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Original Article

IoT-based early fire detection in jungles

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Abstract

Wildfires in forests pose a significant threat to biodiversity, climate, and human safety. Traditional methods of fire detection often result in delayed responses, allowing fires to spread uncontrollably before interventions can be made. This paper proposes an IoT-based early fire detection system tailored for forest environments, utilizing a combination of sensors and wireless communication networks to detect the earliest signs of fire. The system integrates the MQ9 gas sensor, DHT11 temperature and humidity sensor, flame sensor, and ESP32 microcontroller to monitor environmental conditions in real time. The gathered data is transmitted via wireless protocols to a central monitoring system that triggers alerts when dangerous thresholds are detected, enabling rapid response to fire outbreaks. Testing and validation were conducted in controlled environments, demonstrating that the proposed system can provide early warnings with minimal false positives. This approach offers an affordable, scalable solution to enhance forest fire monitoring and prevention, ultimately reducing the destructive impact of wildfires on natural ecosystems.

Keywords: *Wireless Sensor Networks (WSN), Environmental monitoring, MQ9 gas sensor, Sensor data fusion, AI-based fire detection, Disaster management*

Introduction

Forests play a crucial role in maintaining global biodiversity, climate stability, and natural ecosystems. However, wildfires pose a significant threat to these environments, causing widespread damage to flora, fauna, and human settlements. Forest fires can escalate quickly, and delayed detection often leads to uncontrollable destruction. In recent years, the frequency and intensity of wildfires have increased due to climate change and human activities, making it imperative to develop reliable, efficient early warning systems.

Traditional fire detection methods, such as satellite monitoring and ground patrols, often fail to provide real-time alerts. These systems are limited by delayed data transmission, high costs, or inadequate coverage in remote and densely forested areas. As a result, early detection, which is essential to prevent the spread of fires, remains a challenge.

This research proposes an innovative solution using the Internet of Things (IoT) and Wireless Sensor Networks (WSN) to develop a robust early fire detection system for jungle environments. IoT enables real-time monitoring by deploying multiple sensors throughout the forest to detect early signs of fire, such as a rise in temperature, gas emissions, or the presence of flame. These sensors communicate wirelessly and transmit data to a central server, enabling immediate action when danger thresholds are crossed.

The system's key components include the ESP32 microcontroller, MQ9 gas sensor, DHT11 temperature and humidity sensor, and flame sensor, all of which provide a comprehensive monitoring solution. This paper presents the design, implementation, and testing of this system, with a focus on real-time data collection and the ability to send rapid alerts to forest authorities or firefighting teams.

The objective of this research is to demonstrate that IoT-based systems can offer a more effective, scalable, and cost-efficient method for early fire detection in forests. By leveraging IoT technology, this system can significantly reduce the time between fire detection and response, minimizing the potential for widespread damage.

1. Overview with Problem Statement

Forest fires, or wildfires, are among the most devastating natural disasters, capable of destroying vast areas of land, displacing wildlife, and threatening human lives and property.

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Forest ecosystems, while naturally resilient to periodic fires, are increasingly vulnerable due to the effects of global warming and human encroachment. The increased frequency and intensity of wildfires demand urgent and innovative approaches to mitigate the damage. The need for early detection is paramount, as even a small fire can rapidly spread over large areas in a matter of hours, making timely intervention crucial.

Traditional fire detection methods, such as manual observation towers, satellite imaging, and air patrols, are often inadequate for early- stage fire detection. These systems either suffer from delayed reporting or are not practical in covering vast, remote, or densely forested regions. The delay in detecting and responding to fires results in significant damage before firefighting teams can be mobilized. Moreover, traditional systems are expensive to implement and maintain, limiting their use in resource-constrained regions.

2. Objectives of the Study

The primary aim of this study is to design, implement, and evaluate an IoT-based early fire detection system for jungles, utilizing real-time monitoring of environmental parameters such as temperature, humidity, gas concentration, and flame presence. The specific objectives of the study are as follows:

1. Early Detection of Fires
- Objective: To design a system that can detect early signs of fire in jungle areas using an array of sensors, such as flame sensors, gas sensors (MQ9), and temperature and humidity sensors (DHT11).
Goal: Ensure prompt detection to minimize the damage caused by forest fires.

