Real-Time Forest Fire Detection and Monitoring System Using IoT Sensors and Convolutional Neural Networks

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Abstract

Forest fires pose a severe threat to ecosystems, wildlife, and human life, often resulting in large- scale environmental and economic losses. Traditional fire detection methods, such as satellite monitoring and manual surveillance, suffer from delays and limited coverage. To address this, the proposed system integrates Internet of Things (IoT) technology with a Convolutional Neural Network (CNN)-based deep learning model for real-time and accurate forest fire detection. IoT sensors deployed in forest areas continuously monitor environmental parameters such as temperature, humidity, and gas concentrations. Additionally, surveillance cameras capture images which are analyzed by a trained CNN model to detect fire-related features.When abnormal patterns indicating a potential fire are detected, the system automatically generates alerts to notify authorities and emergency responders.

Forest fires pose severe threats to environmental sustainability and human safety, necessitating timely and accurate detection systems. This study presents a comprehensive approach by integrating methodologies from remote sensing and IoT technologies to enhance forest fire detection. By leveraging satellite imagery and remote sensing standards, the system applies an Extreme Learning Machine (ELM) model to process and classify spatial patterns associated with fire outbreaks. Complementarily, an IoT-enabled framework collects real-time environmental data using sensors, which is then analyzed through a hybrid machine learning model combining decision trees, support vector machines, and deep learning techniques.

Keywords

-Forest Fire Detection, Internet of Things (IoT), Convolutional Neural Network (CNN), Deep Learning, Real-Time Alert System, Fire Prediction.

Introduction

Overview Particularly in nations with abundant forests like India, forest fires are growing more common and more severe. The primary causes of this increase are human activity and climate change. In addition to destroying forests and wildlife, these fires emit toxic gases into the atmosphere, endangering human health and safety.In India, the majority of forest fires happen from November to May and are frequently started by twigs, dry leaves, and other combustible objects. Forest fires in November 2021 released approximately 176 million tons of carbon dioxide into the atmosphere in a single month. Serious health problems, such as skin disorders and lung diseases, can result from that type of pollution. Approximately 200,000 forest fires occur annually, harming ecosystems and influencing the lives of those who live nearby[1][2].

Early detection is crucial in managing and controlling these fires. The sooner a fire is detected, the faster

emergency teams can respond, helping reduce damage and protect forests, animals, and communities. Technologies like sensors, satellites, and aerial monitoring are already being used to detect fires early and respond more effectively. Recently, artificial intelligence (AI), particularly deep learning techniques like Convolutional Neural Networks (CNNs), is playing a major role in fire detection. These systems analyze images from satellites, drones, and cameras to automatically identify signs of fire. CNNs are trained to recognize what fire looks like by learning from thousands of images, which helps them detect fires quickly and accurately. This project focuses on building a reliable fire detection system using CNNs. By helping forest officials spot fires in their early stages, we can respond faster, minimize the damage, and better protect our environment and the people who depend on it.

These systems analyze images from satellites, drones, and cameras to quickly spot fires. Models like VGG16,ResNet-50, and InceptionV3—trained using transfer learning—work with other tools like Random Forest and SVM can detect fires more accurately and with fewer false alarms. They are an excellent choice for remote or low-resource locations because they are quick, dependable, and reasonably priced [3]. One of the largest threats to our forests today is deforestation, which is frequently caused by illicit mining, logging, and other human endeavors. The majority of plant and animal species on Earth live in forests, which make up around 31% of the planet's surface. Additionally, they sustain the livelihoods of more than 16 billion people.But despite their importance, forests are disappearing at an alarming rate—and deforestation is responsible for about 17% of global carbon emissions. Countries like China and India are among the top contributors to this problem. To protect what's left of these vital ecosystems, technology is stepping in. AI-powered monitoring tools are now helping track deforestation more effectively, offering a better chance at preserving forests before it's too late.

At the same time, forest fires continue to be a major concern. Whether sparked naturally or by human actions, these fires can destroy vast areas of forest, wipe out wildlife habitats, threaten nearby communities, and even damage roads and power lines.For years, detecting these fires relied on basic sensors or people keeping watch from lookout points. But these methods often fall short—especially in remote or thickly wooded areas where spotting fires quickly is tough. There can be delays, blind spots, or even missed warnings. Luckily, newer technology is changing the game. Satellite imagery and Internet of Things (IoT) sensors now allow for faster, more accurate detection of fires.[9][10].

