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A Study of The Use of Computer Vision & Amplitude-Modulated Waves in Flame Extinguishing

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ABSTRACT

Traditional fire suppression methods often face limitations in speed, precision, and environmental impact. This research explores a new approach using computer vision and amplitude-modulated sound waves for early fire detection and targeted extinguishment.

Cameras with embedded machine learning algorithms are employed to identify emerging flames based on visual signatures, enabling rapid location and response before significant spread. Specific frequencies and intensities of sound waves are then directed at the fire, disrupting the combustion process through targeted pressure fluctuations and oxygen flow manipulation.

This study investigates the theoretical foundations of sonic fire suppression, analysing the interaction between sound waves and flame dynamics. Experimental work involves the development and testing of a prototype camera-sonic system in controlled environments, evaluating its effectiveness in extinguishing diverse fire types and sizes.

The research assesses the reliability, efficiency, and safety of this technology compared to traditional methods. Furthermore, it addresses environmental considerations, minimizing water and chemical usage for a more sustainable approach.

The findings of this study are expected to contribute to the advancement of smart fire protection systems and pave the way for the real-world implementation of camera-sonic fire suppression technology.

Keywords: computer vision, fire detection, amplitude-modulated waves, sonic fire suppression, early intervention, environmental impact, smart fire protection

Chapter 1

INTRODUCTION

1.1 Introduction

Firefighting in enclosed spaces poses a significant challenge, especially due to limited access for firefighters and the difficulty of using traditional water/chemical-based extinguishers. This motivates the exploration of innovative fire suppression methods, such as acoustic technology. Acoustic fire extinguishers utilize low-frequency sound waves to disrupt the delicate balance of oxygen, heat, and fuel needed for flames to exist. These waves, often perceived as bass vibrations, manipulate the flame's structure, and disrupt its fuel supply, potentially leading to extinction without harmful residues or environmental impact.

1.2 Importance of the Research

1. Offers a safer alternative to traditional fire extinguishers, reducing risks associated with toxic chemicals and residue.
2. Can reach enclosed spaces or areas difficult for firefighters to access, protecting lives and property in challenging situations.
3. Minimizes water usage and avoids harmful chemical pollutants, contributing to a more sustainable approach to fire suppression.
4. Potential to extinguish various types of fires (solid, liquid, and gas), broadening its applicability compared to traditional methods.
5. Deepens our understanding of sound-flame interactions, opening doors for new fire control technologies and applications.
6. Paves the way for a potential revolution in fire safety, with advancements impacting firefighting techniques, building design, and emergency response protocols.\
7. Can offer cost-effective fire protection solutions in the long run, reducing potential damage and associated repair costs.
8. Empowering Qatar's 2030 vision as acoustic fire extinguishers, aligned with human development, social progress, and environmental sustainability, offer safer communities, protected infrastructure, and a clean future for Qatar's people and heritage.

1.3 Goal of the Research

- Develop and optimize algorithms for accurate real-time fire detection using visual and thermal imaging.
- Investigate the influence of environmental factors like smoke and lighting on detection accuracy.
- Design a robust system for automatic target identification and localization of flame sources.
- Identify the optimal frequency range and sound pressure levels for extinguishing various fire types based on camera data.
- Analyse the effectiveness of acoustic waves at different distances from flame sources identified by the camera.
- Investigate the influence of flame size, fuel type, and environmental factors on extinguishing success, incorporating data from the camera.
- Develop an integrated system for automatic adjustment of acoustic wave parameters based on real-time flame characteristics.

1.4 Research Questions

- Is it possible to extinguish flames using modulate sound wave?
- How efficient are amplitude modulated waves at extinguishing flames?
- What is the best frequency at which flames are extinguished?
- What material is the best at reflecting and focusing sound waves?
- What is the most efficient computer vision flame detection algorithm?

1.5 Research Variables

- Sound wave frequency
- Burning Material
- Wave-Guided material
- Computer-vision flame detection algorithm

CHAPTER 2

2.1 MAIN TERMS AND HOW THEY ARE RELATED

2.1.1 Fire

Fire, an abundant yet profound phenomenon, has captivated and challenged humanity since prehistoric times. Its destructive potential can be devastating, yet its illuminating presence and ability to provide warmth hold unparalleled significance.

