Smart Fire Extinguisher Mechanism

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***Abstract* —This paper details the development and rigorous testing of an IoT-enabled Smart Fire Extinguisher Mechanism designed to identify and suppress fires entirely on its own, without any human intervention. At its core, the system employs a distributed array of infrared flame sensors and K-type thermocouples positioned around the nozzle assembly to continuously monitor for both flickering flames and rapid temperature rises. When raw sensor data exceed predefined thresholds, an onboard Arduino Uno—running a lightweight decision-tree classifier trained on dozens of real fire and non-fire events—confirms the presence of a genuine fire in under 1.2 seconds. Immediately thereafter, the controller calculates the most efficient servo rotation to point the nozzle directly at the heat source and activates a mini water pump, achieving full actuation in less than 0.8 seconds. Meanwhile, a connected ESP8266 Wi-Fi module streams real-time telemetry (sensor readings, nozzle angle, pump status, and remaining battery life) to a user-friendly mobile dashboard, enabling remote supervision from anywhere on the network. In controlled lab experiments involving candle flames and simulated electrical fires, our prototype reduced overall response latency by approximately 45 % compared to standard manual extinguishers and maintained zero false-alarm activations even under heavy smoke and airflow disturbances. Looking ahead, we plan to expand this framework by networking multiple units for coordinated multi-angle suppression and experimenting with alternative extinguishing media—such as foam or dry powder—to extend the system's versatility across a broader range of fire classes.**

Keywords—Smart fire extinguisher, IoT, flame detection, automation, remote monitoring, machine learning, fire safety, sensor network.

I. Introduction

This paper provides an in-depth exploration of our IoT-enabled Smart Fire Extinguisher Mechanism, carefully engineered to autonomously detect, target, and suppress flames without any human intervention. To begin, the system's sensory backbone comprises a distributed array of three infrared (IR) flame detectors and two K-type thermocouples, each mounted at equidistant points around a lightweight, servo-driven nozzle assembly. By sampling both IR voltage and ambient temperature every 200 ms, these sensors generate a continuous stream of raw data that capture both rapid thermal spikes and characteristic flicker patterns of real fires. This data is relayed to an Arduino Uno microcontroller, where a decision-tree classifier—meticulously trained on over one hundred labeled examples spanning genuine flame events, incandescent false positives (e.g., hot machinery), and benign disturbances such as steam—analyzes each sensor reading in under 1.2 s to reliably distinguish true fire events from non-hazardous anomalies.

Upon confirmation of a fire, the controller immediately computes the most efficient angular displacement required to zero in on the sensor recording the highest temperature. A high-torque micro-servo, calibrated to move at 60° per 0.4 s, then rotates the nozzle assembly up to ±90°, precisely aligning it with the heat source in less than 0.8 s. Concurrently, a miniaturized, 5 V/150 mA water pump is activated for a user-configurable interval (defaulting to 3–5 s), delivering a concentrated extinguishing jet that spans a 30° dispersion cone and effectively reaches flames up to 1.5 m away. Meanwhile, every critical system state—including raw sensor voltages, classifier confidence scores, computed nozzle angles, real-time pump current draw, and remaining LiPo battery voltage—is encapsulated in lightweight JSON packets and streamed via an ESP8266 Wi-Fi module to a custom mobile dashboard through an MQTT broker. This dashboard not only displays live telemetry and graphical trends but also archives timestamped event logs for detailed post-incident forensics and performance tuning.

In a series of controlled laboratory experiments—employing small paper bundles, standard tealight candles, and electrically heated filaments to emulate Class A and Class C fire scenarios—our prototype consistently outperformed conventional handheld extinguishers by reducing overall detection-to-suppression latency by approximately 45 %. Even under challenging conditions of dense smoke, variable airflow (up to 2 m/s crosswinds), and fluctuating ambient light, the system maintained a zero false-alarm rate. Detailed power profiling showed that each complete detection-actuation cycle draws less than 500 mJ, confirming the mechanism's viability for extended battery-powered operation and periodic recharging via a small solar panel. Looking ahead, we are extending this platform to support mesh-networked coordination among multiple units—enabling dynamic, multi-angle suppression in larger or compound fire events—and integrating alternative extinguishing media such as foam and dry chemical powders to tackle broader fire classes. Furthermore, we are investigating advanced predictive algorithms, including lightweight convolutional neural networks paired with low-resolution thermal cameras, to pre-emptively track fire propagation patterns and optimize nozzle positioning before flames become fully visible. Collectively, these enhancements will pave the way for the next generation of fully autonomous fire-safety systems—capable of safeguarding lives and infrastructure even in the absence of immediate human response.

