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IOT BASED AUTONOMOUS FIRE FIGHTING ROBOT CAR

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ABSTRACT

Fire accidents pose significant risks to life and property, necessitating the development of fast and reliable autonomous firefighting systems. In this work, we present an AI-based fire-fighting robot that integrates embedded systems with edge intelligence for real-time fire detection and response. The proposed system utilizes an ESP32-CAM [2] module combined with a lightweight deep learning model developed using Edge Impulse to perform on-device image-based fire classification. Unlike traditional flame sensor-based systems, the proposed approach leverages visual data to improve detection accuracy and adaptability under varying environmental conditions. The ESP32-CAM captures real-time images and processes them through the trained model to identify the presence of fire. Upon detection, the system transmits control signals to an Arduino[1] Uno, which functions as the central decision execution unit. Based on the received inputs, the Arduino [1] controls the robot's movement via an L298N motor driver and directs the robot toward the fire source. A servo-controlled nozzle and water pump mechanism are activated when the robot reaches proximity to the fire, enabling precise extinguishing. The system is designed with a multi-component architecture including DC gear motors for mobility, a transistor-based switching circuit for pump control, and a stable battery power supply for reliable operation. Experimental results demonstrate that the proposed system achieves efficient fire detection and autonomous response with minimal latency, making it suitable for small-scale and indoor fire safety applications. This work highlights the potential of combining edge AI with robotic systems to create intelligent, cost-effective, and scalable firefighting solutions.

INDEX TERMS: Fire detection, ESP32-CAM, Edge AI, embedded systems, autonomous robot, deep learning, image classification, fire-fighting system.

I. INTRODUCTION

Fire accidents remain one of the most critical hazards in residential, industrial, and commercial environments, often leading to severe damage to property and loss of human life. Rapid detection and immediate response are essential to minimize the impact of such incidents. Conventional firefighting methods rely heavily on human intervention, which can be slow, risky, and inefficient, especially in hazardous or inaccessible areas. Therefore, the development of automated and intelligent fire detection and extinguishing systems has become an important area of research.

Traditional fire detection systems commonly use flame sensors, smoke detectors, or temperature sensors. While these methods are simple and cost-effective, they often suffer from limitations such as false triggering, limited detection range, and inability to accurately determine the direction and intensity of the fire. These constraints reduce their effectiveness in dynamic and real-world environments.

With the advancement of artificial intelligence and embedded systems, vision-based fire detection has emerged as a more robust and adaptive solution. In particular, edge AI devices such as the ESP32-CAM[2] enable real-time image acquisition and processing directly on hardware with limited computational resources. By leveraging machine learning techniques, such systems can analyze visual patterns such as color, texture, and shape to detect fire more accurately compared to traditional sensor-based approaches.

In this work, we propose an **AI-based fire-fighting robot** that integrates embedded control systems with edge intelligence for autonomous fire detection and response. The system utilizes an ESP32-CAM [2] module combined with a lightweight deep learning model developed using Edge Impulse to perform real-time fire classification. Unlike conventional systems that rely solely on flame sensors, the proposed approach processes visual data to enhance detection reliability under varying environmental conditions.

Upon detecting fire, the ESP32-CAM communicates with an Arduino Uno[1], which serves as the central control unit responsible for executing movement and actuation decisions. The robot navigates toward the detected fire source using DC motors controlled via an L298N motor driver. A servo-controlled nozzle and a water pump mechanism are employed to accurately target and extinguish the fire once the robot reaches a safe proximity.

The proposed system combines mechanical design, embedded programming, and artificial intelligence to create a compact, cost-effective, and autonomous fire-fighting solution. This approach demonstrates the potential of integrating edge AI with robotics for real-time hazard detection and mitigation in small-scale environments.

II. LITERATURE REVIEW: PREVIOUS METHODS

Early fire detection systems primarily relied on conventional sensing techniques such as flame sensors, smoke detectors, and temperature sensors. These systems were widely used due to their simplicity and low cost; however, they were limited by factors such as short detection range, sensitivity to environmental conditions, and inability to accurately determine the direction and intensity of fire. In many cases, these systems produced false alarms due to external light sources or failed to detect fire in complex environments.

To improve reliability, multi-sensor-based systems were introduced, combining infrared (IR) sensors, gas sensors, and temperature sensors. While these approaches enhanced detection accuracy, they increased system complexity and still lacked intelligent decision-making capabilities. Additionally, such systems were unable to adapt dynamically to varying lighting conditions or detect fire based on visual characteristics.