2. Real-Time Data Monitoring and Alerts
Objective: To develop a system that continuously monitors environmental parameters and sends real-time alerts upon detecting fire hazards.
Goal: Utilize GSM or other communication technologies to immediately notify stakeholders (forest rangers, authorities) for rapid response.

3. Integration of Multi-Sensor Data
Objective: To integrate multiple sensors (flame, smoke, temperature, and humidity) into a single IoT platform for more reliable and comprehensive fire detection.
Goal: Enhance the system's sensitivity to fire risks by combining data from various sources.

4. Cost-Effective Solution for Remote Areas
Objective: To create a low-cost, sustainable fire detection system that can be deployed in remote or forested areas with limited infrastructure.
Goal: Make the technology accessible and scalable for large forest areas, focusing on affordability and ease of deployment.

5. System Scalability and Sustainability
Objective: To design a modular and energy- efficient system that can be easily scaled to cover large forest regions.
Goal: Ensure the system's long-term operation by using low-power sensors and incorporating renewable energy solutions (e.g., solar power).

6. Contribution to Fire Prevention Technology
Objective: To contribute to the field of fire prevention by providing a more efficient, faster, and cost-effective alternative to existing fire detection systems.
Goal: Reduce the environmental impact of forest fires by enabling earlier detection and intervention.

These objectives collectively aim to advance the current state of fire detection technology, providing a reliable, efficient, and scalable solution for fire-prone jungle areas.

1. Scope of the paper

This paper discusses the development of a design and development study for an IoT-based forest fire detection system specially designed for jungles. The work done under this study includes system design, development, testing, evaluation, and analysis in comparison with other existing fire detection technologies. Some of the key areas covered by the paper are as follows:

1. System Design and Architecture
Scope - The scope of this research is the elaboration of the design of the IoT-based fire detection system that integrates multiple sensors such as flame, smoke, temperature, and humidity sensors along with ESP32 microcontroller.
Coverage: It aims at developing and implementing a system to be applied in remote jungle territories for early detection of fire indicants with minimum false alarm rates and maximum energy conservation.

2. Hardware and Software Implementation
Scope The paper discusses some of the hardware implemented in this research on the ESP32, MQ9 gas sensor, DHT11, flame sensor, and GSM module. The paper also discusses software algorithms applied while handling data and triggering alert signals.
Coverage: The paper will implement software, covering sensor data acquisition, data processing, and alert conditions communicated to the GSM modem for possible notification.

3. Experimental Arrangement and Measurement
The scope within the technical paper entails the experimental setup made to test the performance of the system in detecting its fire dangers; this then involves the testing and verification of the system about flame and smoke detection through different ranges and conditions for various scenarios on their alarm mode.

Results would be presented as a discussion on accuracy in detection, system reliability, functionality in different environmental settings, effectiveness of the GSM module in sending real-time alerts.

4. Analysis of Data and Findings
- Scope: This research covers the examination of collected data whereby findings are evidenced through tables, graphs, and statistical evaluations for the

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presentation of the system's precision in detection, response duration, and the holistic efficacy of fire determination.
Coverage: This piece of work would comparatively evaluate the existing fire detection technologies on an evaluative basis, along with the different benefits and possible enhancement by the proposed system.

5. Problem and Constraints

- Scope: This study will explore the various challenges and constraints encountered in the process of developing and evaluating the IoT- based system, including issues related to sensor calibration, environmental influences on accuracy, and restrictions concerning power supply.
- Coverage: The above-mentioned challenges and proposed recommendations for future improvements, such as integrating AI to make for predictive analytics and robust communication reliability, are also covered in detail.

Research Focus 6: Contributions to the Domain of Fire Detection Scope: To contribute towards the state-of-the-art in terms of fire detection technologies and put forward an efficient early fire detection solution using IoT, with lower cost and a scalable approach, in forest environments. - Coverage: The findings will give a basic outline of further questions and innovations into more sophisticated fire alarm systems designs, which might also be applicable to other areas such as disaster relief and environmental monitoring. --- The scope of this paper is to cover the comprehensive development of an IoT-based early fire detection system that will go into design, implementation, testing, and eventually evaluation on practical application in jungle and forest environments.

