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AI Based Rockfall Prediction and Alert System for Open-Pit Mines

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Abstract - *This project presents the design and implementation of an AI-based rockfall prediction and alert system for open-pit mines using Drone technology. The system uses a Drone equipped with environmental sensors such as temperature, moisture, vibration, and pressure sensors to collect real-time environmental data from mining areas. The collected data is transmitted wirelessly to a monitoring system using an ESP32 microcontroller.*

The system continuously monitors environmental conditions and analyzes sensor data to identify abnormal changes that may indicate slope instability or potential rockfall events. Parameters such as sudden increases in vibration, excessive moisture levels, and abnormal pressure variations are used as indicators of possible rock movement.

When the system detects unsafe conditions beyond predefined threshold values, an automated alert mechanism is activated. The alert system includes buzzer alarms and warning notifications to inform workers and supervisors about potential hazards.

This solution provides a real-time monitoring and early warning system that helps improve worker safety and reduce accidents in open-pit mining environments. The proposed system offers a cost-effective and reliable approach for monitoring hazardous mining zones using sensor technology and automated alert mechanisms.

1. INTRODUCTION

This project demonstrates an **AI-based rockfall prediction and alert system**, a Drone-assisted and remotely controlled monitoring platform equipped with an ESP32 communication module for real-time data transmission. Because the Drone is designed for exploration in hazardous mining environments and incorporates sensors such as temperature, moisture, vibration, and pressure, it is ideal for applications such as open pit mine safety, industrial inspections, and disaster prevention.

Because of its aerial mobility, the Drone outperforms traditional fixed monitoring systems in terms of coverage and efficiency across uneven and inaccessible mining surfaces. The ESP32 module ensures seamless wireless communication, allowing operators to remotely monitor conditions in real time. Moreover, the integrated environmental sensors provide valuable data that supports the early detection of dangerous situations such as slope instability, excessive vibration lead to rockfall.

This system enables better decision-making, reduces human exposure to risky circumstances, and improves overall safety. Its compact Drone design, wireless connectivity, and sensor integration make it a versatile tool for a wide range of industrial and research applications. Because it is designed to be used in hazardous and inaccessible mining zones, the AI-based rockfall prediction system is a valuable solution for companies and research fields focused on occupational safety and risk management. By monitoring slope conditions and detecting early warning signs, it reduces the risks to human inspectors and workers in mining operations.

In disaster response, the Drone may explore locations where traditional monitoring systems face difficulties, including collapsed mine sections, unstable slopes, or areas exposed to extreme environmental conditions. In remote or challenging mining locations, such as deep open pits or mountainous regions, it can also be utilized for environmental monitoring to investigate temperature, humidity, and vibration levels. The planned integration of a **rover system** will further enhance ground-level monitoring, providing a hybrid aerial-terrestrial solution for comprehensive hazard detection.

The system is also ideal for military surveillance, geological exploration, and search-and-rescue operations where real-time data collection and monitoring are crucial due to its compact size and adaptability. Furthermore, the modular architecture makes upgrades simple and adaptable to different missions and future improvements. Its ability to process data autonomously can be further enhanced by integrating artificial intelligence and machine learning algorithms, enabling it to recognize danger patterns, detect anomalies, and choose the best course of action in unfamiliar situations.

In addition to being helpful for mining safety applications, the real-time data collection feature can be used in agriculture to track soil moisture, air quality, and environmental stability. When fitted with waterproofing and ruggedization improvements, its adaptability across many terrains makes it appropriate for geological surveys and even marine research. The ESP32 module's low power consumption guarantees extended operation in remote areas, and with integrations of solar or other renewable energy sources, it may be able to operate for extended periods without direct human assistance.

2. PROBLEM STATEMENTS

A) Unstable Geological Conditions : Open pit mines are characterized by steep slopes and exposed rock surfaces that are highly vulnerable to instability. Continuous excavation, blasting, and drilling weaken the geological structure, creating cracks and fractures that can lead to sudden rockfalls. These unstable geological conditions are difficult to monitor using traditional methods, as manual inspections cannot cover large areas effectively and often miss early warning signs. Without a predictive system, workers and equipment remain at risk from unexpected slope collapses.

