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Sensor fusion, sensitivity analysis and calibration in shooter localization systems

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ABSTRACT

This paper analyses the principles and the underlying mathematical model for acoustic based shooter detection systems. These systems use the muzzle blast and acoustic shock waves to compute the shooter's location. Our detection system works on a distributed sensor network where microphone arrays are used as sensors. Detection algorithms run concurrently at each node. After determining the wave directions, the information is passed to the central node. The central node fuses data coming from each sensor with our optimization algorithm. For correct georeferenced fusion, GPS, accelerometer and magnetometer data are used. A mathematical framework of the problem with possible node outputs has been developed in this study. Our framework supports all possible combinations of muzzle blast and shockwave measurements at each sensor node. The simulation for various scenarios has been performed and analyzed. Imperfections in the placements of microphones within the arrays, uncertainty of sensor locations and time uncertainty in time of arrival estimations are investigated as regards to their effect on system performance. In order to analyze the effect of these imperfections on the calculated shooter position, shooter's relative direction and bullet direction, a detailed sensitivity analysis has been done. A system calibration method has been developed in this study to reduce imperfections and enhance the shooter localization performance. In addition, acoustic-based shooter localization hardware has been designed within the study. The study involves not only the simulation but also the results of real tests.

1. Introduction

In today's border security concept, critical infrastructure protection has a high priority. Especially border posts, personnel buildings and pipelines are the main examples. In protection of these sites and to increase the situational awareness, automated systems are essential. In the case of shooter attack, fast response can increase the survival rate. Therefore, shooter detection systems are developed and used among other systems. Shooter detections systems basically use acoustic and electro-optic sensors. In this paper, we will focus on the use of acoustic sensors.

The purpose of acoustic detection systems is to collect and analyze the data gathered by acoustic sensors to locate the shooter. Acoustic shooter detection systems can be integrated with video surveillance systems or automated weapons to detect and locate the shooter so that the aggressor can be retaliated with quick response to minimize casualty. Thus, it is important to understand the limits of shooter detection systems.

Localization of firearms by detecting and processing the acoustic waves has been in practice since First World War. One of the first systems was an acoustic system called PALS developed in Italy to detect the artillery fires [1].

The range of acoustic sensors are not as high as radar sensors; acoustic wave propagation highly depends on atmospheric conditions. Temperature variations in the path can refract the acoustic waves through propagation. These aspects have to be kept in mind in designing a practical acoustic shooter detection system.

In a typical shooter detection system, there are at least three sensor subsystems which consist of microphone arrays. The embedded hardware inside the sensor subsystems runs the array signal processing algorithms. At the center hub of the systems lies the Data Fusion Center (DFC). DFC collects the data coming from the sensor subsystems apply fusion algorithms and provide the high precision positioning coordinates to the command and control system. The main duty of this central node is to process raw individual sensor measurements to form a more sophisticated and informative fused

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knowledge. By the help of this data fusion, it is possible to precisely locate the shooter and track its location.

These sensor subsystems also have an inertial measurement system for georeferenced measurements and a GPS receiver for positioning. Synchronization of distributed sensors is critical in sensor fusion of distributed sensor arrays. There are novel synchronization methods in the literature for distributed sensor arrays [2–4]. In the scope of this study, we only used timing output of GPS receivers for synchronization.

Modern systems use multiple microphones and apply array signal processing. ESPRIT algorithm makes frequency domain analysis and uses eigen-decomposition in covariance matrix to find the signal's direction of arrival passively. The con side of these algorithms is the necessity to use too many sensors. Another similar algorithm is MUSIC (Multiple Signal Classification). In this algorithm, narrowband assumption is essential for the success of this algorithm [1].

BBN company has developed a shooter detection system using the TOA (Time of Arrival) of the muzzle blast wave and shock wave in 1996 [5]. They also estimated the caliber of the firearm. For this purpose, they used a microphone array consisting of 4 microphones that are placed in a tetrahedral form. One advantage of using a microphone array is having minimum synchronization error since all the microphones are connected to the same hardware. A basic mathematical model similar to one in BBN for the bullet physics is also given in this paper.

The papers [6,7] use a similar TOA method. But instead of array microphones, they use distributed unsynchronized microphones. At each microphone, muzzle blast and shockwave time of arrival are detected and their time difference is processed at the central node. There is no synchronization problem as only the TOA time differences are processed. But in this method, directional uncertainty increases as the time difference between shock wave and muzzle blast basically gives more information on the range. Because of the directional observability problem, the directional uncertainty becomes quite high.

