ENHANCED DECISION SUPPORT SYSTEM FOR WILDFIRE DISASTER RESPONSE AND MANAGEMENT (DISASTERAWARE)

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Approval of the thesis:

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ABSTRACT

**ENHANCED DECISION SUPPORT SYSTEM FOR WILDFIRE DISASTER RESPONSE AND MANAGEMENT (DISASTERAWARE)**

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This thesis proposes a generalized estimation framework for acoustic based shooter localization system relying on time of arrival (ToA) and direction of arrival (DoA) of gunshot acoustic events, namely muzzle blast and shockwave. This framework is valid in case both acoustic events are present or one of them is missing. Furthermore, it provides a solution not only for a single shooter but also for simultaneous multiple shooters. As regards to details, this thesis proposes a DoA estimation method based on beamforming for simultaneous multi shooter detection in reverberant environment. A system calibration method for adjusting microphone positions in the microphone array and estimating local speed of sound to enhance shooter localization accuracy is also proposed in this thesis. Finally, this thesis proposes an architecture and a hardware design for the implementation of this acoustic based shooter localization system.

Keywords: Shooter Location Estimation, Simultaneous Multiple Acoustic Source Detection, Beamforming, Acoustic System Calibration, Acoustic Embedded System Design

ÖZ

**Afet Müdahalesi ve Yönetimi İçin Gelişmiş Karar Destek Sistemi (DISASTERAWARE)**

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Yüksek Lisans, Elektrik ve Elektronik Mühendisliği Bölümü

Tez Yöneticisi : Prof. Dr. Mehmet Kemal Leblebicioğlu

Eylül 2017, 104 sayfa

Bu tez, atış kaynaklı namlu sesi ve şok dalgasından elde edilen varış zamanı ve varış yönü bilgilerinden faydalanan akustik tabanlı atış konum tespiti yöntemi sunmaktadır. Bu sunulan yöntem hem her iki akustik olayın hem de akustik olaylardan birinin eksik olduğu durumda geçerlidir. Bu yöntem sadece tek atış kaynağı için değil ayrıca eş zamanlı ve çoklu atış kaynak tespitine de olanak sağlamaktadır. Bu bağlamda, eş zamanlı ve çoklu atış kaynak tespiti için hüzme oluşturma temelli bir varış zamanı tespit yöntemi bu tezde anlatılmaktadır. Bunların yanı sıra, bu tezde atış konum tespiti doğruluğunun arttırılması için mikrofon dizinindeki mikrofon pozisyonlarını doğru olarak ayarlamak ve ortam ses hızını tahmin etmek için sistem kalibrasyon yöntemi sunulmaktadır. Ayrıca, akustik tabanlı atış konum tespitine yönelik olarak donanım mimari ve tasarımı bu tez içinde sunulmaktadır.

Anahtar Kelimeler: Atış Konum Tespiti, Eşzamanlı Çoklu Akustik Kaynak Tespiti, Hüzme Oluşturma, Akustik Sistem Kalibrasyonu, Akustik Gömülü Sistem Tasarımı

DEDICATION

To my beloved wife Emine, and our sons Kuzey, Rüzgar, and Atlas — for their endless love, patience, and encouragement throughout this journey. You are the calm after every storm and the light guiding every decision.

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I would like to express my deepest gratitude to my supervisor, Prof. Dr. Mehmet Kemal Leblebicioğlu, for his invaluable guidance, patience, and continuous support throughout this research. His insightful feedback, constructive criticism, and calm mentorship have shaped both this dissertation and my professional perspective. His encouragement, especially during times of fatigue and uncertainty, always inspired me to stand up again and move forward with renewed determination.

I would also like to express my sincere appreciation to Dr. Tolga Sönmez for his thoughtful suggestions, constructive approach, and valuable guidance throughout this study. His perspective and contributions have greatly enhanced the academic and methodological depth of this work.

I would also like to extend my heartfelt thanks to Furkan and İlayda for their sincere support and companionship throughout this journey. While I aim to be a role model for them, they, in turn, believed in me and inspired me with their trust and shared vision. I see them not only as colleagues but as true siblings walking the same path toward growth and purpose.

Finally, and most importantly, I owe my deepest gratitude to my wife, Emine, and my sons, Kuzey, Rüzgar, and Atlas. This achievement would not have been possible without their love, patience, and sacrifices.

