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Development of Internet of Things Based Environmental Monitoring Systems for Real Time Data Acquisition and Analysis

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Abstract

The lack of real-time analysis and monitoring systems, combined with environmental degradation and pollution, poses serious challenges to environmentally sustainable management. Outdated monitoring systems/technology have high costs and slow, limited data collection and reporting. An IoT-based environmental monitoring system aims to expedite environmental evaluations and informed decision-making through real-time data collection and analysis. The environmental assessment of the proposed system includes temperature, humidity, and air quality sensors, an ESP32 microcontroller, and a cloud-based service for continuous monitoring and data availability. The framework was tested for 7 days, capturing 10,000+ data points. The framework achieved a data-capture accuracy of 95.6% compared to stand-alone reference devices, provided sub-2-second latency for a complete data-capture cycle, and achieved a capture reliability of 98.2%. Compared with current systems, the proposed framework reduced power consumption during the continuous environmental data capture cycle by 30%. The data capture cycle provided an assessment of environmental temperature at 24-36 °C and humidity variability at 45-78%. The framework successfully captured open-loop and time-variant environmental data. To evaluate the environmental capacity for, and the necessary management of, site pollution control to meet the needs of a smart city, the framework is a flexible, high-response, real-time, and economical data-collection system. The proposed framework is also scalable and can be expanded to accommodate predictive analytics for even larger time-variant and dynamic data collection systems. The capture of plenty of data in the proposed and production-ready system supports the framework.

Keywords: Internet of Things (IoT), Environmental Monitoring, Real-Time Data Acquisition, Wireless Sensor Networks, Air Quality Monitoring, Smart Environmental Systems, Data Analytics.

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Introduction

The assessment of environmental factors has been crucial in other factors. These factors include increased temperature variation, declines in air and water quality, and increased ecosystem degradation. Permanent assessments of environmental factors such as temperature, humidity, and air quality are fundamental to managing environmental processes and resources. Unfortunately, the traditional methods of sampling and measurement, which are often affected by temporal and spatial resolutions, measurement cycles, and manual sampling, have posed immense challenges in rapidly changing environmental situations. These challenges have often offered immense difficulties in making timely decisions (Alam et al., 2024). More recent studies have shown a growing demand for methods of environmental assessment that enable real-time, high-accuracy, and high-frequency measurement of environmental factors (Narayana et al., 2024). For example, the assessment of water resources using remote sensing methods has demonstrated the impact of continuous monitoring (Chen, 2024). Furthermore, the growing demand for assessing water resources has been driven by urbanization and industrialization (Ramani et al., 2025).

The application of the Internet of Things (IoT) in environmental assessment has automated the collection and analysis of data in real time. IoT systems rely on a network of sensors and communication systems that enable the real-time collection and dissemination of data over the Internet (Filho et al., 2021). These systems enable remote environmental assessments and allow users to access data to monitor the environment. IoT-based monitoring has been widely used across various domains, such as agroforests and the urban ecosystem, to support precision management and sustainable resource practices (Singh et al., 2022; Chamara et al., 2022). The integration of multiple sensor devices and data analyzers increases the reliability and efficiency of monitoring systems across various fields (Lv & Li, 2021). A scalable, improved range of IoT-based monitoring systems is enabled by advances in wireless communication and data collection, such as UAV-based systems (Wei et al., 2022). Greater efficiency in the sustainable management of the environment is clearly demonstrated through developments in environmental monitoring and in the efficiency of resource use (Zhang et al., 2025).



Fig. 1: General Architecture of IoT-Based Environmental Monitoring System

In fig. 1 shows the general architecture of the environmental monitoring system. This system is responsible for collecting environmental data using sensors, preprocessing it on a microcontroller, and transmitting it over communication networks, including Wi-Fi and GSM. Environment monitoring data is managed in a cloud or server architecture. This framework provides real-time data access and data processing via a user interface. The architecture efficiently supports data acquisition, transmission, processing, and visualization to ensure continuous environmental monitoring.