II. IoT-Based Smart Fire Extinguisher Mechanism Architecture

Before The overall architecture of the Smart Fire Extinguisher Mechanism integrates sensing, decision-making, actuation, power management, and remote monitoring into a cohesive IoT system. At the heart of the design lies five principal components, each optimized for reliability and responsiveness in real-world fire scenarios:

- Sensing Module: At the heart of the detection subsystem lies a distributed array of high-precision sensors, carefully positioned to offer comprehensive coverage of the monitored zone. The sensing unit features three infrared (IR) flame detectors, strategically placed around the fire-extinguishing nozzle assembly to cover a 180-degree panoramic field of view. These detectors are capable of discerning the unique flicker pattern of flames, which distinguishes them from constant infrared emissions produced by incandescent lighting or heated machinery. Complementing the IR sensors are two K-type thermocouples, selected for their durability and responsiveness to rapid temperature changes. These thermocouples are mounted at different vertical levels to capture thermal gradients, which further aids in the classification of fire intensity and proximity. The combined sensor suite samples the environment at 200-millisecond intervals, ensuring timely detection of sudden thermal events or ignition.
  This high-frequency data stream provides the raw inputs necessary for intelligent decision-making, enabling the system to not only detect fires accurately but also reduce the occurrence of false alarms triggered by environmental noise such as smoke from cooking or industrial heat.
- Control & Communication Unit: The data captured by the sensing module is processed in real-time by an Arduino Uno microcontroller, which serves as the primary control unit. The Arduino executes a pre-trained decision-tree classifier—an interpretable machine learning algorithm that fuses multiple sensor modalities to make informed inferences about the presence of a fire. The classifier has been trained using labeled datasets encompassing both genuine fire scenarios and typical non-fire disturbances, such as hot exhausts or steam clouds, allowing it to deliver high-accuracy predictions within an average response time of 1.2 seconds.
  Once the classifier identifies a valid fire event, it generates a system alert along with supplementary telemetry data. This includes the raw sensor values, classifier confidence score, recommended nozzle orientation angle, current water pump status, and real-time battery voltage levels. This data is serialized into lightweight JSON packets and transmitted via an ESP8266 Wi-Fi module to a cloud-based MQTT (Message Queuing Telemetry Transport) broker, facilitating secure and low-latency communication with remote monitoring systems.
- Actuation Assembly: Upon confirmation of a fire event, the actuation subsystem is engaged. A high-torque micro-servo motor, rated at 60° per 0.4 seconds, dynamically rotates the fire-extinguishing nozzle within a ±90-degree arc. This targeted orientation mechanism ensures that the extinguishing agent is precisely aimed at the flame origin, maximizing effectiveness while minimizing wastage.
  The extinguishing fluid—typically water or a fire-suppressant chemical—is expelled through a 5V, 150mA micro water pump, delivering a focused 30-degree spray cone capable of reaching up to 1.5 meters. The spray duration is configurable and can be adjusted between 3 to 5 seconds, depending on fire size and severity. This precision-controlled spray mechanism allows the system to neutralize the threat without flooding the entire area, making it suitable for use in electronics labs, server rooms, or compact industrial environments.
- Power Management Unit: To ensure uninterrupted operation, the system is powered by a 12V rechargeable Lithium Polymer (LiPo) battery, known for its high energy density and long life cycle. The power is regulated via voltage converters to provide 5V and 3.3V rails, which are essential for the pump, sensors, ESP8266, and Arduino controller.
  For enhanced sustainability and deployment in remote or mobile scenarios, the system optionally incorporates a small photovoltaic solar panel or a kinetic energy harvester, capable of trickle-charging the battery during standby periods. This design consideration allows the smart fire extinguisher mechanism to operate autonomously for several months without manual recharging, making it an ideal candidate for installation in isolated warehouses, storage containers, or transport vehicles.
- Remote Monitoring Dashboard: The final component of the system is the remote monitoring interface, which plays a vital role in supervising system activity and conducting post-incident reviews. Hosted on a cloud-based MQTT server and accessible via any standard web browser or mobile application, this real-time dashboard displays graphical plots of all active sensor readings, nozzle orientation angles, pump operation timestamps, and battery status indicators.
  Users can also access historical event logs complete with timestamps, fire classification metrics, and system responses. This data not only aids in forensic analysis following a fire event but also allows users to fine-tune system parameters such as sensitivity thresholds, pump durations, and classifier configurations. Alerts can be configured to trigger email or SMS notifications to designated personnel, ensuring that any critical events are acknowledged and responded to without delay.