Forest fires are turning into a major environmental crisis, destroying huge areas of forest, killing wildlife, and leading to massive economic losses. The problem is even worse in remote or densely wooded regions, where spotting a fire early can be really tough. Traditional methods like basic sensors or watchtowers often just aren't enough—they can be slow, have a limited range, and miss early signs of danger. By the time a fire is noticed, it's often already out of control. These systems can alert authorities in real time, giving them a head start to respond before things spiral out of control. To overcome these challenges, modern technologies like Convolutional Neural Networks (CNNs) and the Internet of Things (IoT) are now being used. CNNs are a type of deep learning model that can analyze images from drones, satellites, or surveillance cameras to detect early signs of fire, such as smoke or flames. These models learn from large sets of fire and non-fire images, allowing them to accurately identify patterns and spot potential outbreaks faster than humans can.[11][12]

At the same time, IoT sensors placed throughout forest areas monitor real-time environmental data like temperature, humidity, and gas concentrations. When these sensors detect abnormal conditions such as sudden heat spikes or unusual gas levels—they can send immediate alerts to forest authorities. This combination of visual analysis through CNNs and on-the-ground monitoring via IoT creates a more responsive and accurate early warning system.[13][14]

Forest fires present a major ecological and economic threat, often causing irreparable damage to the environment and biodiversity. Traditional sensor-based fire detection systems face limitations in scalability and real-time monitoring, especially in large and remote forest areas. To address these challenges, deep learning techniques, particularly Convolutional Neural Networks (CNNsand the YOLO (You Only Look Once) object detection model, have emerged as effective solutions.[15]

Literature Review

Real Time Smart Forest Fire Detection and Monitoring System Using IoT and Machine Learning‖, Forest fire monitoring systems are becoming more advanced with the help of technology. One subsystem was developed for the Qin ling Mountains in China, where Wireless Sensor Networks (WSNs) are used to detect early signs of fire by tracking changes in temperature and humidity. These sensors use Zigbee for communication. To save energy, a grid- based algorithm was used to reduce unnecessary data transfer and extend battery life, with accuracy remaining high (error less than 11%). Forest fires are becoming a bigger threat to nature, people, and the planet's climate. The old ways of spotting fires—like lookout towers, patrols, and basic sensors—often don't work well, especially in remote areas where there's not much data. But thanks to new technologies, that's starting to change.Today, tools like Artificial I ntelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) are helping us predict, detect, and manage forest fires much more effectively. For example, AI can now scan satellite images to spot signs of fire and alert authorities quickly, giving them more time to respond.

In India, the Interactive Forest Monitoring System (IFMS) has been used to track fires and has reached about 77% accuracy. In Madhya Pradesh, experts used weather data and satellite images to assess fire risk, even without ground-level fuel data. They used a drought index called NMDI instead and built a smarter fire danger system, which turned out to be about 82% accurate.Similar efforts are happening around the world. In Romania, researchers looked at satellite images from 2000 to 2015 to track forest loss. They used a tool called NDVI to measure vegetation health and found that over 150,000 hectares of forest were lost—mostly due to illegal logging. These insights have helped in planning forest recovery and stopping further damage [1][2].

Forest Fire Prediction and Management using AI (Artificial Intelligence), ML (MachineLearning) and Deep Learning Techniques‖ Deep learning, particularly **Convolutional Neural Networks (CNNs)**, has proven to be highly effective for fire detection. These models are trained on large datasets of fire and non-fire images, allowing them to recognize visual patterns like flames and smoke. This approach significantly reduces false positives caused by sunlight, fog, or other similar visuals.Advanced object detection models like **YOLO (You Only Look Once)**, including the newer **YOLOv5 and YOLOv8** versions, are being implemented for real- time fire detection from video feeds. YOLOv8, for example, has demonstrated high precision and recall in identifying fires in real-time footage, making it ideal for drone and surveillance applications.In image-based detection systems, techniques like **color segmentation** using HSV and YCbCr color models, and **motion analysis** through frame differencing, help distinguish real flames from non-fire heat sources. [3][4]

A Smart IoT-Enabled Wildfire Monitoring and Early Detection System using Convolutional Neural Networks and Sensor Data Analysis‖ New technologies are making forest fire detection faster and more reliable. By combining smart sensors (IoT devices) with computer vision tools, these systems can spot fires early and send alerts quickly. For example, some systems use models like YOLOv5 to detect flames in images, while sensors check the environment for things like smoke, heat, and humidity to confirm if a fire is real. Tools like thermal and infrared cameras, along with GPS, help find the exact location of a fire. Data is shared using mobile networks or cloud services, so it's easy to access in real time. Devices like ESP32 are used in wireless networks to constantly monitor forest conditions, and drones with special cameras can

watch large or remote areas. If a fire is detected, alerts can be sent to phones or trigger on-site alarms.
These smart systems are faster, more accurate, and better at avoiding false alarms. They are also scalable, meaning they can be used in both small and large forests. Overall, they represent a big step forward in managing and preventing wildfires.[5][6].