Emine, the love of my life, not only stood beside me but also organized, managed, and coordinated every aspect of our family life so that I could devote myself fully to this doctoral journey. Her unwavering support and understanding kept everything together when the demands of research were overwhelming.

To my sons, Kuzey, Rüzgar, and Atlas, I hope this dissertation serves as an example that perseverance, curiosity, and discipline can turn even the most challenging dreams into reality. You are my greatest inspiration and the true meaning behind this effort.

Thank you all — this accomplishment belongs as much to you as it does to me.

TABLE OF CONTENTS

[ABSTRACT v](#_Toc211766880)

[ÖZ vi](#_Toc211766881)

[DEDICATION vii](#_Toc211766882)

[ACKNOWLEDGEMENTS viii](#_Toc211766883)

[TABLE OF CONTENTS ix](#_Toc211766884)

[LIST OF TABLES xi](#_Toc211766885)

[LIST OF FIGURES xii](#_Toc211766886)

[LIST OF ABBREVIATIONS xiii](#_Toc211766887)

[CHAPTERS 1](#_Toc211766888)

[2. INTRODUCTION 1](#_Toc211766889)

[3. ACOUSTIC PROPERTIES OF GUNSHOT 2](#_Toc211766890)

[3.1 Overview of Gunshot Acoustics 2](#_Toc211766891)

[4. ESTIMATION FRAMEWORK 3](#_Toc211766892)

[4.1 Derivation of the Estimation Framework 3](#_Toc211766893)

[5. TIME AND DIRECTION OF ARRIVAL ESTIMATION 5](#_Toc211766894)

[5.1 Overview 5](#_Toc211766895)

[6. SYSTEM MODEL AND CALIBRATION 7](#_Toc211766896)

[6.1 System Model 7](#_Toc211766897)

[7. SYSTEM DESIGN 9](#_Toc211766898)

[7.1 Overview 9](#_Toc211766899)

[8. SIMULATION AND TEST RESULTS 10](#_Toc211766900)

[8.1 Overview 10](#_Toc211766901)

[9. CONCLUSIONS AND FUTURE WORKS 12](#_Toc211766902)

[9.1 Conclusions 12](#_Toc211766903)

[REFERENCES 14](#_Toc211766904)

[APPENDICES 18](#_Toc211766905)

[A. ANALYTICAL EXPRESSION OF MUZZLE BLAST 18](#_Toc211766906)

[B. ANALYTICAL EXPRESSION OF SHOCKWAVE 19](#_Toc211766907)

[C. MODEL OF REFLECTION AND REVERBERATION 20](#_Toc211766908)

[D. SPHERICAL COORDINATE SYSTEM 22](#_Toc211766909)

LIST OF TABLES

**TABLES**

[Table 3.1: Description of Parameters in Geometry of Estimation Framework 4](#_Toc211766649)

LIST OF FIGURES

**FIGURES**

[Figure 3.1: Geometry of Estimation Framework with respect to ith Sensor 3](#_Toc211766650)

[Figure 4.1: Block Diagram of Acoustic Event Analysis in a Sensor Node 5](#_Toc211766651)

[Figure 5.1: Acoustic Shooter Localization System Model 7](#_Toc211766652)

[Figure C.1: Multiple Reflection IIR Filter (a) and All Pass Reverberator (b) 21](#_Toc211766653)

[Figure C.2: Overall Block Diagram for Reverberation 21](#_Toc211766654)

Figure D.1: Spherical Coordinate System................................................................. 22

LIST OF ABBREVIATIONS

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CHAPTER 1

CHAPTERS

# INTRODUCTION

Security is a prominent need throughout the history of humanity. It is true not only for the individuals but also for the countries; therefore, the governments allocate funds for military and civil security systems. Regular security systems basically consist of wide area surveillance, perimeter protection, and distributed intrusion detection subsystems. Security system solutions vary and extend to enhance situational awareness according to the resultant requirements for threat analysis.

CHAPTER 2

# ACOUSTIC PROPERTIES OF GUNSHOT

## Overview of Gunshot Acoustics

Shooter localization methods use the speed of sound as a system parameter which is completely dependent on environmental parameters such as temperature, humidity, pressure, and air density (Bohn, 1988). In fact, this thesis assumes dry air for practical calculation of the local speed of sound so the speed of sound can be calculated as (1).

