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CYBER PHYSICAL SYSTEM FOR ENVIRONMENTAL MONITORING USING IOT AND EDGE COMPUTING

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Abstract
Environmental monitoring has been considered an essential aspect of sustainable development, climate studies, and health protection. Conventional environmental monitoring techniques involve manual measurements or the use of sensors that may not offer real-time data analysis or remote access to the data obtained from the sensors. In order to overcome the disadvantages associated with conventional environmental monitoring techniques, a Cyber-Physical System (CPS) architecture is presented in this paper that integrates Internet of Things sensors with wireless communication networks and edge computing with data analytics on the cloud computing environment. In the CPS architecture presented in this paper, environmental sensors are used to obtain environmental parameters such as temperature, humidity, air quality, and moisture from the physical environment. The sensors used to obtain environmental parameters communicate with the cyber environment to process the data obtained from the sensors. Experimental results obtained with Raspberry pi and IoT clouds confirm the CPS architecture presented in this paper as a reliable environmental monitoring system.
Keywords: Cyber Physical Systems, Internet of Things, smart sensors, Edge computing, Wireless Sensor Network.

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1. Introduction

Environmental monitoring is considered a key area of concern in recent times because of climate change, urban pollution, and the need to ensure a healthy and sustainable approach to managing resources.

Traditional monitoring systems are mostly done through manual data collection and monitoring stations, which are not necessarily scalable in their approach to monitoring and do not allow for real-time monitoring. With advancements in Cyber Physical Systems (CPS) and Internet of Things (IoT) technologies, it is now possible to integrate sensing systems, communication systems, and computing systems in monitoring systems to carry out real-time analysis of data in the environment.

Cyber-Physical Systems embody the concept of monitoring and controlling physical systems through the deployment of computational and communication systems. It integrates sensors, embedded systems, and cloud computing to develop intelligent monitoring and control systems. According to Monedero et al., the deployment of CPS-based environmental monitoring systems has the potential to enhance the accuracy and efficiency of ecological monitoring through the application of sensing systems and machine learning algorithms [1].

Another important aspect of modern environmental monitoring systems is the inclusion of Wireless Sensor Networks (WSNs). WSNs include distributed sensors that can measure environmental parameters and communicate with centralized systems to process the obtained information. It has been established that WSNs can be used to collect considerable amounts of information and conduct real-time environmental assessment [4].

In recent research, the integration of IoT platforms with cloud computing for the implementation of remote environmental monitoring systems has been demonstrated. Ullo and Sinha emphasized the fact that IoT monitoring systems offer scalability, real-time data visualization, and remote accessibility for environmental monitoring systems.

In this context, the paper proposes the architecture of a Cyber-Physical System for environmental monitoring, which includes IoT sensors, wireless communication, and edge and cloud computing. The proposed system aims to provide real-time monitoring of environmental parameters with improved reliability and scalability.

The major contributions of the paper can be listed as follows:

1. Designing a Cyber-Physical System architecture for environmental monitoring.
2. Implementation of an IoT-based sensing platform for environmental data collection.
3. Integration of edge computing and cloud analytics with the real-time monitoring.
4. Performance evaluation of the implemented system.

2. Literature Review

Several studies have been conducted to investigate the potential of Cyber-Physical Systems and IoT technologies to be used in environmental monitoring applications.

Monedero et al. developed a CPS architecture that utilized deep learning algorithms to analyze environmental sound data. The CPS architecture was able to classify ecological patterns with high accuracy, indicating the potential of CPS and artificial intelligence technologies to be used in environmental monitoring applications [1].

Ullo and Sinha have given a detailed review of IoT-based environmental monitoring systems. The authors have stressed the need to integrate the sensor technology, communication networks, and data analysis platforms. This research paper has clearly shown that the IoT technology can improve the efficiency of the environmental monitoring systems [2].

In another instance, Barrenetxea et al. developed a wireless sensor network that was used to conduct environmental monitoring using a system that was referred to as SensorScope. This system was able to demonstrate the ability to conduct environmental monitoring over a wide geographical area using a network of distributed sensors. This makes the system suitable for use in applications that involve climate studies and ecological studies[4].

Oliveira et al. developed a wireless sensor network architecture that was used to conduct environmental monitoring with long-range communication capabilities. The experimental results obtained from the use of the system were able to demonstrate communication over distances that were more than 3 km[8].