Enhancing the Accuracy of Forest Monitoring Through AI to Reduce Carbon Footprint‖ New technologies are playing a big role in spotting and tracking forest fires before they get out of control. Tools like artificial intelligence (AI), machine learning (ML), remote sensing, and wireless sensors are helping detect fires more quickly and accurately. Some systems even work in near real-time, giving early warnings to help stop fires from spreading. But there are still some challenges. These systems often deal with huge amounts of data and require trained experts to manage and understand it all. To make fire detection faster and more accurate, researchers are now using a method called transfer learning. This means they take powerful AI models—like VGG16, VGG19, ResNet-50, and InceptionV3—that were already trained to recognize images, and fine-tune them specifically to detect fires. Since these models have already "learned" a lot from large image datasets, they can be adapted quickly and work well for fire detection. Some researchers are also using a mix of different models, known as ensemble models. These combine techniques like SVMs, Boosted Regression Trees (BRTs), and MARS to improve predictions about where fires are likely to happen. Using more than one model increases the chances of catching early warning signs more accurately.In some cases, using these pre-trained models with image data has proven to be just as effective as using expensive sensor systems—making it a smart, cost-effective solution for early fire detection [7][8].

This study looks at using the Extreme Learning Machine (ELM) model to detect forest fires from satellite images by analyzing factors like temperature and vegetation. ELM helps classify fire- prone areas quickly and accurately while keeping computing costs low, making it good for monitoring large, remote forests in real time.Another part of the research describes a system that uses IoT sensors to collect live data on temperature, humidity, and gas levels. This data is analyzed by a mix of machine learning methods—like decision trees, support vector machines, and deep learning—to improve prediction accuracy. Using several algorithms together helps reduce false alarms and makes fire detection more reliable. [9][10].

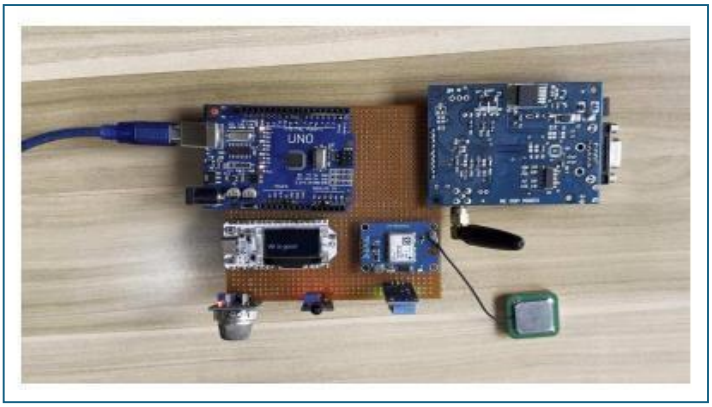
This research looks at how using Convolutional Neural Networks (CNNs) can help spot forest fires from pictures. CNNs learn to spot fires by analyzing many images of both fires and non- fires, helping reduce false alarms from things like sunlight or red objects. They're more accurate and flexible than older rule-based methods. A system called Forest 4.0 uses wireless sensors to monitor forests in real time, tracking things like gas levels and weather. It sends data using LoRaWAN, and researchers are working to solve challenges like covering large areas, avoiding delays, and keeping sensors powered. These smart systems allow faster responses to fire outbreaks. With better accuracy and real-time updates, they help protect forests and nearby communities more effectively. They suggest using solar power and strong communication networks to make sure everything runs smoothly. The concept of Forest 4.0 envisions a smart forest ecosystem powered by advanced tech like AI, IoT, LoRaWAN, and WSNs. These systems continuously monitor forest conditions, optimize data transmission, and reduce manual labor. To address power limitations in remote forests, solar-powered nodes and low-energy communication protocols are being tested.At a larger scale, these AI-driven systems not only help prevent fires but also support broader goals like reducing carbon footprints, protecting biodiversity, and managing climate change impacts. As the technology matures, the focus is shifting toward building more sustainable, resilient, and intelligent ecosystems. [11][12].

