Design and Development of Intrinsically Safe Lightning Arrester System for Firework Industries

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Abstract

The fireworks production process is highly risky for lightning-related accidents due to the presence of explosive substances and exposure to severe weather conditions. The existing fire protection system depends on ineffective surge and grounding management techniques without any automated emergency service in real-time. This article discusses the design and implementation of a fundamentally safe, affordable, IoT-enabled lightning protection and early alert system developed for the fireworks industry. This model combines environmental sensing, artificial lightning modeling, electrical fault monitoring, fire detection and automated fire control. Weather conditions such as temperature, humidity, rainfall, noise levels and water levels are continually monitored to detect the irregular variations caused by simulated lightning strikes using voltage and current sensors. The experimental results show fire detection (~0.3s), automated fire protection activation within 1.5s, reliable cloud data updates every 15s, and WhatsApp alert notifications sent within 6–8s. This system operated continuously for 8 hours with stable performance and achieved AI-based weather risk prediction accuracy of approximately 82%. These results confirm that the proposed work is an effective smart safety measure for improving lightning-related fire protection in fireworks manufacturing industries.

Keywords: Lightning Protection, Firework Safety, IoT, ESP8266, Embedded Systems, Flame Detection, AI Weather Prediction.

1. Introduction

Firework manufacturing industries operate in highly dangerous environments due to the presence of flammable substances such as oxidizers, metallic powders and pyrotechnic mixtures. In fire-affected areas, particularly during the monsoon seasons, there is a high chance of fire and explosion caused by direct lightning strikes, which create electrical surges. Even minor fires can cause major accidents with severe human, material, and economic losses.

Traditional fire protection systems used in industries are based on ineffective techniques such as lightning rods, grounding networks and surge protection systems. The existing methods are effective in directing high-current lightning strikes but fail to provide real-time data related to fire accidents and internal electrical issues. As a result, additional dangers such as electrical surges, unpredictable fires and internal explosions remain undetected until damage occurs.

Recent advances in embedded technologies, affordable sensors and Internet of Things (IoT) technology have allowed the development of smart safety systems suitable for continuous monitoring, real-time decision-making and autonomous rescue operations. However, the current IoT-based systems depend on environmental monitoring or warnings, lacking of connected actuator mechanisms for rapid risk reduction, especially in highly dangerous firework manufacturing industries.

This article explains the design and implementation of an automatic safe, IoT-based explosion detection and early warning system built specifically for the firework industry to overcome these challenges. The proposed system combines a variety of environmental sensing data with fire-related electrical modeling, rapid voltage and current monitoring, flame detection, automatic fire control, cloud-based monitoring and real-time alarm notification. The system generates a smart safety level performance in current passive lightning detectors by combining existing fire detection methods, fault identification and automated action into one device.

This technology combines explosive prediction monitoring, a controllable electrical stress simulator, automated fire control and cloud-based alerting into a secure system designed particularly of the firework industry. The proposed system handles additional fire damage through early detection, fault diagnosis and rapid reduction for fire accidents when compared to existing lightning protection systems focused on strike diversion. In this work, the term

"lightning arrester system" refers to a useful security device designed to minimize additional risks caused by lightning such as internal surges, explosions and the possibility of fire accidents. This system is not a replacement for traditional surge protection or grounding systems; instead, it improves upon them by providing real-time monitoring, fault detection and automated fire control operations.

2. Literature Survey

Fire safety and risk management have been extensively studied across diverse domains, including industrial facilities, public infrastructure, energy systems, and hazardous material environments, with research evolving from fundamental fire behavior analysis to advanced risk modeling and safety management frameworks. Early foundational work in fire safety engineering emphasizes the physical and chemical principles of fire dynamics, ignition mechanisms, heat transfer, and suppression strategies, forming the theoretical basis for modern fire protection systems [2]. Generating these principles, researchers have explored the design and technical evaluation of automatic extinguishing systems, particularly for flammable liquid service stations, highlighting the importance of rapid detection, system reliability, and compliance with safety regulations to reduce fire escalation and catastrophic losses [1]. Safety classification and regulatory compliance have also received significant attention, with studies providing structured guidance for meeting safety standards in the United States and Canada, emphasizing certification processes, risk categorization, and cross-border regulatory harmonization [3].

In industrial and process-oriented environments, fire and explosion hazards are addressed through systematic risk assessment and case-based analysis. Comprehensive studies on process industries demonstrate how improper handling of hazardous materials, equipment failure, and human error can lead to severe fire incidents, underscoring the need for proactive safety planning and hazard mitigation strategies [4]. Event-based accident analysis has further contributed to understanding accident scenarios, particularly in explosive storage facilities, by modeling event chains and identifying critical failure points that lead to fire or explosion events [9]. Complementing these approaches, advanced computational techniques such as fuzzy Petri nets integrated with HAZID methodologies have been proposed to enhance fire risk assessment accuracy by managing uncertainty and complex interdependencies within industrial systems [10].

Fire safety challenges are also context-dependent, as evidenced in studies focusing on historical theaters and live event environments. Research in heritage structures highlights the difficulty of integrating modern fire safety systems into architecturally sensitive buildings, necessitating customized solutions that balance cultural preservation with safety requirements [5]. Similarly, investigations into live event industries reveal persistent safety concerns related to crowd density, temporary electrical installations, and emergency preparedness, calling for improved safety governance and risk awareness [8]. Beyond physical infrastructure, safety management has increasingly incorporated organizational and innovation perspectives, with studies examining how open systems and online communities contribute to product innovation, safety knowledge dissemination, and continuous improvement in safety-related technologies [7].