In another research by Woo Garcia et al., a solar-powered wireless sensor network for remote environmental monitoring was implemented. This system employed the usage of renewable energy for the sensor nodes to operate continuously without the need for external power supplies [9].

Despite the above advancements, there are a number of challenges that need to be addressed for the implementation of a CPS-based environmental monitoring system. These challenges include energy consumption, scalability of the system, and efficient data processing. Therefore, the aim of this research is to design an integrated CPS system[10]

3. Proposed Architecture

The proposed Cyber-Physical System (CPS) architecture for environmental monitoring integrates Internet of Things (IoT) sensors, wireless communication, edge computing, and cloud analytics to provide real-time environmental data monitoring and analysis. The architecture follows a layered CPS model consisting of four major components: Physical Layer, Edge Processing Layer (Raspberry Pi), Communication Layer, and Cloud/Application Layer.

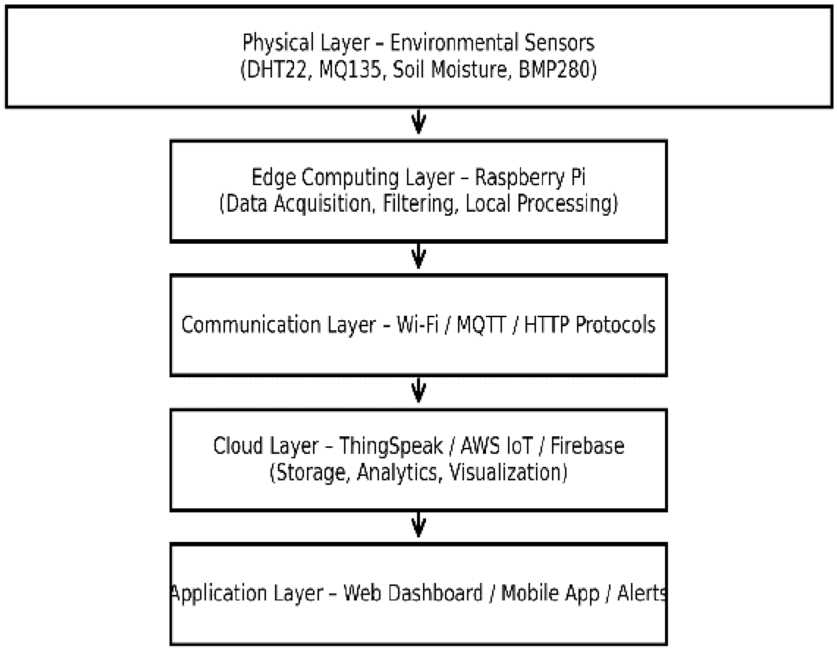

Fig.1 Proposed System Architecture

In the proposed system as shown in figure 1, environmental data are collected through multiple sensors deployed in the monitoring area. These sensors are connected to a **Raspberry Pi single-board computer**, which acts as an edge computing device responsible for local data acquisition, preprocessing, and transmission to the cloud server.

The architecture enables continuous monitoring of environmental parameters while reducing latency through local processing at the edge device.

3.1 Physical Layer (Sensor Layer)

The physical layer represents the interaction between the cyber system and the physical environment. In this layer, multiple environmental sensors are deployed to monitor important environmental parameters.

The sensors continuously collect real-time environmental data and send it to the Raspberry Pi for further processing.

Typical sensors used in the system include:

Sensor	Parameter Measured
DHT22	Temperature and Humidity
MQ135	Air Quality (CO_2, NH_3, Smoke)
Soil Moisture Sensor	Soil moisture level
BMP280	Atmospheric pressure

These sensors are connected to the **GPIO pins of the Raspberry Pi**, which acts as the sensing gateway.

3.2 Edge Processing Layer (Raspberry Pi)

The **Raspberry Pi functions as the edge computing node** in the proposed CPS architecture. It collects raw data from the connected sensors and performs preliminary data processing before sending it to the cloud.

The key functions of the Raspberry Pi include:

- Sensor data acquisition
- Local data filtering and preprocessing
- Edge analytics and anomaly detection
- Data formatting and packaging
- Communication with the cloud server

Edge computing helps reduce network latency and bandwidth usage by performing initial processing close to the data source.

Python-based scripts running on the Raspberry Pi periodically read sensor data and prepare it for transmission using IoT communication protocols.