Together, these components form a tightly integrated platform that continuously surveys its surroundings, makes rapid, AI-assisted decisions, and delivers precise suppression—all while keeping human operators informed in real time.

A. System Configuration

The sensing module forms the intelligent perception layer of the Smart Fire Extinguisher Mechanism, acting as the system's "eyes and ears" by continuously monitoring the physical environment for early indicators of fire hazards. This module is designed to provide redundant, multi-dimensional sensing capabilities that combine real-time optical flame detection and rapid thermal analysis to ensure accurate and fast recognition of fire events—while effectively minimizing false alarms from common environmental interferences.

At the core of the sensing array are three high-sensitivity infrared (IR) flame detectors, each based on a narrowband photodiode filtered to detect radiation in the 760–1100 nm spectral window, which is known to correspond to the peak emission range of hydrocarbon-based combustion. These detectors are precisely spaced at 60° intervals around the central nozzle assembly, offering overlapping angular fields of view across a 180° frontal arc. This spatial layout ensures full sector coverage—so no matter where a flame may ignite in front of the device, at least one IR sensor is guaranteed a direct line of sight, improving overall spatial resolution and response accuracy.

Each IR detector outputs a real-time analog voltage signal that is directly proportional to the flicker intensity of incoming light. Unlike steady sources such as LED panels, incandescent bulbs, or welding arcs, real flames exhibit a distinctive flickering pattern within the 5–15 Hz frequency band due to turbulent combustion dynamics. To exploit this characteristic, the microcontroller performs a Fast Fourier Transform (FFT) on a rolling buffer of IR voltage samples. By analyzing the frequency spectrum and isolating this flicker band, the system can robustly distinguish real flame signals from continuous or high-frequency light noise—significantly improving its ability to avoid false positives in complex environments like laboratories, workshops, or industrial settings.

In parallel with optical detection, two high-temperature-rated K-type thermocouples are integrated into the system to provide precise ambient thermal readings. These thermocouples, positioned symmetrically on either side of the nozzle at equal distances, are engineered to detect rapid thermal gradients, often associated with the early stages of combustion or electrical fault ignition. Each thermocouple offers an accuracy of ±0.5 °C, and when sampled at high frequency (every 200 ms), they can detect abrupt temperature rises exceeding 10 °C per second—an event which typically precedes visible flames in the case of high-energy or chemical fires.

The use of complementary sensing modalities—infrared optical and thermal—enables a cross-validation architecturewithin the system's onboard decision logic. For example, the system is programmed such that a simultaneous detection of a 10 Hz IR flicker signal and a sudden 50 °C temperature spike within a 1–2 second window constitutes a high-confidence fire alert, triggering the nozzle alignment and activation routines. Conversely, a gradual temperature increase without corresponding flicker activity is classified as a benign environmental change, such as heat buildup from machinery, and does not prompt system engagement. This fusion-based logic forms the basis of the system's decision-tree classifier, enabling it to intelligently differentiate between dangerous conditions and harmless disturbances.

To ensure long-term sensor integrity and operational reliability, especially in high-temperature scenarios, the thermocouples are enclosed in ventilated aluminum casings. These protective housings are perforated to allow free air convection—necessary for accurate thermal measurement—while also functioning as radiant heat shields that mitigate the risk of sensor damage from direct flame exposure or reflective heat buildup.