Recent literature has placed strong emphasis on emerging fire risks associated with modern energy systems, particularly battery storage and electric energy infrastructures. Studies investigating battery fire and explosion risks reveal critical gaps in existing safety management practices, highlighting challenges related to thermal runaway, inadequate monitoring, and insufficient emergency response protocols [6]. These findings indicate a growing need for advanced safety management frameworks capable of addressing new technological risks. Overall, the reviewed literature demonstrates a progression from traditional fire safety engineering toward integrated, data-driven, and system-level safety approaches. However, despite significant advancements in risk assessment methodologies and safety system design, many studies acknowledge limitations in adaptability, real-time responsiveness, and predictive capabilities, suggesting opportunities for future research in intelligent, automated, and technology-enhanced fire safety solutions.

3. Existing Work

Firework manufacturing industries operate in highly dangerous environments due to the presence of flammable substances such as oxidizers, metallic powders and pyrotechnic mixtures. In fire- affected areas during the monsoon seasons, there is a   high chances of fire and explosion caused by direct lightning strikes, which create electrical surges. Even minor fires can lead to major accidents with severe human, material, and economic losses.

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existing technologies are useful for controlling high-current lightning strikes but fail to provide real-time data for fire accidents and internal electrical challenges. As a result, additional risks such as electrical surges, unexpected fires and internal explosions go undetected before damage occurs.

Existing lightning protection systems for industries rely on passive methods such as lightning rods, grounding networks and surge protection devices that mainly redirect electricity after an incident occurs. They lack real-time environmental awareness, internal electrical monitoring and automatic danger prevention, rendering them ineffective for highly dangerous situations such as fire accidents.

Advanced techniques such as Early Streamer Emission (ESE) detectors aim to expand strike detection range but these devices are structural in design and fail to handle additional dangers such as internal sparks or early fire accidents. Electrical surge protection and monitoring methods provide sufficient protection for electronic components, but they work in isolation and are not designed for automated safety measures. IoT-based weather monitoring devices provide continuous monitoring of atmospheric data. They focus on showing data and providing notifications with minimal use of controllers or industrial safety processes. Similarly, fire detection systems have different subsystems that require manual involvement combined with lightning diagnosis.

Overall, previous research has failed to design a smart, integrated and automated safety system that involves weather sensing, lightning-related electrical problem detection and rapid emergency responses. This lack has lead to the development of a fundamentally safe, IoT-based lightning protection system that is particularly designed for the operational and safety requirements of the fireworks industry.

4. Methodology

The proposed method involves a system-level design approach that includes requirement analysis, layered architectural design, controlled stress modeling, logic validation and experimental performance evaluations. Each subsystem underwent separate testing to verify predictable behavior, consistency, and built-in security before implementation. This technique was selected based on its safety, scalability, affordability, and suitability for use in the firework manufacturing industry. Direct lightning research and high-energy electrical

impulse generators are unsafe and dangerous for laboratory experiments and small industrial locations. This results in controlled, reduced electrical stress simulation; combined real-time sensing; and automated responses, which were utilized to examine lightning-related additional risks such as internal strikes and early fire accidents. This technique allows for repeated testing while maintaining basic security and practical application.

The technique used for developing the proposed system is completely secure from the lightning detection system including system design, hardware implementation, software development, experimental validation and performance assessment This system's goal is focused on the early identification of lightning-related risks and automatic fire control in the firework manufacturing industry.

Table 1. Hardware Components

Component	Description
Arduino UNO	Central microcontroller for processing sensor inputs and controlling outputs such as relays and alarms.
ESP8266 Wi-Fi Module	Enables communication with cloud platforms like ThingSpeak for remote monitoring and control.
DHT Sensor (Temperature & Humidity)	Measures ambient temperature and humidity.
Rain Detection Sensor	Detects rainfall intensity.
Sound Sensor	Detects loud sounds (e.g., thunder), indicating potential lightning activity.
Water Level Sensor	Monitors water levels to detect heavy rainfall or flood conditions.
Voltage Sensor	Measures voltage levels in the equipment under test.
Current Sensor	Measures current levels in the equipment under test.
LED Bulb	Simulates the electrical equipment being tested.
Capacitors (63k)	Simulate electrical stress conditions such as high-voltage spikes during lightning strikes.

Flame Sensor	Detects sparks or flames caused by electrical surges or faults.
Relay	Controls emergency response actions, such as activating the water pump motor.
Water Pump Motor	Activated to suppress fires when the flame sensor detects sparks.
LCD 16×2 Display	Displays local data and system status for real-time monitoring.

Table 2. Software Components

Software	Description
Arduino IDE	Used to program the Arduino UNO.
Streamlit	Framework used to create a real-time monitoring dashboard for data visualization and alerts.
ThingSpeak	IoT platform used to collect, store, and visualize sensor data in real time.
Twilio API	Used to send WhatsApp alerts for critical situations (e.g., when a flame is detected).
Python	Programming language used for data processing, AI-based weather prediction, and IoT platform integration.
PyCharm	Integrated Development Environment (IDE) used for writing and debugging Python code.

Table 3. Sensor Specifications

Sensor / Component	Parameter	Range	Accuracy	Output
DHT Sensor	Temperature	0 °C to 50 °C	±2 °C	Digital (Signal)
DHT Sensor	Humidity	0 % to 100 %	±5 %	Digital (Signal)
Rain Detection Sensor	Rainfall Detection	Varies with sensor sensitivity	Adjustable sensitivity	Digital (Signal)
Sound Sensor	Sound Level	40 dB to 100 dB	Adjustable	Analog (Signal)

Water Level Sensor	Water Height	0 m to 5 m	N/A	Analog (Signal)
Voltage Sensor	Voltage	0 V to 25 V	±1 % of full scale	Analog (Signal)
Current Sensor	Current	0 A to 5 A	±2 %	Analog (Signal)
Flame Sensor	Flame Detection	Up to 2 m	N/A	Digital (Signal)
Relay	Switching Capacity	10 A (max)	N/A	Digital (Control)
Water Pump Motor	Activation	N/A	N/A	Digital (Control)

The sensors were selected based on a balance of accuracy, reaction time, affordability and compatibility with low-powered embedded systems. These sensors provide sufficient precision for the early detection of risks at an affordable price. This decision creates a proposed approach by cost-effective for small- and medium-sized firework businesses, where price and efficiency are important deployment requirements.