B) Environmental Factors : Environmental conditions such as temperature fluctuations, moisture levels, and pressure changes significantly influence slope stability. Heavy rainfall or groundwater seepage reduces rock cohesion, while extreme heat or cold causes expansion and contraction of rock surfaces, leading to cracks. Pressure variations within the rock mass further contribute to instability. Conventional monitoring systems fail to capture these dynamic environmental changes in real time, leaving mines vulnerable to sudden hazards. A system capable of continuously tracking these environmental parameters is essential for accurate prediction of rockfall events.

C) Human Safety Risks : Mining workers are frequently exposed to hazardous conditions during inspections and operations. Rockfalls can cause severe injuries, fatalities, and destruction of expensive machinery. Manual monitoring requires workers to enter dangerous zones, increasing the likelihood of accidents. In addition, the unpredictable nature of rockfalls makes it difficult to ensure timely evacuation. A proactive monitoring system is needed to reduce human exposure, safeguard workers, and enhance workplace safety in mining environments.

D) Lack of Real-Time Prediction : Most existing monitoring systems focus on post-event analysis, detecting rockfalls only after they occur. This reactive approach does not provide enough time for preventive measures or evacuation. The absence of real-time prediction and automated alerts leaves mining operations vulnerable to sudden disasters, causing both safety risks and operational delays. A predictive system that uses AI to analyze sensor data and provide early warnings is crucial to shift from reactive monitoring to proactive hazard prevention.

3. PROPOSED SOLUTION

A) Drone-Based Data Collection : The system begins with a Drone equipped with multiple sensors — temperature, moisture, vibration, and pressure — that can land in mining areas and collect environmental data directly from slopes and surrounding terrain. Unlike fixed monitoring devices, the Drone provides mobility and flexibility, allowing it to cover large zones, reach inaccessible slopes, and dynamically reposition itself to gather accurate readings. This aerial mobility ensures comprehensive monitoring of unstable geological conditions and reduces the need for human presence in hazardous zones.

B) Wireless Data Transmission : The collected sensor data is transmitted wirelessly to a central server using the **ESP32 microcontroller**. The ESP32 provides reliable IoT connectivity, enabling real-time communication even in remote mining locations. This ensures that data is continuously available for analysis without requiring manual intervention. The wireless transmission also reduces delays, allowing faster response times in case of detected hazards. Additionally, cloud integration allows supervisors to access data remotely, making the system scalable across multiple mining sites.

C) AI-Powered Prediction : Artificial Intelligence algorithms form the core of the system. The server processes incoming sensor data and compares it with historical datasets to identify anomalies. Machine learning models detect patterns such as rising moisture levels, abnormal vibrations, or pressure changes that indicate slope instability. By analyzing these parameters, the AI system predicts the likelihood of rockfall events before they occur. This predictive capability shifts mine safety from reactive monitoring to proactive hazard prevention, ensuring timely evacuation and preventive measures.

D) Real-Time Alert Mechanism : If the AI system identifies a high probability of rockfall, an alert mechanism is immediately activated. This includes buzzer alarms, visual indicators, and notifications sent to supervisors and workers. The alerts provide early warning, allowing timely evacuation and preventive measures. By integrating both local alarms and remote notifications, the system ensures that workers on- site and management teams are simultaneously informed, minimizing risks to human safety and reducing equipment damage.

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4. TECHNICAL DESIGN

4.1) Hardware components:

A) ESP32 Microcontroller : The **ESP32 microcontroller** functions as the central communication and processing unit of the AI-based rockfall prediction system, coordinating the flow of environmental data. To monitor slope stability, it receives inputs from sensors such as temperature, moisture, vibration, and pressure, processes these signals, and transmits them wirelessly to the server for advanced AI analysis. The system can detect anomalies, predict rockfall risks, and trigger alerts because the ESP32 manages the timing and coordination needed for continuous data acquisition and communication. Because of its programmability, built-in Wi-Fi and Bluetooth, and adaptability, it is crucial for integrating multiple sensors, ensuring reliable IoT connectivity, and reacting to different mining conditions in real time.

Fig-4.1.1: ESP32 Microcontroller

B) Environmental Sensors : The system integrates multiple environmental sensors to continuously monitor slope conditions and detect early warning signs of instability. Each sensor plays a crucial role in capturing specific parameters that influence rockfall risks:

- **Temperature sensor :** Detects heat variations that may cause expansion and contraction of rocks, leading to cracks and weakening of slope structures.

