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Microcontroller-based camera with the sound source localization for automated accident detection

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ABSTRACT

This paper is on a microcontroller-based camera controller with sound source localization (SSL). With the rising frequency of highway accidents in Malaysia, there is a pressing need for a reliable detection system. The current approach, involving fixed-angled cameras, necessitates constant human monitoring, proving inefficient. To address this, the study introduces a hybrid camera system incorporating a camera for image capture and a microphone to detect collision sounds. By integrating a pan-tilt (PT) camera controller driven by time difference of arrival (TDOA) inputs, the system can swiftly move toward accident locations. The TDOA method is employed to convert sound arrival time differences into camera angles. The accuracy of the PT camera's rotation angle was analyzed based on the original sound source angle. As a result, this project produced an automated highway monitoring camera system that uses sound SSL to detect car crash sounds on highways. Its PT feature will help cover a large highway area and eliminate blind spots to capture possible accident scenes. The average inaccuracy of the experimental test of the pan and tilt angle of the camera is 19 and 23%, respectively. The accuracy of the pan tilt angle can be increased by adding more analog acoustic sensors.

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1. INTRODUCTION

For the past ten years, road accidents have increased progressively yearly. As the number of vehicle usage rises, the chance for road accidents to occur will also increase. Road accidents will cause traffic congestion which will be inconvenient for road users, as it may delay their travels [1]–[4]. When accidents occur on highways, it is harder for authorities to detect their occurrence, especially at night, when there are fewer highway users. This is because most highways were built far away from civilization, which is inconvenient to rely on highway users' reports of accident occurrences to the authorities. In addition, the current camera system used on highways relies solely on human monitoring to detect if there are any problems on the road. However, it is ineffective because of the fixed camera angle; the authority cannot view the crash when it is in the camera's blind spot [5]. Applying a pan-tilt (PT) camera with sound source localization (SSL) can help detect accidents on the highway faster by automatically panning and tilting to the accident area based on the car crash sound and immediately notifying the authorities for immediate action to clear up the highway lane without relying on human monitoring. This work can be implemented, particularly in areas where car crashes have a high incidence and receive a prompt response from the authorities for early preparation for severe accidents.

PT camera that can pan and tilt to focus on a desired object is suitable for highway monitoring and accident detectors. The current PT camera with surveillance capabilities is also frequently improved by features like night vision, weather resistance, and sophisticated video analytics [6]–[9]. Its ability to pan and tilt 360º according to the received time difference of arrival (TDOA) of the sound at each microphone can help cover a large monitoring area, such as highways. This shows that the PT camera is an essential tool in the security and surveillance field. The technique of locating a sound source concerning a listener is known as SSL [10]. Various methods are used to conduct SSL, such as beamforming, acoustic holography, and the TDOA [11], [12]. Beamforming is a signal processing technique that uses an array of microphones to focus on a specific direction or angle in space where a sound source is located. It works by delaying the signals received by each microphone in the array based on the estimated direction of the sound source. When these delayed signals are combined, they reinforce the sound from the desired direction while canceling out noise from other directions. Beamforming provides high spatial resolution and can be used in real-time applications. It is particularly effective for isolating and localizing single or multiple sources in noisy environments [13], [14]. Acoustic holography is a method for visualizing sound fields in three dimensions. It doesn't just locate sound sources; it creates a complete spatial representation of the sound field. Acoustic holography reconstructs the sound field by measuring the acoustic pressure or particle velocity at multiple points in space and then mathematically processing this data to create a 3D representation of the sound field. It provides a comprehensive view of the sound field, making it useful for understanding complex acoustic environments, such as concert halls or industrial spaces. However, it's less commonly used for pinpointing specific sound sources compared to beamforming or TDOA [15], [16]. TDOA is a technique that relies on the differences in the arrival times of sound signals at multiple microphones to estimate the location of a sound source. By measuring the time, it takes for a sound wave to reach each microphone, you can calculate the time differences between arrivals. These time differences are then used in triangulation algorithms to estimate the source's position. TDOA is relatively simple and can be effective for localizing sound sources in environments with good signal-to-noise ratios. It is often used in applications like gunshot detection systems and microphone arrays [17].