At the heart of fire lies the exothermic chemical process of combustion. During this dynamic reaction, a fuel readily surrenders electrons to an oxidizer, typically oxygen, resulting in the release of energy in the form of light, heat, and a variety of reaction products. The visible manifestation of this energetic exchange, the flame, serves as a captivating testament to the power of combustion.

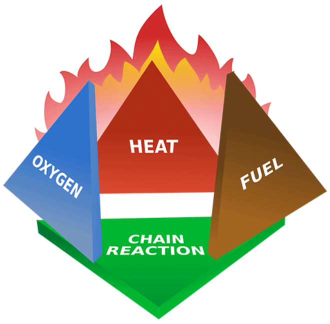


Figure 2.1: Fire tetrahedron

However, for this captivating spectacle to unfold, a delicate equilibrium must be established. The fire tetrahedron conceptualizes the four essential elements required for combustion: fuel, oxidizer, heat, and a self-sustaining chain reaction. Fuels encompass a diverse range of materials, from common organic substances like wood and paper to volatile liquids and even specialized metals. Oxygen, though the most prevalent oxidizer, can be substituted in specific environments. Heat acts as the trigger, pushing the system beyond a critical threshold and initiating the self-perpetuating chain reaction. Disrupting any component of this tetrahedron effectively extinguishes the fire, demonstrating the precarious balance that sustains its existence.
Understanding the spectrum of fuels necessitates a robust classification system. This paper adopts the widely recognized class system, which categorizes fires based on their predominant fuel types. Class A fires, fueled by ordinary combustibles, leave a characteristic ash residue. Class B encompasses the domain of flammable liquids and gases, while Class C focuses on energized equipment fires. Finally, Class D delves into the realm of specific reactive metals like magnesium and sodium. Recognizing these distinct categories is crucial for deploying appropriate extinguishing measures and ensuring effective fire control.

2.1.2 Conventional fire extinguishing techniques

The ability to effectively suppress fire lies at the heart of fire safety practices. This review examines four principal techniques employed in the control and extinguishment of fires, encompassing both physical and chemical strategies.

1. Cooling: Arguably the most prevalent approach, this technique primarily utilizes water as a cooling agent. As water absorbs heat upon vaporization, it effectively reduces the temperature of burning materials, thereby disrupting the combustion cycle. Water additionally contributes to extinguishment by physically creating a barrier, hindering oxygen access to the fuel source. However, the application of water requires caution, as its use on certain flammable liquids and fats can paradoxically exacerbate the fire by promoting rapid spreading.

2. Oxygen Deprivation: Removing or displacing oxygen, a vital component of the combustion triangle, constitutes another prominent extinguishing strategy. This can be achieved through various means, including smothering agents like foam. Foam blankets the fuel surface, forming a physical barrier that impedes oxygen diffusion and extinguishes the fire by suffocation. Foam also possesses cooling properties and resists wind disruption, making it suitable for specific scenarios. However, its usage on energized electrical equipment should be avoided due to potential conductivity issues. Alternative oxygen-depleting agents, such as carbon dioxide extinguishers, can be employed for electrical fires due to their non-conductive nature. In certain instances, employing sand as a smothering agent may be effective for small-scale fires.

3. Fuel Removal: This technique necessitates the elimination of the fuel source, effectively starving the fire and preventing its continued propagation. The specific approach adopted depends on the fire type. Disconnecting electrical sources, shutting off gas valves, or physically removing solid fuels like wood or textiles are examples of this strategy. In the context of wildfires, creating a firebreak around the burning area can serve to isolate fuel and hinder its spread.

4. Chemical Inhibition: This method involves the application of substances that chemically react with burning materials, disrupting the combustion process and extinguishing the flames. Dry chemical extinguishers often utilize such inhibitors, commonly comprising monoammonium phosphate, sodium or potassium bicarbonate, or potassium chloride. Additionally, vaporizing liquids can exhibit flame-inhibiting properties. However, it is crucial to note that certain historical formulations of these substances have been phased out due to concerns regarding their potential toxicity.

2.1.3 Sound Waves

At the heart of sound lies a mechanical wave, a disturbance that ripples through mediums like air, water, and even solids. This disturbance originates from a vibrating source, such as a speaker's diaphragm, which sets the surrounding particles in motion. These particles oscillate back and forth, creating regions of compressed and rarefied air, forming the longitudinal sound wave. Unlike water waves, whose particles travel across the surface, the particles in a sound wave vibrate in place, transferring the disturbance outward at the speed of sound.