Fig-4.1.2: Temperature Sensor

- **Moisture Sensor:** Measures water seepage or rainfall effects that reduce rock cohesion, making slopes more prone to collapse.

Fig-4.1.3: Soil Moisture sensor

- **Vibration Sensor :** Captures ground vibrations generated by blasting, drilling, or heavy machinery, which accelerate slope weakening and trigger rockfalls.

Fig-4.1.4: Vibration sensor

- **Pressure Sensor :** Monitors atmospheric and slope pressure changes that contribute to instability, providing valuable data for predicting sudden collapses.

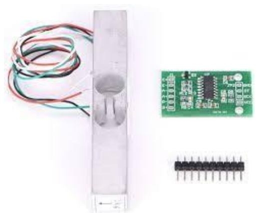

Fig-4.1.5: Pressure sensor

Together, these sensors provide a comprehensive dataset that reflects the dynamic environmental conditions of open pit mines. By transmitting this information to the ESP32 microcontroller, the system ensures that AI algorithms receive accurate, real-time inputs for analysis. This integration of sensors enhances prediction accuracy, reduces human exposure to hazardous zones, and supports proactive safety management in mining operations.

C) Buzzer Module : The **buzzer module** provides immediate audible alerts when the AI system detects rockfall risks. Controlled by the ESP32, it ensures workers are warned instantly, even in noisy mining environments, making it a simple but vital safety feature.

Fig-4.1.6: Buzzer

D) ESP-32 Webcam: For real-time monitoring and surveillance, the ESP32-based webcam which frequently uses the ESP32-CAM module is a small and reasonably priced option. Up to 1600x1200 pixel resolutions are supported by its OV2640 or OV7670 camera sensor. The module's Bluetooth and Wi-Fi connectivity enable remote access and wireless video streaming. It supports JPEG and MJPEG image formats and features a microSD card slot for local storage. GPIO pins for extra sensors and low power consumption

Fig-4.1.7: ESP32 cam

4.2) Components of Drone :

1. **Main Frame Plates:**

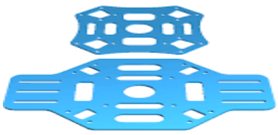

fig-4.2.1: Main Frame Plates

2. Tarot Martin

Fig-4.2.2: Tarot Martin

3. Brushless Motor

fig-4.2.3: Brushless motor

4. Remote

fig-4.2.4: Drone remote

5. Channel Receiver

fig-4.2.5: Channel receiver

6. Electronic Speed Controller

Fig-4.2.6: Electronic speed controller

7. Battery

Fig-4.2.7: Battery

8. KK2 flight controller

Fig-4.2.8: KK2 flight

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4.3) Model Design

A) 3D Parts of model

1. frame arm

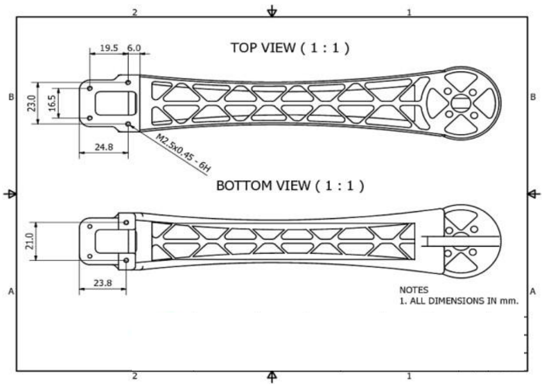


fig-4.3. 1: Frame Arm

B) Overall Design of Model

After assembling all components, the final Drone model is a quadcopter **with** four arms connected to a central body **in an X-shaped structure. Each arm holds** one motor and propeller **for lift and movement. The central frame supports key components like the** flight controller, Battery, and ESCs**. The lightweight and balanced design ensures** stable flight, easy control, and efficient performance**.**