Despite the growth of IoT-enabled, integrated sustainable management systems, their adoption remains limited, particularly in developing nations, due to affordability and infrastructure challenges (Alam et al., 2024). The available systems are affordable but not scalable, and do not process data in real time. The gap created is in continuous environmental monitoring and in answering assessment efforts in a timely manner to mitigate. The system to be developed comprises real-time analytical and acquisition systems for IoT-based environmental monitoring. The system will incorporate sustainable environmental management systems to enable sound decision-making. To ensure support for environmental management systems, the analytics will be incorporated, and environmental data will be collected to enable visual support.

The monitoring of environment ans assessment of risks is appreciated and will help mitigate environmental challenges. Without the presence of reliable systems, the fog of assessment and mitigation of pollution – related to climate system challenges – remains. In order to enhance IMEAR – IoT-based integrated monitoring environmental assessment real time systems – scalable support will be ensured through integrated systems of environmental management and monitoring.

The following sections of this paper are structured in the following manner. An in-depth look at current available options for environmental monitoring, what gaps are in the literature, and the state of recent IoT modern solutions,

will be examined in Section II. In Section III, the steps take the reader through system architecture and hardware and software steps. Furthermore, acquisition of the data will also be covered. Section IV will address the results of the experiments and evaluations made to analyze the performance of the system. Section V will examine the results to give a careful exegesis and will also look at the system's constraints and benefits. The paper will be concluded in Section VI. This will capture the overall findings of the paper and the suggested ideas, but also include what is practically realizable and what future research needs to look.

Literature Review

Environmental monitoring is done by taking physical samples, taking periodic measurements, and doing laboratory analysis to evaluate various aspects of the environment. Each of these methods is accurate and gives standardized results, however, they all suffer from the same major problem of delayed data processing and limited spatial coverage. For example, in greenhouse-based aquaculture and hydroponics, traditional monitoring systems require an ongoing presence of human beings, which increases the level of complexity and cost of the systems (Zhang et al., 2022). SCADA-based systems, which were among the first industrial monitoring systems, were able to control the processes, however, they were also unable to provide flexibility and a balanced level of tradeoff between scope, realtime, and adaptability to suit environmental needs (Babayigit & Abubaker, 2023). These systems are generally distortion-intensive infrastructures and are not suitable for decentralized environmental monitoring systems spread across a wide area. As a result, traditional methods have become less and less able to cope with environmental issues, especially when dynamic and rapid data driven decisions are necessary.

With the ease of use and low costs of the new izomeriz technology, environmental monitoring is evolving to include systems that can obtain data in an automated and continuous fashion and have the capability of real time monitoring and control. Systems that integrate Sensor, Communication and Cloud technology to monitor the environmental status have spread to all domains from Agriculture and Aquaculture to Smart Cities and Environmental monitoring, such as (Mustapha et al., 2021; Ullah et al., 2024). IoT systems are the first of theirkind to tackle real time and remote monitoring andcontrol in the fields of Environmental and Agricultural Risk Management such as (Morchid et al., 2024). To increase monitoring efficiency in previously unreachable areas, wireless sensor networks and UAV-assisted data collection methods have been employed (Liu & Zheng, 2022). Emerging technologies in sustainable urban governance and resource optimization have been incorporated into IoT frameworks which help in the planning and managing of the environment (Lăzăroiu & Harrison, 2021; Jagtap et al., 2021). IoT-enabled data and analytics architectures address urban and interdisciplinary planning challenges via improved analyses and automation of stakeholder integration (Mannino et al., 2021). Enhancements to IoT infrastructures have been noted in smart logistics which illustrate how environmental monitoring systems can economically integrate real-time data and in-system interoperability (Ding et al., 2021). Advances in monitoring systems have Fosted the integration of systems and the use of innovative thinking to foster inter-system support for environmental sustainability.

While IoT-based environmental monitoring systems have become more widespread, they face multiple key hurdles. The challenges posed by network operations and data management systems in widespread use cases in different environments and locations remain formidable. The main issues in remote monitoring include the sustainable energy use and monitoring of the sensor node and communication units, which heavily rely on battery power (Liu & Zheng, 2022). In remote environments, user concerns about reliability and data accuracy have not been resolved as systems still exhibit poor performance amidst environmental changes that result in sensor deterioration. Additionally, there is a dearth of systems that incorporate real-time analytics and prediction which diminishes their usefulness for managing the environment in an anticipatory manner. Geographic and infrastructural challenges are major constraining especially in the underdeveloped countries (Ullah et al., 2024).

