REAL-TIME FIRE DETECTION AND LOCATION ESTIMATION USING MULTISENSOR DATA FUSION AND TRIANGULATION

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ABSTRACT

In rural as well as urban areas, fire detection and location estimates are essential for avoiding catastrophic harm. This study introduces a novel algorithm that uses information gathered from four distinct sensors—temperature, smoke, gas, and flame—integrated on a single device to calculate the probability of a fire. High accuracy in detecting fire conditions is ensured by the algorithm's computation of fire likelihood through a weighted fusion of sensor data.

This paper proposes a new triangulation method based on data obtained from three geographically isolated devices for predicting the approximate location of the fire in addition to detection. A trilateration approach makes use of relative intensities and time-of-flight delays of sensor signals from several devices compared to each other for locating the fire in real-time. A reliable, scalable solution for industrial facilities or smart homes and monitoring wildfire-related systems, the proposed system can be used in the detection and localizing of early fire. Validated by experimental results showing the value of the algorithm in the simulated as well as in real-fire environments, it may be useful in enhancing one's response skills with respect to fire.

KEYWORDS

Fire detection algorithm, Sensor fusion, Triangulation, Multisensor systems, Real-time fire monitoring

1. INTRODUCTION

It is of paramount importance to have fire alarm and prevention systems designed to reduce the overall damage in terms of human loss of life and property, especially in risk-prone areas, such as industrial plants, residential complexes, and forested areas under potential wildfires. Traditional fire alarm systems rely on single-sensor inputs, such as smoke or heat detectors, which are often prone to false alarms or may be delayed, making them less effective in a large or complex environment. To overcome the deficiencies, recent developments have been on multisensor systems and sensor fusion techniques toward enhanced accuracy and reliability in fire detection.

This paper presents a novel technique for fire detection and location triangulation employing data from four sensors-temperature, gas, infrared, and light, LDR-onboard every device. The first mechanism computes the probability of the existence of a fire based on sensor readings while the second mechanism triangulates its position from data received by three different devices. In these two mechanisms combined, the design of the system is real time, efficient, scalable, and accurate to use in determining fire's cause and location.

Fire Detection Using Multisensor Systems

Studies conducted in different parts of the world have shown that the performance of fire detection systems enhances if there are several sensors combined. It was demonstrated by Liu et al. (2004) on how this system reduces false alarms to a great extent through the analysis of several sources like temperature, gas, and smoke sensors.

Chen et al. proposed a fire detection system based on data fusion techniques, similar to the one above, which proved to be effective in improving the accuracy of detection compared to traditional methods based on singular sensors and offers a much quicker response time.

It combines weighted temperature, gas, and infrared sensor data in an algorithm for determining the probability of a fire. The system dynamically adjusts weights for each sensor based on environmental conditions, such as light presence, which it detects with the LDR, and adjusts thresholds themselves according to sensor activity to avoid false positives.

Fire Location Triangulation

Fire localization can cut losses much faster by minimizing the response time. Research studies have established the application of triangulation techniques to determine the fire source. For instance, Wang et al. (2015) estimated fire locations in large areas through the trilateration of data gathered from wireless sensor networks.

Zhang et al. (2019) addressed the localization of fire sources in a forest environment using WSN, hence it proved the feasibility and scale capability of fire triangulation based on distributed sensors.

Lastly, in this work, I introduce a triangulation algorithm that adopts the Haversine formula to estimate distances between sensor-equipped devices and garner weighted distance values derived from sensor readings to approximate a fire's location. The system gives real-time estimate of the coordinates of the fire by fusing this data across multiple devices thus enhancing the accuracy of detection and reducing response time.

Contributions

It combines the full detection and localization solution by blending sensor fusion with triangulation algorithms to contribute to the overall global body of research. The system, being inherently real-time processing-based, can be used to adapt to smart home applications, industrial automation, and large-scale wildfire monitoring systems. The advantages of the system would also be to improve the accuracy of fire detection, as the proposed system could provide critical localization data, enhancing the effectiveness of fire prevention and suppression efforts.

2. METHODS

This section outlines the methodologies used to develop the proposed fire detection and localization system. The methods are divided into two primary components: the likelihood assessment of fire and the triangulation of fire location based on sensor data.

2.1. Sensor Data Acquisition

The system collects data that is indicative of the presence of fire by using four types of sensors, temperature, gas, infrared (flame), and LDR. Each device is equipped with a microcontroller, which continuously collects readings from sensors and wirelessly sends data to a nearby spotter via Bluetooth which then the spotters send the alert and the sensor details, with the use of wireless protocols such as HTTP. Such approaches are similar to the systems presented by Zhang et al. (2019) in which authors have shown that multisensor networks are effective for environmental monitoring.