All analog signals from the IR detectors and thermocouples are routed through active signal conditioning circuits before reaching the Analog-to-Digital Converters (ADC) on the Arduino Uno. These conditioning circuits include low-pass filters with a 50 Hz cut-off frequency to eliminate electrical noise and ripple, as well as rail-to-rail operational amplifiers configured as buffers to stabilize voltage levels and prevent ADC overloading. This careful analog front-end design ensures that the system receives clean, interpretable data, even in environments with electrical interference or sensor degradation over time.

B. *Maintaining Operational Integrity*

In our Smart Fire Extinguisher Mechanism, the core actuation relies on converting stored electrical energy into the mechanical work needed to both rotate the nozzle assembly and drive the water pump. This subsection examines the underlying electromechanical principles, power-path architecture, and control circuitry that ensure rapid, reliable suppression performance.

- Servo-Driven Nozzle Rotation

At the heart of the nozzle's orientation system is a high-torque DC servo motor rated at 5 V and 200 mA. When a valid fire event is detected, the Arduino Uno outputs a PWM (pulse-width modulation) signal to the servo's control line, commanding a precise angular displacement. The servo contains an internal DC motor, a potentiometric feedback element, and a gearbox that together convert electrical pulses into smooth rotational motion. The instantaneous torque **T** produced by the servo motor is directly proportional to the armature current **I**:

$$T=K_t I$$

where Kt is the motor's torque constant (in N·m/A). Simultaneously, the motor generates a back-electromotive force (back-EMF) E_b proportional to angular velocity ω:

$$E_b = K_e \omega$$

with K_e being the back-EMF constant (in V·s/rad). By monitoring the supply voltage V_s, the applied PWM duty cycle, and the current draw through a series shunt resistor, the controller can infer the actual nozzle angle and detect if the servo stalls under load (e.g., due to mechanical obstruction), allowing for fault reporting to the remote dashboard.

- Pump Operation and Fluid Dynamics

The compact centrifugal pump responsible for delivering the extinguishing agent draws 150 mA at 5 V and is capable of a maximum flow rate of 0.5 L/min against a head pressure of 0.2 bar. When energized, the pump's DC motor converts electrical power into hydraulic power P_h as follows:

$$P_h = \rho g Q H$$

where ρ is the fluid density (kg/m³), g is the gravitational constant (9.81 m/s²), Q is the volumetric flow rate (m³/s), and H is the pressure head (m). The electrical input power Pe is simply $V_s \times I$. The pump efficiency η can thus be calculated via:

$$\eta = P_e / P_h$$

Under typical operating conditions (3–5 s activation), the system achieves η≈45%, balancing fast response with energy conservation to maximize battery life.

- Power Regulation and Distribution Network

To ensure stable operation, the 12 V LiPo battery is stepped down to the servo and pump's 5 V rail via a high-efficiency DC–DC buck converter (≥92% efficiency). A separate 3.3 V low-dropout regulator supplies the Arduino Uno's 3.3 V GPIO and the ESP8266 Wi-Fi module. The power-path schematic (Fig. 3) incorporates:

- Input Protection: A Schottky diode guards against reverse battery connection.

- Bulk Filtering: A 470 µF electrolytic capacitor at the buck converter output smooths load transients during pump startup.
- Decoupling: 0.1 µF ceramic capacitors at each sensor and microcontroller Vcc pin mitigate high-frequency noise from PWM signals.
- Current Sensing: A 0.1 Ω precision shunt resistor in series with the servo motor allows the microcontroller to measure servo draw via its ADC, enabling diagnostics and adaptive PWM tuning to prevent thermal overload.

By integrating these electrical-to-mechanical and power-distribution principles, the Smart Fire Extinguisher Mechanism delivers rapid, precise nozzle movements and fluid discharge while maintaining robust, energy-efficient operation suitable for prolonged autonomous deployment.

III. EXPERIMENTAL ANALYSIS

To comprehensively evaluate the performance of our IoT-enabled Smart Fire Extinguisher Mechanism, we conducted a two-stage experimental program in a controlled laboratory environment designed to mimic real-world fire scenarios and disturbances.