Literature Survey

Recent developments in IoT and WSN technologies have shown significant potential in improving forest fire detection. IoT-based systems deploy a network of sensors that monitor environmental parameters like temperature, humidity, gas emissions, and the presence of flames. These sensors are connected to microcontrollers and communicate wirelessly using protocols such as Wi-Fi, LoRa, or Zigbee to transmit data to a central server or cloud platform.

In one study, Kumar et al. (2020) demonstrated an IoT-based fire detection system using temperature and gas sensors to detect abnormal conditions in real time. The system proved to be effective in generating early alerts by monitoring small changes in environmental conditions that may indicate fire hazards. Another study by Singh et al. (2019) employed WSN to improve the accuracy of fire detection in remote areas. Their results showed that WSN can successfully transmit real-time data over long distances, providing early warnings in difficult- to-reach areas.

The integration of edge computing with IoT has emerged as a promising approach to enhance the efficiency of fire detection systems. A recent study by Zhang et al. (2023) investigated an edge-based fire detection system that processes data locally on sensor nodes before transmitting it to the cloud. This architecture reduces latency and bandwidth usage, enabling faster response times to potential fire incidents.

The study highlighted the implementation of machine learning algorithms directly on edge devices, which allowed for real-time analysis of sensor data, such as temperature spikes and gas concentration levels. This approach not only improved detection accuracy but also reduced reliance on constant internet connectivity, making it particularly suitable for remote forest areas. The researchers concluded that incorporating edge computing into IoT fire detection systems significantly enhances their performance and reliability, especially in challenging environments where traditional methods may fail.

Cloud computing has been integrated with IoT systems to enhance the scalability and accessibility of fire detection networks. Cloud-based systems allow for the storage and analysis of large volumes of sensor data from multiple locations, enabling forest authorities to monitor real-time fire risk across vast regions. In a study by Zhang et al. (2022), an IoT-cloud architecture was proposed for forest fire detection, where sensor data was transmitted to cloud servers for processing and analysis. The system provided real-time alerts via mobile devices, making it accessible to both authorities and local communities

2.4 Limitations of Existing Systems

While IoT and WSN-based systems offer several advantages over traditional methods, challenges remain. One of the primary issues is power management for sensors deployed in remote forest locations, where access to electricity is limited. Battery-powered sensors may require frequent maintenance, which can be impractical in dense or inaccessible regions. Another challenge is the accuracy of data transmission, as wireless signals may weaken in dense forests, affecting the reliability of the system.

2.5 System Design

Block diagram

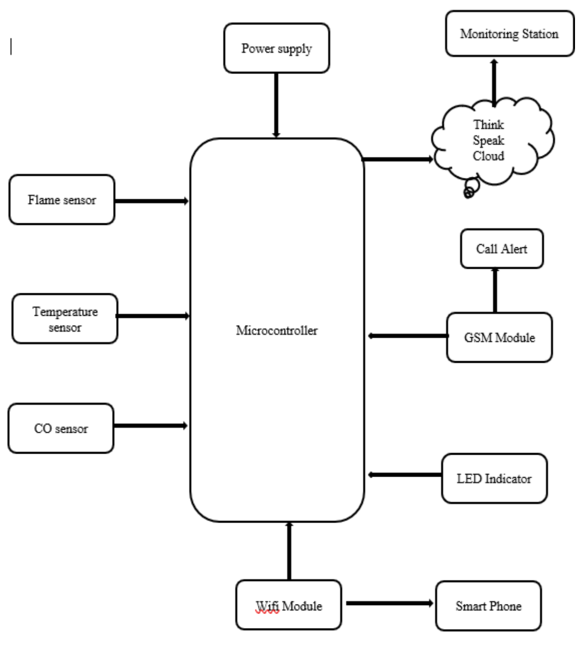

Fig- Iot Based Fire Detection In Jungle

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3. Module Description

The system is divided into three primary modules: Sensing Module, Processing Module, and Communication Module. Each module has a distinct role in ensuring the effective detection and transmission of fire-related data.