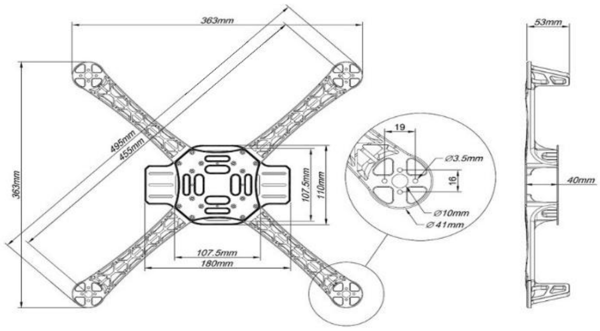


fig-4.3.2: Overall Design of model

C) Block diagram

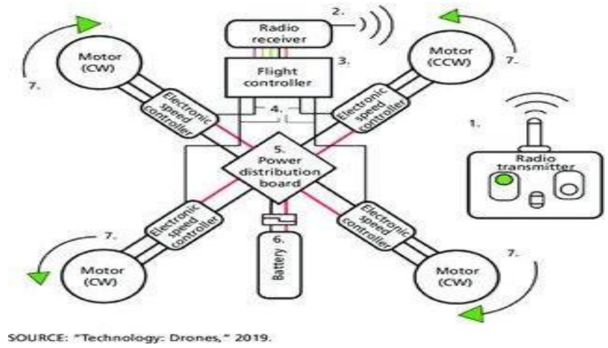


Fig-4.3.3: Block Diagram

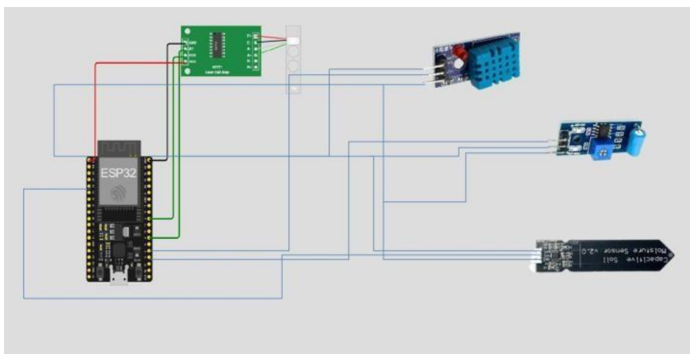
D) Material : For the AI-based rockfall prediction and alert system, **aluminum alloy** is selected for Drone structural parts to ensure stability, durability, and resistance to harsh mining environments while keeping the frame lightweight for efficient flight. Aluminum's strength-to-weight ratio and corrosion resistance make it ideal for reliable monitoring. For demonstration purposes, the prototype is built using **nylon filament**, allowing cost-effective 3D printing and rapid testing before final deployment.

Strong
We 3D Parts Veight Freely

Freely Move

E) Connection Diagram :

The Drone system layout highlights multiple sensors organized around the ESP32 microcontroller, which serves as the central processing unit for environmental monitoring. Each sensor—temperature, moisture, vibration, and pressure—is evenly distributed and connected to ensure balanced data acquisition and reliable performance. This arrangement guarantees uniform signal flow and stable operation, essential for accurate AI-based rockfall prediction in open pit mines.



5. METHODOLOGY

The proposed AI-based rockfall prediction and alert system follows a systematic methodology that includes data collection, data transmission, monitoring, and alert generation. The system uses Drone technology integrated with environmental sensors and a microcontroller to monitor slope conditions in open-pit mining areas.

5.1) Data Collection

The first stage of the system involves collecting environmental data from the mining site. A Drone equipped with sensors such as temperature, moisture, vibration, and pressure sensors is used to gather real-time environmental information. These sensors continuously measure the surrounding conditions that may influence the stability of rock slopes.

The temperature sensor monitors variations in heat that may cause expansion and contraction of rock surfaces. The moisture sensor detects the presence of water or rainfall that can weaken rock cohesion. The vibration sensor measures ground vibrations caused by blasting operations or heavy machinery. The pressure sensor monitors atmospheric pressure changes that may contribute to slope instability.

5.2) Data Transmission

After collecting the sensor data, the information is transmitted wirelessly using the ESP32 microcontroller. The ESP32 acts as the central communication unit of the system and sends the collected data to a monitoring dashboard through wireless connectivity.

This real-time data transmission allows supervisors and operators to monitor environmental conditions continuously without the need for manual inspection in hazardous mining zones.

5.3) Data Monitoring and Analysis

The received sensor data is displayed on a monitoring dashboard where all environmental parameters are continuously observed. The system compares real-time sensor values with predefined threshold limits to identify abnormal conditions.

If the sensor readings exceed safe limits, such as high vibration levels or excessive moisture, the system identifies the situation as a potential rockfall risk.