This study uses the YOLOv8 object detection model to detect forest fires in real-time video. The model was trained on a custom dataset with images of both fire and non-fire scenes, allowing it to accurately identify and locate fires in video footage. YOLOv8 stands out for its speed and precision, performing better than older methods and reducing false detections.
The research also explores another technique that looks at both color and movement to spot fires. By using color models like HSV and YCbCr, the system identifies fire-like colors, and then compares video frames to detect moving flames. This approach works better than traditional heat sensors, which often raise false alarms. The results show that combining color and motion makes real-time fire detection more reliable, especially for surveillance cameras in forests or other monitored areas.[13][14].

This study combines two AI method YOLOv5 and CNN to detect both fire and smoke in forests. The system is trained using videos and images so it can spot and pinpoint possible fires or smoke quickly. The researchers tested different versions of YOLO and chose YOLOv5 because it offers a good mix of accuracy and speed. In this setup, the CNN takes care of classifying what's seen, while YOLO handles locating the fire or smoke in the scene. Using both models together helps improve detection and gives faster, more reliable early warnings [15].

Comparative Analysis

The eight forest fire detection systems reviewed demonstrate a range of technological integrations and methodologies, each with distinct strengths and limitations. Systems such as those by Anbazhagu et al. and Ishu Sharma et al. effectively combine IoT sensors with Convolutional Neural Networks (CNNs) to enable real-time detection and risk assessment, ensuring faster response and higher accuracy, though they require robust infrastructure for deployment. Image-focused approaches like those by Jagmohan Singh et al. and Gayathri et al. utilize CNNs for fire detection in captured images, offering cost-effective and lightweight solutions ideal for small-scale monitoring, albeit lacking environmental context integration. Khushal A et al. present a hybrid IoT and machine learning model using Zigbee-enabled sensor networks, achieving high accuracy and energy efficiency, while Pandey et al. explore broader AI applications in forest monitoring and carbon footprint reduction, focusing more on sustainability than immediate fire detection. Meanwhile, Agarwal and Jha provide a comparative analysis of transfer learning models like ResNet-50 and VGG19, demonstrating high classification accuracy from images alone but limited real-world adaptability due to the absence of sensor data. Lastly, the CNN-based model from the survey paper integrates gas, flame, and vibration sensors with image analysis and GPS-GSM alert systems, offering a practical balance between detection precision and real-time localization. Collectively, these studies underline the evolving role of deep learning and IoT in wildfire management, with hybrid models offering the most comprehensive solutions.



Results/Discussion

Fig.1. Modules for detection of fire, smoke andVibration

Fig.1 Highlights the successful integration of all necessary sensors into the main board for the IoT-based forest fire detection system, demonstrating a wellestablished hardware setup. Figure 2 shows the real-time flame detection process, where a flame sensor is tested for its responsiveness and accuracy by exposing it to a controlled flame or heat source. The system's effectiveness was further validated through extensive field trials conducted in diverse forest environments. These trials, carried out over several months, included 5 tests in dense rainforests, 3 in temperate woodlands, 4 in boreal forests, and 3 in mixed forests, ensuring the reliability of the detection system across different forest conditions.

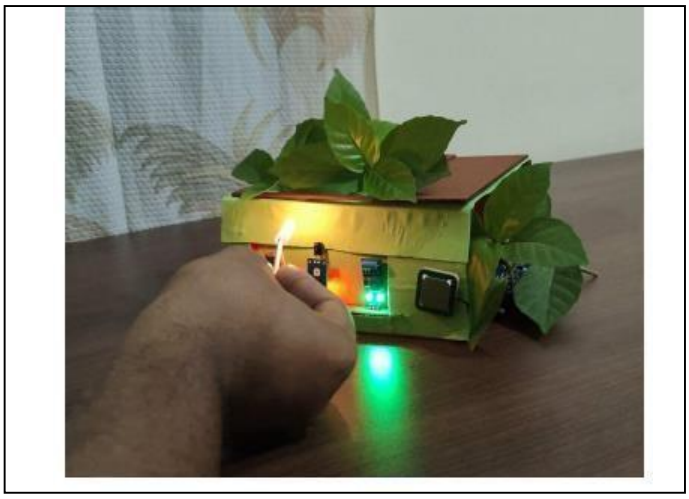


Fig.2. Real time flame detection

Fig.2. illustrates the real-time flame detection process, where a flame sensor is evaluated for its sensitivity and effectiveness in identifying heat or fire sources. During testing, the sensor is subjected to a controlled flame or heat exposure to observe and confirm its operational accuracy. To assess the system's reliability, several trials were carried out in different forest settings over a span of months. These environments included dense rainforests (5 trials), temperate woodlands (3 trials), boreal forests (4 trials), and mixed forests (3 trials), ensuring the system's adaptability and performance across varying forest conditions.[1]



