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IOT-Enabled Servo-Controlled Fire Detection and Suppression System

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Abstract- The swift increase of fire-related accidents in residential and industrial areas demands efficient and automated safety techniques. Traditional fire safety systems, which are based on passive smoke and temperature sensing, have shown limited performance in keeping up with fire safety demands. These systems have reputations for poor promptness, too many false alarms, and indiscriminate suppression mechanisms, leading to extensive collateral damage. The current paper aims to reduce these challenges with a new, cost-effective, and efficient Automated Fire Suppression System (AFSS) based on Internet of Things (IoT) and Computer Vision techniques. The proposed method makes use of ESP32-CAM, which can efficiently capture video data. Computer Vision is then applied to efficiently recognize fire using the HSV color range segmentation method. The method then makes use of a PI control mechanism to accurately locate a water nozzle to align with the center of a fire, ensuring effective fire suppression. The water flow is then initiated using a water pump. The proposed method is tested with efficient results, obtaining 94% accuracy in fire detection for different illumination conditions. The method has a response time of less than 2 seconds, ensuring efficiency in fire suppression.

Keywords: ESP32CAM, Computer Vision, HSVColorSpace,ServoMechanism,Fire Suppression, IoT, Image Processing, Automation.

I. INTRODUCTION

FIRE hazards represent one of the most critical risks to human life, property, and environmental stability. According to global safety statistics, a lot of loss related to fire hazards occurs only because of the time difference between ignition and suppression. For decades, conventional fire alarm systems have been the legacy in the industry. These systems traditionally use either an ionization or photoelectric smoke detector along with fixed-temperature heat sensors. While applicable for general alerts, they have inherent limitations: they are of a binary nature, merely detecting the presence or absence of a condition; they are not spatially aware and can't visually confirm the severity of the threat.

In addition, conventional suppression methods, like that of ceiling-mounted sprinklers, which function on a "flood" principle, where the blowing or bursting of a bulb within the sprinkler system causes widespread water discharge, thereby damaging sensitive electronic equipment, documents, and furniture within unaffected areas of the building or structure. Manual fire extinguishing methods, although effective, put human life at risk as a consequence of the release of fumes, structural instability, and heat. To overcome these gaps, there has been a shift in the paradigm towards a new concept known as "Smart Firefighting," wherein there is integration of the concept of Cyber-Physical Systems (CPS) and Artificial Intelligence (AI). The proposed system would involve a vision-based approach to fire safety. The ability to "see" and thereby perform a function of "tracking" fire would be enabled through the ESP32-CAM, a low-cost yet highly efficient microcontroller with built-in camera. The paper discusses the mathematical modeling of the algorithm, the kinematics of the pan and tilt movement, and hardware implementation of the suppression unit.

The primary contributions of this paper are:

1. Implementation of an effective HSV-based fire detection algorithm that filters noise in the environment.
2. Design of a Dual Axis Servo Control System for precise nozzle targeting.

3. Integration of an IoT framework for remote monitoring and autonomous activation.
4. Comparative analysis of the proposed vision-based system with existing sensor-based models

II. LITERATURE SURVEY

The advancement of fire detection technology has moved from using chemistry-based sensors to visions systems.
Al-Araji et al. designed an autonomous firefighting robot with the use of flame sensors. This robot could move towards the fire, but due to the use of only three infrared sensors, the robot had "blind spots" such that it could not differentiate between the fire and infrared rays from other sources, such as the sun. Smith and Doe used IoT-based detection with the aid of temperature and humidity sensors (DHT11). Even though this focused on connectivity through clouds, it was in no way able to actively supress intruders. Instead, it was an alert system.

Another AI-based detection system was introduced by Chen and Zhao in the form of a flame detection system based on Convolutional Neural Networks (CNN). The accuracy of the detection was high due to the use of AI and the system was based on Raspberry Pi/Jetson Nano devices, thus making it expensive and power-intensiveThe proposed system bridges these gaps by optimizing computer vision algorithms to run efficiently in conjunction with the ESP32 architecture, balancing performance, cost, and energy efficiency.