5.4) Alert Generation

When unsafe environmental conditions are detected, the system automatically activates an alert mechanism. The ESP32 triggers a buzzer alarm and displays warning notifications on the monitoring dashboard.

This early warning alert helps mining workers and supervisors take preventive actions such as evacuating workers from dangerous areas or temporarily stopping mining operations.

5.5) System Operation Flow

The overall system operation follows these steps:

1. Environmental data is collected using sensors mounted on the Drone.
2. Sensor data is transmitted to the monitoring system using ESP32.
3. The monitoring dashboard displays real-time environmental conditions.
4. The system analyzes sensor values and compares them with threshold limits.
5. If abnormal conditions are detected, the alert system is activated.

This methodology ensures continuous monitoring of mining slopes and provides an early warning system to reduce accidents caused by rockfall events.

6. HISTORY

One significant project in the field of AI-based rockfall prediction and alert systems for open-pit mines was conducted by Zhang et al. in 2019. The objective of this research was to develop an automated rockfall detection and early warning system by integrating Drone technology with artificial intelligence.

In this project, unmanned aerial vehicles (UAVs) equipped with high-resolution RGB cameras were used to regularly survey the slopes of open-pit mines. The Drones captured detailed images of mine walls, which were then processed using Convolutional Neural Network (CNN) algorithms. The AI model was trained to detect rock cracks, discontinuities, loose rock blocks, and surface deformation, which are key indicators of potential rockfall events.

The system compared current Drone images with historical slope data to identify changes over time. When the AI detected abnormal crack growth or instability patterns, it classified the area as a high-risk zone. An automatic alert mechanism was then triggered to notify mine safety personnel, enabling timely evacuation and preventive measures such as slope reinforcement.

7. IMPROVEMENT OF QUADRUPED DRONE

The AI-based Rockfall Prediction and Alert System shows significant improvement in monitoring efficiency and safety compared to traditional manual inspection methods. By integrating Drone technology, environmental sensors, and Artificial Intelligence, the system provides continuous monitoring of mining slopes and hazardous areas.

From 2015 to 2025, advancements in Drone technology, sensor accuracy, and AI algorithms have greatly improved the reliability of automated monitoring systems. The integration of real-time data collection and machine learning analysis allows the system to detect early warning signs of rock instability.

Key improvements observed in modern monitoring systems include increased prediction accuracy, faster response time, and better environmental data processing. With AI-assisted analysis, the system can identify abnormal patterns in vibration, moisture, pressure, and temperature levels that may indicate potential rockfall events.

These improvements help mining industries reduce operational risks, protect workers, and enhance overall safety management in open-pit mining environments.

8. ADVANTAGES

The AI-based rockfall prediction system offers several advantages for mining safety and environmental monitoring.

- Early Hazard Detection: The system continuously monitors environmental parameters and detects early signs of rock instability before a rockfall occurs.
- Improved Worker Safety: By using drones and automated monitoring, the need for workers to enter dangerous mining zones is reduced.
- Real-Time Monitoring: Sensor data is transmitted to

the server in real time, allowing supervisors to track slope conditions continuously.

- AI-Based Prediction: Artificial Intelligence algorithms analyze sensor data and detect abnormal patterns that may lead to rockfall events.
- Wide Area Coverage: The drone can easily monitor large and difficult-to-reach areas of open-pit mines where traditional monitoring systems cannot operate efficiently.
- Cost-Effective Monitoring: Compared to large geological monitoring systems, the proposed solution provides a low-cost and scalable safety system for mining industries

9. DISADVANTAGES

- Rising False Alarm Rate: A significant drawback shown in the data is the increase in False Alarms (from 20 to 85). As the sensors become more sensitive, they may struggle to differentiate between actual threats and environmental noise.
- Mechanical Complexity: Quadruped movement requires complex synchronization of motors and joints; if one leg fails, the entire unit often becomes immobilized, unlike hexapods or tracked vehicles.
- High Power Consumption: Maintaining balance and moving four legs simultaneously is energy-intensive, which often leads to shorter Battery life compared to fixed-wing Drones.
- Increasing Costs: The steady climb in "Drone Tech" scores usually correlates with more expensive sensors (LiDAR, thermal) and processors, making the units costly to mass-produce or replace.

10. IMPORTANCE OF AUTOMATED MONITORING IN MINING

Automated monitoring systems are becoming increasingly important in modern mining operations. Open-pit mines often have unstable slopes and hazardous conditions that make manual inspection difficult and dangerous.