Initially, essential environmental and electrical characteristics associated with lightning-related risks were identified. These include temperature, humidity, rainfall, noise levels, water level, voltage changes, current surges and the presence of fire. Appropriate low-cost sensors were selected based on sensitivity, response time and compatibility with embedded platforms. Table 3 contains the characteristics of the selected sensors, Table 2 represents the software components and Table 1 highlights the entire list of hardware components.

The sensing devices have been connected to an Arduino UNO microcontroller, which continually collects sensor data and analyzes it using specified threshold-based computation. A capacitor-based discharge circuit was used to replicate the voltage and current fluctuations caused by lightning. The voltage and current sensors measure these fluctuations to evaluate the system's capacity to identify abnormal electrical activity.

When the control system detects dangers such as electrical surges or early fire incidents, it activates an emergency reaction via a relay module. The relay activates a water pump motor to automatically reduce possible fire chances, decreasing dependence on human involvement.

Basic safety is maintained by electrically separating low-powered control technology from high-power actuator components.

The Arduino UNO sends collected data to the ESP8266 Wi-Fi module using a serial connection for remote monitoring. The ESP8266 transmits sensor data to the ThingSpeak cloud platform frequently. This data is extracted by a Streamlit-based dashboard to display and monitor it in real time. Additionally, an AI-based weather risk prediction system uses previous and real-time environmental data to evaluate lightning risks.

4.1 Threshold Selection and Validation

Threshold values for environmental and electrical features have been established using sensor datasheets, early experimental data, and safety limits applicable to firework manufacturing industries. Temperature and humidity requirements have been developed within the operating limits of firework materials, and limited rainfall, noise levels and water levels were taken to signal unstable thunderstorm situations. Electrical parameters for low voltage and current surges were determined using repeated capacitor discharge tests to differentiate between normal functioning and unsafe transient performance.

Thresholds have been verified directly using multiple tests in normal and simulated failure situations. The values were gradually modified to reduce false activation and provide rapid detection of dangerous situations.

4.2 Detection, Decision, and Actuation Logic

The system uses three stages of computation: detection, decision and execution. During the detection step, sensor data is continually collected and compared to specified thresholds. During the decision stage, the Arduino UNO analyzes environmental and electrical issues to detect dangerous situations such as lightning-related surges or early fire accidents. Once a dangerous situation has been identified, control signals are created to activate the relay module that initiates fire control operation and notification devices. This managed circuitry enables predictable behavior, swift responses and basic security without requiring human involvement.

Finally, system performance was measured experimentally using sensor accuracy, reaction time, communication reliability, alert latency and energy usage. This technique provides a closed-loop safety system that can detect, make decisions, activate and send remote notifications.

5. System Architecture

The overall structure of the proposed fundamental secure lightning detector system is depicted in Figure 1. The architecture uses a layered design approach that includes sensing, processing, communication, application and notifying levels to enable scalability, dependability and automated operation. The data such as authorized current discharge and residual voltage aren't directly applicable because the proposed work is not a surge prevention device. Thus, system performance is measured using detection response time, fault detection accuracy, and reduced efficacy, which are more important for additional lightning risk protection.
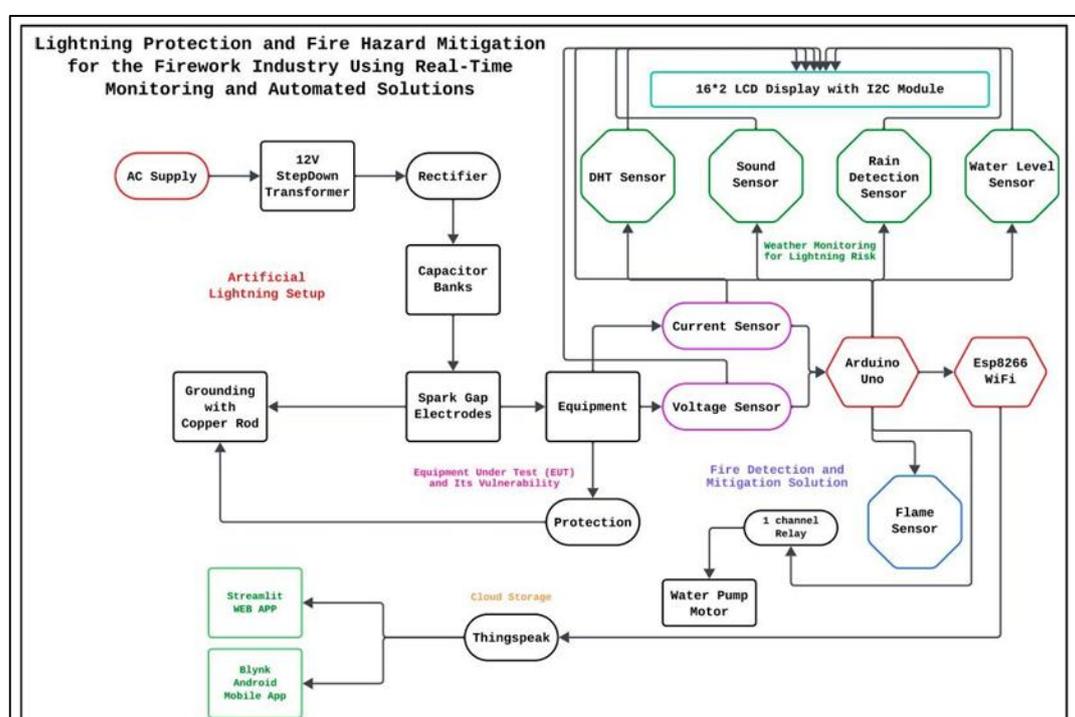
Figure 1. Proposed Block Diagram