With the advancement of robotics, fire-fighting robots were developed to automate detection and extinguishing tasks. These robots typically used microcontrollers such as Arduino[1] along with motor drivers and flame sensors to navigate toward fire sources. Although effective for basic applications, these systems relied on predefined logic and lacked adaptability, limiting their performance in real-world scenarios.

Recent developments in artificial intelligence and computer vision have introduced more advanced fire detection techniques using image processing and machine learning. Methods based on convolutional neural networks (CNNs) and deep learning models have demonstrated improved accuracy by analyzing visual features such as color, texture, and motion patterns of fire. However, many of these approaches require high computational power and are typically implemented on systems such as Raspberry Pi or GPUs, making them less suitable for lightweight embedded applications.

To address these limitations, edge AI platforms such as ESP32-CAM[2] have emerged as efficient solutions for real-time image-based detection on resource-constrained devices. Frameworks like Edge Impulse enable the development and deployment of lightweight machine learning models directly on embedded hardware, allowing real-time inference without the need for cloud processing.

In this work, we build upon these advancements by developing an AI-based fire-fighting robot that integrates embedded control with edge intelligence. Unlike traditional sensor-based systems, the proposed approach utilizes a trained image classification model deployed on ESP32-CAM[2] for real-time fire detection. This enables improved accuracy, adaptability, and autonomous decision-making while maintaining low cost and system efficiency.

III. PROPOSED METHOD: DEVELOPMENT OF AI-BASED FIRE-FIGHTING ROBOT

In this work, we propose an AI-based autonomous fire-fighting robot that integrates edge intelligence with embedded control systems to achieve real-time fire detection and response. Unlike conventional systems that rely on flame sensors and predefined logic, the proposed method utilizes a vision-based approach powered by an ESP32-CAM [2] module and a lightweight deep learning model developed using Edge Impulse. This enables more accurate, adaptive, and intelligent fire detection under varying environmental conditions.

The proposed system consists of four major components: (i) image acquisition and preprocessing, (ii) AI-based fire classification, (iii) decision-making and control unit, and (iv) actuation and extinguishing mechanism. The overall architecture ensures efficient detection, navigation, and fire suppression in a fully automated manner.

Fire Images

No Fire Images

A. Image Acquisition and Preprocessing

The ESP32-CAM[2] module captures real-time images of the surrounding environment in RGB format. These images are resized and normalized to match the input requirements of the trained AI model. Preprocessing ensures that the system operates efficiently within the limited computational resources of the ESP32-CAM[2] while maintaining sufficient feature quality for accurate detection.

B. AI-Based Fire Detection Model

A lightweight image classification model is developed using Edge Impulse. The model is trained on a dataset consisting of fire and non-fire images to learn distinguishing visual features such as color patterns, brightness, and texture.

Given an input image , the model predicts the probability of fire presence as:

$$Y = f_{AI}(X)$$

where represents the classification output (fire / no fire).

A threshold-based decision is applied to determine whether fire is detected in the scene.

C. Decision-Making and Control Unit

Once fire is detected, the ESP32-CAM[2] sends control signals to the Arduino Uno[1], which acts as the central decision execution unit. The Arduino[1]processes these signals and determines the movement of the robot.

The control logic can be represented as:

- Fire detected → Move toward target
- No fire → Continue scanning

The Arduino[1] interfaces with the L298N motor driver to control the direction and speed of the motors.

D. Navigation and Movement Mechanism

The robot is equipped with four BO motors connected through the motor driver. Based on the control signals received, the robot navigates toward the detected fire source using predefined movement logic such as forward motion and directional adjustments.

E. Fire Extinguishing Mechanism

Upon reaching close proximity to the fire, the Arduino activates a water pump through a TIP122 transistor switching circuit. A servo motor is used to control the nozzle direction, allowing targeted water spraying.

The pump operation is controlled as:

$Pump = ON$ if fire proximity condition is satisfied

A flyback diode and capacitor are incorporated to protect the circuit from voltage spikes and noise generated by the pump motor.

F. System Integration and Operation

The complete system operates in a closed-loop manner:

1. Image capture by ESP32-CAM [2]
2. AI-based fire detection
3. Signal transmission to Arduino
4. Robot navigation toward fire
5. Activation of pump and servo for extinguishing

This integrated approach ensures real-time response, improved detection accuracy, and autonomous operation.

G. Key Advantages of Proposed Method

- AI-based visual detection improves accuracy over traditional sensors
- Real-time processing using edge AI (ESP32-CAM[2])
- Fully autonomous operation
- Low-cost and scalable design
- Suitable for indoor and small-scale applications

loss function combining compression efficiency with spectral fidelity. The overall framework is implemented in PyTorch and validated on multiple benchmark hyperspectral datasets.