The AI-based rockfall prediction system helps solve this problem by providing a smart monitoring solution that can detect early warning signs of slope instability. By using drones and sensors, the system collects environmental data from mining areas without exposing workers to risky conditions.

This technology also helps mining companies improve operational efficiency by providing continuous data analysis and early alerts. Supervisors can take preventive actions before a rockfall occurs, reducing accidents, equipment damage, and operational delays.

In addition, automated monitoring systems support safer and more sustainable mining practices by improving hazard detection and minimizing human risk in dangerous environments.

11. IMPACT OF THE SOLUTION :

- Industrial Safety and the Identification of Hazards: The solution acts as an "early warning system." By utilizing thermal and acoustic sensors, the quadruped can identify overheating components or abnormal vibrations that are invisible to the human eye. This proactive detection prevents catastrophic equipment failure and reduces the need for workers to perform dangerous manual inspections.

- Observation of the Environment: Equipped with LiDAR and 360° cameras, these robots provide a continuous "Digital Twin" of the environment. They can map changes in terrain or structural integrity over time, providing high-resolution data on air quality, radiation levels, or chemical presence without risking a human researcher's health.

- Intelligent Farming: In agriculture, the quadruped's ability to walk over uneven furrows and around crops without compacting the soil is revolutionary. They can perform "precision phenotyping"—checking individual plants for pests or nutrient deficiencies—allowing for targeted treatment that reduces overall chemical use and increases crop yields.

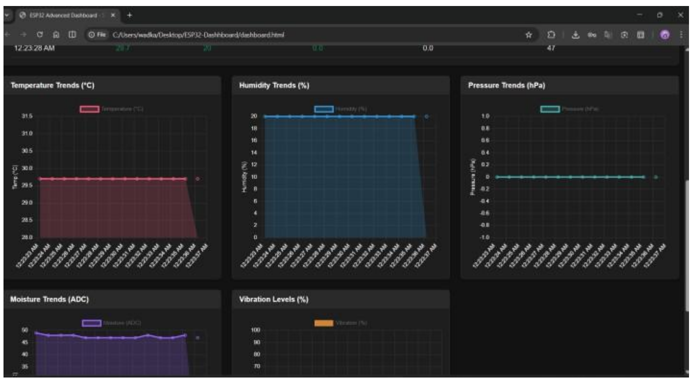
- Military and Monitoring: For defense, these Drones serve as "automated scouts." They can navigate high-risk urban or forest environments to detect IEDs or ambushes. Their impact is a significant increase in "situational awareness," allowing troops to stay behind cover while the robot performs the dangerous task of forward reconnaissance.

- Real-Time Data Collection: The solution bridges the gap between field activity and the office. With 91% AI Efficiency, the robot processes sensor data on-board and streams it instantly to a central dashboard. This allows managers to make data-driven decisions in seconds, such as rerouting a logistics path or shutting down a leaking valve remotely.

- Disaster Response & Rescue :In the wake of earthquakes or collapses, the quadruped is essential for "void exploration." Its small, agile frame can crawl into rubble piles where humans and dogs cannot fit. Integrated sensors detect human body heat and heartbeats, significantly increasing the "Golden Hour" survival rate for victims trapped under debris.