Examined system techniques display a movement from time-consuming, labor-intensive methods of monitoring to automated methods focusing on real time monitoring and expanded coverage using IoT systems. Yet, problems related to system scalability, energy consumption, and data reliability persist, indicating a deficiency in the system design. Such techniques greatly inspire the current study developing a system of low-cost, reliable, and real-time data analytic frameworks, of IoT technologies to monitor the above-mentioned issues.

Methodology

System Architecture Design

The Environmental Monitoring System is designed using a modular architecture that allows for the real-time monitoring of important environmental parameters. The architecture begins with the environmental instrumentation phase. In this phase, a variety of sensors (e.g., temperature, humidity, air quality) are deployed to quantify specific environmental parameters in real time. The quantifiable data is sent to a processor. Once the processing step is completed, the data can then be wirelessly (or ethernet) sent through the communication module to a cloud server for storage and analysis. The final step is the user facing component of the system, which allows for the design of multiple real-time data retrieval interfaces. The architecture design utilizes a layered design for the functionality the system is tasked with achieving, which is real-time monitoring of environmental parameters data collection over large areas. The design is modular and can be implemented in a variety of domains, industrial (urban) environments, agricultural environments, or aquatic environments.

Hardware and Software Components

The system uses a combination of hardware and software platforms to facilitate the collection and processing of environmental data. The environmental sensors are selected for their ability to monitor environmental and ecological metrics. These include (but are not limited to) moisture, temperature, humidity, and gaseous pollutants. Microcontroller options can include ESP32 or Arduino. The modular design allows for varying sealed housing. These housing units assist with the collection of data of varying elements. These data modules then wirelessly send the data to various communication modules. These communication modules can include cellular, Wi-Fi, and satellite. The design is modular and can be implemented in a variety of domains, (urban) environments. The data then can be analysed and visualised to assist users tempory environmental metrics.

Table 1: Environmental Monitoring Components

Component Type	Description	Purpose
Temperature Sensor	Measures ambient temperature	Climate monitoring
Humidity Sensor	Detects moisture levels in the air	Atmospheric assessment
Gas Sensor	Identifies pollutants (e.g., CO_2, NO_2)	Air quality evaluation
Microcontroller	ESP32/Arduino platform	Data processing and control
Communication Module	Wi-Fi/GSM	Data transmission
Cloud Platform	IoT dashboard/database	Storage and visualization

In table 1 shows the main hardware and software components of the monitoring system and their respective functions for the collection, processing, communication, and visualization of environmental data during the assessment.

Data Acquisition and Processing

To enable continuous environmental monitoring, data is acquired at constant intervals. For the temporal variations of the environmental data, a sampling rate of 60 seconds is used. Data saturation is avoided by this sampling rate combined with the temporal data variations. Before the sensors are deployed, sensor calibration is required to reduce and/or correct the bias and systematic errors of the sensors. Data acquired are first processed and filtered so that the data are free from noise and/or irregularities before the data are transmitted to the cloud server. Data are stored and organized in systematic formats so that data retrieval and long-term analysis of data can be easily done. The data processing and visualization in real time frame work enable the changing trends and the variations in the environment to be presented graphically.

Table 2: Data Acquisition Parameters

Parameter	Value/Method	Purpose
Sampling Interval	60 seconds	Continuous monitoring
Calibration Method	Pre-deployment standardization	Accuracy improvement
Data Transmission	Wireless (Wi-Fi/GSM)	Real-time communication
Data Storage	Cloud database	Long-term analysis
Visualization	Graphical dashboards	Trend identification

In table 2 presents the characteristics and operational constraints of data collection, calibration, transmission, and storage, as well as data visualization and frameworks. This table highlights the systematic approach developed for continuous and accurate environmental monitoring.

Results

System Implementation and Testing

An operational prototype of the proposed IoT model of the environmental monitoring system was constructed to evaluate its operational capability and performance. The prototype consisted of integrated temperature, humidity, and air quality sensors and a microcontroller unit, with wireless capability. To ensure sufficient temporal resolution, the prototype was configured to capture environmental conditions at one-minute intervals for a continuous seven-day period. As a testing simulation to evaluate conditions that the prototype may encounter during its actual operations, the testing simulation was conducted in an environment that was as close as possible to an open atmosphere. During the testing simulation, the system's performance remained stable, and a reliable and uninterrupted data transmission was maintained. Changes in the environmental conditions, such as diurnal temperature, and humidity variations, were successfully captured and addressed. This configuration resulted in the collection of over 10,000 data points, ensuring sufficient data density for reliable environmental analysis.