IV. RESULTS AND ANALYSIS

A. System Testing and Dataset Description

To evaluate the performance of the proposed AI-based fire-fighting robot, experiments were conducted using real-time image data captured through the ESP32-CAM [2]module. The dataset consisted of two categories:

Fire images *(flame, candle, lighter, etc.)*

Non-fire images *(normal environment, lights, objects)*

Approximately 100–200 images per class were collected and used to train the model using Edge Impulse. The trained model was then deployed on the ESP32-CAM for real-time testing.

B. Fire Detection Accuracy

The AI model classifies each captured frame as:

- ***Fire detected***
- ***No fire***

The classification is based on learned visual features such as color (red, orange, yellow), brightness, and texture patterns.

The detection condition can be represented as:

$Fire = 1 \text{ if } probability > Threshold$

Experimental results showed that the system achieved:

High detection accuracy in controlled environments

Reliable performance under different lighting conditions

Reduced false detection compared to IR flame sensors

C. Direction and Distance Estimation

Unlike traditional systems using multiple flame sensors, the ESP32-CAM[2] determines direction using image processing:

Left region pixels → Turn left

Center region pixels → Move forward

Right region pixels → Turn right

Distance estimation is performed based on ***fire size (pixel area):***

Small area → Far distance

Medium area → Moderate distance

Large area → Near distance

This allows the robot to make more intelligent navigation decisions.

D. Robot Navigation Performance

The Arduino Uno receives processed signals from ESP32-CAM and controls movement via the L298N motor driver.

Performance observations:

Smooth movement toward detected fire

Faster response compared to sensor-based system

Stable directional control using AI output

E. Fire Extinguishing Efficiency

Once the robot reaches a predefined proximity:

Water pump is activated via TIP122 transistor

Servo motor adjusts nozzle direction

Results:

Accurate targeting of fire

Effective extinguishing in small-scale scenarios

Minimal delay between detection and action

F. Comparative Analysis with Traditional System

Feature	***Flame Sensor System***	***AI-Based System***
Detection Method	*Infrared*	*Image Processing*
Accuracy	*Moderate*	*High*
Direction Detection	*Limited (3 sensors)*	*Precise (pixel-based)*
Distance Estimation	*Not available*	*Available (pixel area)*
Adaptability	*Low*	*High*

The AI-based system clearly outperforms traditional methods in terms of intelligence and flexibility.

G. Performance Indicators

The effectiveness of the system is evaluated using:

Detection Accuracy *→ Correct fire identification*

Response Time *→ Time taken to react after detection*

Navigation Efficiency *→ Ability to reach fire source*

Extinguishing Success Rate *→ Ability to stop fire*

H. Key Observations

AI significantly improves detection reliability

System reduces false positives from external light sources

Real-time processing is successfully achieved on ESP32-CAM[2]

Integration with Arduino[1] ensures smooth control and actuation

I. Conclusion of Analysis

The experimental results demonstrate that the proposed system:

Successfully integrates AI with embedded robotics

Achieves accurate real-time fire detection

Provides intelligent navigation using vision-based input

Improves overall efficiency compared to traditional fire-fighting robots

V. CONCLUSION

In this work, we proposed an **AI-based fire-fighting robot** that integrates edge intelligence with embedded control systems for real-time fire detection and suppression. By replacing conventional flame sensors with a vision-based approach using the ESP32-CAM, the system is capable of detecting fire more accurately through image processing and machine learning techniques. The use of an AI model trained via Edge Impulse enables the robot to identify fire based on visual features such as color, intensity, and spatial patterns.

The proposed system combines AI-based detection with an Arduino-controlled actuation mechanism, allowing autonomous navigation toward the fire source and effective extinguishing using a water pump and servo-controlled nozzle. Experimental results demonstrate that the system achieves improved detection accuracy, better directional awareness, and enhanced adaptability compared to traditional sensor-based fire-fighting robots.

Unlike conventional approaches that rely on fixed logic and limited sensing capability, the proposed method introduces intelligent decision-making, enabling the robot to operate efficiently in dynamic environments. The integration of AI significantly reduces false detections and improves response time, making the system more reliable for real-world small-scale applications.

Overall, the proposed system provides a **cost-effective, scalable, and autonomous solution** for fire detection and suppression, demonstrating the practical potential of combining robotics with edge AI technologies.

The proposed system can be further enhanced in several ways:

- Integration of advanced deep learning models for improved fire and smoke detection
- Implementation of obstacle avoidance and path planning algorithms for better navigation
- Use of multiple cameras for wider field-of-view and 3D detection
- Deployment on more powerful edge devices for faster processing

- Integration with IoT or mobile applications for remote monitoring and control

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