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Original Article

An IoT-Based Real-Time Weather Observatory System

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Abstract *- This study presents an effective system for monitoring and transmitting real-time weather parameter data. The aim is to transform the conventional methods of gathering weather information, enhancing its accuracy, reliability, and accessibility. The developed System involves the use of an ESP32 microcontroller and various sensors for real time acquisition of weather parameters. The weather data is transmitted to the ThingSpeak platform for real time visualization. A prototype was developed to ascertain the effectiveness of the System. The results show that the developed System is capable of transmitting this information in real time. The accuracy of the System was also determined by comparing the acquired weather data against manually measured data. The System holds a significant potential impact across various sectors, including agriculture, disaster management, and research. Its continuous improvement and integration of emerging technologies ensure ongoing relevance and effectiveness in the dynamic field of weather monitoring.*

Keywords *- IoT, Monitoring System, Real-Time, Sensor, Weather Observatory.*

1. Introduction

The systematic and scientific observation of weather serves as the bedrock and foundation of meteorology, providing invaluable and indispensable insights into the behaviour and patterns of the atmosphere. These observations entail the rigorous and systematic recording and analysis of various atmospheric elements, oceanic conditions, and terrestrial parameters using advanced and specialized instruments and equipment.

Temperature, air pressure, wind direction and speed, precipitation, cloud cover, and other factors are among the various weather elements that are meticulously and continuously monitored to provide a wealth of information to scientists, meteorologists, and weather enthusiasts for the formulation of accurate forecasts and climatological models [1].

The essential nature and significance of weather observations extend to a diverse and varied array of stakeholders who rely heavily on this data for various purposes [2]. For instance, construction workers utilize weather forecasts to plan project timelines and ensure the safety of their workforce and materials. Farmers make informed decisions based on weather predictions, determining when to sow, irrigate, fertilize, and harvest crops to optimize yields. Weather observations play a crucial and pivotal role in safeguarding public health, as healthcare systems use this data to anticipate and manage disease outbreaks related to weather patterns.

Weather observation systems have witnessed substantial advancements in recent years. Traditionally, weather data was collected through manual methods and basic instruments [1]. However, with the advent of Automatic Weather Stations (AWS) and remote sensing technologies, real-time data collection has become more efficient and reliable. AWS, equipped with various sensors for measuring parameters like humidity, temperature, wind speed, pressure, and wind direction, has become the backbone of modern weather observation systems.

The major problem this study aims to address is the manual methods of weather data collection, which is time consuming, stress inducing, and error-prone. Weather observation systems are commonly found around us in places like our meteorological centres, schools and agricultural environment. However, they still implement the traditional method of weather data collection/observation where equipment like a thermometer, barometer, rain gauge, etc, are mounted at a permanent location and thus require an individual to make frequent, consistent trips to take the readings manually and record [3]. This poses several risks like inaccurate rates as a result of human error, inconsistent readings and damage to records from fire or water. Hence, there is a need for a smart observatory system [4].

This study presents an IoT-based real time weather observatory system. The conceptualization, design, as well as implementation of a Real-Time Weather Observatory System represents an effort to harness the power of technology and scientific expertise to monitor, interpret, and disseminate real-time weather data.

2. Related Works

Several works have been done in the area of IoT based weather monitoring. For instance, [5] proposed a weather management system with two phases aimed at real-time weather monitoring and prediction using advanced predictive models incorporating deep learning techniques, sensors, public transportation data, and data processing capabilities. In Phase I, the System focuses on training and validating Multilayer Perceptron (MLP) and Long Short-Term Memory (LSTM) models using meteorological sensor data such as temperature, humidity, and air pressure. Phase II involves the application of these trained models to forecast meteorological data over time. The System's effectiveness is assessed by comparing its predictions with actual sensor measurements from the Environment Protection Agency (EPA) and Central Weather Bureau (CWB) at the Taichung observation station, demonstrating accurate one-day weather forecasts and reliable weather monitoring capabilities.

Also, [6] developed a mobile app tailored for an Automatic Weather Station (AWS) as part of a live weather monitoring setup. The System gathered data through an AWS weather sensor, which was then archived on a web server. The Android app accessed these data files, presenting users with up-to-the-minute weather information sourced from the web server.

