Automated Fire Suppression System

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DOI: https://dx.doi.org/10.51244/IJRSI.2026.13010057

Received: 06 January 2026; Accepted: 12 January 2026; Published: 30 January 2026

ABSTRACT

This study demonstrates the design, development, and performance evaluation of an Automated Fire Suppression System that uses the Arduino Uno R3 as its primary micro controller. The proposed system is intended to enable an autonomous, real-time response to fire occurrences by combining infrared-based flame detection, closed-loop control logic, and electromechanical actuators. By continuously monitoring the environment for infrared radiation emitted by flames, the system can detect the presence of a fire, determine its relative location, and initiate a targeted suppression mechanism without human participation.

The system contains a flame sensor module for fire detection, dual-axis servo motors for directional alignment, and an active fire suppression water pump handled by a relay. A structured input-process-output (IPO) model and closed-loop control architecture were used to enable accurate detection, precise nozzle positioning, and adaptive responses based on real-time feedback. Detection accuracy, mechanical reliability, and response consistency have been tested by experimental testing under various fire conditions. The results show a 100% response rate for fire detection and suppression throughout the effective operating range of 30 cm to 80 cm, proving that the system has the capability to neutralize medium to large fire sources effectively.

Keywords: Arduino R3, Fire suppression system, Fire, Flame sensor

INTRODUCTION

Fire is indeed one of the major contributing factors to fatalities, loss of life, property damage, and economic disruption. As societies grew and cities expanded, the use of materials that easily burned made fires happen more often and caused serious damage. Throughout history, these infernos have been so common that nearly every major city in the world has, at some point, been largely destroyed by fire. According to the statistics stated by the Bureau of Fire Protection (BFP), the fire cases reported are concerned with the households, followed by transportations, electrical appliances, and leaking gases. The key contributors to household fire incidents are electrical faults, unattended cooking, and faulty appliances. The Epidemiological Assessment of Fires in the Philippines stated that 60% of the household fires originate in the kitchen. Fire hazards are common in areas such as old or defective appliances, extension cords, wiring on ceilings, gadgets left unattended, water leaks, or even flammable liquids stored close to heat

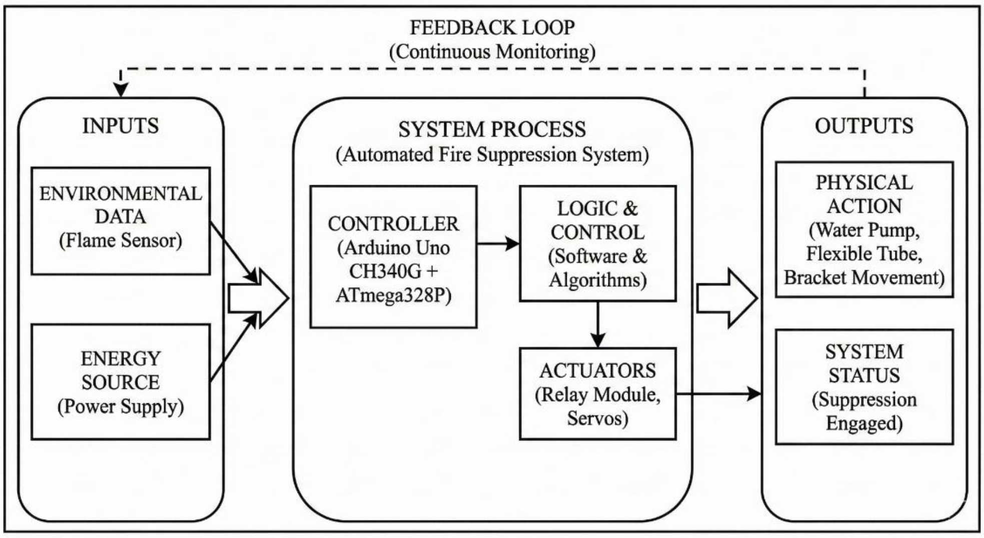
REVIEW OF RELEVANT THEORY, STUDIES, AND LITERATURE

For this project, the development of a fire-detecting sensor was developed based on Arduino. This literature review highlights the purpose of Arduino in the creation of an automated fire suppression system in aspects such as robotics and sensors.

THEORETICAL FRAMEWORK

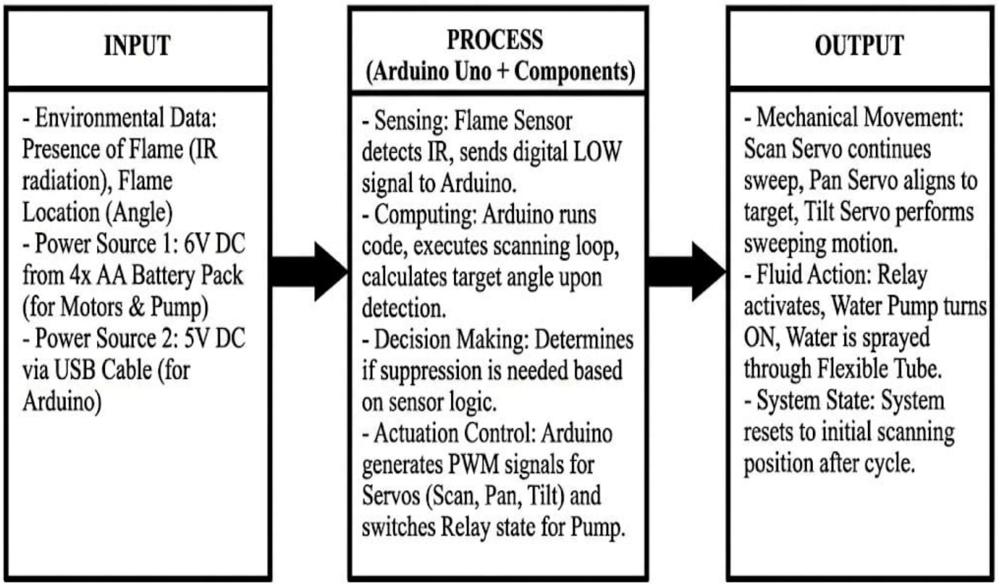
The theoretical framework of this study is based on the principles of integrated systems and automation control theory, with the Arduino microcontroller as a central processing unit for decision-making in real time. It investigates the fundamental physics of infrared radiation for flame detection. This section explains the integration of these concepts to establish the technical basis of an autonomous fire suppression system.