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CHAPTER 3

# ESTIMATION FRAMEWORK

## Derivation of the Estimation Framework

The shooter localization framework relies on DoA’s and ToA’s of muzzle blast and shockwave signals to estimate shooter location and trajectory of the projectile. The formulation of the framework is derived from the geometry depicted in Figure 3.1. The geometry is constructed according to the acoustic properties described in Chapter 2 with the assumptions that the projectile is propagating at a constant speed on a straight trajectory and both of acoustic events are planar waves with respect to the sensor. In detail, the geometry consists of the allocation of sensor nodes and shooter, projectile trajectory, propagation, DoA and associated ToA of shockwave and muzzle blast and assistive geometric parameters. Figure 3.1 illustrates the geometry of estimation framework for a single sensor, this geometry can be generalized for the multi sensor case. Table 3.1 lists the detailed description of parameters in geometry.



Figure 3.1: Geometry of Estimation Framework with respect to ith Sensor

Table 3.1: Description of Parameters in Geometry of Estimation Framework[[1]](#footnote-1)

|  |  |
| --- | --- |
|  | Location of ith sensor |
|  | Shot Time |
|  | ToA of muzzle blast at ith sensor |
|  | ToA of shockwave at ith sensor |
|  | DoA unit vector of muzzle blast with respect to ith sensor |
|  | DoA unit vector of shockwave with respect to ith sensor |
|  | Unit vector of bullet trajectory |
|  | Location of shot in Cartesian coordinates |
|  | Location of imaginary edge for assistive purpose |
|  | Detachment point of shockwave with respect to ith sensor |
|  | Shockwave cone angle |
|  | Miss angle, angle between ith sensor location and the closest point on trajectory to the sensor with respect to the shooter location |

CHAPTER 4

# TIME AND DIRECTION OF ARRIVAL ESTIMATION

## Overview

Acoustic shooter localization requires precision in ToA and DoA measurements, used as essential information in the estimation framework. There are several approaches in the literature for muzzle blast and shockwave detection which can be grouped as time and frequency methods. Lédeczi, et al., (2005) proposes time domain analysis utilizing zero-crossing coder for detection and feature extraction of muzzle blast and shockwave among possible candidates. On the other hand, frequency domain based methods use wavelet analysis to classify acoustic events (Libal & Spyra, 2014; Mays, 2001). Those two methods are not superior with respect to each other, both aim to obtain ToA’s and DoA’s of muzzle blast and shockwave signals in precision.

Each microphone in the array continuously measures and records acoustic signals around. Recordings of each microphone are processed to detect and identify muzzle blast and shockwave and then to extract ToA and DoA of corresponding signals. This signal processing phase can be modeled by a block diagram as depicted in Figure 4.1.



Figure 4.1: Block Diagram of Acoustic Event Analysis in a Sensor Node

CHAPTER 5

# SYSTEM MODEL AND CALIBRATION

## System Model

Acoustic based shooter location estimation framework can be modelled as a functional system which relates ToA and DoA values extracted from the recorded signals to outputs of the estimation framework by means of known parameters such as speed of sound, sensor location, and microphone locations. Acoustic based shooter localization system can be modelled as depicted in Figure 5.1.



Figure 5.1: Acoustic Shooter Localization System Model

According to the system model, signal recordings are inputs and shooter location, shot time, projectile trajectory and projectile speed are outputs. In fact, projectile speed and trajectory are available in case of the multi sensor network and trajectory passing between sensors. Besides, parameters such as speed of sound, microphone locations,

CHAPTER 6

# SYSTEM DESIGN

## Overview

Acoustic shooter localization systems simply consist of a microphone array, processor unit, and a power unit. Microphone arrays can be used as a separate unit as well as they can be mounted on the sensor board. It is important that microphones on the array should confirm the predefined geometry. Furthermore, microphones can be ordinary electret or they can be MEMS for more sensitive and small-in-size applications. Sensor board should have appropriate peripherals and interfaces for microphones and other supplementary units and it is important that it has computational capability required for the algorithms used in shooter localization.