3.1 Sensing Module

This module consists of sensors responsible for collecting environmental data. These sensors detect anomalies that indicate potential fire incidents:

- MQ9 Gas Sensor:
  - Measures gas concentrations (e.g., carbon monoxide and methane) in the air.
  - Outputs an analog voltage proportional to the detected gas levels.
  - Triggered when gas levels exceed a predefined threshold, indicating a potential fire.

- DHT11 Sensor:
  - Captures temperature and humidity data.
  - Provides digital output to the microcontroller.
  - Helps detect abrupt increases in temperature or drastic drops in humidity, often precursors to a fire.

- Flame Sensor:
  - Detects the presence of visible flames using infrared radiation.
  - Outputs digital signals to the microcontroller for immediate response.

3.2 Processing Module

This module processes sensor data, applies detection algorithms, and makes decisions based on thresholds.

- Microcontroller (ESP32):
  - Serves as the central processing unit.
  - Collects data from sensors via analog or digital inputs.
  - Executes pre-programmed detection logic.
  - Monitors power consumption to enhance energy efficiency.

- Detection Logic:
  - Step 1: Read data from sensors.
  - Step 2: Compare the values against predefined thresholds.
  - Step 3: Trigger an alert if the combined conditions suggest a fire.

3.3 Communication Module

This module ensures real-time transmission of alerts and data logs to external systems or personnel.

- GSM Module:
  - Sends SMS alerts to predefined mobile numbers.
  - Supports GPRS for transmitting data logs to cloud platforms or servers.

- Cloud Integration (Optional):
  - Stores historical data for trend analysis and predictive insights.
  - Can integrate with visualization tools for monitoring.

3.4 Power Supply Module

The system is powered by a rechargeable battery or a solar panel for sustainable operation in remote locations. A voltage regulator ensures stable power delivery to all components.

4. Proposed System:

Thus, the proposed system is an IoT-based early-stage fire detection mechanism designed specifically for jungle ecosystems, where advanced sensors integrate real-time data processing and communicating technologies to detect potential fire hazards at the initial stage. Alerts can be provided in real-time, thus decreasing the damage that may incur.

4.1 Goals of the Developed System

- Early Warning: Detection of fire hazard through monitoring environmental variables that include temperature, humidity, gas concentration, and the presence of flame.
- Real-time Alerts: Sends real-time alerts in the form of an SMS or cloud- based notification.
- Cost-Effectiveness: Use low power, low-cost components to deploy sustainably and at scale.
- Accessibility: Can operate in very remote, dense jungle environments with minimal infrastructure.

4.2 System Design

- The architecture of the system categorizes into three layers:
- Sensor Layer: Collects real-time environmental data.
- Processing Layer: Detect anomalies in sensor readings.
- Communication Layer: It sends alerts and data logs to the users.

4.3 Properties of the Designed System

- Multi-Sensor Integration
- MQ9 Gas Sensor: It senses lethal gases such as methane and carbon monoxide.
- DHT11 Sensor It senses temperature and humidity, thereby detecting abnormal alterations.
- Flame Sensor: Detects visible flames.
- Advanced Microcontroller: ESP32
- Efficiently processes data obtained from sensors.
- Has other connectivity options through Wi-Fi and Bluetooth.
- GSM-Based Communication
- It sends SMS alerts for real-time notification.
- It supports GPRS for transferring data to cloud servers.
- Energy efficiency
- Low-power sensors and microcontrollers allow extended functionality in remote locations.
- Solar-powered options available for sustainable deployment.
- Data Logging and Analytics.

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- It collects environmental data logs for historical purposes and system optimization.
- Possibly, integrate with AI/ML algorithms for predictive analysis and anomaly detection.

4.4 Advantages of the Suggested System

- Real-time monitoring quickly responds to situations because critical parameters are constantly tracked.
- Cost-Effective Deployment Uses cost- effective hardware which is suitable for massive deployment.
- Scalability: The modular design facilitates easy addition of sensors or the communication module.
- Reliability: High accuracy of detecting fire indicators using data at various levels.