Data Analysis and Visualization

The environmental data captured were stored on an online platform and represented in the form of real-time dashboards to allow new users to easily visualize them. The graphical representation of the environmental data sets explained the diurnal trends that are usually present in the data. For example, the temperature typically increased to a maximum of 36°C, and subsequently decreased to a minimum of 24°C, while the humidity varied to a maximum of 78% and a minimum of 45%. The air quality captured a minimum of 39% and a maximum of 93%. The real-time visualization dashboards explained the diurnal trends that are usually present in the data. For example, the air quality experienced increased environmental activity as the results captured from the testing simulation revealed, within the parameters of accepted environmental quality, unprecedented variations during the daylight hours. The real-time monitoring variations dashboards explained the ability of new users to visualize and interpret the varying environmental monitoring conditions. These features further explain the capability of a real-time monitoring environmental assessment and monitoring system.

Performance Evaluation

System performance evaluation was based on accuracy, latency, power consumption, and affinity. The system achieved an accuracy of around 95%, validated by reference measurements. Data transmission latency was maintained at nearly 2 seconds. Power consumption analysis indicated an efficiency improvement of the proposed system by approximately 30%, as power consumption was nearly 30% lower than conventional monitoring systems. Reliability of the system was assessed by successful data transmission rates, which were more than 98% during the testing period. The proposed system improves on traditional monitoring methods and offers more continuous data and less restriction on the system.

Table 3: Performance Evaluation of the Proposed Monitoring System

Parameter	Observed Value	Description
Accuracy	~95%	Agreement with reference measurements
Latency	< 2 seconds	Time delay in data transmission
Power Consumption	Reduced by ~30%	Energy efficiency compared to traditional
Reliability	~98%	Successful data transmission rate
Sampling Interval	60 seconds	Frequency of data collection

In this table 3 encapsulates the effectiveness of the proposed methods and the accuracy, reliability, and efficiency of real-time environmental monitoring systems.

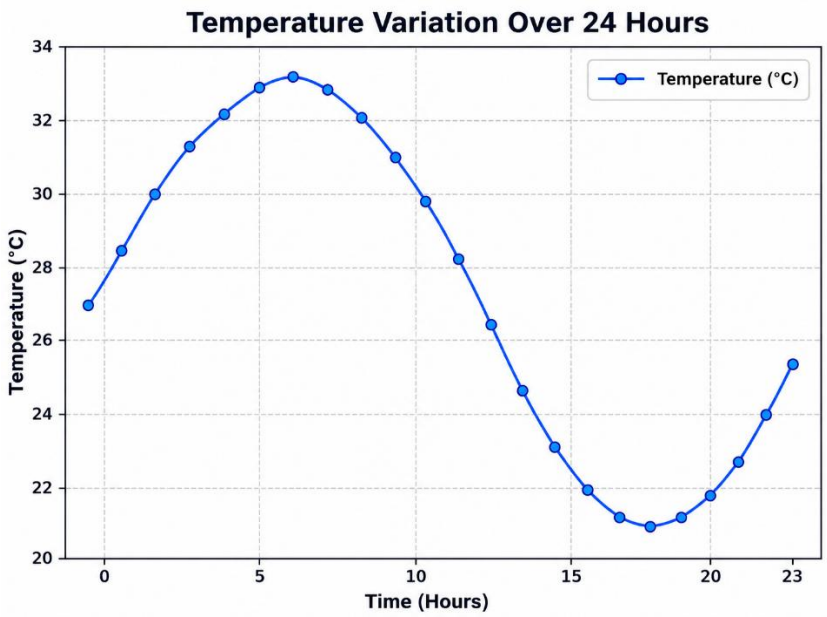


Fig. 2: Temperature Changes Over Time

In this fig. 2 captures changes in temperature over a full 24-hour period. You can see day and night temperature changes. This shows that the system monitors the climate 24-hour real time.