Similarly, [7] recommended an Internet of Things (IoT)--powered weather station as a solution to overcome energy limitations and ensure uninterrupted functionality. The investigation delved into the essential requirements and challenges involved in developing a precision farming weather station at the component level.

The adoption of citizen weather stations for accessing weather information has increased significantly, driven by their cost-effectiveness and provision of real-time data. However, their integration into operational weather prediction systems has been gradual. Ref [4] To tackle this challenge, efforts were made to integrate observations gathered from Netatmo's network of citizen weather stations into the automated public weather forecast production process. This integration was designed to address discrepancies in weather model outputs caused by unaddressed factors such as cold pools, inversions, urban heat islands, and intricate coastlines.

Ref [8] Developed and executed a weather station setup leveraging an Arduino board and various peripherals to capture data on temperature, humidity, wind speed and direction, ozone gas levels, atmospheric pressure, and rainfall. The System utilized a Narrowband Internet of Things network (NB-IoT) for transmitting data to a MySQL database server using the Constrained Application Protocol (CoAP).

Ref [9] Showcased an Internet of Things-enabled Smart Garden equipped with a weather station to monitor plant growth and predict rainfall probabilities. The System incorporated sensors such as the DHT11 Temperature and Humidity Sensor, Soil Moisture Sensor, Barometric Pressure Sensor, and Light Intensity Module Sensor. Its user-friendly design ensures accessibility for various users, including farmers, researchers, and children.

Summarily, the evolution of weather management systems has seen significant advancements over time, with several key works contributing to this progression. In the past, weather monitoring primarily relied on basic sensors and manual data collection methods. However, [5] indicates a notable shift by proposing a weather management system that incorporates advanced predictive models, deep learning techniques, and real-time data from sensors and public transportation sources. This approach represents a leap forward in the accuracy and timeliness of weather predictions. Concurrently, [6] introduces a mobile app tailored for an Automatic Weather Station (AWS), reflecting the growing trend towards mobile technology integration in weather monitoring setups. Furthermore, [7] recognizes the potential of Internet of Things (IoT) technologies in overcoming energy constraints, laying the groundwork for continuous and efficient weather monitoring systems. In the context of citizen weather stations, [4] integrated data from citizen weather stations into automated forecast production processes, aiming to enhance the accuracy of weather models. This integration reflects a broader trend towards leveraging crowdsourced data for improving weather monitoring capabilities. Collectively, these works illustrate the historical context and evolution of weather management systems, from basic sensor setups to sophisticated IoT-enabled solutions, contributing to more accurate and accessible weather monitoring capabilities.

3. Research Methodology

3.1. System Overview

The weather observatory system comprises several key components, each serving a specific function in the collection and transmission of weather parameter data. These components include:

3.1.1. Sensors

These are the front-line data collectors that interact directly with the environment [10]. In order to measure important meteorological parameters, including temperature, humidity, wind direction and speed, air pressure, and precipitation, a variety of sensors have been carefully chosen and integrated.

3.1.2. Data Logger

This component acts as the intermediary between the sensors and the central processing unit. It records and stores the sensor data, ensuring its integrity and reliability during transmission [11]. For the System, the data logger is embedded in the microcontroller forming an integral part of the microcontroller capabilities.

3.1.3. Microcontroller

The microcontroller serves as the brain of the System, facilitating communication with the sensors, data logging, and data transmission. We have chosen ESP8266 for its processing power, Wireless Communication (WIFI) module, and compatibility with our chosen sensors.

3.1.4. Communication Module

To enable real-time data transmission, the System is equipped with Wi-Fi. This ensures the seamless flow of data from the hardware to the cloud storage. The chosen microcontroller comes with an inbuilt Wi-Fi module, thereby ensuring the seamless transmission of sensor data to the cloud for visualization [12].

3.1.5. Power Supply

An integration of solar panels and lithium batteries to ensure uninterrupted operation, especially in remote and off-grid locations.