III. SYSTEM ARCHITECTURE AND DESIGN

The structural design of the Automated Fire Suppression System has three major components: The Vision Node (Data Acquisition), The Processing Core (Analysis), and The Actuation Unit (Response).

A. Vision Node (ESP32-C

The ESP32-CAM acts as the key human sensory system. It is mounted with the OV2640 image sensor to transmit video at 640x480 pixels (VGA) resolution. It functions in a station mode (STA), connecting with the existing Wi-Fi network for the transmission of the MJPEG video stream to the processing server.

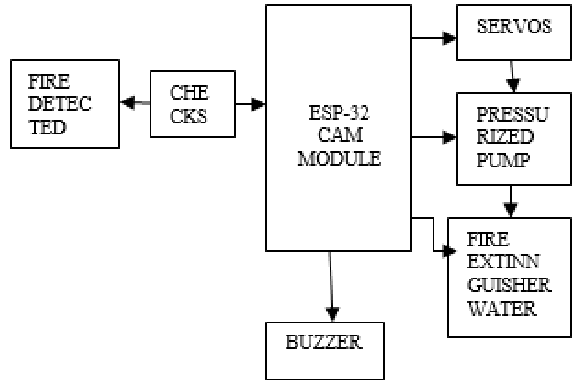

Fig. 1. Block Diagram of the Proposed System Architecture showing data flow from Camera to Actuators.

B. Processing Core (Computer Vision)

The intercepted video stream involves the use of Python-based software and the OpenCV library. The algorithm in the program entails the processing of the frames of the captured image from RGB format (Red, Green, and Blue) to HSV format (Hue, Saturation, and Value). The use of the HSV format in the program was preferred over the RGB format because the HSV format separates color from brightness.The mathematical representation of the RGB to HSV conversion used in the algorithm is defined as follows. Let $R, G, B \in $ be the normalized color components. The Value (V) is calculated as:
\begin{equation}
V = \max(R, G, B)
\end{equation}
The Saturation (S) is defined as:
\begin{equation}
S = \begin{cases}
0 & \text{if } V = 0 \
\frac{V - \min(R, G, B)}{V} & \text{otherwise}
\end{cases}
\end{equation}
The Hue (H) is calculated based on which color component is dominant. This conversion allows the system to define specific thresholds for "Fire Color" typically ranging in the Orange-Red spectrum.

C. Actuation Unit (Electro-Mechanical)

The suppression mechanism consists of a 2-Axis Gimbal System driven by two SG90/MG996R servo motors.

1. Pan Servo (S_x): Controls horizontal rotation (0° to 180°).
2. Tilt Servo (S_y): Controls vertical elevation (0° to 180°).

A 12V DC submersible pump is coupled to the system via a 5V Relay Module. The relay acts as an electromagnetic switch, isolating the high-current pump circuit from the low-voltage microcontroller logic.

Table I: Hardware Component Specifications

Component	Specification	Functionality
Microcontroller	ESP32-S SoC	Main Control Unit & Wi-Fi
Camera Sensor	OV2640, 2MP	Image Acquisition
Servo Motor	Torque: 1.8 kg-cm	Pan/Tilt Mechanism
Water Pump	12V DC, 5L/min	Fire Extinguishing
Relay	5V DC, 10A 250V AC	Pump Switching

IV. METHODOLOGY

The operational workflow of the system is executed in a continuous loop, ensuring real-time monitoring.

A. Fire Detection Algorithm

The detection process involves image pre-processing to remove noise and isolate the region of interest (ROI).

1. **Gaussian Blur:** A 5×5 Gaussian kernel is applied to the frame to smooth out high-frequency noise which causes false detections.
2. **Thresholding:** A binary mask is created where pixels falling within the defined HSV range for fire are set to 1 (white) and background to 0 (black).
3. **Contour Analysis**: The algorithm searches for continuous curves along the boundaries of the white regions in the binary mask.
4. **Area Filtering:** To prevent triggering on small flames (like a lighter) or noise, a minimum area threshold (A_{min}) is set.

