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CYBER-PHYSICAL SYSTEM FOR ENVIRONMENTAL MONITORING

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Abstract: Cyber-Physical System for Environmental Monitoring addresses the growing challenges posed by rapid environmental pollution, urbanisation, and industrialisation by providing an intelligent and automated monitoring solution. Traditional environmental data collection methods are slow, geographically limited, and lack real-time analytical capabilities. This project presents the design and implementation of an IoT-integrated Cyber-Physical System (CPS) that enables continuous, real-time environmental monitoring and analysis.

The system uses a Raspberry Pi 4 as the central processing unit, interfaced with low-cost sensors including the DHT11 for temperature and humidity, MQ135 for air quality, BMP180 for atmospheric pressure, and an LDR for light intensity measurement. These sensors collect real-time environmental data that are processed locally and transmitted wirelessly via the Raspberry Pi's built-in Wi-Fi to the ThingSpeak cloud platform using HTTP/MQTT protocols. The cloud layer supports data storage, visualization, and remote analysis through interactive dashboards, enabling timely decision-making.

The integrated CPS architecture successfully combines sensing, computation, and communication, while automated alerts are triggered when environmental parameters exceed predefined thresholds, enabling proactive responses to hazardous conditions. The system ensures accuracy, scalability, low power consumption, and cost-effectiveness, making it suitable for deployment in smart cities, industrial zones, and agricultural environments.

Moreover, this project establishes a foundation for future advancements such as AI-driven predictive analytics and edge computing to support autonomous environmental control. Overall, the developed system contributes to sustainable environmental management and aligns with UN Sustainable Development Goal 13 (Climate Action) by promoting intelligent, data-driven monitoring for a safer and cleaner environment.

I. INTRODUCTION

The increasing challenges posed by environmental degradation, air pollution, and climate change have created a strong demand for intelligent systems capable of efficiently monitoring and managing natural resources. Traditional environmental monitoring approaches rely heavily on manual data collection and laboratory analysis, which are time-consuming, resource-intensive, and limited in spatial coverage. Recent advancements in the Internet of Things (IoT), embedded systems, and cloud computing have accelerated the development of smart and autonomous Cyber-Physical Systems (CPS) that effectively bridge the gap between physical environmental processes and computational intelligence. A Cyber-Physical System integrates physical components such as sensors and actuators with cyber components involving computation, networking, and automated decision-making. In the context of environmental monitoring, CPS enables continuous data acquisition, real-time processing of sensor information, and intelligent responses based on analytical models. The convergence of IoT and CPS technologies supports pervasive sensing, actionable insights, and predictive environmental management.

This project focuses on designing and implementing a CPS-based environmental monitoring system that measures real-time temperature, humidity, air quality, and atmospheric pressure through low-cost sensors connected to a Raspberry Pi 4. The collected data is transmitted to the ThingSpeak cloud platform using the device's built-in Wi-Fi module for storage, visualization, and analysis. The system offers a scalable, low-power, and user-friendly solution for tracking environmental variations, generating alerts for pollution thresholds, and supporting data-driven decision-making.

The proposed system provides real-time visualization, cloud-based analytics, and remote accessibility, making it a valuable tool for smart city applications, industrial pollution management, and climate research initiatives.

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II. LITERATURE SURVEY

Ref. No.	Authors / Year	Title / Source	Methodology / Approach	Key Findings / Contributions	Limitations / Research Gap
[1]	G. Mois et al., 2016	A Cyber-Physical System for Environmental Monitoring, IEEE TIM	WSN integrated CPS for air-quality tracking.	Energy-efficient CPS with real-time monitoring and fault tolerance.	Limited scalability and cloud integration.
[2]	M. A. Kumar & K. Kumar, 2017	Adaptive CPS for Monitoring Environmental Status, IJIRSET	Adaptive sensor feedback via Arduino setup.	Demonstrated low-cost adaptive CPS for environmental analysis.	Lacked IoT cloud connectivity and analytics.
[3]	P. Padher & V. M. Rohokale, 2018	CPS for Environmental Monitoring, IJSNDC	IoT-enabled sensing and CPS-based data control.	Enhanced responsiveness via cyber-physical coordination.	Energy optimization not addressed.
[4]	Z. Xu et al., 2022	Robust Simulation of CPS for Environmental Monitoring, Applied Sciences	CPS simulation for construction-site environments.	Achieved robustness and fault resilience in CPS modeling.	Implementation limited to simulation study.
[5]	A. D. Deshmukh, 2016	Low-Cost Environment Monitoring Using Raspberry Pi and Arduino, IJARCCE	ZigBee-based hybrid IoT network with Arduino & Pi.	Demonstrated hybrid IoT system for low-cost monitoring.	Power management and scalability gaps.
[6]	G. Jadhav et al., 2016	Environment Monitoring System Using Raspberry Pi, IRJET	IoT with DHT11 + gas sensors; ThingSpeak cloud.	Enabled live data visualization on ThingSpeak.	Few parameters monitored; lacks analytics.
[7]	Y. A. T. Acquaah & R. Kaushik, 2023	Normal-Only Anomaly Detection in CPS Sensors, IEEE Access	ML-based anomaly detection in CPS sensor data.	Improved reliability and early-fault detection.	Focus only on anomaly detection.
[8]	Í. Monedero et al., 2021	CPS for Environmental Monitoring Based on Deep Learning, Sensors	CNN-based pattern recognition on IoT datasets.	Achieved high prediction accuracy for pollution levels.	Computationally intensive.
[9]	S. R. Laha et al., 2022	Advancement of Environmental Monitoring Using IoT, AIMS Env. Sci.	IoT sensors + cloud analytics review.	Provided architectural insight into IoT-driven monitoring.	No prototype validation.
[10]	S. Barroso et al., 2023	CPS for Smart Building (SmartCampus), JAIHC	CPS optimizing water usage via IoT framework.	Demonstrated smart-campus sustainability use-case.	Focused on water; not general environment.