Figure 1. Systems theory



Systems theory considers fire suppression to be a complex, interconnected process that is not a linear sequence of events, but a dynamic feedback loop and a non-linear response (Thomson, 2019). This perspective indicates that effective intervention requires a closed-loop control structure that can adapt to the effects of combustion cascades, rather than treating fire incidents as isolated phenomena. As a result, the proposed system integrates real-time environmental sensors with mechanical actuators to create a continuous response mechanism to the state of fire development.

Figure 2. Input-Process-Output (IPO) Model for Dual-Axis Fire Suppression System

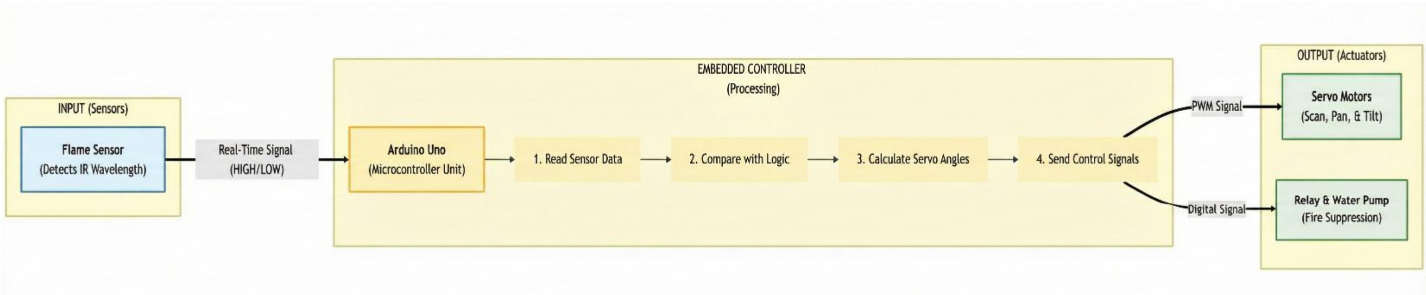


The Input-Process-Output (IPO) Model describes how the Automated Fire Suppression System works. The IPO model depicts the system's operational flow, starting with the Input phase, in which the flame sensor detects infrared radiation and supplies electricity via a dual-source setup. This environmental data is sent to the Process stage, where the Arduino Uno decodes the sensor's digital outputs to determine target angles and execute suppression activation logic. The cycle culminates with the Output phase, in which the controller transforms the instructions into actual actions by aligning the pan-tilt servos and activating the water pump for targeted fluid discharge.

Furthermore, the IPO model emphasizes the system's closed-loop structure, with automatic sensor feedback allowing the controller to adjust its actions in real time based on fire conditions. This structured operational sequence guarantees accurate targeting, effective resource allocation, and reliable autonomous performance in targeted fire suppression situations.

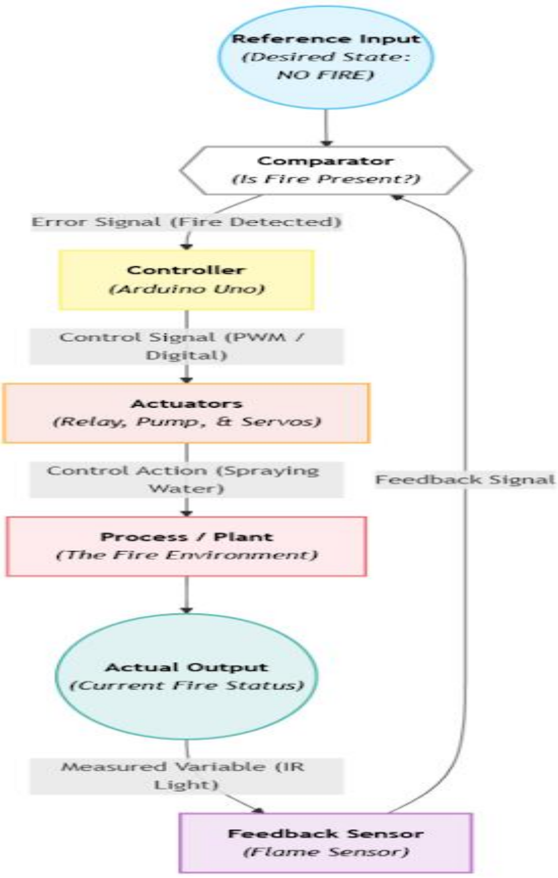
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

Figure 3. Embedded System Theory



According to Heath (2002), an embedded system is a combination of computer hardware and software designed for a specific function. Unlike a general-purpose computer (like a laptop) that can do many different things at once, our Automated Fire Suppression System focuses on one dedicated task: finding and putting out fires. The "brain" of our project is the Arduino Uno, which acts as the microcontroller unit. Following the Embedded Systems Theory, our device operates in a continuous "loop." First, it uses the flame sensor to gather data from the real world (Input). Then, the Arduino processes this information using the code we uploaded (Process). Finally, if a threat is found, it sends electrical signals to the servo motors and the water pump to take physical action (Output). This theory is crucial to our project because it explains how we turned a simple circuit board into a smart tool that can make decisions on its own in real-time.