3.3 Communication Layer

The communication layer is responsible for transmitting environmental data from the Raspberry Pi to the cloud platform.

In the proposed system, **Wi-Fi communication is used for data transmission**. The Raspberry Pi sends sensor data to the cloud server using lightweight IoT communication protocols such as:

- **MQTT (Message Queuing Telemetry Transport)**
- **HTTP REST API**

MQTT is preferred due to its low bandwidth requirement and efficient communication between IoT devices and servers.

The communication layer ensures secure and reliable data transmission between the physical environment and the cyber infrastructure.

3.4 Cloud and Application Layer

The cloud layer is responsible for **data storage, analysis, and visualization**. Once the Raspberry Pi transmits the environmental data, the cloud platform stores and processes the information.

Popular IoT cloud platforms that can be used include:

- ThingSpeak
- AWS IoT Core
- Firebase
- Blynk IoT Platform

The cloud server performs several functions:

- Real-time data storage
- Data analytics and visualization
- Historical data analysis
- Alert generation for abnormal environmental conditions

Users can access environmental monitoring data through **web dashboards or mobile applications**.

Graphical dashboards display parameters such as temperature, humidity, air quality, and soil moisture in real time.

3.5 System Architecture Workflow

The complete system workflow operates as follows:

1. Environmental sensors measure parameters such as temperature, humidity, air quality, and soil moisture.
2. Sensor data are collected by the **Raspberry Pi edge device** through GPIO interfaces.
3. The Raspberry Pi performs initial data preprocessing and formatting.
4. Processed data are transmitted to the cloud platform via Wi-Fi using the MQTT protocol.
5. The cloud platform stores and analyzes the environmental data.
6. Users access the monitoring system through a web dashboard or mobile application for real-time visualization and alerts.

This architecture ensures efficient environmental monitoring with real-time data access, scalability, and improved system reliability**.**

4. System Workflow

The proposed system begins by collecting environmental data through distributed sensors deployed in the monitoring environment. The sensors measure parameters such as temperature, humidity, air quality, and soil moisture. These sensor readings are transmitted to an ESP32 microcontroller, which processes and formats the data. The microcontroller then sends the data to the cloud server using Wi-Fi communication.

The cloud platform stores the incoming data and performs data analysis and visualization. Users can access the monitoring system through a web dashboard that displays environmental parameters in real time. If any environmental parameter exceeds predefined threshold values, the system generates alerts for users.

5. Hardware Implementation

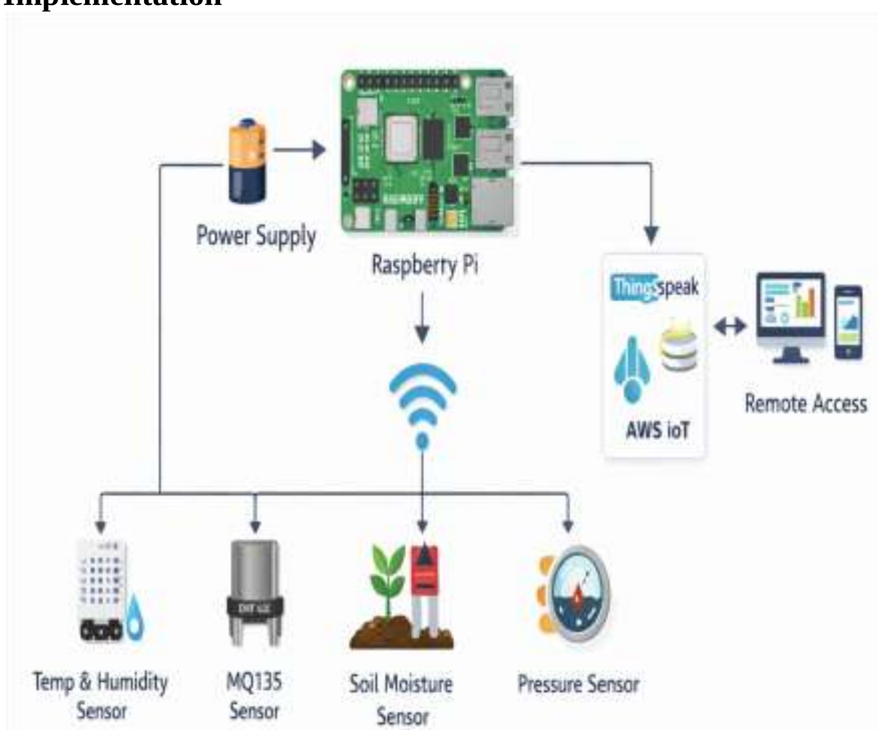

Fig.2 Hardware Implementation using Raspberry pi

The hardware components used in the proposed system are listed below.