3.2. System Architecture

The architectural design of the weather observatory system is a critical aspect that underpins its functionality. The System is designed as a distributed network of sensors, data loggers, and a central processing unit. Data collected by sensors are relayed to the data logger, which subsequently communicates with the central processing unit for further processing and transmission. The data flow within the System is carefully structured to optimize real-time monitoring and minimize data latency. For simplicity of maintenance, scalability, and adaptability, the design of the System has been carefully prepared. Figure 1 depicts the system architecture block diagram, and Figure 2 presents the system circuit diagram.

From Figure 1, it can be seen that the temperature sensors, air pressure sensors, humidity sensors, rain sensors, and light visibility sensors take weather parameter readings from the atmosphere. This gathered data is picked by the microcontroller and transferred to the microcontroller (ESP8266) for logging and processing. The gathered data is transferred to the cloud for storage utilizing the microcontroller's Wi-Fi capabilities. The transmitted data is then visualized on the cloud platform where further analytics would be carried out.

The circuit diagram for the System showing the interconnections of the different sensors and microcontroller for the System is shown in Figure 2. The integration process involved careful calibration, placement, and synchronization of the sensors to ensure data accuracy.

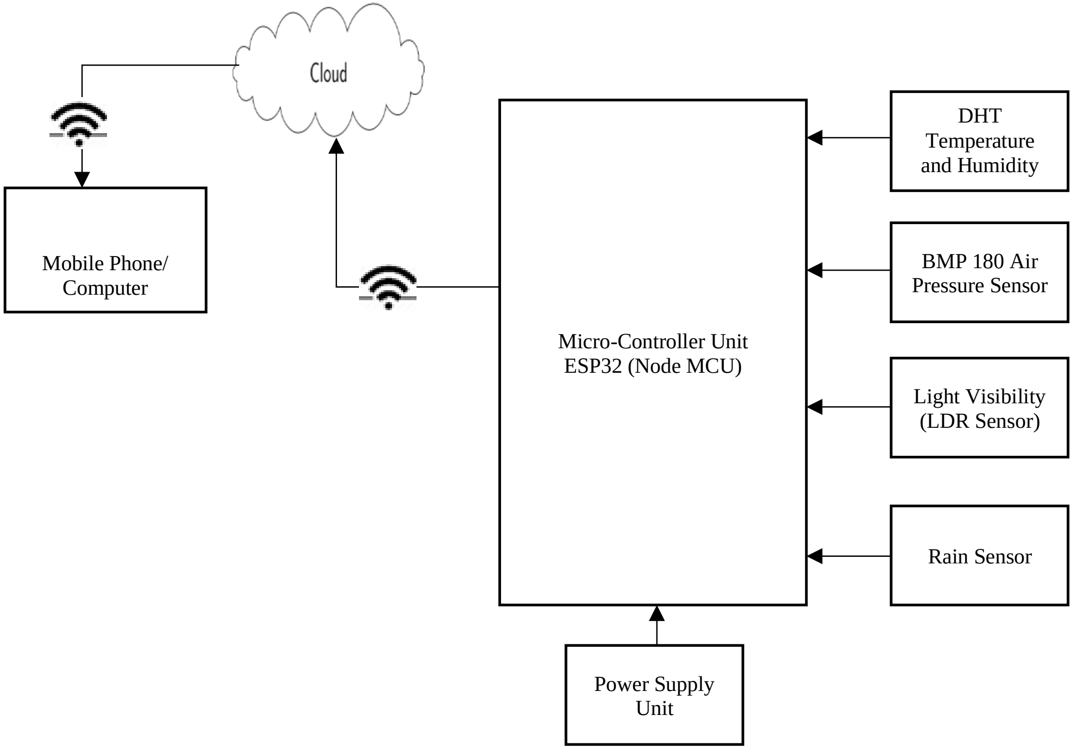


Fig. 1 System architecture

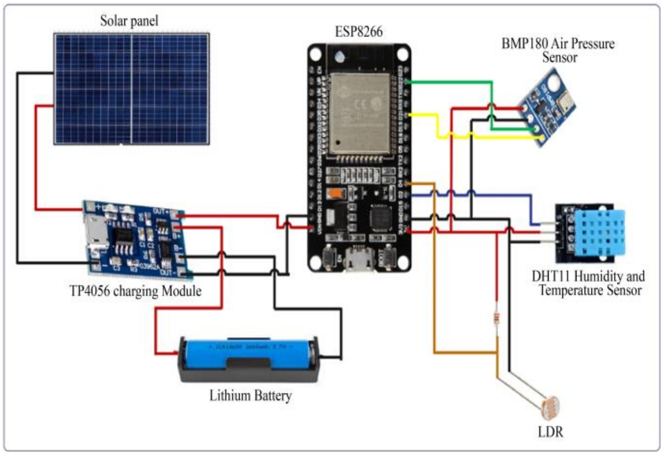


Fig. 2 Circuit diagram

3.3. Power Supply Unit

A dedicated power circuit was developed to provide power supply to the System continually. The power supply unit utilizes a Solar System and Lithium battery for uninterrupted power supply. A lithium battery, a solar panel, a lithium battery charge management circuit, and a DC/DC step-up/step-down converter circuit make up the power supply module. A polymer lithium battery, which has a cell