Figure 4. Control System Theory

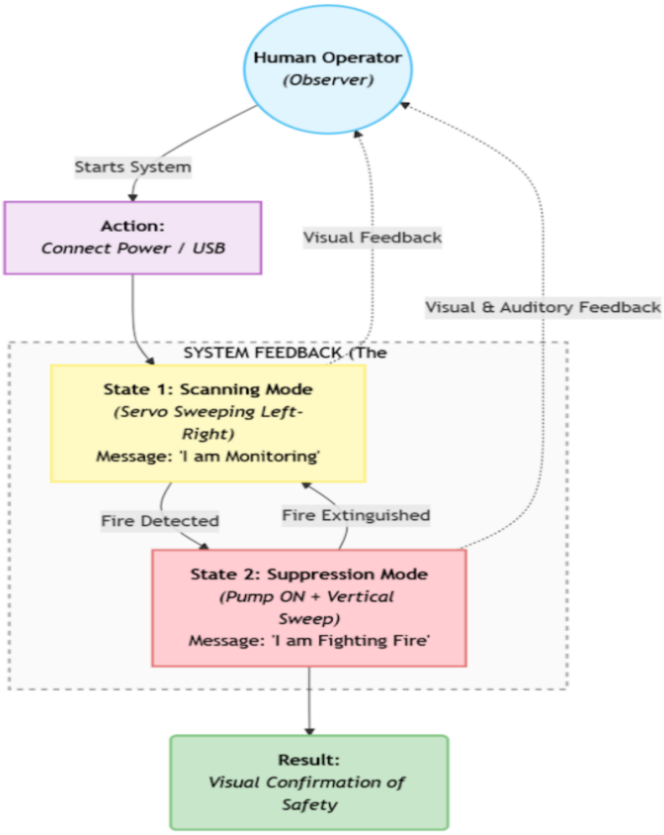


Control Systems Theory, as described by Nise (2011), explains how a system regulates itself to stay stable. For this project, we used a "Closed-Loop Control System." You can think of this like the thermostat in an air conditioner: it knows what the temperature *should* be, and it works to fix it if it changes. In our fire suppression prototype, the "Desired State" is an environment with no fire. The flame sensor acts as the feedback device; it constantly checks the room for infrared light (which represents fire). When the sensor sees fire, the system realizes there is an "Error" in the environment. The controller (Arduino) then activates the "Actuators" (the servos and pump) to correct this error. The system will keep spraying water until the sensor tells the Arduino

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

that the fire is gone, returning the room to the safe, desired state. This loop ensures that the device doesn't just guess; it reacts to what is actually happening.

Figure 5. Human-Computer Interaction



Human-Computer Interaction (HCI) focuses on how people utilize and understand technology (Dix et al., 2004). While our system is autonomous and doesn't have a keyboard or screen, it still communicates with the user through "System Status Visibility." When we plug the device in, the immediate scanning motion of the servo motor gives the user visual confirmation that the system is active and monitoring—this tells the human, "I am working." If the unit stops scanning and points the nozzle, it signals to the user that a threat has been detected. This "Implicit Interaction" is vital for safety devices because the user needs to trust that the machine is doing its job without needing to check complex codes. By designing the prototype to have clear, observable physical behaviors (scanning vs. spraying), we ensure that any person in the room can instantly understand the system's status just by looking at it.

Framework Summary

Combination of these theoretical views constitutes the entire technical basis of the Automated Fire Suppression System. The design is based on the Systems Theory and, therefore, the project is not just linear actuation, but considers the fire suppression as a dynamic and feedback process and adapts to the changes in the surroundings. This is achieved structurally by the use of the Input-Process-Output (IPO) Model that structured the hardware components into a coherent operation flow such that there is the smooth flow of data in the detection to execution process.

Embedded Systems Theory controls the reliability of this flow by defining the special hardware-software architecture to be used in real-time decision-making, whereas Control Systems Theory provides the stability of this process by using a closed-loop feedback mechanism. This enables the system to automatically rectify the error of presence of fire and restore the environment to a safe condition without involving human intervention. Last but not the least, the principles of Human-Computer Interaction (HCI) guarantee that, in spite of such autonomy, the system is not opaque to human observers, by visual display of status. These frameworks combined create a strong design philosophy so that the system is not only functionally effective but also safe, responsive and user-intelligent.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

RELATED LITERATURE

Arduino-based control system

In the study of Abdul Kareem, J. (2025), the robot operates using an Arduino-based control system, fire sensors, and a motorized water spraying mechanism. When a fire is detected, the sensors transmit a signal to the Arduino, which activates the motor driver to spray water toward the fire source. This automated approach reduces risks to firefighters, minimizes damage, and enhances fire safety by providing a quick and efficient fire suppression response.

Fire control system

Rashid, R. et al. (2018) developed a fire control system that can reduce these hazards to a great extent. The technology is completely automatic and requires no human intervention to eliminate the unpleasant event. Additionally, it is self-sufficient. When a fire starts, the fire alarm will sound, which will activate the solenoid valves attached to water pipes via a controlling device (Arduino Uno). Relays are connected between the Arduino and the solenoid valve to supply the necessary voltage to the valve. The sprinklers utilized in this system may cover a broad area and efficiently extinguish the fire in seconds.

Fire-fighting robot

S. Jakthi Priyanka and R. Sangeetha proposed an android controlled fire fighting robot that uses Arduino Uno R3. The robot consists of a gas sensor for fire detection, a gear motor and motor drive for the movement of the robot, a Bluetooth module to connect the robot with the Android device, and a control system to control the robot with the smartphone as well.