CHAPTER 7

# SIMULATION AND TEST RESULTS

## Overview

This chapter involves all simulation and test results performed for described work in this thesis. The assumptions, requirements, and models used in these simulations are described in the corresponding sections of this chapter. All the simulations in these chapters are coded and performed in MATLAB® 2015. All simulation software is coded by the author by using basic MATLAB® functions except optimization and statistics. The built-in function "*fmincon*" of MATLAB® Optimization Toolbox is used for constrained nonlinear optimization and the built-in functions "*randn*" and "*unifrnd*" of MATLAB® Statistics Toolbox are used for statistical processes such as noise generation, randomization of parameters in simulations (MATLAB R2015a).

The organization of this chapter is in accordance with the chapter orders in the thesis. Firstly, simulation and test results of estimation framework described in Chapter 3 are provided in section **Error! Reference source not found.**. The estimation for shooter location, shot time, projectile trajectory and projectile velocity are performed according to the type of signal detection and number of sensors deployed in the field for a single shot.

Detection of simultaneous multiple shooter localization with the WB-SRPBF method described in section **Error! Reference source not found.** is provided in section **Error! Reference source not found.**. Furthermore, elimination of reverberation by using the WB-SRPBF method and common output functions is provided in section **Error! Reference source not found.**.

Finally, the effects of system parameters on estimation framework and enhancement in performance of the framework depending on the TDoA based system calibration method proposed in Chapter 5 is provided in section **Error! Reference source not found.**.

CHAPTER 8

# CONCLUSIONS AND FUTURE WORKS

## Conclusions

The thesis proposes a generalized shooter location estimation framework which is valid when both gunshot related acoustic events are present or when one of them is absent for some reason. The performance of the framework for detection of only muzzle blast, only shockwave, and both of them are simulated and analyzed separately. Furthermore, the output of estimation related to each case is analyzed. This analysis shows that shooter location and shot time can be estimated if muzzle blast exists and projectile trajectory and projectile speed can be estimated if shockwave exists and trajectory line passes between the sensors. However, if there is a single sensor deployed in the field, it can only provide DoA and ToA of the detected signal. A minimum number of two sensors are required for a gunshot related estimation. However, there is a special case such that even if there is a single sensor in the field, the framework can output shooter location and shot time provided that the sensor detects both muzzle blast and shockwave. The simulations corresponding to each case show that the framework estimate actual values with a high precision.

The thesis also analyzes estimation methods for ToA and DoA of the gunshot acoustic events which are essential information in the shooter estimation framework. The thesis involves two different methods, namely TDoA technique and beamforming technique called WB-SRPBF. TDoA technique is used for single shooter localization and system calibration since it requires low computational time. On the other hand, WB-SRPBF technique is used for simultaneous multiple shooter localization in reverberant environments. Furthermore, reflection elimination method utilizing both WB-SRPBF DoA estimation and common output functions of the localization framework is provided in the thesis. Simulations corresponding to multiple shooter localization and reflection elimination show that the proposed methods work successfully for simultaneous multiple shooter localization in a reverberant environment.

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APPENDICES

APPENDIX A

1. ANALYTICAL EXPRESSION OF MUZZLE BLAST

Fransler et al. (1993) have proposed an analytical expression of muzzle blast signal shown in (2). In detail, the total wave muzzle blast signature is divided into two regions namely positive phase for positive values of overpressure and negative phase for negative values of pressure. While positive phase is described by Friedlander wave equation (Baker, 1973), negative phase is described by Reed’s (1977) wave equation with a modification so that summation of integral of positive and negative phases is equal to zero (Fransler et al., 1993).

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The analytical expression of muzzle blast (2) is utilized to perform tests and simulations in Chapter 7. In order to handle more realistic signals instead of ideal ones, measurements such as noise, reverberation and delays are taken into consideration by straightforward mathematical operations and signal processing methods. In detail, reflections and reverberations are simulated by the method described in Appendix C and additive white Gaussian noise is applied to signal to obtain desired SNR.

APPENDIX B

1. ANALYTICAL EXPRESSION OF SHOCKWAVE

Acoustic shockwave signals generated by supersonic projectile can be described with an analytical expression. Whitham (1952) has studied the properties of "N" shaped shockwave signal. He associated the shockwave wavelength to the caliber and length of the projectile, and the closest distance from the measurement point to the bullet trajectory (Whitham, 1952). In this concept, shockwave signals can be expressed analytically as shown in (3) while taking into account the peak amplitude and period (4) and (5) of shockwave (Libal & Spyra, 2014).