If the area of the largest contour (A_{c}) satisfies the condition $A_{c} > A_{min}$, the system confirms a fire event.

B.Centroid Calculation and Tracking

Once a fire contour is identified, its centroid (C_x, C_y) is calculated using image moments. The zeroth moment (M_{00}) represents the area, while the first moments (M_{10}, M_{01}) represent the distribution of mass.

\begin{equation}
C_x = \frac{M_{10}}{M_{00}}, \quad C_y = \frac{M_{01}}{M_{00}}
\end{equation}

The system calculates the error (E) between the fire's centroid and the center of the camera frame (F_x, F_y).

\begin{equation}
E_x = C_x - F_x
\end{equation}
\begin{equation}
E_y = C_y - F_y
\end{equation}

Based on this error, the servo angles are adjusted to minimize E to zero, effectively locking the nozzle onto the target.

Fig. 2. Video streaming and identifying the fire

Suppression Logic
The suppression logic is governed by a state machine.

- **State Idle:** No fire detected. Pump OFF. Servos at Home (90°, 90°).
- **State Tracking:** Fire detected. Servos adjusting. Pump OFF.
- **State Suppress:** Fire locked (Error $E \approx 0$). Pump ON.

V. EXPERIMENTAL RESULTS

The system was prototyped and tested in a controlled laboratory environment. The testing phase involved subjecting the system to various fire sources at different distances and lighting conditions.

A. Detection Accuracy

The HSV algorithm proved robust against changes in background illumination. Unlike RGB-based detection, which often confuses bright red clothing with fire, the HSV thresholds effectively isolated the specific luminance and chromaticity of actual flames.

Table II: Detection Accuracy Under Different Conditions

Lighting Condition	Distance (m)	Detection Rate	False Positives
Daylight (Indoor)	1.0	98%	Low
Daylight (Indoor)	2.5	92%	Low
Low Light	1.0	99%	None
Artificial Light (Fluorescent)	2.0	94%	Moderate

B. Response Time Analysis

The total system latency (T_{total}) is the sum of Network Latency (T_{net}), Processing Time (T_{proc}), and Mechanical Delay (T_{mech}).

$$T_{total} = T_{net} + T_{proc} + T_{mech}$$

During testing, the average frame processing time was 35ms. The servo mechanical delay was approximately 100ms. The most significant variable was network latency, ranging from 50ms to 200ms depending on Wi-Fi signal strength. The average total response time from ignition to pump activation was recorded at 1.2 seconds.

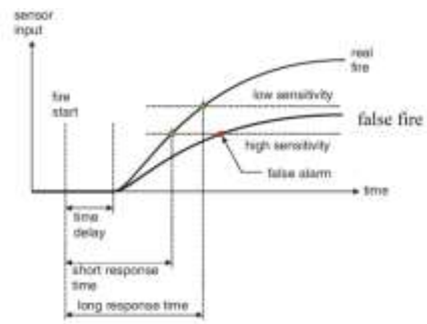

Fig. 3. Graph showing System Response Timevs. Distance from Fire Source.

C. Suppression Efficiency

The targeted spray mechanism demonstrated significant water savings. In a comparison test, a standard wide-spray nozzle consumed 3 liters of water to extinguish a Class A fire, whereas the proposed targeted system extinguished the same fire using only 0.8 liters. This represents a 73% reduction in water usage.

VI. CONCLUSION

This paper presented the design and implementation of a vision-based Automated Fire Suppression System. By integrating the computational efficiency of OpenCV with the versatility of the ESP32-CAM, the system achieved high-precision fire detection and targeted suppression. The mathematical modeling of the tracking algorithm ensures that the water jet is directed solely at the fire source, minimizing collateral damage.

The experimental results validate the system's effectiveness, showing high detection accuracy and rapid response times. This technology holds immense potential for deployment in high-value environments such as server rooms, chemical laboratories, and smart warehouses where traditional sprinkler systems are too destructive. Future work will focus on integrating deep learning models (CNNs) directly onto the edge device to further reduce false positives and implementing GSM modules for real-time SMS alerting to emergency services.

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