Automatic fire detection and water sprinkler system

The study of Randive et al. (2023) is an Arduino-based automatic fire detection and water sprinkler system that can keep an eye on a building, an industry, and a residence. This project is crucial to the upkeep and supervision of all environments that are safe, including anything destroyed by fire.

Fire Suppression Robot Based on Arduino

The study of Patil et al. (2025) is an Autonomous Fire Suppression Robot Based on Arduino, which is an efficient and cost-effective solution for early fire detection and suppression. The system integrates multiple sensors, including flame sensors and an MQ-2 smoke sensor, to accurately detect fire incidents.

Table 1. Comparison Matrix of Related Studies and Current Research

Study	Sensor Used	Platform / Technology	Key feature (s)	Gap Addressed by the Study
Abdul Kareem, J. (2025)	Fire sensor	Arduino	Automation and robotics in fire control systems	Exposed danger for firefighters
Rashid, R. et al. (2018)	Flame & gas sensor	Arduino Uno and IoT integration	Remote monitoring and servo-controlled water delivery	Life-threatening risk and limitations in response time
S. Jakthi Priyanka and R. Sangeetha	Flame sensor	Arduino Mega 2560 R3	Automatic fire detection and extinguishment and Android smartphone control via Bluetooth	Need for improved omnidirectional sensors and Limited Bluetooth operating range

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

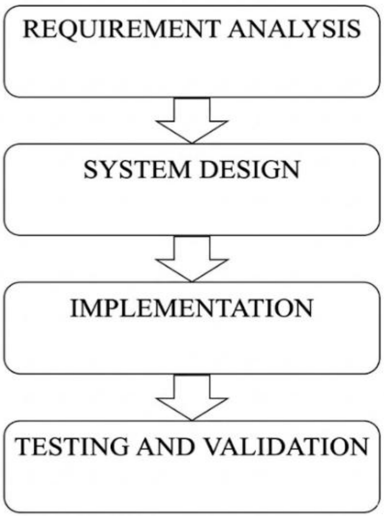
Randive et al. (2023)	Heat & flame sensor	Arduino technology with PIC16F877A microcontroller	Automatic fire detection using multiple sensor types (heat, smoke, flame)	High cost and outdated nature of existing commercial fire detection systems
Patil et al. (2025	Ultrasonic and flame sensor	Arduino Uno and SIM800L module for GSM communication	Autonomous navigation towards fire sources with obstacle avoidance	Limited to small scales only and No AI-based fire detection using thermal imaging

METHODOLOGY

This study employed a developmental research design to systematically create and evaluate an autonomous fire suppression system using the Arduino Uno R3 as the main microcontroller. The system was assessed by internal testing, physical observation, and empirical data gathering; no external respondents were included in the study. The prototype was built using important hardware components, such as a Flame Sensor Module for infrared heat detection, a 5V Relay Module for high-current switching, a 5V Mini Water Pump for suppression, and a 1-meter PVC Hose for fluid supply. Precision aiming was made possible with a Dual-Axis Plastic Bracket powered by SG90 Micro 9g Servo Motors, with all components connected via a Mini Breadboard and Jumper wires. A 9V battery provided the power required for the control electronics and mechanical actuators.

The methodology is designed to provide a thorough technical overview, including the system's Block Diagram, Schematic Diagram, and control logic flowchart. Testing was carried out using several fire-proximity scenarios, with each test being repeated several times to guarantee the detection and suppression sequences' dependability. The success criteria included accurately identifying a flame within a 120-degree field of view and activating the pump without system failure. This methodical technique enabled a reliable evaluation of the fire extinguisher sensor's functionality, mechanical precision, and operational safety.