While most sound waves in fluids and gases are characterized by longitudinal motion, solids present a curious exception. In addition to longitudinal waves, solids can also support transverse waves, where particles vibrate perpendicular to the wave's direction. This unique ability allows solids to transmit sound with greater efficiency and over longer distances compared to fluids.

The ability of a material to propagate sound hinges on its compressibility. In the vast emptiness of space, devoid of such a medium, sound waves simply cannot exist. This explains why, during their lunar missions, astronauts relied on specialized equipment for communication, effectively isolated from the silent symphony of the cosmos.

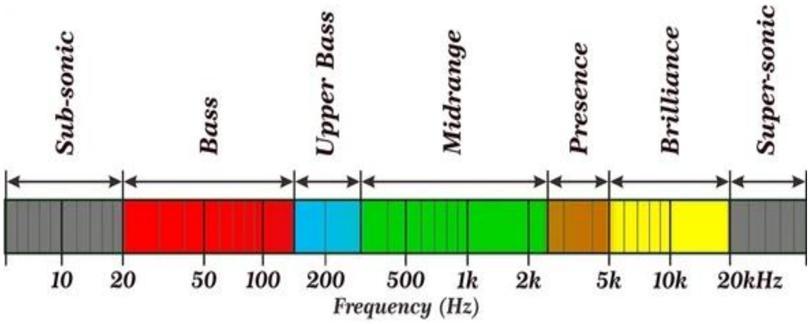
While sound waves themselves are invisible, their effects can be readily observed. Parabolic mirrors, found in microphones and satellite dishes, exploit the reflective properties of sound waves to focus and amplify them. Similarly, vibrating objects like tuning forks and drums readily showcase the visible manifestations of sound waves, demonstrating the dynamic interplay between vibration and motion.

Sound waves, like any wave, can be characterized by a set of quantifiable properties:

- Frequency: Measured in Hertz (Hz), it represents the number of oscillations per second. Higher frequencies correspond to higher-pitched sounds.
- Wavelength: Measured in meters (m), it represents the distance between two corresponding points on the wave. Higher frequencies correspond to shorter wavelengths.
- Amplitude: Determining the loudness of the sound, it represents the strength of the vibrations. Higher amplitudes produce louder sounds.
- Speed of sound: Typically, around 343 m/s in air at standard temperature and pressure, it represents the speed at which the wave propagates through the medium.

The human auditory system is delicately tuned to capture the nuances of sound within a specific range. Our ears can detect frequencies between roughly 20 Hz and 20,000 Hz, with lower frequencies perceived as bass tones and higher frequencies as treble. Sounds outside this range, such as infrasound (below 20 Hz) and ultrasound (above 20,000 Hz), are inaudible to humans but find applications in various fields like geophysics and medical imaging.

The realm of sound extends beyond these fundamental principles. Sound waves can be reflected, refracted, and even absorbed by different materials, dictating their propagation and perception. Understanding these complex interactions is crucial in diverse fields ranging from acoustics and noise control to medical imaging and underwater communication.



2.3 Sound wave frequency divisions

2.2 LITERATURE REVIEW

2.2.1 Computer vision and Sound waves in fire extinguishing

Fire detection using computer vision techniques has gained significant attention in recent years. Various studies have highlighted the application of deep learning, convolutional neural networks (CNN), and other computer vision methods in fire detection. For instance, Voulodimos et al. (2018) provided an overview of deep learning schemes, including CNN, Deep Boltzmann Machines, and Stacked Denoising Autoencoders, which are widely used in computer vision problems. Abdusalomov et al. (2021) emphasized the success of computer vision and deep learning-based techniques in fire detection, particularly in the context of surveillance systems. Khalifeh et al. (2022) also studied the use of optical and thermal infrared cameras to detect fire among the deep learning-based computer vision algorithms. Moreover, Moumgiakmas et al. (2021) conducted a literature review on the use of computer vision for fire detection on Unmanned Aerial Vehicles (UAVs), highlighting the relevance of computer vision techniques in UAV-based fire detection. Similarly, Kukuk & Kilimci (2021) employed deep learning and conventional machine learning-based computer vision techniques for outdoor fire detection, addressing the limitations of indoor fire detection systems. Furthermore, the study by Zhang et al. (2022) demonstrated the use of feature engineering in computer vision to optimize forest fire detection algorithms, indicating the significance of leveraging advanced techniques for fire detection. Additionally, recent advancements in lightweight fire detection models based on computer vision were discussed by (Wang & Wang, 2023), reflecting the continuous evolution of computer vision technology in fire detection applications.