III. METHODOLOGY

Step 1 Sensor Layer

- Sensors (DHT11, MQ135, BMP180, LDR)
- Real-world measurements — temperature, humidity, gas levels (CO_2/NH_3/CO), atmospheric pressure, and light intensity.
- DHT11, MQ135, BMP180, LDR.
- Sensors wired to appropriate GPIO/ADC pins on Raspberry Pi (or via an ADC/Arduino if required).

Step 2 Data Acquisition & Signal Conditioning

- Convert raw analog signals (e.g., MQ135, LDR) to digital; apply simple conditioning (filtering, scaling, calibration).
- ADC module (MCP3008) or Arduino interface; Python scripts for sampling.
- Clean digital sensor values ready for processing.

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Step 3 Raspberry Pi 4

- Read sensor values, perform preprocessing (debounce, median filter), temporary storage (local CSV/DB), basic analytics (moving average), timestamping.
- Raspberry Pi 4 (built-in Wi-Fi), Python 3.x (libraries: RPi.GPIO, Adafruit_BMP, etc.).
- Pre-processed data packets.

Step 4 Connectivity & Data Transmission

- Communication Module (Wi-Fi / MQTT / HTTP)
- Securely transmit preprocessed sensor data to the cloud. Supports intermittent connectivity
- MQTT or HTTP REST (ThingSpeak uses HTTP/MQTT).
- Use TLS/secure API keys for ThingSpeak.

Step 5 Cloud Storage & Database (ThingSpeak)

- Cloud Ingestion & Storage
- Persist incoming data, provide channel storage, historical logs for analysis.
- ThingSpeak (or alternative: AWS IoT, Azure IoT Hub).
- Time-series data accessible via API.

Step 6 Visualization & Dashboard

- End-User Dashboard / Visualization
- Real-time charts, historical trends, KPIs, and status indicators (gauge, line plots). Provides remote access (web/mobile).
- ThingSpeak built-in custom web dashboard (Flask/Django).
- Operators, researchers, city administrators.

Step 7 Alerting & Notifications

- Alert/Notification Engine
- Threshold-based alerts (SMS/email/push) and anomaly triggers if pollutant levels exceed safe limits.
- ThingSpeak React apps / external services (IFTTT, Twilio) or local scripts on Pi.
- Immediate notifications for hazardous conditions.

Step 8 Actuation & Feedback (Optional)

- Trigger local actuators (fans, purifiers) or control signals to mitigate detected hazards. Can be automatic or operator controlled.
- Relay modules, actuators controlled via Pi GPIO.
- Include failsafe and manual override.

Step 9 Data Analytics & Predictive Modeling (Future/Advanced)

- Analytics / ML / Edge AI
- Offline or edge ML for forecasting (pollution trends), anomaly detection, and decision support.
- Python (scikit-learn, TensorFlow), MATLAB, edge inference on Raspberry Pi or Jetson Nano for heavier models.

Step 10 Maintenance & Scalability

- Device Management & Scalability Layer
- OTA updates, device health monitoring, sensor calibration schedule, power management, and deployment planning for multiple nodes.
- Custom scripts, remote SSH, device registry (cloud)

IV. CONCLUSION

Cyber-Physical Systems (CPS) play a vital role in advancing modern environmental monitoring by tightly integrating sensing, computation, and real-time communication. Through distributed sensor networks, intelligent data processing, and automated decision-making, CPS enables continuous and accurate observation of environmental parameters such as air quality, water quality, temperature, humidity, and pollution levels. This leads to faster detection of hazards, more efficient resource management, and proactive responses to environmental changes. Overall, CPS enhances sustainability efforts by providing reliable, scalable, and adaptive monitoring solutions, making it an essential technology for protecting ecosystems and supporting informed environmental governance.

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