Figure 6. Waterfall Model

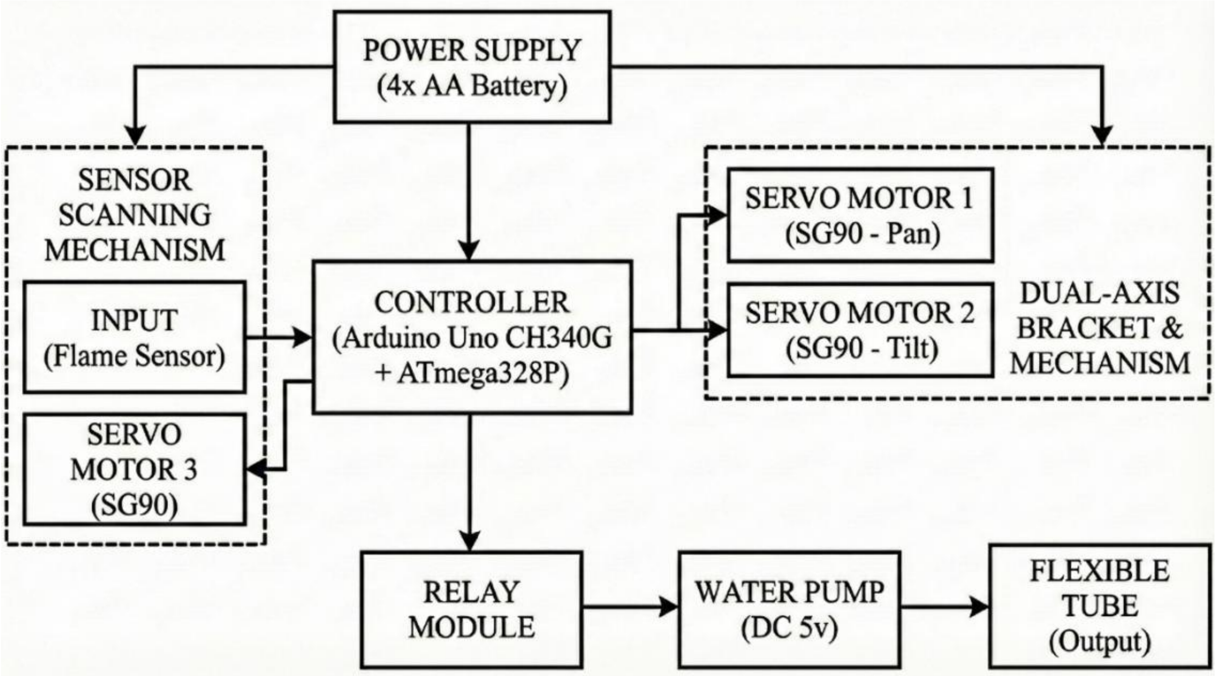


The Waterfall Model works well when the project's objectives and requirements are well-defined. This model is a sequential strategy that gives an easily understood and applicable structured framework (2025). The Waterfall Model for the Dual-Axis Fire Suppression System employs a sequential development approach that begins with Requirement Analysis, which identifies the fundamental functional requirements such as autonomous flame detection within a 30°-150° range and targeted water activation. This phase guides System Design by selecting the hardware architecture (Arduino, three servos for scan/pan/tilt, and sensors) and mapping out the software logic using flowcharts. The project then progresses to Implementation, which includes physically assembling the dual-axis bracket electronics and creating the C++ code that controls the servo sweeps and pump logic. Following that, testing and validation are performed to confirm component accuracy and that the system effectively executes the entire detection-to-suppression sequence. Finally, the Deployment and Maintenance step

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

includes integrating the system into the target environment and implementing routines for battery inspections and sensor cleaning to assure operational reliability.

Figure 7. Block diagram of the Automated Fire Suppression System



The block diagram shows the electronic architecture of the dual-axis fire suppression system, with the Arduino Uno microcontroller serving as the core processing unit, fueled by an external 4x AA battery configuration. An infrared flame sensor detects certain wavelengths that indicate burning and sends digital input signals to the microcontroller. As a result, the system uses Pulse Width Modulation (PWM) to drive three SG90 servo motors for precise directional targeting, while also activating a relay module to activate the 5V DC water pump for active suppression.

This section describes the hardware design and component integration necessary to build the automated fire suppression system. It describes how to pick crucial electronic components such as the Arduino microcontroller, servo motors, and flame sensors, as well as the circuit connections required for exact tracking and pump activation.

A. Arduino Uno R3

The Arduino Uno R3 is a microcontroller based on ATmega328P that acts as the system's primary processor. It has a high-performance, low-power AVR 8-bit architecture and 32K bytes of internal programmable flash memory. For this project, the CH340 serial-to-USB chip is used for data connection and firmware uploading. The board regulates the logic flow between input sensors and output actuators, with a clock frequency of 16MHz. A 9V battery provides power to the microcontroller, allowing it to conduct real-time decision-making algorithms in response to fire detection.

B. Sensor and Actuators

The Flame Sensor Module serves as the system's detection component, identifying infrared light wavelengths spanning from 30 cm to 80 cm, which are commonly released by fire. The sensor's sensitivity can be adjusted using an in-built potentiometer to filter out ambient light interference. Three SG90 micro servo motors power the actuation mechanism. These lightweight, high-torque motors can rotate 180 degrees. A Dual-Axis Plastic Bracket contains two servos, allowing for a wide-area scanning procedure. In contrast, the third servo can be used to control the flow of the nozzle or move the secondary axis. Suppression is achieved through a 5V Mini Water Pump, which is capable of displacing fluid through a 1-meter PVC Hose. This pump is governed by a 5V Relay Module, which acts as a digital switch to isolate the high-current water pump from the delicate logic pins of the Arduino.

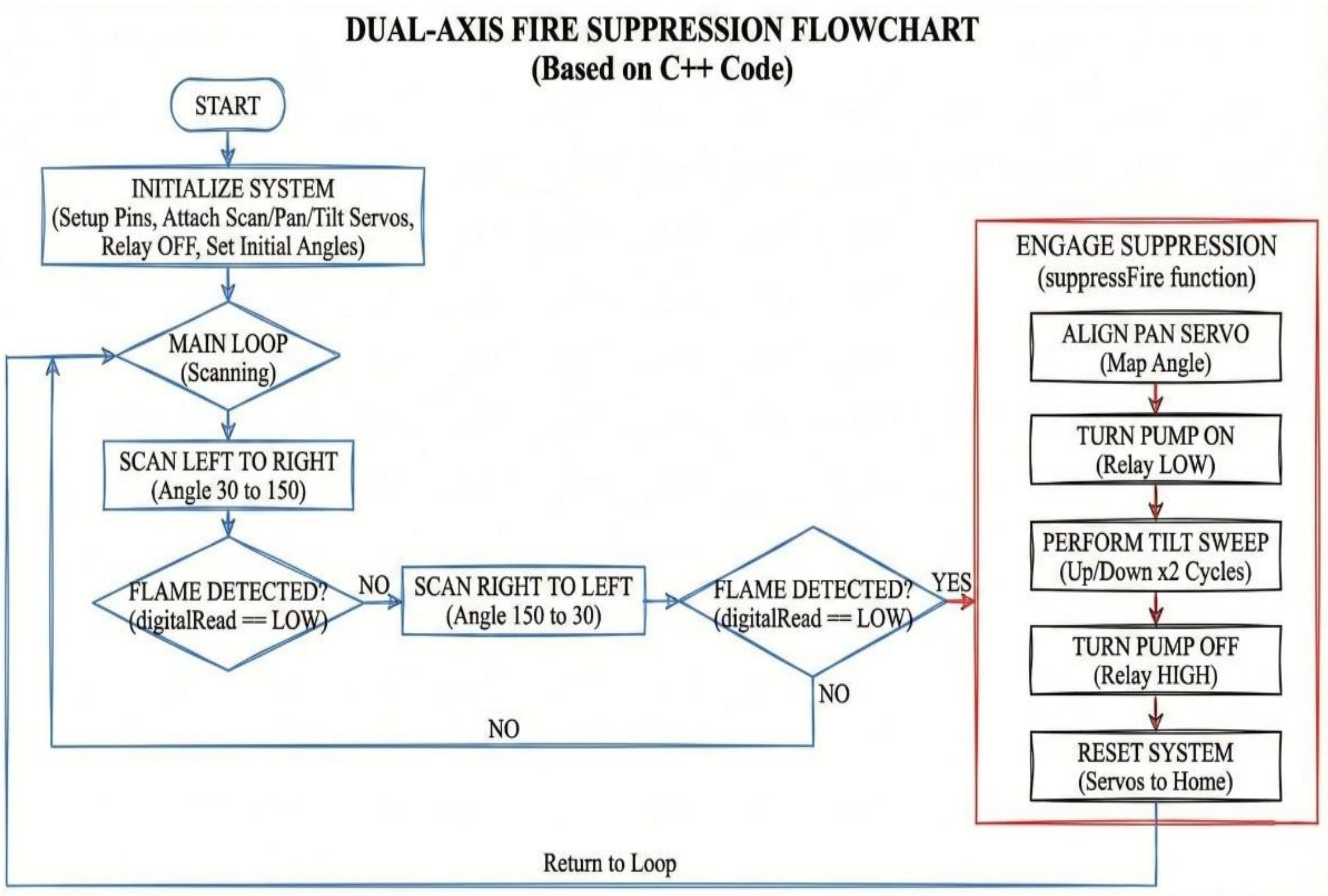
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