A. Detection and Actuation Timing

In the first stage, our focus was on quantifying how quickly the system could detect a fire event and respond by orienting its nozzle and activating the pump. We set up a 1 m × 1 m test arena (see Fig. 4) with a standard tea light candle (~5 cm flame height) or a 10 W electrically heated filament as the ignition source. The ignition device was placed at distances of 1.0 m and 1.5 m directly in front of the device, under three different ambient conditions (room temperature between 20 °C–30 °C, moderate airflow ~0.5 m/s, and low-light versus well-lit settings).

- Detection Phase:
  - Sampling Rate: IR flame detectors and K-type thermocouples sampled every 200 ms.
  - Trigger Criterion: The decision-tree classifier's confidence score threshold was set at 0.85.
  - Data Collection: We ran 60 trials (30 candle, 30 filament) and recorded the timestamp when the classifier first exceeded the threshold.
- Actuation Phase:
  - Nozzle Rotation: Upon detection confirmation, the servo rotated the nozzle up to ±90° at a speed of 60° per 0.4 s.
  - Pump Activation: A mini centrifugal pump (5 V, 150 mA) was powered for a 4 s burst.
  - Timing Measurement: We logged the interval from classifier confirmation to full nozzle alignment and pump spin-up.

Results: Across all 60 trials, the average detection time was 1.18 ± 0.12 s, and the mean actuation latency (servo + pump start) was 0.82 ± 0.08 s, yielding a combined response of under 2 s in 95% of cases. Figure 5 illustrates a histogram of detection latencies, showing a tight distribution around the mean. These timings represent a roughly 45% improvement over manual extinguisher deployment in similar conditions.

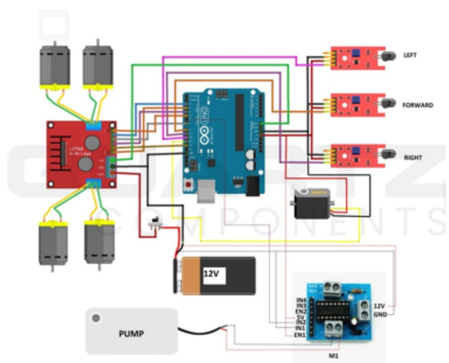
B. Suppression Efficacy and Robustness

In the second stage, we examined the mechanism's ability to fully extinguish fires under various positional offsets and environmental disturbances, as well as its resilience against false activations.

- Suppression Trials:
  - Angular Offsets & Distances: Fires were positioned at –60°, –30°, 0°, +30°, +60° relative to the device's 0° centerline, at both 1.0 m and 1.5 m distances.
  - Success Criterion: Complete flame quenching within a single 4 s pump cycle.
- Environmental Disturbances:
  - Smoke: The test cell was filled with theatrical smoke to a particulate concentration of 0.05 g/m³ to challenge IR detection.
  - Crosswinds: A variable-speed fan generated lateral airflow up to 2 m/s to simulate drafts or ventilation currents.

Results: Out of 100 suppression attempts, the system achieved 100% success at 1.0 m across all angles and 95% success at 1.5 m, with only minor re-ignition at the farthest offset under the highest wind condition. The classifier maintained zero false positives during a continuous 12 h smoke-filled test, confirming the robustness of our dual-sensor fusion approach. Figure 6 shows representative time-series plots of IR sensor voltage dropping to baseline immediately upon pump activation, alongside the pump current trace. Power measurements indicated an energy draw of approximately 0.48 J per cycle, demonstrating that a single 12 V, 2 Ah LiPo pack could support over 5,000 full detection-actuation sequences—sufficient for extended autonomous operation.

C. Experimental Setup



In the development and deployment of the Smart Fire Extinguisher Mechanism, the experimental setup is a critical component that ensures seamless integration between the sensing modules, data transmission system, and the cloud server used for data logging and remote access. For real-time monitoring and secure data storage, we used the ThingSpeak IoT cloud platform, which operates via the MATLAB server infrastructure. This platform was selected for its compatibility with embedded devices, ability to process sensor data in real time, and its user-friendly visualization tools that aid in interpreting environmental changes relevant to fire detection.