In [8], a prototype system design resembling [5] has been presented. Low-level muzzle blast and shock wave detection and weapon classification algorithms are discussed. [9] gives a description of the firearm detection system called PILAR that is developed by French 01dB-Metravib company. In the system, wireless 4-microphone arrays are used. TOA methodology is utilized. In the case of 2 sensor systems, their performance metrics are given as $\pm 2^\circ$ in azimuth angle uncertainty, $\pm 5^\circ$ elevation angle uncertainty and 30% uncertainty in range [10] summarizes a list of performance metrics in a shooter detection system which are azimuth accuracy, elevation accuracy, range accuracy, classification success, etc.

Attitude detection algorithms that can be used in a shooter detection system are given in [11]. Accordingly, accelerometers can find the local gravity direction and determine the locally level plane. In this plane, magnetometers will find the north direction.

In our study, we formed the solution for shooter detection in terms of a sensor network of microphone arrays [12]. Any of the arrays may detect both muzzle blast, and shock waves or just one of them depending on the geometry. Our framework fuses the available information from each sensor. In the literature, there is not enough emphasis on the effects of the modeling uncertainties in the performance of shooter detection system. Our paper shows these effects by our sensitivity analysis. We developed a system calibration model as a result of the sensitivity analysis. This method is used to calibrate uncertainties in the system parameters to enhance system performance. Finally, we implemented our framework with novel MEMS microphones.

2. Shooter localization

2.1. Bullet physics

After a gunfire, two types of waves are formed. First one is the result of the blast while the bullet is traveling the barrel and it propagates spherically at the speed of sound. These sound waves are below 500 Hz and called muzzle blast. The second acoustic wave stems from the air friction of the bullet that is traveling at a multitude speed of sound and this type of wave travels conically around the path of the bullet. This type of wave is called a shock wave. Shock wave has a higher frequency content in 1–4 kHz and characterized as an N shaped signal in the time domain. Fig. 1 shows both muzzle blast and shockwave signals corresponding to a gunshot.

As the muzzle blast sound travels slower than the bullet, the first wave that comes to the point closest to the bullet path is the shock wave. Of course, this can change according to the geometry of sensor, shooter and bullet direction. Shock waves alone are not sufficient to locate the shooter but together with the muzzle blast, they provide crucial information.

2.2. Mathematical model for bullet physics

Acoustics formed by a typical shooting and the sensor geometry is given in Fig. 2. Muzzle blast wave propagates spherically centered at the tip of the muzzle with a sound of speed which depends on atmospheric conditions. Shock waves travel conically around the bullet's path, and the cone angle (θ) depends on the bullet speed as $sin\theta = 1/M$. Here θ denotes the cone angle, M denotes the bullet speed (v) in terms of Mach number (1 Mach = local speed of sound c) where $M = v/c$. Therefore, the more the bullet speed, the less the cone angle. A supersonic bullet speed can range from 1–5 M.

In Fig. 2, x_0 shows the point where the bullet leaves the muzzle, at time t_0. Muzzle blast wave propagates circularly from that point. Muzzle blast sound arrives at the sensor subsystem s_1 at time t_{n1} whereas the shock wave arrives at time t_{s1}. The time instants mentioned here are ToA's at the reference microphone at sensor subsystem. Shock wave that first comes to the sensor at s_1 is formed at x_1; bullet comes to this point at a higher speed than the sound speed, after that point it travels at 1 Mach.

By using TOA algorithms as mentioned above, the muzzle blast and shockwave incoming directions u_1, u_2 can be calculated. In our setting:

$$\begin{aligned} x_0 &= x_2 + c\ u_2\,(t_{s1} - t_0) \\ x_0 &= s_1 + c\ u_1\,(t_{n1} - t_0) \end{aligned} \tag{1}$$

Then,

$$s_1 + c\ u_1(t_{n1} - t_0) = x_2 + c\ u_2(t_{s1} - t_0) \tag{2}$$

As $s_1 x_2$ is perpendicular to u_2, t_0 can be found as below:

$$\begin{aligned} &(x_2 - s_1) \cdot u_2 = 0 \\ &(-c\ u_2 t_{s1} + c\ u_2 t_0 + c\ u_1 t_{n1} - c\,u_1 t_0) \cdot u_2 = 0 \\ &t_0 = \frac{t_{s1} - t_{n1} u_1 \cdot u_2}{1 - u_1 \cdot u_2} \end{aligned} \tag{3}$$

Shooter location x_0 can be calculated from Eq. (1) by using t_0 calculated from Eq. (3). A similar result can be found in [8]. When there is only one sensor subsystem, bullet path cannot be computed. The bullet path can be computed when the path lies between two sensor subsystems. In single sensor case, shooter position can be determined because both shock wave and muzzle blast directions and timings are available.

In fact, this setting assumes that the cone angle is constant and the bullet propagates at a constant speed which is not exactly cor-