4.5 Workflow of the Proposed System

- Data Collection: Sensors obtain measurements of temperature, humidity, gas concentration, and flame detection.
- Data Processing:
- ESP32 processes sensor inputs.
- Detection algorithms compare values against thresholds.
- Alert Generation:
- The system alerts the occurrence of abnormalities. It sends out alerts using the GSM module through SMSs. Data Transmitted: The logs could also be transmitted to a cloud platform for further storage and analysis.

Challenges and Limitations

Although the proposed IoT-based early fire detection system has significant advantages, there are also some challenges and limitations. The issues facing these problems must be addressed to optimize performance and make wider deployments more practical:

1. Sensitivity and calibration of sensors

Task: Sensors, like the MQ9 and DHT11, must be calibrated on a regular basis to maintain their original accuracy. Changing sensitivities in the sensors may lead to false signals or missed signals.

-Limitation: Calibration processes may require periodic manual intervention, increasing maintenance requirements.

2. Environmental Factors

Demand: Environmental influences such as heavy downpour, gusting winds, or thick fog may hamper sensor readings, thereby lowering system accuracy.

Limitation: The flame sensor would fail to detect a fire in the scenario where smoke or foliage obscures the fire from view.

3. Short range communication:

Challenge: Cellular areas that are remote with poor network connectivity have a limited range in GSM modules.

- Limitation: The absence of dependable network infrastructure in jungle terrains may impede the timely transmission of alerts

4. Energy Dependency

Problem: In such places, the system relies on batteries or solar panels for its operation.

Limitation: Longer periods of cloud cover or equipment failure may even lead to shutdowns, hence system downtimes.

5. Cost of Widescale Rollout Challenges are:

The system is cost-effective compared with traditional methods. However, its massive deployment across vast areas of the jungle calls for significant initial investment.

Limitation: Scalability increases the system so that it may cover large forests with financial and logistically related limitation.

6. False Alarms

Challenge: Environmental anomalies such as gas emissions from decaying organic matter or rapid temperature changes may trigger spurious reports. - Limitation: Excessive false alarm rates result in ineffective response efforts- this thus affects reliability of the system over time.

Recommendations for Future Efforts

1. Advanced Sensors: High sensitivity transducers should be used which can tolerate surroundings better. 2. Improved Communication: Lora WAN or satellite communication should be added for guaranteed dependable connectivity in remote areas.

3. Energy Harvester: Research cutting-edge energy-harvesting techniques to minimize reliance on power sources. 4. AI Integration: Incorporate machine learning algorithms that try to minimize false alarms and maximize detection accuracy. 5. Modular Design: Develop modular systems to be easily rolled out and maintainable over large forested areas. Addressing all these difficulties, the system can be made robust, reliable, and scalable for real applications.

Conclusion of the Survey

The survey conducted on existing fire detection systems underlines the urgency of innovation requiring new, real-time solutions tailored towards forest environments. Traditional methods, like satellite imaging and manual surveillance, perform well for wide scale monitoring but generally carry a cost in terms of delay, inefficiency in fire detection, and high expenses. Ground-based systems are much better accessible but have specific issues related to variability and scaling in the environment.

Large gaps in current technologies can be seen here, ranging from minimal integration of multiple sensing parameters to challenges in remote operation and a dearth of cost-effective solutions. These limit the motivation toward an Internet of Things (IoT)-based approach aimed at delivering affordability, scalability, and real-time functionality.

Our proposed system would overcome the stated issues by incorporating key technologies such as advanced sensor appliances, microcontrollers, and GSM-based communication for fast fire hazard detection and reporting. Combining temperature, humidity, gas, and flame detection sensors addresses all of the factors of an early jungle fire. Therefore, this research confirms the potential of IoT as a transformative tool in forest fire management, which provides timely detection alongside enormous savings on cost and resource Please inform me if you would like to refine or further elaborate on this conclusion.

Results

Test Parameter	Total Cases	Successful Detections	Detection Accuracy (%)
Flame Detection	**50**	**47**	**94%**
Smoke Detection (CO)	**50**	**46**	**92%**

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Conflicts of interest
There are no conflicts of interest.

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