capacity of 3.6 A·h and a nominal voltage of 3.7 V, is utilized. This provides the System with the necessary power from the lithium battery. The output voltage of the lithium battery is adjusted using PT1301 step-up and TPS62007 step-down converters to match the unique working voltage needs of each module. Figure 3 shows the structural diagram of the power supply.

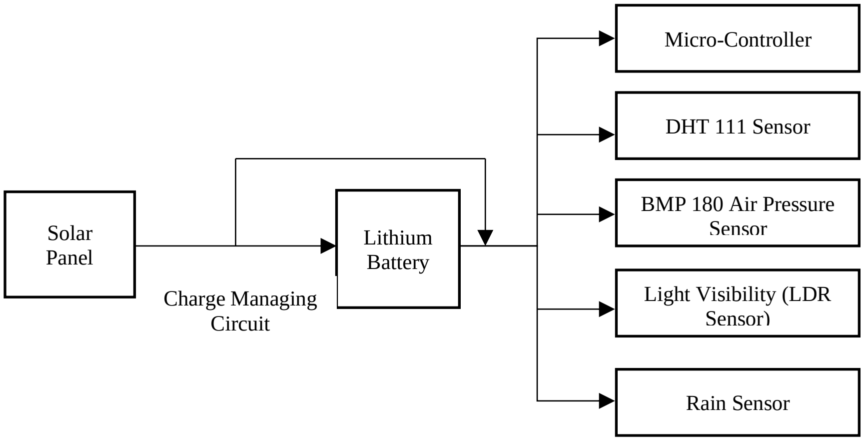


Fig. 3 Power Supply Unit

3.4. Data Storage and Visualisation

For Real-time data visualization, the ThingSpeak cloud platform is utilized as the cloud gateway to pull data from the hardware to the cloud. Data is then transmitted via a REST API to Firestore, a Google database solution for mobile and web applications for storage. The developed web application then continuously pulls data from the database for visualization and analytics.

4. Results and Discussion

4.1. Prototype Design and Implementation

The design of the weather observatory system consists of a robust architecture aimed at easy integration of various sensor technologies. The architecture is modular, allowing for the addition or removal of sensors with minimal disruption to the overall System. Key components include Temperature sensors, Humidity sensors, Pressure sensors, and solar panels (Power sources). The CAD model for the proposed system hardware is shown in Figure 4, while Figure 5 shows the developed hardware system.

4.2. IoT-based Real Time Weather Monitoring

The weather data obtained is visualized on the cloud platform via a web application developed. The data is transmitted to the web using Thingspeak as a gateway for visualization and further analytics. Figure 6 shows a dashboard showing the current weather parameters at that instant time for an environment.

Figures 7 to 11 present the plots of the various sensor data obtained over time, offering insights into multiple environmental variables. The plots encompass a range of parameters such as temperature, humidity, pressure, light intensity, and rainfall data, providing a comprehensive view of how these factors fluctuate over the observed period.