Fig.3: Training and Validation Accuracy of CNN Model

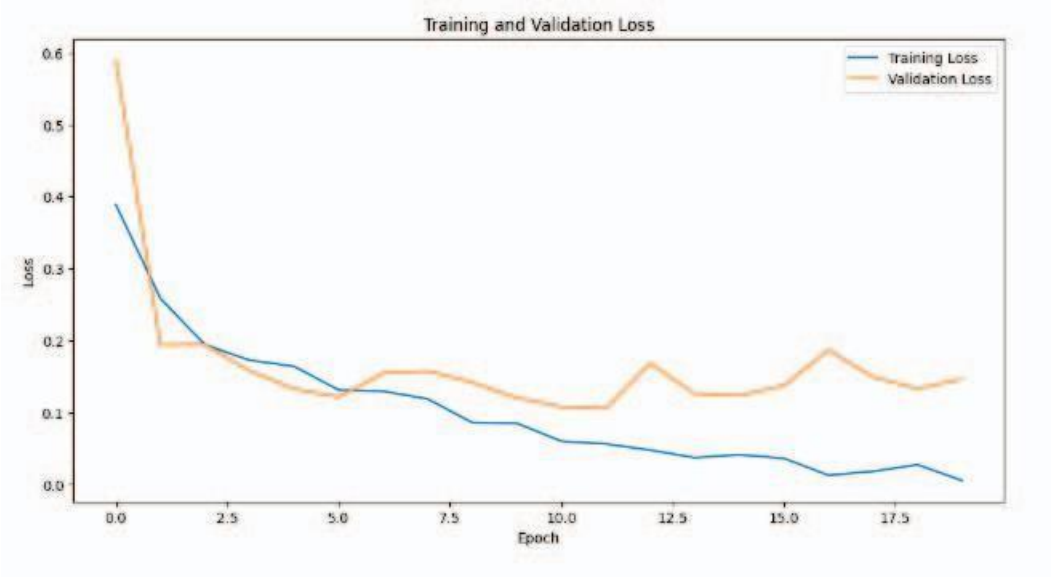


Fig.4. Training and Validation Loss of CNN Model

This research presents an experimental analysis comparing the performance of several machine learning models— SVM, XGBoost, AdaBoost—and a CNN model for fire detection. Image of a confusion matrix for the CNN model used to classify fire and non-fire images. The matrix compares the true labels (actual conditions) with the predicted labels from the model.

- The top-left cell (23) represents true negatives, where 23 non-fire images were correctly identified as nonfire.
- The top-right cell (2) indicates false positives, where 2 non-fire images were incorrectly predicted as fire.
- The bottom-left cell (3) shows false negatives, where 3 fire images were incorrectly predicted as non-fire.
- The bottom-right cell (22) represents true positives, where 22 fire images were correctly identified as fire. Overall, the matrix reflects how well the model distinguishes between fire and non-fire, with more correct predictions than errors, indicating good performance.[3] The results of the IoT-based forest fire detection system demonstrate its high effectiveness and reliability. By integrating IoT sensors with a CNN model, the system achieved strong performance in real-time fire detection with minimal false alerts. Training over 50 epochs showed consistent improvement, with training accuracy increasing from 59.38% to

94.73%, and validation accuracy reaching 94.9%, indicating the model's strong ability to generalize to unseen data. Similarly, the Area Under Curve (AUC) metric, which measures the model's ability to distinguish between fire and non-fire events, improved from 0.6735 to 0.9881 during training, and the validation AUC stabilized at 0.989, confirming the model's precision. These results validate the system's suitability for early forest fire warnings. Additionally, its scalability makes it useful in different forest environments, and it can be deployed using smart drones or integrated with disaster management systems for real-time
alerts and risk assessment.[5]