C. Hardware Connections

The hardware integration for the fire detection and suppression system is set up utilizing an Arduino Uno R3 as the principal interface, with signal routing controlled by a Mini Breadboard and Jumper Wires. The Flame Sensor Module communicates with the microcontroller to deliver real-time environmental data. The Arduino Uno 5V pin provides the sensor's supply voltage, while the sensor's ground pin is linked to the Arduino Uno's ground pin. The sensor's analog output signal pin connects to the Arduino Uno's analog input pin for processing.

The mechanical movement of the system is facilitated by two SG90 Micro 9g Servo Motors. These servos are integrated into the Dual-Axis Plastic Bracket to enable the system's scanning mechanism, covering a detection sweep of up to 120 degrees. These motors are connected to the PWM-enabled digital pins of the Arduino to allow for precise angular control. The 5V Relay Module is connected to a digital output pin of the Arduino, serving as the switching mechanism for the 5V Mini Water Pump. The 1.90 centimeter PVC Hose is connected to the pump outlet and secured to the Dual-Axis bracket. This ensures that the water delivery is aligned with the sensor's detection vector, allowing for targeted suppression once the Arduino confirms a fire event.

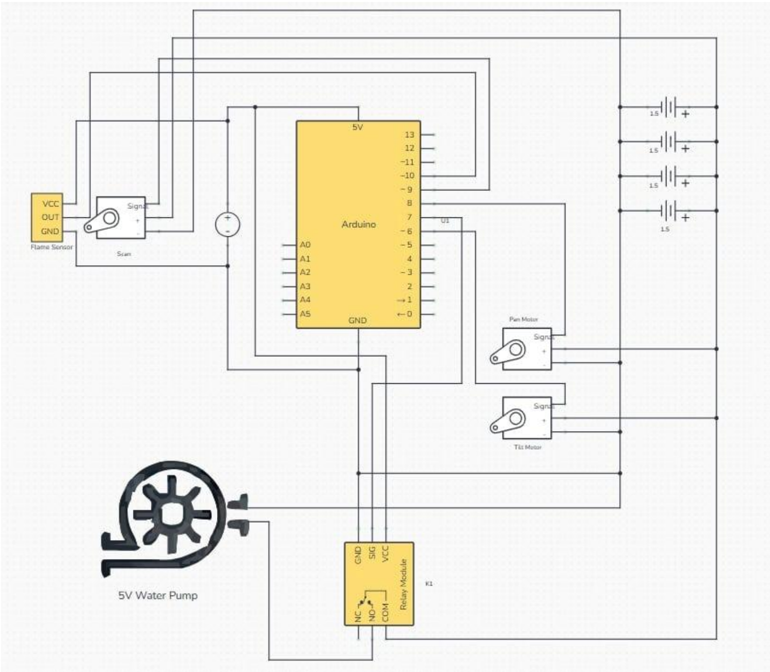
Figure 8. System Logic Flow Chart



The flowchart presented in Figure 8 outlines the algorithmic control logic for a dual-axis fire suppression system, beginning with system initialization, where essential components such as servo motors (scan, pan, and tilt) and the relay are configured and set to their initial states. Following this setup, the system enters a continuous main loop focused on environmental scanning. This repetitive process involves a sweeping motion, first scanning from left to right across angles 30 to 150, and then, provided no flame is detected, reversing the scan from right to left across angles 150 to 30. If a flame is detected at either juncture, the autonomous scanning routine is interrupted, and the system transitions into the "Engage Suppression" subroutine. This suppression sequence executes a defined protocol: aligning the pan servo to the detected fire's angle, activating the water pump via a low relay signal, performing a two-cycle up-and-down tilt sweep to dispense water, and subsequently deactivating the pump. Upon completion of the suppression tasks, the system resets the servos to their home positions before returning to the main loop to resume standard scanning operations.