2.2. Likelihood Assessment Algorithm

The probability of fire is calculated through sensor readings based on weighted algorithms that regard the significance of each type of sensor. Different weights are given to each sensor according to prior studies, such as Kumar and Ghosh (2021), that emphasize the possibility of fusing the data for precision.

Weight Calculation: The algorithm utilizes the following weights:

- Infrared (Flame) Sensor: 0.4
- Gas Sensor: 0.4
- Temperature Sensor: 0.2

This weighting scheme allows the system to prioritize more sensitive indicators of fire, such as infrared radiation and gas levels, while still incorporating temperature data as a supplementary input.

- **Normalizing Sensor Readings**: Each sensor reading is normalized to a scale of 0 to 1, where the maximum possible reading is set based on historical data for the specific sensor types. This normalization process, outlined by **Liu et al. (2004)**, helps in aggregating data from multiple sensors efficiently.
- **Likelihood Calculation**: The likelihood of fire presence is determined using the formula:

$$Likelihood = Scaling\ Factor * ((Normalized\ Gas * 0.4) + (Normalized\ Flame * 0.4) + (Normalized\ Temperature * 0.2))$$

The scaling factor adjusts based on the number of active sensors, enhancing the robustness of the system in various conditions.

2.3. Triangulation Algorithm

Once the fire is detected the system uses a triangulation algorithm to determine the location of the fire by data coming from three devices. This technique makes use of the Haversine formula to deduce distances from the geographic coordinates.

Haversine Formula: The formula computes the distance between two points on the Earth's surface given their latitude and longitude:

$$\mathrm{a} = \sin^2\left(\frac{\Delta\mathrm{lat}}{2}\right) + \cos(\mathrm{lat}_1) \cdot \cos(lat_2) \cdot sin^2\left(\frac{\Delta\mathrm{lon}}{2}\right)$$

$$\mathrm{c} = 2 \cdot \mathrm{atan2}\left(\sqrt{a}, \sqrt{1-a}\right)$$

$$\mathrm{d} = \mathrm{R} \cdot \mathrm{c}$$

where R is the Earth's radius (approximately 6,371 kilometers), Δlat is the difference in latitude, and Δlon is the difference in longitude.

Weighted Distance Calculation:

The system calculates weighted distances from the fire's estimated location based on likelihood scores derived from the sensor data. This weighting considers factors such as infrared readings, gas sensor outputs, and temperature data. The formula for calculating weight based on sensor readings is:

$$Weight = (2 \times IR\ State) + Gas\ State + (\frac{Temperature\ State}{100})$$

The distance is then calculated as inversely proportional to the weight:

$$Distance = \frac{Weight}{1}$$

Final Location Estimation: Once the system has calculated how far each sensor is from the fire, it combines the data from all three sensors to estimate the fire's location. It does this by averaging the locations of the sensors, but it gives more importance (weight) to the sensors that are closer to the fire. This helps ensure the fire's location is pinpointed accurately. The formula for the final location coordinates is:

$$Estimated\ Latitude = \frac{\sum(Latitude_i \times Distance_i)}{\sum Distance_i}$$

$$Estimated\ Longitude = \frac{\sum(Longitude_i \times Distance_i)}{\sum Distance_i}$$

How the Location Calculation Works

Suppose you have several heat sensors placed in different known locations (each with a known latitude and longitude). Each sensor detects the intensity of heat, and from that, you can calculate how far away the fire might be from each sensor. This distance is the equivalent of the "Distance_i" in the formula.

Weighted Contribution: Sensors that are closer to the fire (shorter distance) provide more accurate data about its location, so their latitudes and longitudes contribute more heavily to the final estimated position. This is similar to the idea of "weighting" in the formula. The closer the sensor is to the fire, the more it influences the estimated fire location.

Averaging the Position: The formula calculates an average of the latitudes and longitudes of the sensors, but it gives more weight to the sensors that are closer (with smaller distances). This results in an estimated latitude and longitude for the fire's location, just as in the formula. The sum of the products of latitude/longitude and distance is divided by the sum of distances to give you a weighted average that pinpoints the fire's approximate location.

Real World Example:

If you had three heat sensors:

- Sensor 1 detects heat from a fire and is 10 meters away.
- Sensor 2 detects heat but is 30 meters away.
- Sensor 3 detects heat but is 50 meters away.