In summary, the main differences between these SSL methods lie in their principles and methodologies. Beamforming focuses on isolating and enhancing sound from specific directions, acoustic holography creates a 3D representation of sound fields, and TDOA estimates source locations based on time differences in sound arrival. The choice of method depends on the specific application, the complexity of the sound environment, and the level of detail required for source localization. Since this paper’s focus is detecting the crash sound on an isolated highway, TDOA is the best choice. TDOA is also crucial for several uses, such as robotics, surveillance, and voice recognition. This paper primarily focuses on the localization of sound sources and does not consider other types of localization. SSL techniques significantly differ between indoor and outdoor environments, with this work primarily targeting an outdoor environment, specifically highway areas. The utilization of an adaptive pan and tilt camera allows for visual target tracking, given its 360° view, enabling coverage of a wide range based on the location of the vehicle crash sound. Figure 1 shows the overall process flow of the system.

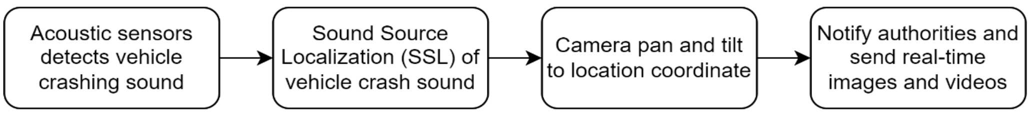


Figure 1. Microcontroller-based camera with SSL overall framework

Therefore, the main objectives of this work are first, to design a pan and tilt camera controller based on SSL input using a microcontroller board and second, to investigate the angle accuracy of the PT camera movement using SSL. By implementing a hybrid camera system using a microcontroller-based PT camera controller with sound location identification using SSL, an automated camera control system that automatically turns the camera towards the source of car crash sound is ideal for solving the issue of detecting highway accidents at any time. This paper comprises an introductory section, background context, and an exposition of the research inquiry regarding SSL through the application of the TDOA method for ascertaining sound direction. Following this is the methodology section, which elucidates the research techniques and data collection methods employed in SSL via TDOA. Subsequently, the paper presents results and discussions that elucidate the study's discoveries about the precision of camera movement when employing TDOA at varying distances between sensors. In conclusion, this paper offers a summary of the system's accuracy in pinpointing sound sources using the TDOA method and directing a camera toward the detected sound source.

2. RESEARCH METHOD

This section describes the methodology employed for the microcontroller-based camera with an SSL system. The process begins with capturing the vehicle crash sound using acoustic sensors. The captured sound is then processed through the hardware implementation of the SSL algorithm, determining the location coordinates of the crash, which are used to make decisions regarding the motorized camera's movement (pan and tilt) toward the crash location.

2.1. Sound source localization

The SSL technique is the best method for pinpointing a sound source's direction or location in a certain environment. The goal of SSL is to locate a sound's spatial coordinate, which is often expressed in terms of azimuth, elevation, and distance. In this paper, the angle of rotation of the camera's motor depends on how quickly sound reaches each sound sensor module. Figure 2 illustrates the SSL application concept for the hardware configuration. As seen in the illustration, four sound sensor modules must be employed. The sound sensor modules M1 and M2 are used to determine the camera's tilting angle (y), while M3 and M4 are used to determine the camera's panning angle (x). The camera can turn toward the sound source by determining the camera's panning and tilting angles (x and y values).