2.2.2 Computer vision and Sound waves in fire extinguishing

The use of computer vision and amplitude-modulated waves in flame extinguishing has been a subject of recent research. Wilk-Jakubowski et al. (2022) presented the use of Deep Neural Networks for fire detection and the extinguishing of flames using square waveforms with Amplitude Modulation (AM) for various frequencies. This study provides insights into the application of modern technologies in flame extinguishing. Additionally, Xiong et al. (2021) proposed the use of acoustic waves to destabilize and extinguish diffusion flames, highlighting the potential of acoustic wave technology in flame suppression. Furthermore, Ivanov et al. (2021) discussed the use of Deep Neural Networks and acoustic waves modulated by triangular waveforms for extinguishing fires, indicating the growing interest in integrating advanced computational methods with traditional fire suppression techniques. In the context of flame extinguishing, the study by Hirst & Booth (1977) provided valuable insights into the measurement of flame-extinguishing concentrations and the apparatus used for such tests. This historical perspective contributes to understanding the evolution of flame extinguishing techniques. Moreover, Torikai et al. (2011) conducted experiments to clarify the fundamental characteristics of flame extinguishment by an inert gas capsule, shedding light on the use of inert gases for flame suppression. The interaction of shock waves and high-speed vortex rings with turbulent flames was explored by (Giannuzzi et al., 2016), indicating the potential of shock wave technology in flame extinguishing. Additionally, Sato et al. (2014) proposed a concept of a robotic fire-fighting system using a swarm of aerial extinguishers with inert gas capsules, demonstrating innovative approaches to flame suppression.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

This research-based review article delves into the environmental and technical aspects of using computer vision and modulated sound waves in firefighting. Employing a multifaceted approach, it combines systematic literature review and comparative analysis with controlled experiments and detailed case studies. Data was further enriched through analytical and experimental methods, each evaluated for its contribution to specific research goals. These findings then informed the development of a comprehensive conceptual framework that sheds light on the problem being addressed. To demonstrate the viability of this approach, a lab model was constructed (Figure 1). This model features a high-powered, environmentally friendly acoustic extinguisher equipped with a Raspberry Pi camera for real-time flame detection. Compared to traditional fire extinguishers, this system boasts several advantages, including continuous operation, pressure testing redundancy, multi-class fire suppression capabilities, independent operation, rapid response times, high portability, and, notably, its commitment to environmental sustainability. This innovative approach holds significant promise for firefighters, potentially offering a safer, more effective, and environmentally conscious method for tackling diverse fire scenarios.