Component	**Description**
ESP32 Microcontroller	Data acquisition and communication
DHT22 Sensor	Temperature and humidity measurement
MQ135 Sensor	Air quality monitoring
Soil Moisture Sensor	Soil moisture detection
Power Supply	System power management

The sensors are connected to the Rasberry pi using analog and digital input pins. The microcontroller collects sensor data and transmits it to the cloud server using Wi-Fi communication.

6. Software Implementation

The software architecture consists of:

1. Arduino IDE for microcontroller programming
2. MQTT protocol for data communication
3. Cloud IoT platform for data storage
4. Web dashboard for data visualization

The microcontroller program continuously reads sensor data and sends it to the cloud platform at predefined intervals.

7. Experimental Results

The proposed system was implemented and tested in a controlled environment. Sensor readings were collected continuously and transmitted to the cloud platform for visualization.

The experimental results demonstrated the system's ability to provide real-time environmental monitoring with reliable data transmission. Graphs generated from the cloud platform showed variations in environmental parameters over time.

Performance metrics evaluated include:

5. Sensor accuracy
6. Data transmission delay
7. System reliability
8. Power consumption

The results confirm that the CPS-based monitoring system provides efficient and scalable environmental monitoring.

The proposed Cyber-Physical System for environmental monitoring was implemented using a Raspberry Pi and multiple environmental sensors. The system was tested in a controlled environment to evaluate its performance in terms of sensor accuracy, data transmission delay, and system reliability. Sensor readings were transmitted to the cloud platform and visualized through a web dashboard.

Table 1. Sample Environmental Sensor Readings

Time	Temperature (°C)	Humidity (%)	Air Quality (ppm)	Soil Moisture (%)
10:00 AM	28.5	62	320	45
10:10 AM	29.1	60	330	44
10:20 AM	29.4	59	340	42
10:30 AM	30.2	58	355	41

The results show that the system successfully captures environmental parameters and transmits the data to the cloud platform in real time.

Table 2. Sensor Accuracy Evaluation

Sensor	Measured Parameter	Measured Value	Reference Value	Error (%)
DHT22	Temperature	29.4 °C	29.0 °C	1.37
DHT22	Humidity	60 %	61 %	1.63
MQ135	Air Quality	340 ppm	345 ppm	1.44
Soil Moisture Sensor	Soil Moisture	42 %	43 %	2.32

The experimental evaluation shows that the sensors provide high measurement accuracy with less than 3% error**.**

Table 3. System Performance Evaluation

Performance Metric	Observed Value
Average Data Transmission Delay	1.8 seconds
Data Packet Loss	1.2 %
System Uptime	98.6 %
Power Consumption	4.5 W
Sensor Sampling Interval	10 seconds

The results indicate that the system provides reliable environmental monitoring with minimal delay and stable data transmission**.**

Table 4. Comparison with Existing Environmental Monitoring Systems

Method	Technology	Parameters Monitored	Real-Time Monitoring	Edge Computing
WSN-Based System	Wireless Sensor Network	Temperature, Humidity	Yes	No
IoT Monitoring System	IoT Sensors	Multiple Environmental Parameters	Yes	Limited
Cloud-Based Monitoring	Cloud Computing	Environmental Data	Yes	No
Proposed CPS System	IoT + Edge + Cloud	Temperature, Humidity, Air Quality, Soil Moisture	Yes	Yes

The proposed CPS system demonstrates better scalability and real-time monitoring capability compared to traditional monitoring systems.

Applications

The proposed CPS environmental monitoring system can be applied in several domains:

1. Smart agriculture
2. Air pollution monitoring
3. Industrial environmental monitoring
4. Forest fire detection
5. Smart city infrastructure

Conclusion

This paper proposed a design and implementation approach for a Cyber Physical System in Environmental Monitoring using IoT Sensors and Cloud Computing Platforms. An experiment was conducted to show the effectiveness of the proposed system in collecting environmental data and presenting real-time visualization using cloud computing platforms. Future work will be done in terms of incorporating machine learning techniques in predictive analytics for environmental monitoring and energy efficiency in sensor networks.

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