Fig. 4 3D CAD Model of the weather observatory system

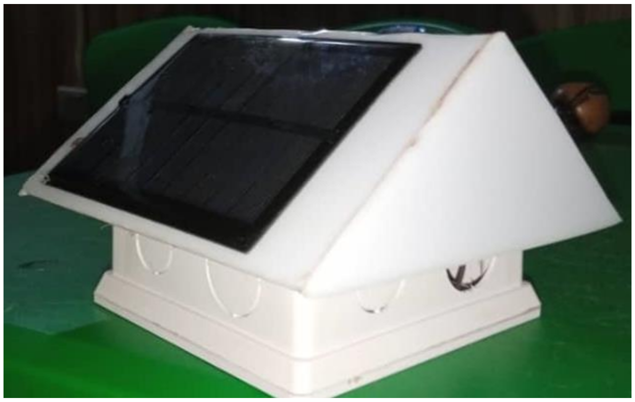


Fig. 5 Prototype of weather observatory system

24.10°C

24.10°C
Temperature

38.00%
Humidity

920.67mb
Pressure

503Ω
Light intensity

1
Rainfall

Fig. 6 Dashboard showing current weather data

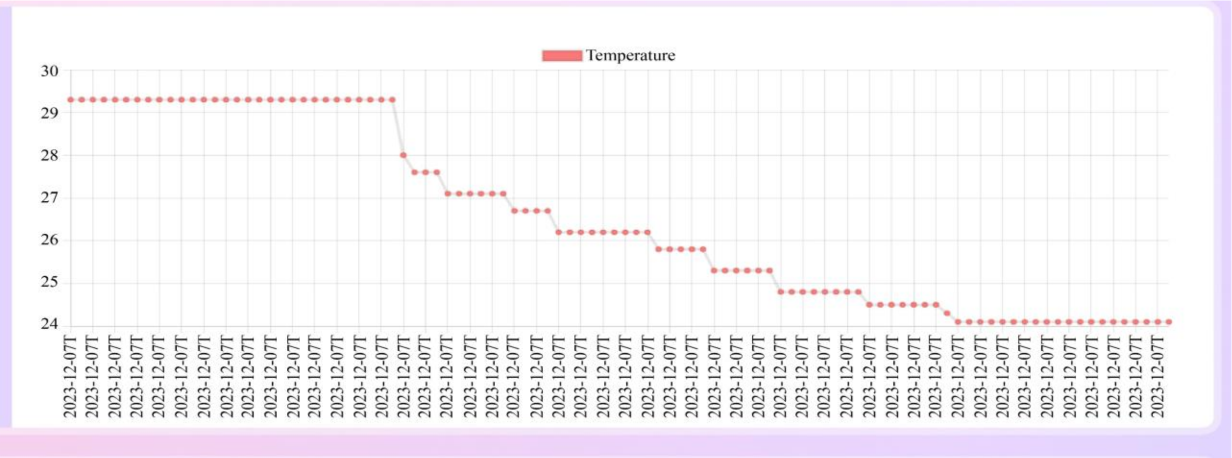


Fig. 7 Plot of temperature data

Fig. 8 Plot of humidity data

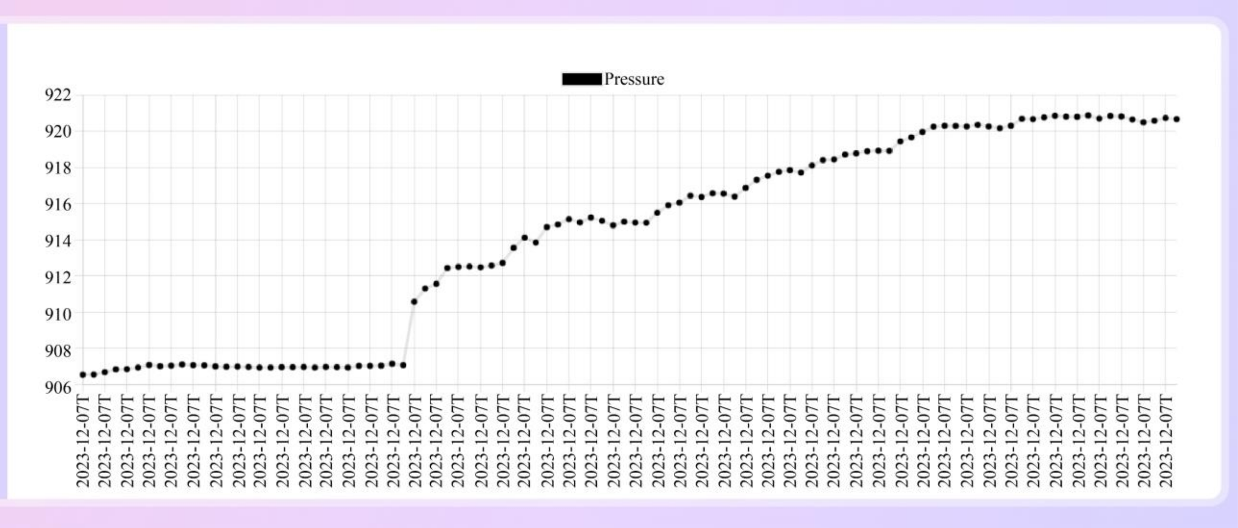


Fig. 9 Plot of pressure data

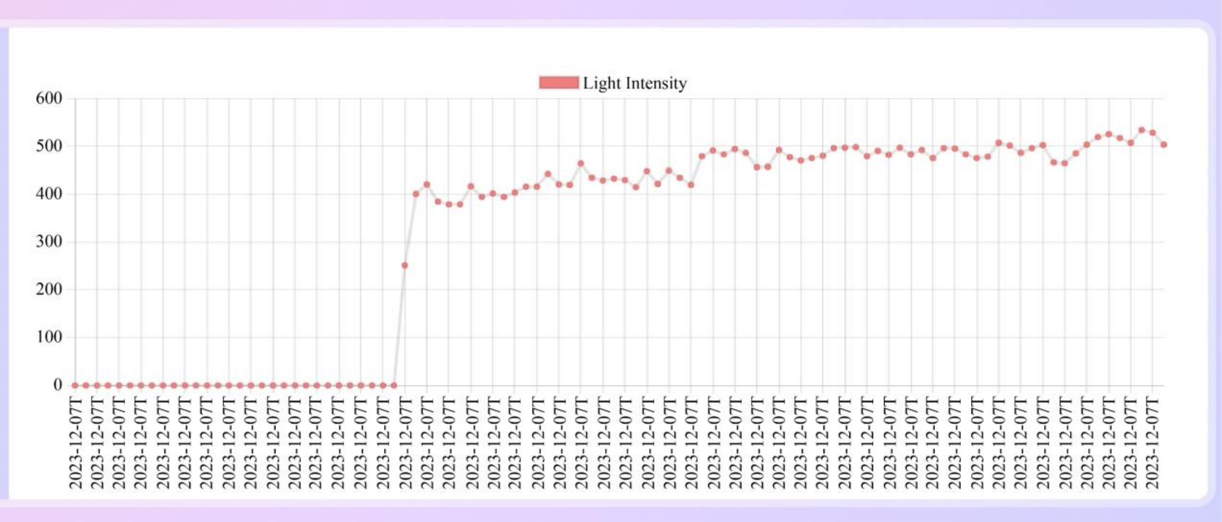


Fig. 10 Plot of light data

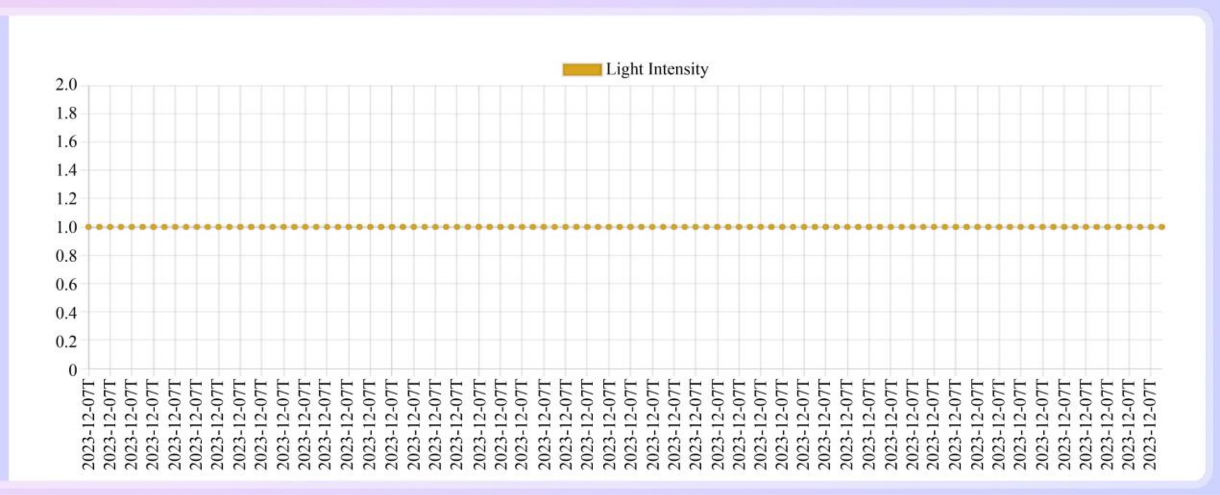