12. RESULT

➢ ESP32 Based Real-Time Multi-Sensor Monitorin Dashboard



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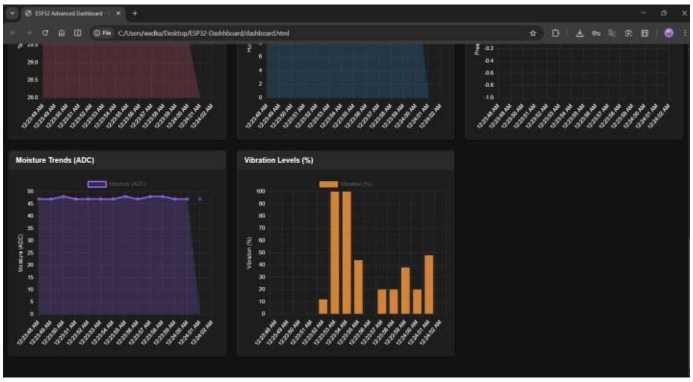
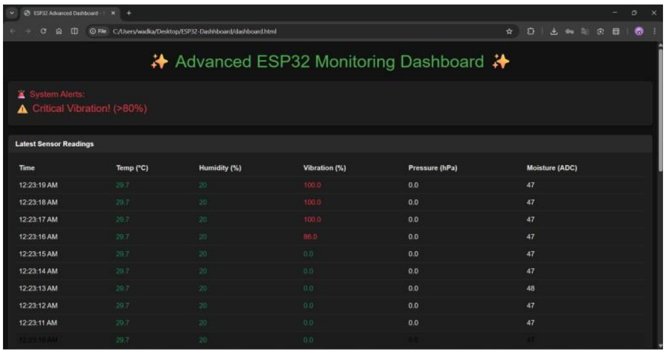
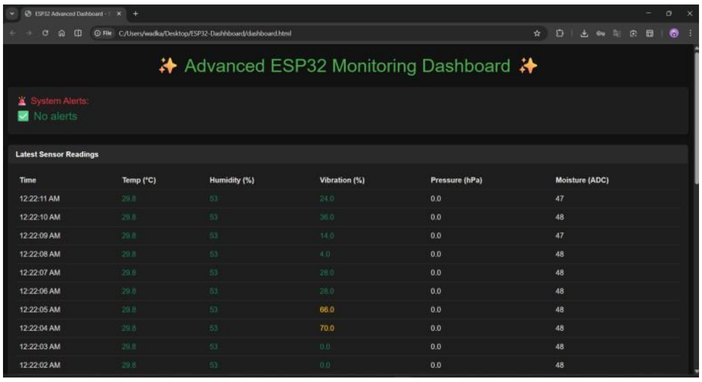
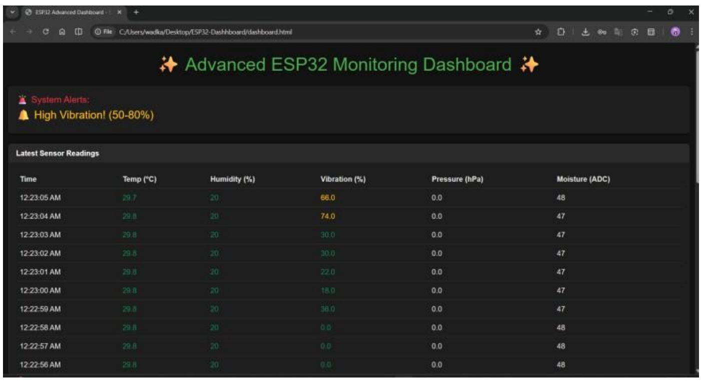




➢ Normal Condition of ESP32 Monitoring Dashboard **Figure :** *Advanced ESP32 Monitoring Dashboard showing normal operating conditions. All sensor readings such as Temperature, Humidity, Pressure, Moisture, and Vibration are within safe limits and no system alerts are generated.*



➢ Alert Condition in ESP32 Monitoring Dashboard
Figure: *Advanced ESP32 Monitoring Dashboard showing an alert condition. The system detects high vibration levels (50–80%), which triggers a warning message in the System Alerts section.*



➢ Critical Alert Condition in ESP32 Monitoring Dashboard
Figure: *Advanced ESP32 Monitoring Dashboard showing a critical alert condition. The system detects very high vibration levels (greater than 80%), which triggers a critical warning in the System Alerts section.*

13. CONCLUSION

In this project, an AI-based rockfall prediction and alert system for open-pit mines has been designed and developed to improve safety in hazardous mining environments. The system uses a drone equipped with environmental sensors such as temperature, moisture, vibration, and pressure sensors to collect real-time data from mining areas.

The collected data is transmitted using the ESP32 microcontroller and continuously monitored through a dashboard system. By analyzing sensor readings and detecting abnormal changes in environmental conditions, the system can identify potential rockfall risks and generate early warning alerts.

The proposed system helps reduce the need for manual inspection in dangerous mining zones and provides a safer and more efficient monitoring solution. The alert mechanism enables workers and supervisors to take preventive actions before a rockfall event occurs, thereby reducing accidents and equipment damage.

Overall, the developed system demonstrates the potential of integrating drone technology, sensor monitoring, and automated alert mechanisms to enhance safety and risk management in open-pit mining operations. Future improvements may include integrating additional sensors, improving prediction accuracy, and expanding the system for large-scale mining environments.

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