5.1 Sensing Layer

The sensing layer consists of various environmental and electrical sensors used to monitor fire formations and impacts. A DHT11 sensor measures temperature and humidity, while rainfall and water level sensors detect moisture. A sound sensor detects intense sound waves similar to thunder. Lightning-related electrical anomalies can be recreated using a capacitor-based circuit discharge, the voltage and current variations are measured with voltage and current sensors. A fire sensor continually checks for sparks or fires near sensitive devices.

The sensing layer uses a combination of digital and analog sensors that communicate with the Arduino UNO via GPIO and ADC channels. Environmental sensors collect data in low quantities, making them suitable for environmental monitoring, while electrical sensors detect rapid unexpected modifications during surge simulation, allowing real-time complex data collection with minimal delay.

5.2 Processing and Control Layer

The control and processing layer depends on the Arduino UNO microcontroller, which serves as the primary decision-making unit. All sensor data is collected in real time and analyzed against specified limits. The controller performs the relevant control steps when unexpected environmental or electrical conditions are identified. A relay connection creates electrical distance between the microcontroller and high-power devices providing built-in security. When a fire is detected, the relay activates a water pump motor to immediately reduce any fire dangers.

The Arduino UNO's processing layer implements threshold-related decision providing predictable and low-latency responses. Sensor data is handled directly to prevent cloud delay, allowing for rapid responses during major incidents like spark or fire detection.

5.3 Communication Layer

The communication layer provides cloud connection and remote data access. The Arduino UNO transfers processed sensor data to the ESP8266 Wi-Fi module using a UART connection. It sends data to the ThingSpeak cloud platform via HTTP POST requests. This allows for continuous data tracking, remote accessibility and historical data evaluation.

The system prevents unauthorized access using network- and application-level protections. Cloud communication is controlled using private API keys provided by the ThingSpeak platform and the dashboard has been limited to authorized users via credential-based authentication. The ESP8266 software requires data transmission commands from assigned devices to reduce the possibility of unauthorized control or manipulation of data.

This layer uses a UART-based serial connection between the Arduino UNO and the ESP8266 module to provide accurate data transmission. HTTP-based data transmission to the cloud is performed at scheduled times to satisfy real-time monitoring requirements while reducing network traffic.

5.4   Application and Visualization Layer

In the application layer, a Streamlit-based dashboard collects data from ThingSpeak via REST API. The dashboard provides real-time graphical representations, tabular evaluations and system status alerts that allow operators to monitor environmental conditions, electrical values and system performance remotely. An AI-based system analyzes the collected data to identify lightning and weather-related danger levels to improve early warning capabilities.

The visualization layer uses REST APIs to analyze cloud-based data and displays the data in real-time graphs. This layer allows for historical pattern analysis and remote monitoring of situations without creating physical connection to the workplace.

5.5   Alert and User Interaction Layer

The alerting layer ensures that key incidents are identified in a timely manner. When threshold failures occur, the system sends warnings using the Twilio API for events such as flame detection, major electrical fluctuations, and high-risk environmental circumstances. WhatsApp notifications are sent to verify the individuals providing rapid responses when operations are remote. It also ensures that warnings are sent on time, even when networks are overloaded.

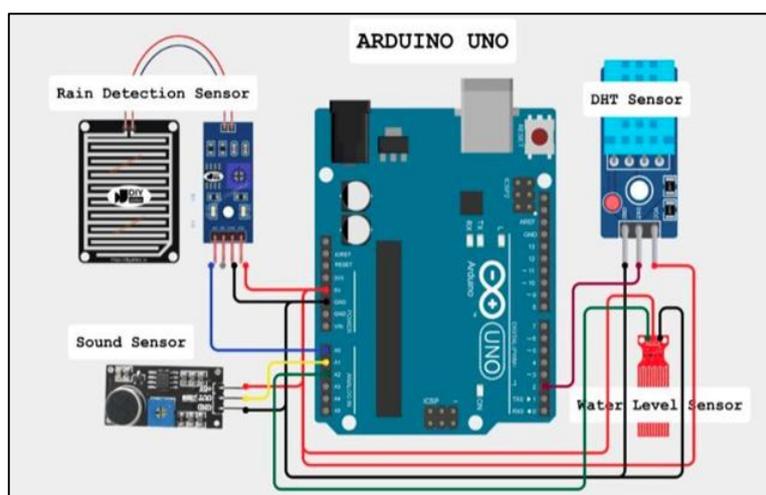## 6.   Implementation and Experimental Setup