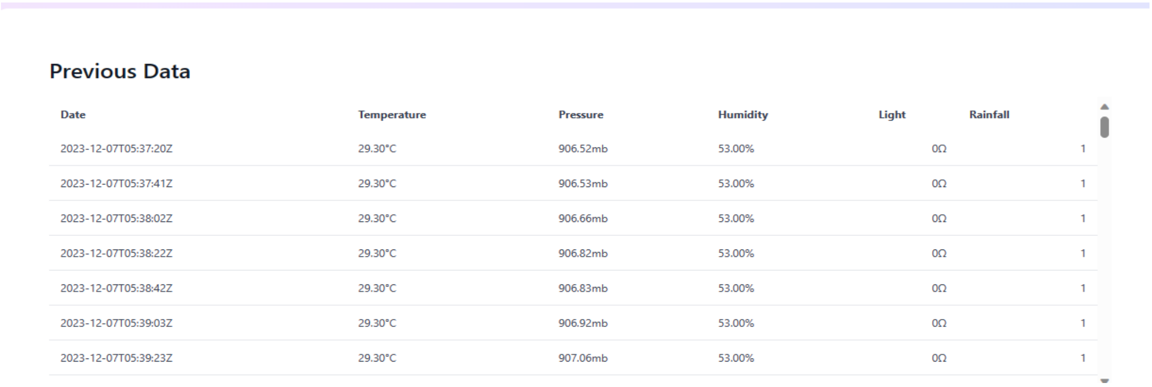


Fig. 11 Plot of rainfall data



Previous Data

Date	Temperature	Pressure	Humidity	Light	Rainfall
2023-12-07T05:37:20Z	29.30°C	906.52mb	53.00%	0Ω	1
2023-12-07T05:37:41Z	29.30°C	906.53mb	53.00%	0Ω	1
2023-12-07T05:38:02Z	29.30°C	906.66mb	53.00%	0Ω	1
2023-12-07T05:38:22Z	29.30°C	906.82mb	53.00%	0Ω	1
2023-12-07T05:38:42Z	29.30°C	906.83mb	53.00%	0Ω	1
2023-12-07T05:39:03Z	29.30°C	906.92mb	53.00%	0Ω	1
2023-12-07T05:39:23Z	29.30°C	907.06mb	53.00%	0Ω	1

Fig. 12 Log of weather data

In addition to showing the current data, the System is also capable of storing data to be accessed at a later point in time. Figure 12 shows a log of data stored previously.

4.3. Performance Evaluation

The evaluation of the sensor-based weather observatory system's performance is a critical step in ensuring its reliability and accuracy for real-time weather monitoring. With the hardware and dashboard successfully developed, the focus shifts to assessing how well the System aligns with actual weather data.

Table 1 shows historical weather data gathered on the 20th of December 2023 between 02:00 hours and 22:000 hours.

Table 1. Comparison of weather data (Meas.) with metrological sources (Act.)