Figures and Tables

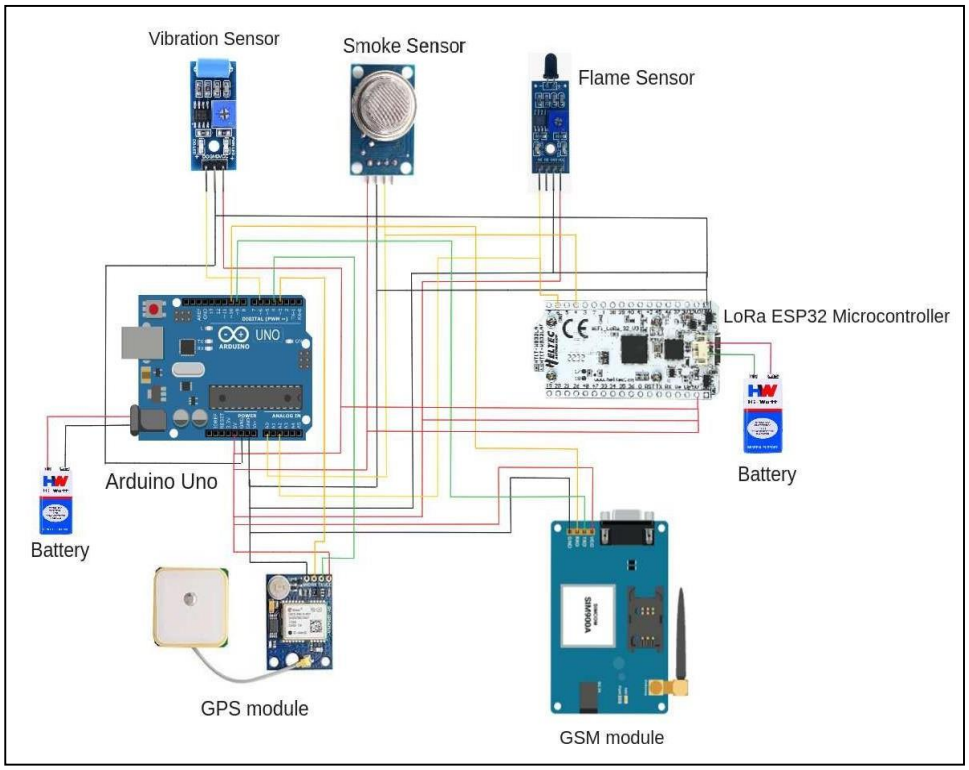
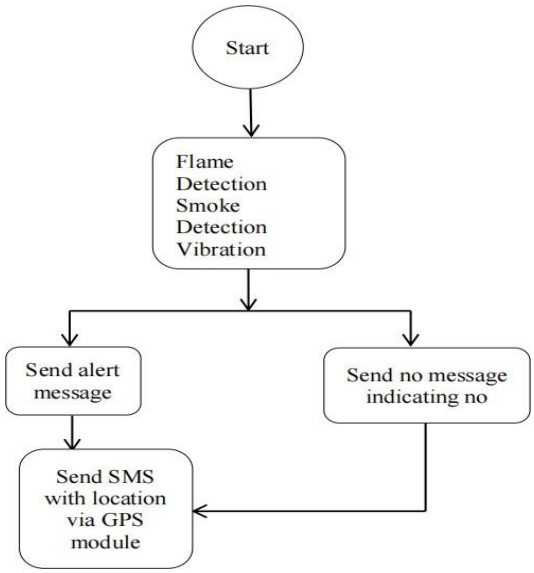


Fig.5. Circuit Diagram of forest fire detection

Fig.5 Shows the proposed system integrates various sensors and communication modules to detect forest fires and illegal logging activities in real time. It is built around gas, flame, and vibration sensors that monitor environmental conditions and detect anomalies. Implementation Steps:

1. Assemble hardware and connect sensors to microcontrollers.
2. Develop and upload software for data handling and communication.
3. Test the system for reliability and accuracy.
4. Deploy in forest areas with ongoing monitoring and maintenance.



By combining smart sensors, GPS tracking, and image analysis with real-time alerts, this system provides an efficient solution for forest fire prevention and illegal logging control, supporting for Fig.6. Flowchart of design and implementation

Methodology

The proposed system integrates various sensors and communication modules to detect forest fires and illegal logging activities in real time. It is built around gas, flame, and vibration sensors that monitor environmental conditions and detect anomalies.