Figure 4. Hardware Prototype of the Proposed System

The proposed system was implemented and validated using a laboratory experimental setup integrating environmental sensors, electrical stress simulation, control circuitry, and

emergency actuation components. The complete hardware prototype developed for experimental validation is shown in Figure 4.
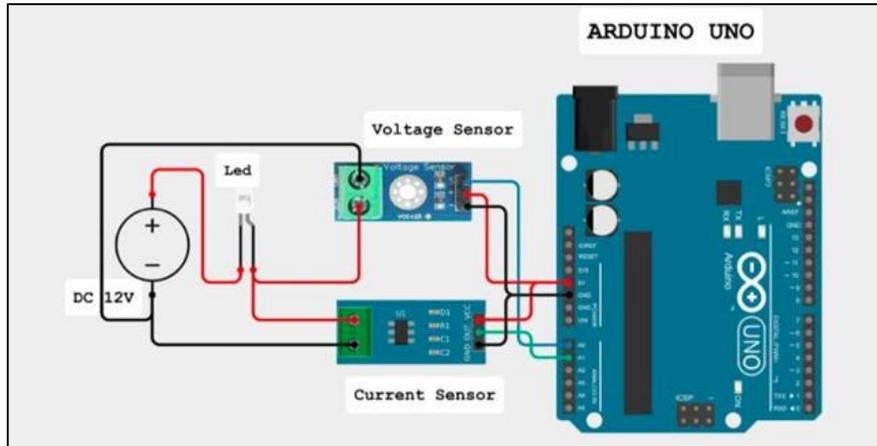

Figure 5. Environmental Sensing Module

The environmental sensing module including temperature, humidity, rain, sound, and water level sensors is illustrated in Figure 5, highlighting the multi-parameter sensing approach adopted for lightning precursor detection.
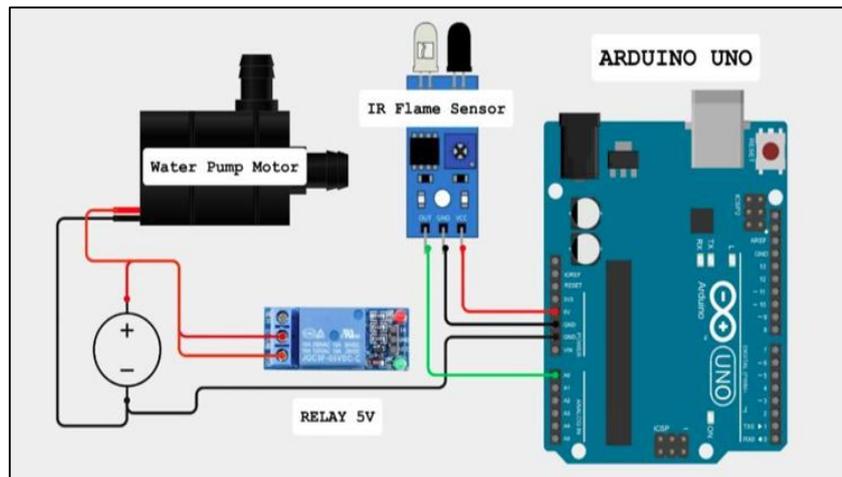

Figure 6. Lightning Surge Simulation Circuit

To evaluate the system's response to lightning-induced electrical stress, a capacitor-based surge simulation circuit was employed, as shown in Figure 6, enabling the controlled generation of transient voltage and current anomalies.
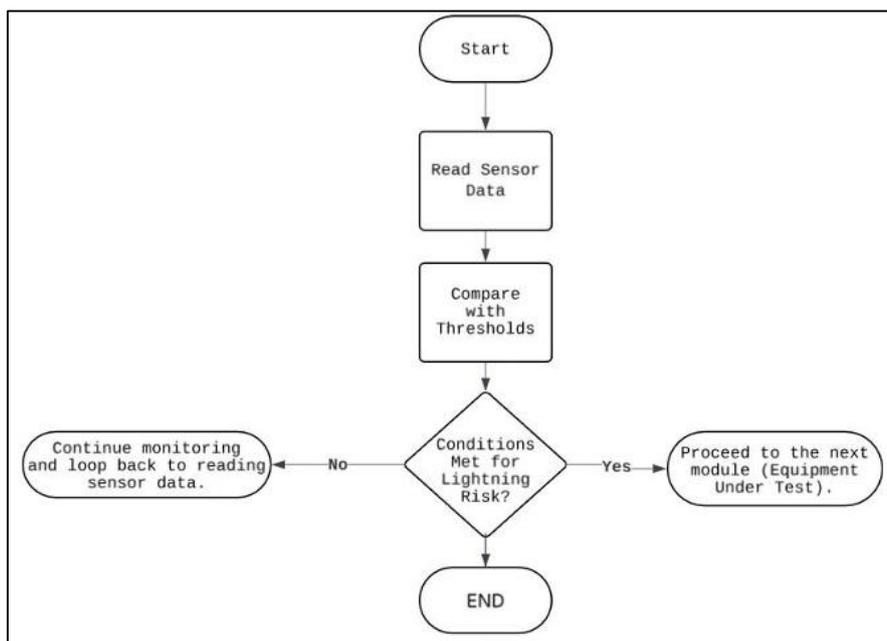
Figure 7. Flame Detection and Fire Suppression Unit

The flame detection and automated fire suppression mechanism implemented using a flame sensor, relay, and water pump motor is shown in Figure 7, demonstrating autonomous emergency response capability.
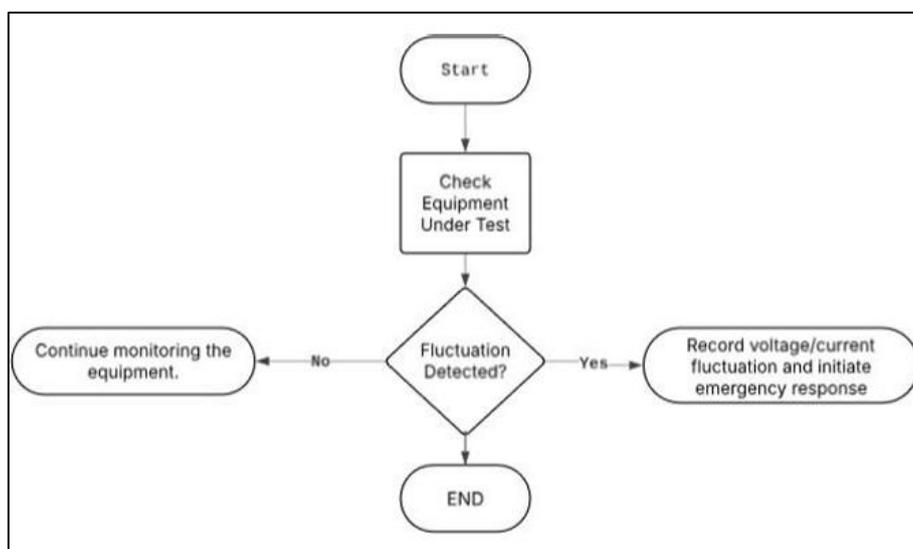