Time	**Temperature (ºC)**		**Humidity (%)**		**Pressure (mbar)**	
	Act.	Meas.	Act.	Meas.	Act.	Meas.
02:00	22	21	65	64	1012	1008
03:00	20	21	65	64	1012	1008
04:00	20	21	73	72	1012	1008
05:00	20	21	78	77	1012	1008
06:00	20	21	78	76	1013	1010
07:00	19	20	83	81	1013	1010
08:00	19	20	83	82	1013	1010
09:00	25	23	61	63	1015	1013
10:00	28	26	45	47	1015	1013
11:00	29	27	43	41	1015	1013
12:00	30	30	40	40	1014	1013
13:00	32	31	33	31	1014	1013
14:00	34	33	32	30	1011	1008
15:00	34	33	32	31	1011	1008
16:00	35	33	30	30	1011	1008
17:00	34	34	34	33	1011	1008
18:00	34	34	34	33	1012	1008
19:00	29	27	43	42	1013	1010
20:00	29	27	43	42	1013	1010
21:00	28	26	45	44	1014	1013
22:00	23	22	69	67	1014	1013

The Root Mean Square Error (RMSE) was calculated for temperature, humidity, and pressure based on the provided data. For temperature, the RMSE was approximately 1.0 degrees Celsius, indicating the average deviation between the actual measured temperature and the values predicted or measured by the System. The RMSE for humidity was around 0.5%, reflecting the average difference between the actual humidity and the System's estimates. Regarding pressure, the RMSE was approximately 1.6 millibars, showing the typical error between the actual pressure values and the System's readings. These RMSE values help assess the accuracy and performance of the System in predicting or measuring these environmental parameters. The RMSE values reflect the System's overall accuracy in predicting or measuring these environmental parameters. While the RMSE for temperature and pressure suggests relatively close agreement between actual and predicted values, the lower RMSE for humidity indicates even better accuracy in humidity estimation. These findings highlight the System's strengths and areas for potential refinement, particularly in scenarios where precise measurements are crucial for decision-making or control systems.

4.4. Discussion of Results

The weather observatory system's design features a robust architecture that facilitates the seamless integration of various sensor technologies, ensuring flexibility for adding or removing sensors without disrupting the System. Key components such as temperature sensors, humidity sensors, pressure sensors, and solar panels for power sources contribute to the System's functionality. The System's hardware is depicted in a 3D CAD model (Figure 4) and a prototype (Figure 5), showcasing its physical structure.

The System enables real-time weather monitoring through an IoT-based approach, where weather data is visualized on a cloud platform via a web application developed for this purpose. The data transmission to the web platform utilizes Thingspeak as a gateway for visualization and further analytics. A dashboard (Figure 6) displays the current weather parameters, providing instant insights into the environmental conditions. Plots of sensor data over time (Figures 7 to 11) offer a comprehensive view of temperature, humidity, pressure, light intensity, and rainfall, aiding in understanding how these variables fluctuate.

Moreover, the System has data storage capabilities, allowing access to historical weather data at a later time (Figure 12). The performance evaluation of the System involved comparing measured weather data with meteorological sources. The Root Mean Square Error (RMSE) calculations for temperature, humidity, and pressure indicated the System's accuracy in predicting or measuring these parameters. The relatively low RMSE values for temperature and pressure suggest close agreement with actual values, while the even lower RMSE for humidity indicates precise estimation capabilities. These results underscore the System's effectiveness in real-time weather monitoring and highlight areas for potential refinement to enhance accuracy further.

5. Conclusion

In conclusion, the weather observatory system's design and development have been meticulously outlined, showcasing a robust and adaptable architecture. The initial design phase highlighted the seamless integration of diverse sensor technologies, enabling easy scalability and customization. This flexibility allows for the effortless addition or removal of sensors, minimizing operational disruptions. Moving forward, the development phase successfully realized the envisioned System, encompassing both hardware components and a user-friendly web dashboard. The System's performance underwent rigorous evaluation, with a focus on data validation and comparison alongside established meteorological data. This analysis reaffirmed the System's accuracy and reliability in capturing environmental parameters.

Moreover, the dashboard's performance was scrutinized for responsiveness, data clarity, and intuitive user interaction. The outcome underscored the dashboard's effectiveness in providing real-time insights and facilitating informed decision-making. Overall, the weather observatory system stands as a testament to effective design, development, and performance evaluation, offering valuable contributions to meteorological data collection and analysis.

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