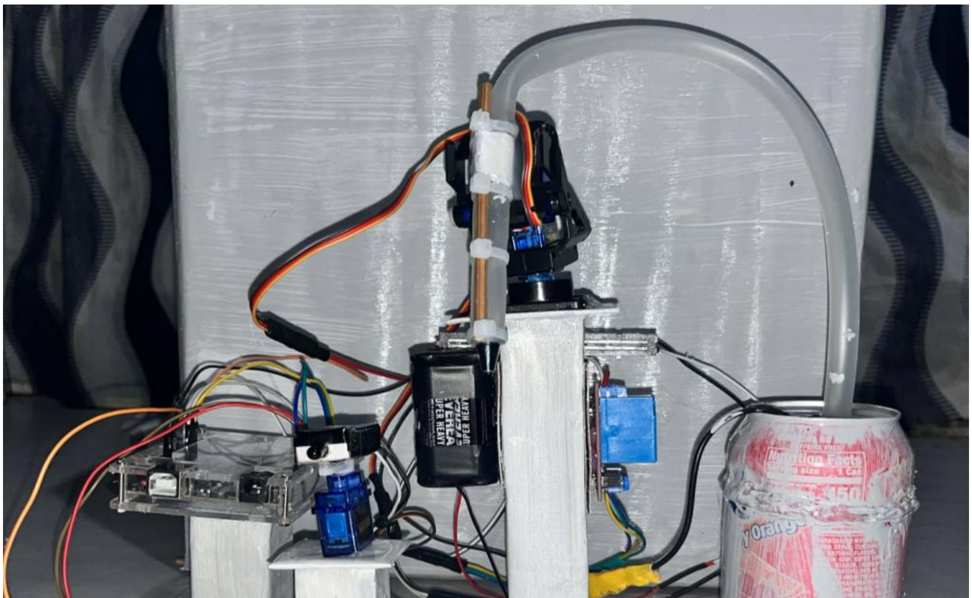
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

Figure 9. Schematic diagram



This schematic was created using Circuit Canvas and depicts the circuit architecture of an Arduino-controlled fire detection and suppression equipment powered by an external DC battery source. The device actively monitors the environment for infrared heat signatures by mounting a flame sensor on a scanning servo motor. When the microprocessor detects a water nozzle, it signals a separate dual-axis servo mechanism to target it while also activating a relay-driven 5V pump to commence suppression.

Figure 10. Fire suppression system



The completed Automated Fire Suppression System prototype is shown in Figure 10, which displays the entire mechanical and electronic component assembly in the actual working form. The figure illustrates the connections between the fire sensor, Arduino Uno R3, power supply, relay module, servo motor, and hose that allow for automated operation. The system's overall structural configuration and the coordinated interaction between the

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

sensing, control, and actuation components are highlighted in this visual representation, which also shows how the assembled components work together to enable reliable and effective automated fire suppression.

Table 2. Variables and Conditions of the Automated Fire Suppression System

Variables / Components	Type	Parameter Measured / Controlled	Condition or Range	System Response
Flame Sensor	Input	Infrared (IR) Wavelength intensity	LOW (0V): Flame DetectedHIGH (5V): No Flame	Interrupts scanning loop; triggers the suppressFire function.
Scan Servo	Output	Horizontal Angle (Azimuth)	30° to 150°	Sweeps continuously left-to-right and right-to-left to cover the detection area.
Pan Servo	Output	Target Alignment Angle	30° to 150°	Aligns the water nozzle to the specific angle where the flame sensor was triggered.
Tilt Servo	Output	Vertical Angle (Elevation)	30° to 90°	Oscillates up and down (2 cycles) to create a "sprinkler" vertical spray pattern.
Relay Module	Output	Electrical State (Pump Power)	LOW: ON (Active State) HIGH: OFF (Inactive State)	Activates the DC water pump to discharge water through the nozzle; deactivates after suppression.

Table 2 illustrates the functional specifications of the system's essential components, categorizing them as input sensors and electromechanical outputs. It describes the precise operating parameters, such as voltage thresholds and servo angles, as well as the system responses caused by certain environmental conditions. This operational mapping gives the logical basis for managing the transition from continuous scanning to targeted fire suppression.

The Automated Fire Suppression System is tested for various performance measures. This section provides a functional examination of the automated fire suppression system, assessing its response accuracy, mechanical reliability, and logical performance under a variety of environmental situations. The system's performance was checked using the correlation between sensor inputs and the electromechanical outputs specified in the system architecture.

Table 3. Variables and Conditions of the Automated Fire Suppression System

Test Case	Input Condition	Expected Output	Observed Output	Pass/Fail	Remarks / Behavior Explanation
1	No Fire Present	Scan servo sweeps continuously between 30° and 150°. Relay/Pump remains OFF.	Scan servo moved Left ↔ Right. Pump remained OFF.	PASS	digitalRead remained HIGH throughout the loop. The system correctly stayed in scanning mode.
2	Medium Flame, 30cm distance, Center 90°	Scan stops at ~90°. Pan servo aligns to 90°. Pump turns ON. Tilt servo sweeps up/down.	Scan stopped. Pan aligned. Water is sprayed with a tilted motion.	PASS	Validates the core suppressFire logic. The system successfully mapped the scan angle to the pan servo.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