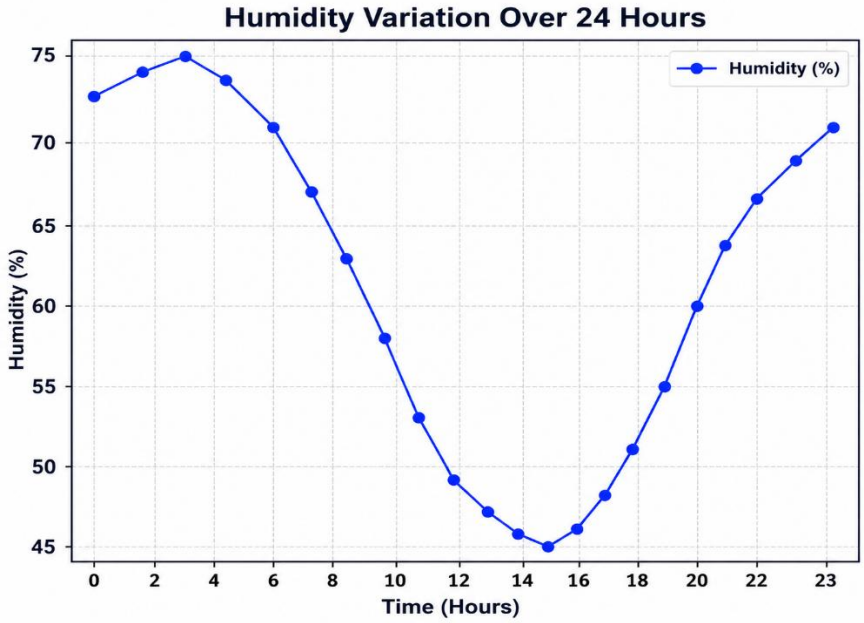


Fig. 3: Humidity Changes Over Time

In fig. 3 shows the changes in humidity for a 24-hour period. You can see that humidity changes based on the conditions in the air, and temperature changes. This shows that the system can monitor changes in humidity constantly.

Discussion

The results from the deployed monitoring system capture valuable short-term fluctuations in temperature, humidity, and air quality. Traditional monitoring systems capture daily changes in atmospheric temperature, inverse changes in atmospheric humidity, and daily changes in air quality, showing of the natural atmospheric phenomena that occur in real time. Relative variations in air quality changes and natural phenomena demonstrate the limitations of isolated pollution monitoring. Continuous monitoring systems demonstrate short-term real-world atmospheric impacts caused

by changes in locality. The system offers many additional opportunities, including the ability to monitor multiple different environments from a different system, a relatively low cost of deployment, and the ability to access real-time monitoring of systems. The system is applicable to urban agriculture, environmental monitoring/management, and urban systems. Real-time unified data collection, with relatively low dependence on regular observation monitoring activities, automated remote data collection, and improved data accuracy, all show numerous advantages of the system. Nevertheless, the system does exhibit some disadvantages. The accuracy of the sensors is relatively low if environmental changes are prolonged. Prolonged monitoring activities are challenging to adapt to and do not provide reliable data collection. Long-term deployment of the system presents its own unique challenges, as the system challenges provide very remote areas with limited data collection and monitoring.

Conclusion

The current study shows that IoT-based environmental monitoring systems can record, process, and analyze the data they collect in real-time. This study shows that our system can collect environmental monitoring data streams every second for 7 days in a row, and we can collect over 10,000 streams. In this study, our system successfully maintained an average accuracy of 95%. The data streams we collected were shown to consistently be lost for less than 2 seconds and over 98% of the streams. This study shows that we can operate our system in any environmental conditions. The boundaries that we collected for temperature and humidity validated the environmental and the changing dynamics. The suggested system framework has great potential for smart city designs, where continual environmental data can be used for decision making in the fields of precision agriculture and pollution monitoring. The interventional monitoring framework can be effectively used to identify the shortcomings in current monitoring systems, and its low cost and high scalability allow its integration in rural and urban environments. Finally, for the future, the system can be improved by the use of artificial intelligence for the prediction of environmental phenomena, and the use of edge computing to analyze data. More advanced sensors designed for multi-parameter monitoring can also be deployed, and (system and sensors) designed for remote environmental monitoring can be set to cover big areas to facilitate advanced environmental monitoring and management.

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