-correlation between the recorded acoustic signals is used to calculate the bearing of the acoustic source. Two microphones with spacing (L) are used to receive the acoustic signal radiated from a source makes an angle (θ) with the normal to a reference line between the sound detectors as described in Figure 3. The spacing between the source and the sound detectors is much larger than (L). For linear arrays, the maximum frequency of operation is given by $c/2L$, c represents the velocity of sound, and L is the spacing between two elements of the array [21]. Taking into account the condition to avoid the effect of the grating lobes that the microphone spacing must be less than or equal to one-half of the minimum wavelength and is calculated from**;**

$$L \leq \frac{\lambda_{min}}{2} \; or \; L \leq \frac{c}{2f_{max}} \tag{1}$$

The two microphones are separated by distance L equal 10 cm and mounted on a box houses the electronic components. The signal radiated from the sound source received the two microphones with delay ΔT between them:
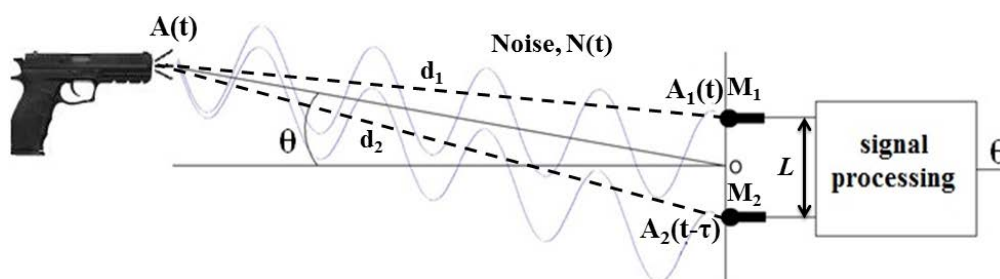
$$\Delta T = \frac{L \sin \theta}{c} \tag{2}$$

Figure 3. Description of the physical setup.

let $A(t)$ is the unknown acoustic signal emitted by the sound source, $A_1(t)$, and $A_2(t)$ are the observed acoustic signals recorded by the two microphones, $N(t)$ is the noise, and M_1, M_2 are the known positions of the microphones, $\tau_1 = d_1/c$, and $\tau_2 = d_2/c$ are the time of arrival from the sound source to microphone1,

and microphone 2, respectively, and the time difference of arrival between the sound detectors is $\Delta T = \tau_1 - \tau_2$. The recorded signals can be expressed by;

$$A_1(t) = A(t - \tau_1) + N_1(t) \tag{3}$$
$$A_2(t) = A(t - \tau_2) + N_2(t) \tag{4}$$

The signals $A_1(t)$ and $A_2(t)$ detected by the sound detectors are the same signals with delay ΔT:

$$A_2(t) = A_1(t - \Delta T) \tag{5}$$

The cross correlation $A_{12}(\tau)$ of the two signals;

$$A12(\tau) = \int_{-\infty}^{\infty} A1(t') A2(\tau - t') dt' \tag{6}$$

$$A_{12} = A_{11}(\tau - \Delta T) \tag{7}$$

The cross-correlation $A_{12}(\tau)$ of the two acoustic signals can be considered as the autocorrelation A_{11} of the detected signal from the microphone (M_1) but with delayed time $\tau = \Delta T$. The maximum of the autocorrelation of a signal is at $\tau = 0$, consequently, the maximum of $A_{12}(\tau)$ is at $\tau = \Delta T$. This maximum of the cross-correlation is be used to determine the direction of the sound source. Source bearing angle can be calculated from:

$$\theta = \arcsin(c\Delta T / L) \tag{8}$$

The following steps are followed for detecting and direction finding of the acoustic source:

- Studying the fundamental acoustic parameters to detect the acoustic threat such as acoustic signatures, the transmission loss of the signal as propagates through the channel, and the environmental noise.
- Signal from the source is detected and recorded (this simulates the acoustic signature of the acoustic source).
- Convert the signal from time domain to frequency domain, and identify the spectral components of the signal.
- Identify the received signal.
- If the signal is identified then calculate the cross-correlation of the detected signals, calculate delay time, and estimate the bearing of the sound source.

4. Experimental results and analysis

The system was integrated and tested in the lab. Serial communication is established between the microcontroller and the computer and the system is controlled by MATLAB code. The two signals were captured by the microphones and one of them is delayed version of the same signal. According to analysis and algorithms of cross correlation, the time delay and the angle of the source are calculated. The angle is displayed on the LCD, and the microcontroller is used to move the servo motor to the calculated direction of the sound source. For this purpose, three different audio signals represent different guns and rifles sounds are used to generate the sound and simulate the acoustic threats. In the paper, we denote these signals as gun 1, gun 2, and rifle. The spectral content of the received audio sound signals of the gun 1, and rifle in the form of a spectrogram is shown in Figure 4.
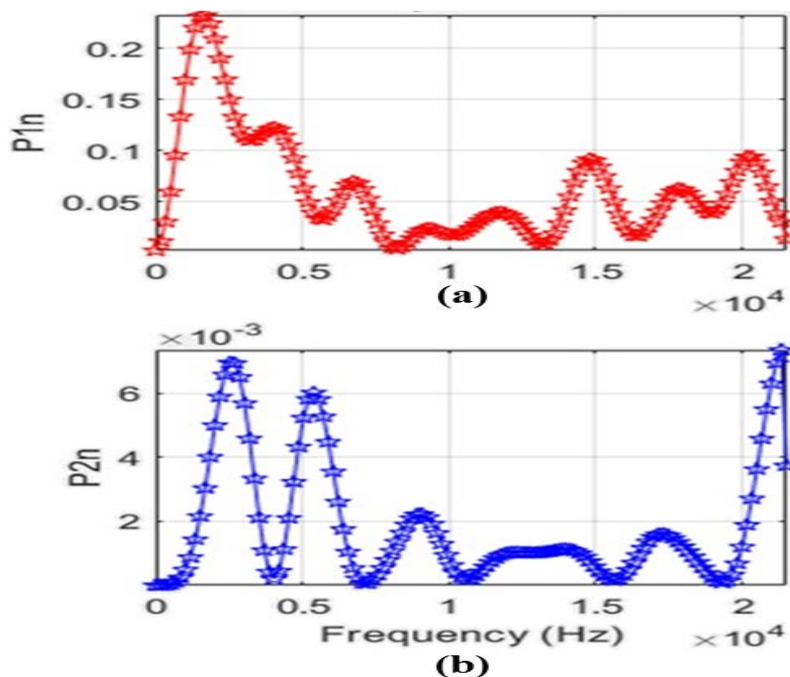
Figure 4. The spectral content of the received audio sound signals of the gun 1 (a), and rifle (b).