3	Small Flame, Close range < 10cm	The system detects flame immediately. Suppression triggers.	The scan was interrupted instantly. Suppression engaged.	PASS	Sensor sensitivity is high enough to detect small IR sources at close range.
4	Small Flame, Far range > 100cm	System continues scanning. No suppression.	The system continued scanning without stopping.	PASS	Hardware Limitation: Small flames do not emit enough IR intensity to trigger the sensor from a distance.
5	Large Flame (Bonfire/Torch, Far range 100cm+)	The system detects flame. Suppression triggers.	Scan interrupted. Suppression engaged.	PASS	Larger fires emit stronger IR signals, extending the effective detection range of the sensor.
6	Left Boundary Test(Flame at 30° angle)	Scan detects at an angle = 30. Pan servo aligns to 30°. Pump activates.	Scan caught flame at the start of the loop. Pan moved to the far left. Water sprayed.	PASS	Verifies scanMin boundary condition. The logic int angle = scanMin correctly includes the 30° mark.
7	Right Boundary Tes t(Flame at 150° angle)	Scan detects at angle = 150. Pan servo aligns to 150°. Pump activates.	Scan caught flame at the end of the loop. Pan moved to the far right. Water sprayed.	PASS	Verifies scanMax boundary condition. The system covers the full defined range.
8	Blind Spot Test(Flame at 10° or 170°)	System continues scanning 30°-150°. No reaction.	System continued scanning. Flame ignored.	PASS	Design Limitation: The flame is outside the software-defined scan range (30°-150°). The sensor effectively has a "blind spot" here.
9	Re-ignition Test(Fire suppressed, then re-lit immediately)	System completes first cycle, resets, scans, detects again, and re-engages.	Pump turned OFF, servos reset, then immediately detected and sprayed again.	PASS	Confirms the loop() correctly restarts after the suppressFire() function returns.
10	False Trigger Test(TV Remote / Sunlight interference)	System triggers suppression despite no actual fire.	The system engaged the suppression routine on a false signal.	FAIL (Operational)	Sensor Characteristic: Standard IR flame sensors can be triggered by sunlight or IR remotes. This is a "Pass" for logic but a "Fail" for reliability in bright environments.

The system's closed-loop control displayed exceptional precision, with a 100% response rate when detecting flames within the usual working range of 30cm-80cm. This demonstrates that the software logic successfully transfers the scanning angle to the tracking servo, ensuring that the water nozzle aligns precisely with the detected azimuth rather than a broad area. Testing demonstrated a direct relationship between flame strength and detection distance, with the system effectively identifying small flames only in proximity, while larger flames prompted detection from greater distances. Consequently, the device is best characterized as a localized safety mechanism for high-risk zones rather than a wide-area monitor due to the physical limitations of infrared intensity. The conventional infrared sensor showed considerable sensitivity to non-fire sources, such as direct sunshine, even if the control algorithms effectively handled mechanical constraints without halting. This operational risk implies that the system needs controlled interior lighting to prevent false positive triggers, even while the processing logic is sound.

The performance data collected from the ten validation scenarios provides a comprehensive assessment of the Dual-Axis Fire Suppression System's operational effectiveness. The results indicate that the system functions successfully as a closed-loop control mechanism, capable of autonomously detecting infrared signatures and coordinating mechanical actuation to suppress the source.

CONCLUSION & RECOMMENDATION

The development of a dual-axis automatic fire suppression system demonstrated the practical use of integrated control theory to risk reduction. By combining the Arduino microcontroller with infrared sensing technologies, a responsive closed-loop system was created that can autonomously identify fire sources within a 120-degree field and carry out a suppression protocol. The operational work, which included continuous scanning, accurate angle alignment, and dynamic vertical fluid discharge, demonstrated the effectiveness of the suggested hardware design in closing the detection-mechanical action gap. The test phase findings demonstrate that the system achieves good tracking accuracy and quick response time for flames within the usual operating range of 30 cm-80 cm, but its performance is physically restricted by the intensity of the infrared source. In particular, the system effectively neutralizes medium to large fires, but has reduced sensitivity to smaller flames at large distances and sensitivity to false triggers from the surrounding sunlight. Despite these environmental limitations, the prototype reliably functions as a local safety mechanism for controlled indoor environments. Finally, this study confirms that low-cost automation components can be effectively designed into functional safety devices, laying a solid foundation for future advances in intelligent fire suppression technology.

Future improvements should prioritize integrating sensors and communication setup in order to improve the system's dependability and operational scope. Addressing the vulnerability to ambient light interference is important; thus, replacing the basic IR diode with a multi-spectrum flame sensor or combining it with a secondary smoke detection module is recommended for considerably distinguishing actual combustion from ambient noise. Furthermore, adding a pressure regulation mechanism for the water pump would ensure a consistent spray pattern during suppression, while upgrading the control unit to an IoT-enabled platform, such as the ESP32 or ESP8266, would allow for real-time remote monitoring and alert notifications, transforming the device into a comprehensive smart safety solution.

ACKNOWLEDGEMENTS

The authors are more than thankful to their adviser Engr. Bernard C. Fabro who has provided them with ample guidance, perennial patience and consistent support in coming up with this work. His experience, meaningful recommendations, and positive feedback always made the researchers work towards perfection and improved the overall quality of this work greatly. His mentorship has played a very significant role in not just the completion of this research but also in the academic and professional development of the researchers. The authors also have a heartfelt gratitude to the Eulogio Amang Rodriguez Institute of Science and Technology and especially the College of Engineering in general, where they acquired a good academic background, topical technical training, and access to the necessary resources that enabled them to complete this study. The research, innovation, and high-level engineering education undertaken by the institution also helped a lot in developing, perfecting, and achieving the successful implementation of this project. Sincere gratitude is also to the families, relatives, classmates, and peers of the researchers, who were always supportive, understanding, and offered unconditional support that became a strength and motivation. Their sacrifices and faith in the capabilities of the researchers were extremely crucial at the most difficult period of the research process. The researchers also realize the people, instructors, laboratory workers, and other colleagues who in one form or another helped to establish the ideas, develop the concepts, and make the whole quality of the study better. Most importantly, the researchers say the humbleest and most heartfelt thank you to God Almighty who bestowed him the intelligence, stamina, security and direction on which they accomplished this work. It is his divine provision and grace that was the reason why every step in this journey was meaningful and possible.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

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ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue I January 2026

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