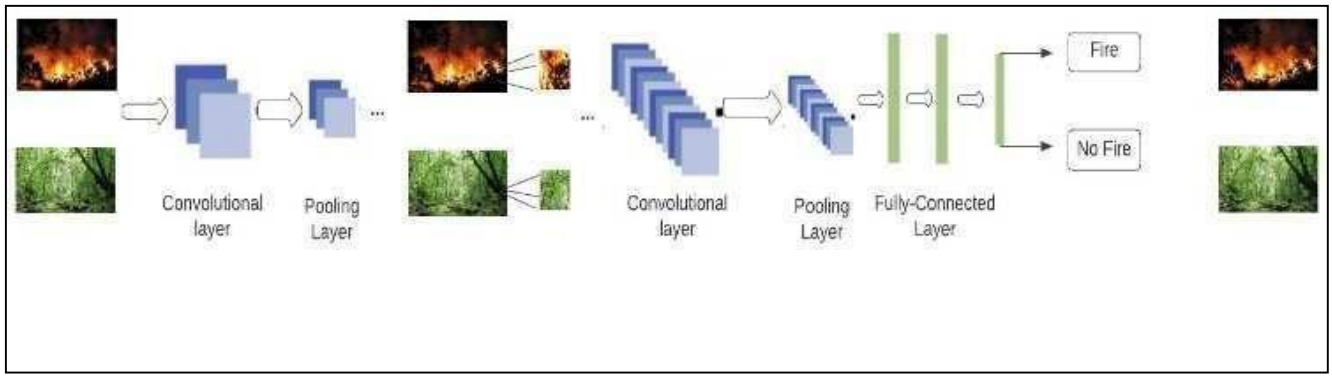
Hardware Components:

- **Gas Sensors:** Identify smoke particles, offering early fire detection.
- **Flame Sensors:** Detect infrared radiation from active flames for accurate fire identification.
- **Vibration Sensors:** Spot illegal tree cutting by sensing ground vibrations. Sensors like **ADXL345 accelerometers** measure intensity and direction.
- **IR Blaster:** Sends signals to activate firefighting tools or alert systems.
- **Camera Module:** Captures real-time images and videos for visual monitoring and detection.
- **GPS Module:** Provides precise location tracking.
- **GSM Module:** Sends alerts and data to forest authorities using mobile networks.
- Microcontrollers (ESP32/Arduino Uno): Central control units that gather sensor data, process it, and manage communication efficiently.

Software Components:

- **Data Acquisition:** Code running on microcontrollers continuously gathers sensor readings.
- **Data Processing:** Algorithms analyze sensor input to detect fires or illegal logging, using thresholds or pattern recognition methods.
- **Communication:** Uses SMS via the GSM module to send alerts to forest officials.
- **Image Processing:** Software analyzes captured images to detect smoke, fire, or logging activity.

- **User Interface:** A dashboard displays sensor data and alerts in real-time, helping authorities act quickly.[1]



1. Input image 2.Feature Extraction and classification 3. Output detection result Fig.7.

Proposed Architecture

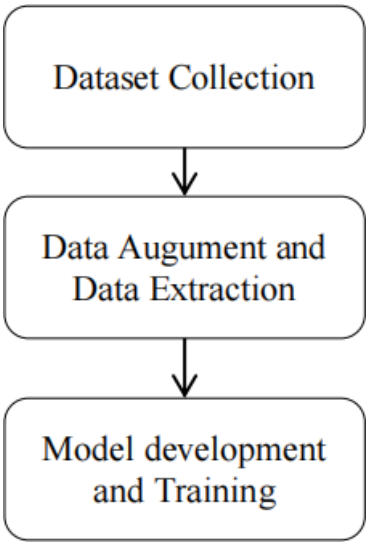


Fig.8. Modules

A. Dataset Overview

The project uses a set of images showing forest areas with and without fire. These images are processed through a deep learning model using layers like Convolutional, Global Average Pooling, Dense, and Dropout. To help the model learn better, the images are slightly modified (rescaled and augmented) before training. The model's final layer tells whether fire is present in the image or not.

Main Steps in the Model:

- Collecting the dataset
- Enhancing and extracting features from images
- Developing and training the model

B. Model Development and Training

A Convolutional Neural Network (CNN) is used for image classification. The image dataset is divided into two sets—training (for learning) and testing (for checking accuracy). The model includes several layers and uses ReLU and Softmax functions to make predictions.

It uses:

- Categorical crossentropy as the loss function (to improve accuracy)

Key Steps in the Process:

1. Load and split the image dataset.
2. Create generators for training and testing data.
3. Build the model using layers like Conv2D, Pooling, Dense, and Dropout.
4. Use InceptionV3 as the base model.
5. Train the model and track accuracy and loss.
6. Test the model using random images to see if correctly detects fire.