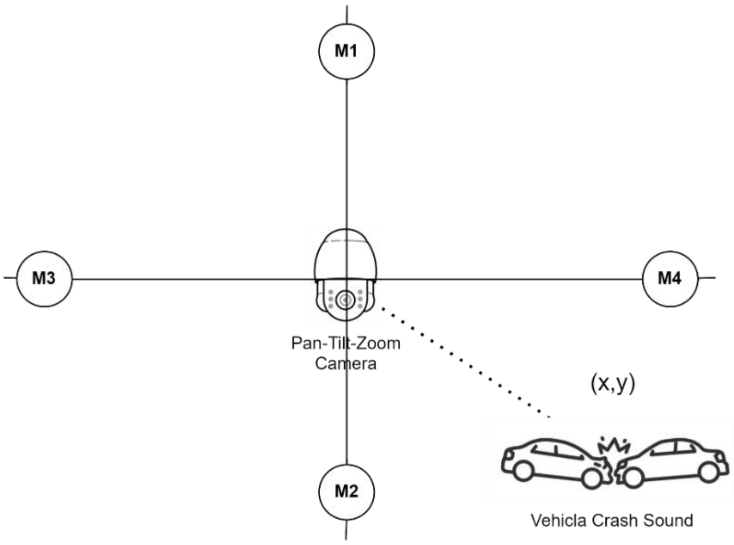


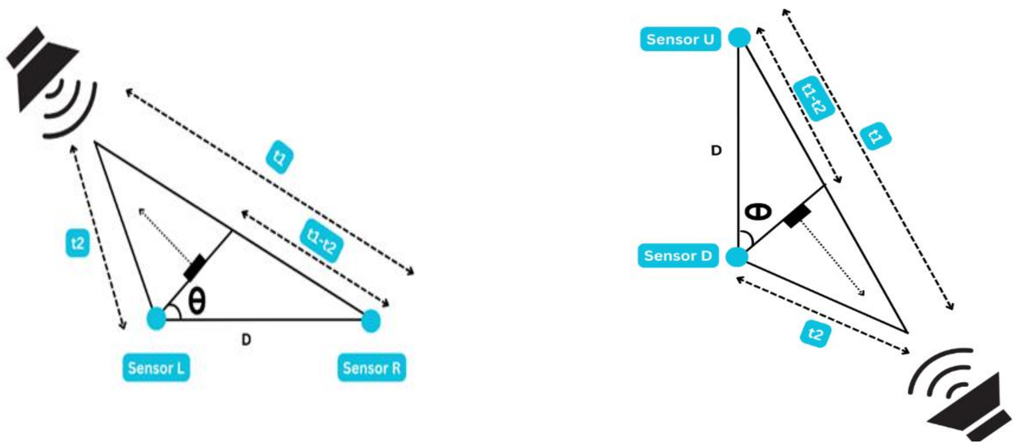
Figure 2. SSL concept

2.1.1. Sound source localization using time difference of arrival

There are several techniques for SSL, and one of them is the TDOA method. The TDOA approach uses the time delay between the arrival of a sound signal at several sensors or microphones, which estimates the direction or position of a sound source. The angle at which the sound source will arrive at the sensor array may be determined by comparing the times at which the sound will arrive at each sensor. Based on Figure 2, it will then be divided into two parts, which are the panning and tilting parts. Figure 3 explains how the camera's rotation angle is obtained based on the TDOA of the sound source at every possible position for both panning and tilting. Figure 3(a) shows the sound source for panning and Figure 3(b) for tilting respectively. The positive and negative angle values represent the difference between the time of arrival of the sound at each of the microphones. However, for sound in the middle position for both panning and tilting the time taken for the sound to reach both sound sensor modules should be the same, hence no difference in the time of arrival, resulting in the camera staying still. The angle of the camera's motor rotating can be obtained by deriving the trigonometric formula based on the information we have. The equation derived based on the triangle is as (1).

$$\theta = \sin^{-1}\frac{t_1 - t_2\ x\ c}{D} \quad (1)$$

t1 refers to the time taken for the sound to reach the furthest sound sensor module, while t2 refers to the time taken for the sound to reach the nearest sound sensor module. D is the distance between two sound sensors, which is set at 30 cm. c is the speed of sound, which is fixed at 343 m/s. Sensor L and sensor R represent the sensor location when panning (horizontally), while sensor D and sensor U represent the sensor when tilting (vertically).



(a) (b)

Figure 3. Illustration of TDOA in (a) panning and (b) tilting

2.1.2. Camera pan and tilt control

The angle determined by the TDOA method is converted into stepper motor steps to move the mechanical component, which is the stepper motor for the camera's panning and tilting. In (2) demonstrates the motor rotation angle acquired from the TDOA algorithm, to pan and tilt the camera in the direction of the proper sound source.

$$Motor\ Steps\ = \frac{\theta}{1.8} \quad (2)$$

Where θ is the motor rotation angle (panning or tilting) obtained from the TDOA process. 1.8 is the value of revolution per degree.