Figure 8. LCD Display Output of System Status

For local monitoring during experimentation, a 16×2 LCD display was integrated to show real-time sensor readings and system status, as presented in Figure 8.

7. Results and Discussion

The proposed fundamentally secure lightning detector system was tested in a controlled laboratory environment to determine its sensing accuracy, reaction time, communication dependability, and emergency response efficiency. The results of environmental monitoring, electrical modeling, fire detection, cloud connection and fire alarm systems are discussed in the following subsections.

Each performance variable has been evaluated using repeated experimental tests. Environmental sensing tests were executed in 10 different test runs, while electrical stress and fire detection processes were performed 8 times to verify consistency. The reported values represent the average of the data from these studies.

7.1 Sensor Performance and Environmental Monitoring

The environmental sensor detects that the device worked consistently and reliably. Temperature and humidity values measured using the DHT11 sensor remained within the expected operational range of 25–40 °C and 40–80 % RH. During testing, a temperature of 27.2 °C and humidity of 57 % RH were observed, indicating normal ambient conditions. The rain sensor activated after 0.7 seconds of water contact showing accuracy suitable for tracking rainfall during the monsoon. Similarly, the water level sensor accurately detected threshold violations when the storage unit reached about 70%. Accurate and continuous environmental monitoring provides early detection of lightning-related situations from an industrial perspective, allowing firework manufacturing industries to take preventive measures before dangerous situations arise.

The reliability and response of environmental sensors indicate that lightning-related risks in the fireworks industry can be detected when an accident occurs. Rainfall, increased humidity, and audible thunder features serve as early notification indicators for thunderstorm activity instead of direct risk signals. This shows that preventive safety measures may be implemented in advance, changing industrial lightning protection from a reactive approach to a predictive monitoring-based method.

The sound sensor successfully detected thunder-like acoustic events simulated through high-intensity sound inputs exceeding 60 dB, with a minor delay of approximately 0.5 to 1 s. The observed performance of all sensors and corresponding inferences are summarized in

Table 5, validating the effectiveness of the environmental monitoring layer for lightning precursor detection.

Table 5. Sensor Data and Observations

Sensor	Expected Outcome	Observed Data	Inferences
DHT11	Temperature: 25–40 °CHumidity: 40–80 %	Detected 27.2 °C and 57 % RH during testing	Normal performance
Rain Sensor	Output 0 (Dry), 1 (Wet); triggers on rainfall	Output switched to 1 on water contact within 0.7 s	Highly sensitive and reliable
Sound Sensor	Detects thunder-like sounds (simulated by clap/tap)	Triggered when noise level exceeded 60 dB	Small delay of ~0.5–1s
Water Level Sensor	Detects water height crossing predefined threshold	Triggered when tank reached 70 % capacity	Good threshold control
Flame Sensor	Detects spark/fire within 1 m	Detected 12 V capacitor arc instantly	Immediate trigger; ideal for spark response
Voltage Sensor	Detects voltage drop during capacitor discharge	Voltage dropped from 12 V to 6.2 V	Accurate logging during simulation
Current Sensor	Detects current surge during capacitor release	Detected spike up to 0.82 A during event	Consistent and stable output

7.2 Electrical Stress Simulation and Transient Fault Detection

Lightning-related electrical demand was simulated using a capacitor-based circuit discharge. During discharge situations, the voltage sensor registered a significant voltage reduction from 12 V to 6.2 V, while the current sensor measured transient surges of up to 0.82 A. The results aligned with theoretical expectations for unexpected energy discharge, indicating accurate detection of unanticipated electrical circumstances. The aim of the fake lightning device is not to match the size of actual lightning signals but to replicate the electrical stress effects caused by lightning coupling in internal circuits. Low-voltage capacitor discharge allows for the controlled development of rapid unpredictable situations such as surges and

internal sparking maintaining   laboratory security and consistency. The measured current spikes (~0.82 A) show unexpected conditions suitable for producing sparking and device stress without complete hardware failure, enabling safe and accurate experiments.

The recorded temporal reduction in voltage and current surge shows that additional lightning impacts within internal circuits may be determined without using complete lightning energy. This research highlights that internal arcing and surge-related faults compared to direct strike currents provide a significant   cause of early fire detection in low-voltage fireworks manufacturing devices. As a result, monitoring temporal abnormalities is more important for industrial safety than high-energy strike redirection.

The simulated lightning-related fluctuations are comparable to the surge features specified in IEEE lightning protection and surge protection standards [11, 12], demanding rapid response times and high-current impulsive conditions to evaluate protective systems.