Model Parameters

Parameter	Value
Batch Size	14
Dropout	0.2
Activation Function	Softmax
Optimizer	RMSprop
Loss Function	Categorical CE
Epochs	10

The model was trained on a Kaggle dataset of 1900 images (950 fire, 950 non-fire), sized 250x250 pixels. The dataset was carefully prepared by removing irrelevant parts like people or equipment to ensure accuracy[4]. The Fig.5 explains the step-by-step process followed to develop a forest fire detection system using Convolutional Neural Networks (CNN)

1. Data Collection and Preparation

- A diverse image dataset was created, containing pictures of forest areas with fire (positive) and without fire (negative) to ensure balance.
- All images were resized to the same resolution and their pixel values were standardized for better processing.
- Data augmentation techniques such as random flips and rotations were used to increase the variety and help prevent the model from overfitting.
- Images were manually labeled as ―fire‖ or ―non-fire‖ to ensure accurate classification during training.

2. Dataset Splitting

The dataset was divided into three parts:

- 70% for training
- 15% for validation
- 15% for testing

This helped in building, tuning, and evaluating the model properly.

3. CNN Model Design

The CNN model included:

- Convolutional layers to extract important features from images
- Pooling layers to reduce data size and complexity
- Dropout layers to avoid overfitting

- Fully connected layers to make predictions

4. Training the Model

- **Stochastic Gradient Descent (SGD)** was used to optimize the learning process.
- A proper learning rate was selected to train the model efficiently.
- The model learned through back propagation, which adjusted weights based on errors using thecategorical cross-entropy loss function.

5. Hyperparameter Tuning

Key settings like batch size, number of layers, and learning rate were adjusted using the validation set to improve model performance and accuracy.

6. Model Evaluation

The model's accuracy and reliability were measured using several metrics:

- **Accuracy** – Overall correctness
- **Precision** – Correctly predicted fires out of all predicted fires
- **Recall** – Detected actual fires correctly
- **F1 Score** – Balance between precision and recall
- **AUC-ROC Curve** – Model's ability to distinguish between fire and non-fire images

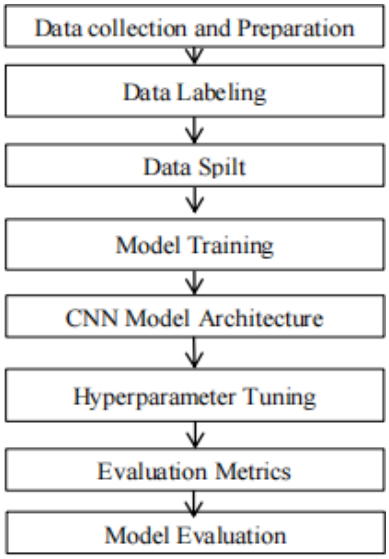


Fig. 9. Proposed Research Methodology for Forest Fire Detection with IoT Devices

1. Research Philosophy

This study follows the Pragmatism Philosophy, which focuses on real-world experiences and practical outcomes. It helps gather useful knowledge based on human interaction with AI tools in forest monitoring systems. This approach supports data collection that reflects actual use and consequences of AI technologies.

2. Research Design

A descriptive research design is used to clearly explain how AI tools are improving forest monitoring accuracy. It also helps highlight the types of tools and technologies
used in this field.

3. Research Approach

The study uses an inductive approach, which means it builds knowledge by observing specific cases and drawing general conclusions. This helps develop theories about how AI is being applied in forest monitoring.

Data Collection and Analysis

1. Data Collection Methods

- Primary Data: Collected through interviews with three forest professionals in India. Their opinions and real-life experiences with AI tools were gathered to provide direct insights.
- Secondary Data: Sourced from platforms like Google Scholar, research articles, and websites to explore a broader range of information.

2. Data Analysis

- The collected data was organized and analyzed using thematic analysis, a method that helps find patterns and important insights in both new (primary) and existing (secondary) information. This combined approach provides a clear and balanced understanding of how AI is used in forest monitoring, drawing on expert views as well as published research.

Conclusion

This study shows a new way to detect forest fires and monitor the environment by combining sensors with smart computer programs called artificial intelligence (AI). Using devices like Arduino and ESP32 with different sensors, along with AI that looks at pictures, the system can spot fires, ground changes, and forest health problems in real time. It also uses GPS and GSM technology to send quick alerts with exact locations so help can arrive fast.Tests show the system works well and can reliably find fires, even with challenges like bad image quality or changing weather. This smart system helps protect forests better and offers a promising way to manage and prevent wildfires in the future. Overall, it's an important step toward keeping forests safe using smart and automatic tools.

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