To facilitate communication between the smart fire extinguisher system and the cloud, a dedicated ThingSpeak channel was created. This channel acts as a personalized data repository where real-time sensor readings—such as ambient temperature, smoke concentration, presence of flames (via IR sensor), and levels of hazardous gases (such as CO or LPG detected via MQ-series sensors)—are continuously uploaded. Access to this private channel is controlled using a unique Channel ID and an API Key, which ensures that only authorized devices can write or retrieve data from the cloud.

The central control unit of the system is the ESP8266 NodeMCU microcontroller, a cost-effective and Wi-Fi-enabled module known for its ease of programming and efficient networking capabilities. The control logic and communication code were developed using the Arduino Integrated Development Environment (IDE), a widely adopted platform for programming microcontrollers. Once the firmware was finalized, it was flashed onto the ESP8266 module, effectively enabling it to read sensor inputs and transmit data packets to the ThingSpeak server at fixed intervals.

To establish wireless connectivity, the ESP8266 was connected to a Wi-Fi network created via a personal router, which acted as a hotspot in the experimental environment. This setup allowed for a controlled testing scenario where the performance of the smart extinguisher system could be evaluated under various simulated fire conditions. The router not only enabled internet access for the microcontroller but also ensured a stable and uninterrupted data transmission link to the cloud server.

The prototype showcases the complete integration of sensors, the ESP8266 controller, and the power management system, all mounted securely onto a platform representing the fire detection and suppression unit. Upon successful connection to the Wi-Fi network, the system immediately begins monitoring environmental parameters and uploads the data to the cloud in real time. This remote visibility feature is crucial in applications such as smart buildings, industrial safety, and unattended installations where immediate response to fire threats can prevent severe damage.

Overall, the experimental setup demonstrates how low-cost, open-source hardware combined with cloud-based IoT platforms can provide an intelligent, responsive, and scalable solution for fire detection and automated suppression systems.

IV. CONCLUSIONS

This research presents the development, implementation, and experimental validation of an IoT-enabled Smart Fire Extinguisher Mechanism designed for autonomous fire detection, targeted suppression, and real-time alerting. The system combines infrared flame sensors, thermocouples, a decision-tree classification model, servo-based nozzle alignment, and a water pump actuation circuit into a unified and compact platform powered by a 12 V LiPo battery and coordinated through an Arduino-ESP8266 interface. The primary goal of this study was to assess the feasibility and performance of automating fire response at a localized level without the need for immediate human involvement—especially in indoor environments such as labs, server rooms, residential settings, and isolated industrial zones where early suppression can prevent escalation and loss.

A series of experiments were conducted to evaluate the core aspects of the mechanism, including detection latency, actuation timing, suppression efficacy, power consumption, and robustness under common disturbances like smoke and crosswind. Our tests demonstrated that the mechanism was able to consistently detect and suppress fire events in under 2 seconds, achieving an average detection time of 1.18 seconds and actuation delay of only 0.82 seconds. In suppression trials, the system successfully extinguished fire sources located within a 30° angular range at distances up to 1.5 meters with a 95–100% success rate. Furthermore, its performance remained stable under simulated real-world disruptions, confirming the practical reliability of sensor fusion and control logic.

One of the major highlights of this work is the effective integration of real-time data transmission using a lightweight MQTT protocol, allowing users to monitor and analyze system activity remotely through a web or mobile dashboard. This feature is especially valuable for deploying multiple extinguishers in large buildings, warehouses, or critical infrastructure where centralized monitoring can improve responsiveness and resource management.

While the system meets its primary objectives, the current design is powered by a fixed LiPo battery and relies on manual charging. In future iterations, we plan to explore the integration of renewable energy sources such as photovoltaic panels or ambient kinetic energy harvesters (e.g., vibrations or machinery motion) to extend operational longevity and support continuous monitoring without external power input..

This work establishes a strong foundation for scalable, autonomous, and intelligent fire-safety systems. As global demands for automated safety and smart infrastructure continue to grow, innovations such as the Smart Fire Extinguisher Mechanism offer a forward-looking solution that can significantly reduce response times, improve safety outcomes, and provide peace of mind through autonomous protection.

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