The formula would use these distances and the sensor locations to calculate the fire's estimated latitude and longitude, giving Sensor 1 more influence because it's closest to the fire.

This approach provides an approximate location for the fire, utilizing triangulation principles and weighted data. This methodology aligns with studies such as Wang et al. (2015), which demonstrate the success of trilateration techniques in fire localization.

2.4. System Testing and Evaluation

The proposed system will be tested under control conditions and in real-life deployments. Key performance indicators (KPIs) will include detection accuracy, response time, and false alarm rates. These data will be subjected to analysis of the overall system performance for different types of environments, varying from residential buildings to industrial sites.

3. LITERATURE REVIEW

These developments are mainly based on numerous studies conducted and focused on sensor technologies, algorithm development, and data analysis techniques. This literature review synthesizes some of the recent research conducted that would be relevant to the proposed algorithm for fire detection and localization.

3.1 Multisensor Integration

Combining many types of sensors, for example, temperature, gas, and infrared, proved to increase the accuracy of fire detection systems. Zhang et al. 2019 published a work proving that the use of several sensor types will increase detection rate and reduce false alarms by using fused data techniques at one time that take advantage of the strength of one type of sensor in proper ways.

Similarly, Kumar and Ghosh (2021) said that multisensor methods may possibly bring a better solution for reliable fire detection, wherein it will be applicable to dynamic environments, and single-sensor systems are potentially bound to fail.

3.2 Algorithmic Approaches

These problems have faced the solutions in the form of presentation of many algorithms that estimate the probability of fire occurrence by using sensor observations. Liu et al. (2004) proposed an algorithm called weighted sensor data interpretation, which gives different weights to the sensors with various reliabilities and sensitivities.

This concept is followed by Wang et al. in their paper of 2015, in which they used ML algorithms to predict the onset of fire with enhanced accuracy than the classical approaches.

Zhou et al. (2020) further support the concept using weighted values for the calculation of the likelihood of the fire's presence. They discuss fuzzy logic systems which can be interpreted to sensor data, at the same time assess risks providing this basis to integrate uncertainty in the detection process.

3.3 Triangulation Techniques

Various applications of triangulation methods in fire location have been successful. The Haversine formula, commonly used for distance calculation from coordinates, has been adopted across several studies for enhancing location accuracies. For example, Andersson et al. have utilized the Haversine method in environmental monitoring, underlying its feasibility in positioning applications.

In addition, Morrison and Farooq (2019) proved the potential effectiveness of trilateration techniques in any emergency response scenario; this can be similar to the triangulation approach proposed within the study.

Results from such studies would emphasize just how critical accurate location estimation is in generating timely responses to emergencies, bringing about further underlining of the necessity of having precise fire localization systems.

3.4 Real-World Applications

This is, therefore, the real-world applicability which will improve fire safety measures. It was reported that some research by Cox et al. (2020) implemented multisensor fire detection systems in industries with positive results in reducing responses to incidents. At the same time, case studies conducted by El-Masri and Jbara (2021) in residential areas can be called a guide on how effective sensor networks could mean proactive fire prevention measures.

4. CONCLUSIONS

The paper proposes a new methodology for fire detection and localization that combines multisensor information such as temperatures, gases, infrared, and light-dependent resistors. From the evidence, it is noted that multisensor integration enhances the accuracy of detecting the phenomenon and eliminates false positives as suggested by Zhang et al. (2019) and Kumar and Ghosh (2021) in other literature.

This research expands the current methods by using a weighted algorithm that assesses the likelihood of fire, depending on the weights that different types of sensors possess based on Liu et al. (2004) and Wang et al. (2015).

This method of triangulation in approximating the fire location was improved by the use of Haversine formula, which further reiterated the effectiveness of the former in distance determination with regard to geographical coordinates. As did Andersson et al. (2017) and Morrison and Farooq (2019), in general, the whole agreement was set upon the establishment that precise location estimation is critical in emergency response situations.

More importantly, the practical applicability of these technologies enhances their potential contribution to fire safety significantly across the different sectors of practice. Case studies from Cox et al. (2020) and El-Masri and Jbara (2021) depict a crucial aspect of proactive fire prevention and rapid intervention using multisensor systems, making this study pertinent to reality

In short, this research manages to fill the gaps that were still left open in fire detection systems and contributes towards enriching fire safety technology by advanced algorithms and methodologies. To be precise, future work should be put in the line of improving algorithms and furthering their integration into the broader fire safety frameworks with a potential scope of improving applicability and effectiveness in practical use. This system may have a key impact on public safety and emergency management in terms of giving timely and accurate response to fire incidents.

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