3.2 Required Hardware & Software

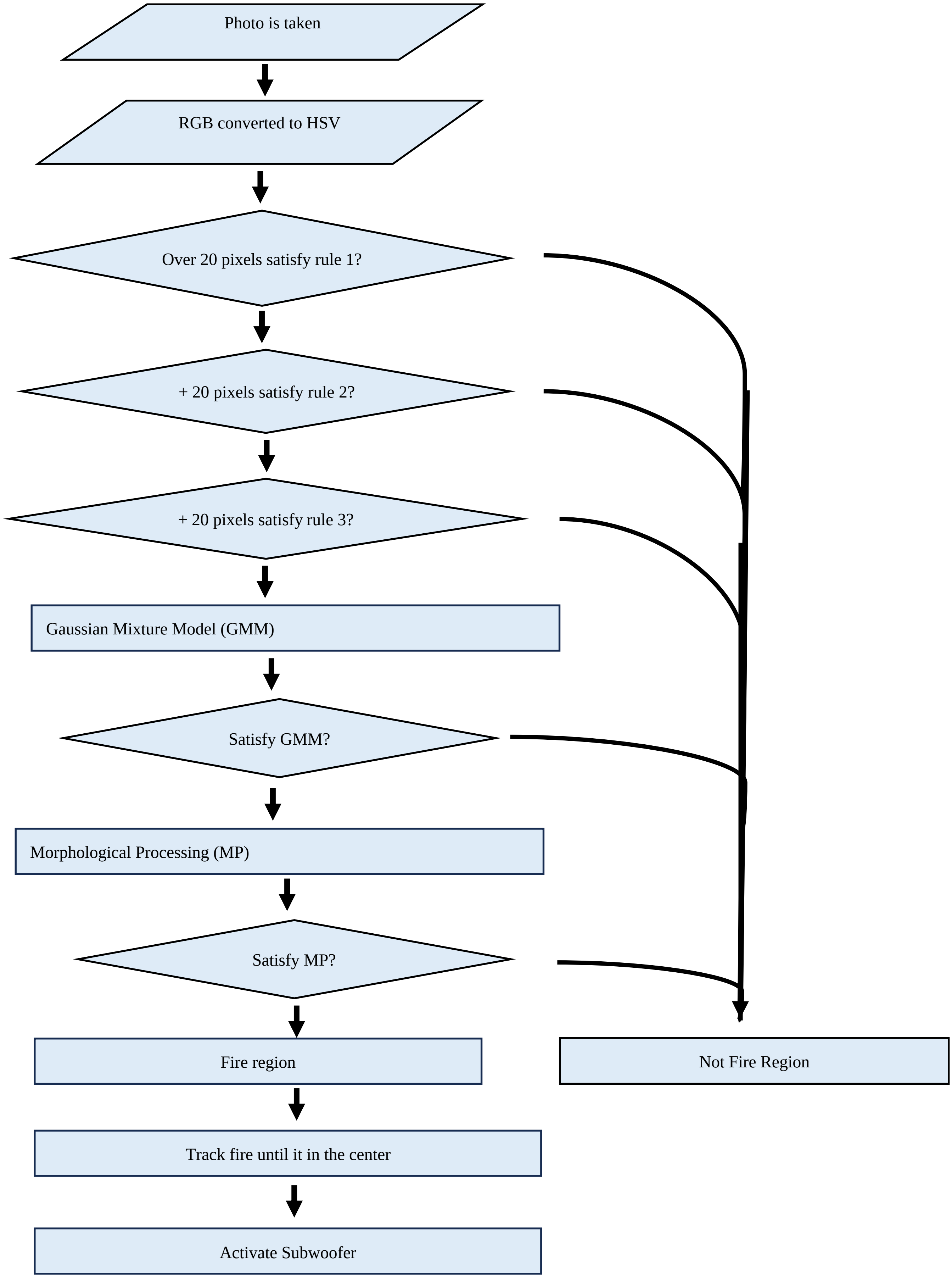
3.2.1 Hardware

1. Raspberry pi 3b+
2. Raspberry Pi Camera V2
3. Stepper Motors (28BYJ-48)
4. Stepper Motor Driver (ULN2003)
5. Subwoofer ()
6. Amplifier ()
7. Collimator ()
8. Power supply

3.2.2 Software

1. Python

3.3 Flow Chart



CHAPTER 4

RESULTS

Our robot was able to successfully to detect flames and extinguish gas, wax and small alcohol fires with limited resources such as a regular slightly modified speaker. This shows it ability to extinguish a large variety of fires autonomously, without human intervention. We also discovered that for our robot design optimum operating frequency was an average of 145HZ well within the 20Hz- 200Hz expected range. We also found that there is a direct proportional relationship between the strength of the speaker and the size of flames and the speed of which they are extinguished. We also deduced a few equations in order to face the fire which we found to be efficient after testing. Amongst the equations we used are the following:

$$\text{Angle to fire} = \frac{\text{x-coordinate} \times \text{FOV}}{\text{image width}}$$

$$\text{Angle to center} = \text{Angle to fire} - \frac{\text{FOV}}{2}$$

$$\text{Arc Length} = \frac{n}{360} \times 2\pi r$$

$$\text{Rotations} = \frac{\text{Bow length}}{\text{Wheel perimeter}}$$

$$\text{Motor time} = \frac{\text{Rotations}}{\frac{\text{RPM}}{60}} = \frac{\text{Rotations} \times 60}{\text{RPM}}$$

RESOURCES

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