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The analytical expression of shockwave in (3) which is relied on the amplitude and period shown in (4) and (5), is used to perform tests and simulations in Chapter 7. Equation (3) leads to theoretical shockwave signal, thus, effect of reverberation and reflection, described in Appendix C, and additive white noise is applied to ideal signal to obtain more realistic shockwave signal likewise muzzle blast signals described in Appendix A

APPENDIX C

1. MODEL OF REFLECTION AND REVERBERATION

Acoustic signals are subject to reflection due to surrounding physical obstacles or solid surfaces since it is a physical phenomenon. Hence, solid surfaces cause multipath reflections and reverberation in urban or open terrains for gunshot acoustic events. In other words, gunshot related recorded signals involve not only the original signals but also the reflections with delays according to the path. This phenomenon is applied to muzzle blast and shockwave signals generated ideally, described in Appendix A and Appendix B, for simulation and test purpose in Chapter 7.

The reflected signal is another signal which has a similar waveform of an original signal with a delay depending on the difference between the path of the original signal and the reflected signal. Furthermore, it has lower frequency components more than higher frequency components since higher frequencies are absorbed much more than lower frequencies. In addition, multipath reflections cause continuous stream with decaying amplitude which is called reverberation. A reflected signal can be simply expressed with a gain factor  less than 1 and time delay  as shown in (6).

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Equation (6) can be used to simulate single reflected signal but it lacks real conditions such as decaying multiple reflections and reverberation. Schroeder (1962) has proposed a method for simulating the effect of reflection and reverberation by using a combination of comb filters. Infinite impulse response (IIR) and all pass comb filters shown in Figure C.1 are applied to ideal muzzle blast and shockwave signals to obtain decaying multiple reflection effects. In detail, Multipath reflection IIR filters are used to simulate multiple decaying reflected signals adjusted by delay and gains. Then, cascaded all-pass reverberator filters are applied to the sum of outputs of those filters to obtain more natural reverberation. Finally, the output of all-pass filters is summed with the original signal. The overall block diagram is illustrated in Figure C.2. The delays of IIR filters can be set according to arbitrary reflection path lengths by (7) and delays of all-pass filters are set among the same set since all-pass filters are used for reverberation. Decay factors can be set randomly providing it is less than 1.



Figure .1: Multiple Reflection IIR Filter (a) and All Pass Reverberator (b)



Figure .2: Overall Block Diagram for Reverberation

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| --- | --- | --- |
|  |  | (7) |
|  |  |  |

Muzzle blast and shockwave depicted in **Error! Reference source not found.** and **Error! Reference source not found.** in Chapter 2 are obtained with the topology shown in Figure C.2 with proper delays and gain factors.

APPENDIX D

1. SPHERICAL COORDINATE SYSTEM

This section describes the spherical coordinate system used throughout this thesis as depicted in Figure D.1. All angular representations, notations, and DoA represented in the spherical coordinate system are subject to descriptions in this section.



Figure .1: Spherical Coordinate System

In the spherical coordinate system illustrated in Figure D.1, the azimuth angle is denoted by **defined in the -plane from the axis with range of [0 2] and elevation angle is denoted by **defined from the projection line in the -plane to the axis in the range of [-]. Radius is defined as the distance from the origin to a point on the sphere.

This thesis uses the spherical coordinate system to describe DoA unit vectors which have a radius equal to 1; thus, all DoA vectors in the spherical coordinate system are denoted with azimuth and elevation angles. In other words, directional information is described with (**, **and the range is described with as a conventional representation in the order shown in (8).

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|  |  | (8) |

DoA unit vectors are also represented in the Cartesian coordinate system throughout the thesis. The coordinate conversions from the spherical to Cartesian and Cartesian to spherical are shown in (9) and (10) for a point, respectively.

|  |  |  |
| --- | --- | --- |
|  |  | (9) |
|  |  | (10) |

There is a conventional representation for DoA and propagation direction of acoustic sources throughout the thesis. For example, direction of propagation of acoustic waves denoted by **, ** as shown in **Error! Reference source not found.** means that the waves move toward the location of sensor from the direction defined by azimuth angle of ** and elevation angle of **. On the other hand, this is not the DoA of source, DoA is equal to opposite direction of **, ** as shown in Figure 3.1, as an assumption. Those assumptions are made for sake of simplicity in sign operations.

1. All locations in the estimation geometry illustrated in Figure 3.1 are in 3D Cartesian coordinates. [↑](#footnote-ref-1)