Table 6. Sample Sensor Output (Observed)

Time (s)	Temperature (°C)	Humidity (%)	Rain	Flame	Sound	Voltage (V)	Current (A)
0	27.2	57	0	0	0	12.0	0.10
10	27.5	59	0	0	1	11.92	0.12
25	28.1	60	1	0	1	11.8	0.14
40	28.4	62	1	1	1	6.2	0.82
45	28.4	62	1	1	0	6.1	0.81

Table 6 shows representative time-dependent sensor outputs collected during lightning modeling illustrating the system's capacity to detect sudden voltage and current deviations, as well as environmental changes. This feature is necessary for detecting internal arcing and surge conditions that might lead to fires in firework manufacturing locations. In industrial firework settings, accurate detection of temporal electrical anomalies is essential, as internal arcing and surge situations may remain undetected until a fire occurs.

7.3   Flame Detection and Emergency Fire Suppression

The fire sensor displayed a high response detecting fire generated by a 12 V capacitor within seconds. The calculated fire detection response time was about 0.3 seconds. When the Arduino UNO detected a fire, it activated the relay module, and the water pump motor within 1.5 seconds. This rapid and automated response allows for quick fire control reducing the risk of fire transmission.

The efficiency of the fire detection and rapid response system demonstrates the system's suitability for fire-sensitive situations, as even a minor fire can cause serious accidents. In industrial safety, the ability to detect and manage explosions in fire-sensitive workplaces in less than a second minimizes fire spread. The water pump generated a predicted flow rate suitable to reach the observed test region. During experimental testing, the water spray extinguished the simulated sparks within seconds of activation, preventing permanent fire creation and showing better focused fire control.

The second fire detection and rapid response system demonstrates that fire control is essential in fireworks manufacturing procedures. The results show that preventing fire spread is more dependent on response latency than control intensity.

5.4   Cloud Communication and Remote Monitoring

The Arduino UNO connected to the ESP8266 Wi-Fi module and published the processed sensor data to the ThingSpeak cloud platform. Figure 9 shows the ESP8266 cloud connection, illustrating the built-in system combined with the IoT platform. Data changes identified every 15 seconds allow for real-time monitoring.

The continuous cloud connection and remote monitoring demonstrating that lightning protection methods are not limited to physical locations. Continuous remote monitoring enables centralized tracking of various firework units, which is useful in extreme weather circumstances when human involvement is limited. This demonstrates the viability of scalable, distributed safety systems for physically distributed industrial locations. Remote monitoring provides centralized control of distributed firework units by reducing dependence on on-site workers during severe weather.
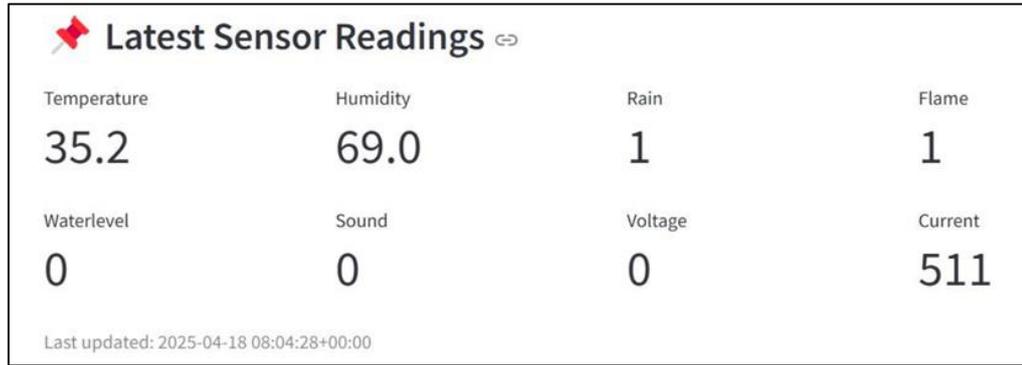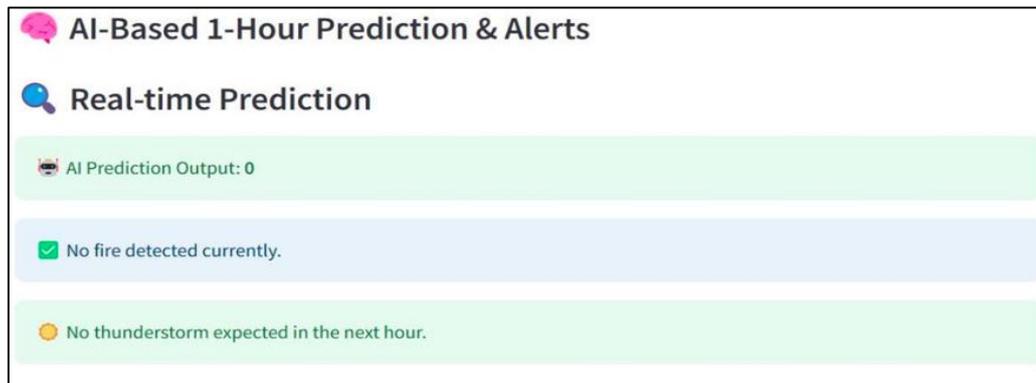
Figure 9. ESP8266 Cloud Communication Module

Figure 10. ThingSpeak Real-Time Data Visualization

Figure 11. Streamlit Monitoring Dashboard

Figure 10 shows a real-time representation of environmental and electrical parameters on the ThingSpeak dashboard illustrating the efficiency of cloud-based data collection and evaluation. Additionally, a Streamlit-based dashboard was developed to provide a user-friendly monitoring platform. Figure 11 depicts the dashboard presenting real-time graphs, system