2.1.3. Accuracy of camera rotation angle

For assessing the precision of the camera's rotation angle, the camera is tested with various angles of sound sources, covering both panning and tilting movements. To indicate the accurate angle and distance of the sound source, the prototype is placed in front of an angle and distance indicator, as illustrated in Figure 4. 30 cm distance between the sound sensor left/down (L/D) and sound sensor right/up (R/U) is the minimum distance of the two sensors without interfering with each other signal.

The results obtained from this experiment will yield valuable insights into the camera's tracking capabilities, aiding in the refinement and enhancement of its performance in real-world scenarios where precise SSL is critical. In this section, the researcher delves into examining how the distance between the sound source and the sound sensor modules affects the precision of the camera's rotational angle. The primary objective is to grasp how altering the separation between the sound source and the sensors can impact the camera's capacity to precisely follow and align itself with the source of sound. To achieve this, two distinct distances have been selected for experimentation: 10 and 20 cm. This distance is considered as the current sound sensor used (omnidirectional microphone) can only detect an amplitude of ±2.5 V, if the sound source is too far from the sensor, it will not be able to detect the signal. Any variance in the arrival time of these waves can subsequently influence the accuracy of the TDOA calculations, ultimately affecting the camera's capability to accurately discern the direction of the sound source.

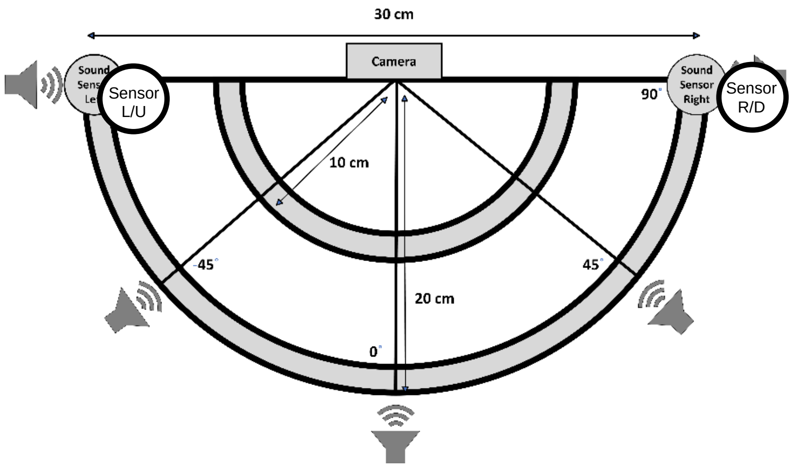


Figure 4. Angle and distance indicator for panning/tilting

2.2. Hardware implementation

The hardware implementation used an ATmega328p-based Arduino UNO microcontroller to control the pan and tilt movement of the camera. A motor driver module (dual H-Bridge) enables the Arduino to control the speed and direction of a motor [18]–[21]. Figure 5 shows the hardware setup used for this paper. It consists of two sound sensors for panning and another two for tilting. The camera is placed in the center of the system to capture the image of the location of the sound. The stepper motor is used to control the camera movement.

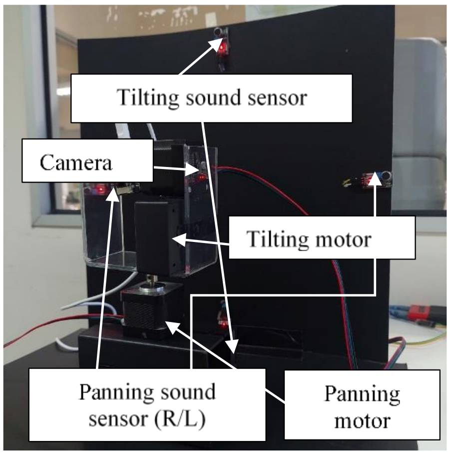


Figure 5. The microcontroller-based camera with SSL prototype

TDOA is a technique used to determine the direction or position of a sound source by analyzing the time difference between when the sound arrives at different sensors or microphones. By processing the data from the sound sensors, the microcontroller calculates the angle of arrival of the sound source about the sensor array. It determines the precise direction from which the sound is originating. Once the microcontroller has calculated the camera angle, it proceeds to control the camera motor. The camera motor is responsible for adjusting the camera's position to align it with the sound source accurately. The microcontroller sends commands to the motor to pan (horizontal movement) and tilt (vertical movement) the camera toward the calculated angle. The motor responds to these commands and repositions the camera accordingly. With the camera now pointing in the direction of the sound source, the final step is image capture. The camera, in its newly adjusted position, captures an image of the sound source. By following this flow, the system can accurately locate the sound source, reorient the camera for optimal alignment, and capture visual data of the source. The integration of TDOA-based SSL with motorized camera control provides an intelligent and automated solution for sound visualization and tracking.