The cross correlation between output signal from two microphones for gun 1 as audio sound source is shown in Figure 5 (a). While the auto correlation of the same signal of single microphone is shown in Figure 5 (b) for comparison. It can be seen that at the lag, the peak of the correlation output occurs. This lag represents the time delay between the signals. The correlation sequence peaks when the lag is 0.3 ms which represent the time delay between the two signals. Delay between the received signals is calculated using cross correlation function to determine the sound source direction which is 15°.
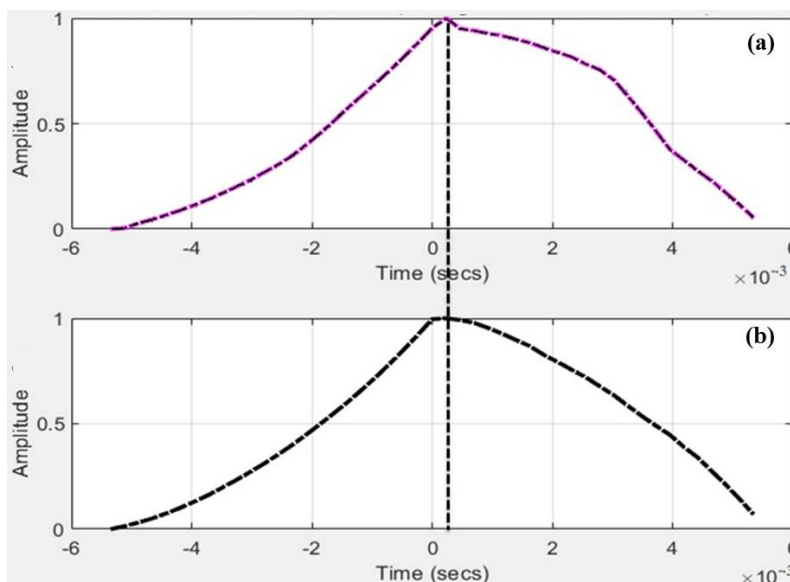

Figure 5. cross correlation between output signal from two microphones.

For signal identification, the three investigated signals are recorded as reference signals and the normalized cross correlation of the received sound signal and the recorded signals is calculated as shown

in Figure 6. The matching level of the measured signals compared to the recorded reference signal of gun 1 is shown in Table 1. It is easy to set a certain matching level for signal identification.
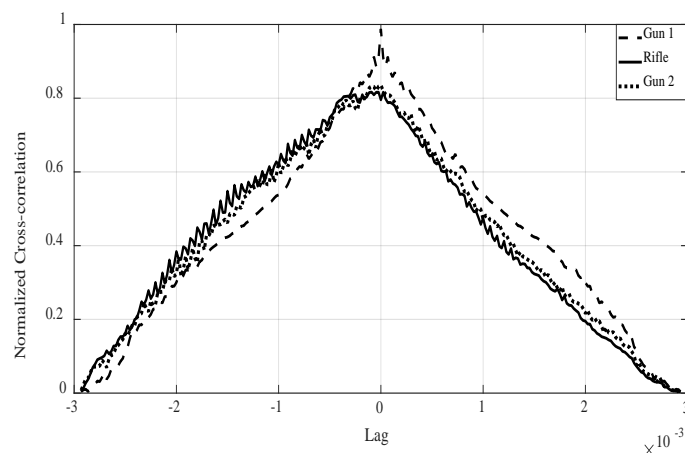

Figure 6. Normalized cross correlation of the three measured signals (gun 1, gun 2, and rifle) compared to the reference signal of gun 1.

Table 1. The matching level of the measured signals compared to the recorded reference signal of gun 1.

Measured signal	Matching level (%) (Reference signal is Gun 1)
Gun 1	99.2
Gun 2	83.56
Rifle	81.65

The accuracy of the signal identification is 100% but the accuracy of direction finding is about 60%. This can be attributed to using only two microphones in the experiment, and the room reverberation or the reflections from the room walls that form many sources of sound to the system. This causes inaccurate calculation of the sound source direction.

5. Conclusion
The proposed system is used to estimate the direction of acoustic threats using two microphones that can emulate the detection of the muzzle blast of a gunshot. In the experiment, the incoming signals were detected, recorded, identified and processed to determine the sound source direction based on TDOA. The proposed system showed a good performance. The accuracy of calculations can be enhanced by taking into account some considerations like using microphones with better sensitivity, number of the microphones in the array, optimizing the spacing between the microphones, and testing the system in open field to avoid the reflections of the signal from the flat surfaces or walls that causes inaccurate calculation of the sound source direction. The system can be developed to be mounted either at a fixed location or on a moving vehicle.

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