performance indicators and historical patterns that allow operators to analyze system performance and environmental risk situations remotely.
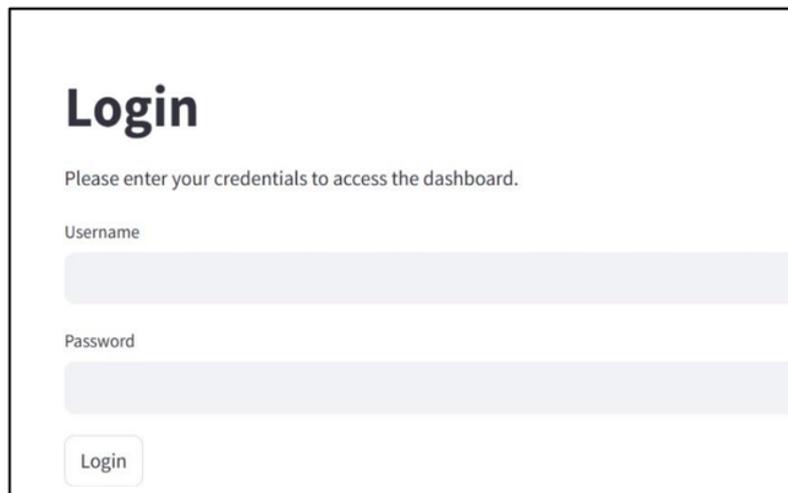
7.5 Alert Generation and System Reliability

Figure 12. WhatsApp Alert Notification Interface

Critical situations such as fire detection and high-risk environmental conditions, resulted in automatic alarm alerts using the Twilio API. Figure 12 illustrates the WhatsApp alert display generated during fire accidents. Alert response times range from 6 to 8 seconds, which is within the acceptable 10-second threshold, providing accurate notifications to authorized users. Rapid communication leads to immediate manual involvement in industries reducing possible damage and delay.

The detected alert time and maintained system availability show that human-machine collaboration is critical in industrial safety systems. While automated control reduces immediate risks, rapid warnings enable awareness and responsiveness. This dual-layer response method improves operational durability by combining automatic action with qualified manual decisions.

Table 7. Performance Evaluation

Metric	Measured Value	Expected / Ideal	Status
Sensor Accuracy	± 2 °C (Temperature), ± 4 % RH (Humidity)	± 5 % acceptable	Met

Spark Detection Response Time	~0.3 s	< 1 s	Excellent
Water Pump Activation Delay	1.5 s after spark detection	< 3 s	Satisfactory
Dashboard Refresh Rate	Every 15 s (ThingSpeak)	Every 15–30 s	Met
WhatsApp Alert Delay	6–8 s	< 10 s	Effective
System Uptime	8 hours continuous operation	> 6 hours	Reliable
AI Prediction Accuracy	~82 % match with actual values	> 75 % acceptable	Good
Power Consumption	1.2 A (full load)	< 1.5 A acceptable	Efficient

The system performed continuously for 8 hours reaching the minimal dependability requirements of 6 hours. Table 7 provides a complete performance evaluation of the proposed system including major factors such as sensor accuracy, response time, warning delay, power consumption and AI prediction accuracy.

The results of the experiment show that the proposed system effectively combines environmental sensing, electrical fault detection, automatic fire control, cloud-based monitoring and real-time warning into a single safety system. The proposed method improves environmental awareness and automated response time addressing all types of lightning-related risks When compared to existing passive lightning protection systems. Sub-second spark detection, rapid fire control, dependable cloud connectivity and suitable AI-based risk prediction accuracy highlight the system's applicability for use in fireworks manufacturing processes. Future studies may focus on permanent field implementation and integration with industrial-based lightning protection systems.

Table 4. Step-by-Step Data Flow

Step	Action	Technology
1	Sensors collect environmental and electrical data	DHT11, rain sensor, flame sensor, etc.

2	Arduino reads and processes the collected data	Arduino UNO
3	Based on decision logic, actuators are activated or deactivated	Relay and Water Pump
4	Processed data is sent to the ESP8266 via serial communication	UART Communication
5	ESP8266 uploads data to the ThingSpeak cloud platform	Wi-Fi (HTTP POST)
6	Streamlit dashboard retrieves data from ThingSpeak	Python with REST API
7	Dashboard visualizes data using graphs, tables, and alerts	Streamlit
8	When thresholds are exceeded, alerts are sent via Twilio	WhatsApp Notification
9	Operator receives alerts and monitors the system remotely	Remote User

The results show that lightning-related risks in the firework industry are mainly caused by direct energy attacks, transient surges and activation delays. The measured sub-second spark detection and rapid control demonstrate that early action is more important than high-energy diversion in firework places. It also illustrates the need for advanced, response-driven safety systems in fire-sensitive industrial environments. It shows that early detection, fast decision-making, and focused reactions are efficient methods to reduce lightning-related fire risks in the fireworks industry instead of depending on high-energy diversion. The findings support a paradigm shift toward intelligent, response-driven lightning safety systems that complement conventional protection infrastructure by addressing secondary and delayed ignition hazards.

8. Conclusion

The proposed model involves an IoT-based lightning detection, early warning system and automatic safety measures for the fireworks industry, which was developed and experimentally tested. This proposed system combines environmental sensing, lightning-related electrical stress detection, fire sensing, automatic fire control, cloud-based monitoring and real-time notification to reduce the limitations of existing passive lightning protection

systems. The experimental evaluation showed that the sensor performed accurately in fire detection, requiring 0.3 seconds and automated fire control activation in 1.5 seconds after fire detection. Cloud data transfer occurred every 15 seconds a constant reload time and emergency notifications were sent in 6 to 8 seconds. The system worked continuously for 8 hours with an energy usage of 1.2 A and AI-based lightning risk prediction accuracy was achieved at 82%. These evaluated results illustrate the proposed system's value in providing rapid detection, autonomous response and remote monitoring for early fire accidents in firework manufacturing conditions. Future work will focus on the continuous implementation and integration of high-performance lightning current and surge sensors, improving the accuracy of AI prediction models with larger datasets and scalability using SCADA or mobile application connections.

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