3. RESULTS AND DISCUSSION

The sound source's estimated angle versus the motor rotation's actual angle based on TDOA is recorded. For panning, the negative angle values represent the camera's left side, while the positive angle values represent the camera's right side. For tilting, the negative angle values are downwards, while the positive values are upwards. As shown in Figure 6 is the angle inaccuracy for panning and tilting. The panning rotation accuracy is much better compared to tilting. However, the percentage error is high at 90 and -90° for both panning and tilting. This is due to the mechanical position of the sound sensor module. Although the sound sensor modules used are omnidirectional, they only detect sound accurately when the sound is applied in front of the sound sensor module [22], [23]. On average the error or inaccuracy for panning is 19% and for tilting is 23%. To overcome this problem, applying more sound sensor modules can improve the accuracy of the camera rotation angle [24].

Next, the estimated angle of the sound source and the camera panning and tilting angle for two different distances between the sound source location and sound sensor, which are 10 and 20 cm, are recorded. As shown in Figure 7, for five iterations, the average error of the panning and tilting angle at 20 cm does not have a vast difference compared to 10 cm. However, some angles at 20 cm are still more accurate compared to 10 cm. This might be due to the small time difference between the sounds reaching the sound sensor [25], [26].

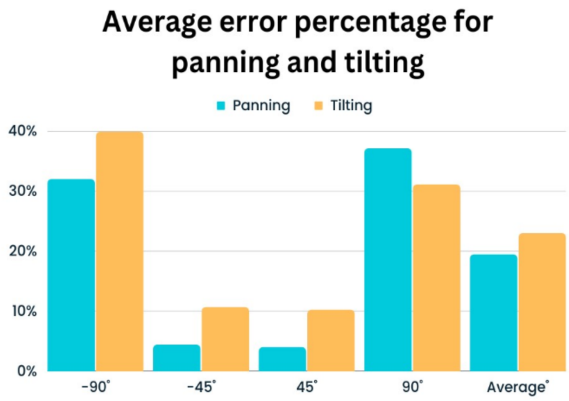


Figure 6. Average inaccuracy for panning and tilting motor

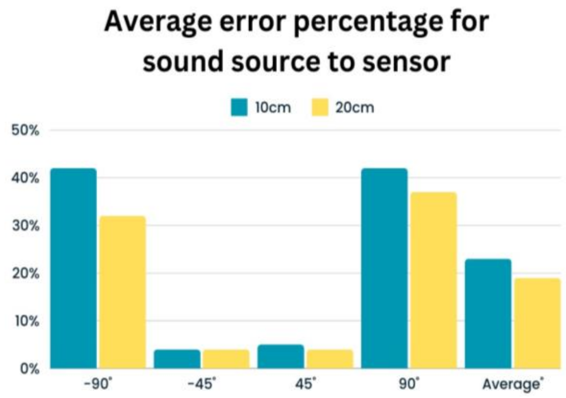


Figure 7. Average inaccuracy for panning and tilting motor with different distance

4. CONCLUSION

In conclusion, a microcontroller-based camera controller that utilizes TDOA is designed to detect car crash sounds on highways. This automated camera control system to detect highway accidents can help authorities provide immediate action to save the victims by moving the camera toward the car crash sound, hence reducing the involvement of human resources to monitor and patrol the highways constantly. Moreover, using a PT camera helps eliminate blind spots in possible accident areas and provides images and videos of the accident scene. The accuracy of the camera's tilt and pan angle were analyzed by comparing the real tilting and panning angle to the calculated and converted values of the coordinates to produce precise evidence of the car accident to be shown to the authorities. To attain greater precision in detecting car crash sounds, it is recommended to integrate sound and image recognition technology into the existing system. This enhancement ensures that the system becomes more adept at distinguishing car crash sounds from other ambient noises. This approach allows for a more dependable and comprehensive means of detecting and confirming car crash incidents.

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