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Development of Community-Based Three-Dimensional Printed Weather and Hydrologic Monitoring System with Cloud Data Storage and Web Application

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The Philippines, located in the western Pacific region, ranked first on the list of global disaster hotpots out of 192 countries in the World Risk Index Report in 2022. The Philippines was also identified as one of the most vulnerable to disasters caused by extreme natural events that include storms and flooding. Digitalization and emerging technologies that enable advanced warning and create responsive systems are the tools to prepare affected communities for natural events. This project develops an advanced system that enhances community preparedness and aids decision-making during extreme weather conditions like heavy rainfall, gusty winds, flooding, and extreme heat. The system can sense several parameters that include wind speed, wind direction, temperature, relative humidity, barometric pressure, precipitation, solar irradiance, ultraviolet rays' intensity, and flood water level. The sensing components transmit the readings to an attached microprocessor board that translates and sends the data to the cloud for storage, processing, and analysis. The processed data are fed into a web application that is built to disseminate precise weather information to the community and to the authorities to help them make informed decisions during hazardous weather conditions. The project employs three-dimensional (3D) modeling and printing, and standardized testing of system components for prototyping. The operation of each component of the weather and hydrologic monitoring system was validated through comparison with calibrated weather parameter measuring devices. Results reveal that the developed system provides weather data with an accuracy of 98.54 % to 99.71 % against calibrated weather parameter measuring devices. The monitoring system is also designed to accommodate artificial intelligence to enable precise localized weather forecasting.

1. Introduction

The hazards posed by human-induced climate change must be recognized and addressed if the Sustainable Development Goals (SDGs) are to be accomplished by the 2030 (WMO, 2021). Based on current climate models and empirical data, the global average temperatures are projected to increase at an accelerated rate in comparison to previous estimations (Lee, 2021). Rising temperatures will result in hazardous weather extremes and rising sea levels. Projections show that climate change is expected to increase the frequency, severity, duration, and spatial distribution of a variety of extreme weather events (Grossman, 2018). Climate change and its effect in weather conditions will affect many sectors, including water resources, agriculture and food security, ecosystems and biodiversity, human health, and coastal zones (UNFCC, 2006). According to the United Nations University – Institute for Environment and Human Security, floods and other weather-related disasters are already costing the global economy 50 to 60 billion USD per year, much of it in developing nations. The number of people living in flood-prone areas will roughly double due to more extreme weather systems driven by global

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climate change, rising sea levels, and continued deforestation (UNU-EHS, 2004). Weather patterns and climate conditions are two of the most essential aspects that influence the quality of life in most communities.

Due to limited financial capability, most developing nations cannot implement widespread and localized meteorological data collection methods that use expensive weather stations. This inability to collect localized weather data results to lack of comprehensive monitoring of local weather conditions. The collection of comprehensive meteorological data is one of the fundamental conditions for the accuracy of weather forecasts. If the meteorological data collected is insufficient, the publicly available weather forecast information would be incorrect (EPA, 2022). Satellite-based meteorological data collection has its limitations. Satellite data cannot provide real-time and hyper-localized data. Also, when collecting data remotely, there can be various interferences or disturbances that add unwanted noise to the observations (Dubovik, 2021). Most existing weather monitoring and forecasting systems are not specifically designed for localized weather information. This results in a delayed community response, and sometimes damage to properties and casualties. Utilizing real-time measurements significantly enhances the outcomes in precision agriculture, forest management, ecophysiology, and similar domains. Moreover, the growing impact of climate change underscores the importance of computing risk indices to notify both the public and local authorities about potential extreme events (Ioannou et al., 2021). Developing a hyper-localized weather monitoring system can provide data at much higher spatial resolution compared to satellites. Some weather phenomena, such as localized thunderstorms, small-scale temperature inversions, and microclimates, might not be adequately captured by satellites. Ground-based weather stations play a crucial role in climate studies and long-term climate monitoring. They provide consistent and reliable data for understanding regional climate patterns and trends.

Moreover, this system plays a role in sustainability efforts because it provides highly accurate, real-time weather data which enables optimized resource allocation in agriculture, renewable energy, and disaster management. This precision promotes sustainable practices, such as efficient farming, renewable energy optimization, and smart building systems. Additionally, the system is self-sustaining because it is powered by solar energy. Furthermore, the components are 3D printed to ensure that less resources are utilized and less waste is produced.

The purpose of the project was to develop a weather station that provides real-time and localized weather information through cloud data service and web application. Specifically, the project aimed to build a ground weather monitoring station that can provide real-time data on wind speed, temperature, heat index, humidity, water level, and barometric pressure. It also aimed to develop a web application that can disseminate accurate data to the public or concerned agencies, and an alarm system using sirens. The development of a localized weather monitoring system with a user-friendly web application has the potential to empower individuals, communities, and decision-makers.

2. Methods

The study started with gathering data on different weather parameters in a specified location in the province of Bataan in the Philippines. The gathered data were processed and analyzed to provide information on what system components and specifications are needed in the weather monitoring stations.

Two different options for the structural design were provided and evaluated using computer-aided design as presented in Figure 1. The succeeding steps in the project included the fabrication of the prototype through conventional metal fabrication for the structure and 3D printing for other complex parts of the weather station. The final steps in the prototype development are the programming of sensors, controllers, and other electronic components and the design and development of the web application with cloud data service.

2.1 Structural Design and Fabrication

Two options for the structure of the weather station were considered in the project. The first design is a 7-foot device that uses a series of sensors for environmental parameters and utilizes seven water level sensors for flood monitoring. The second design is a 10-foot device that utilizes an ultrasonic sensor to measure the water level. The placement of the components of the device which is critical in the fabrication and operation of the device were varied in the two designs. The advantage of first design is the ease of access to the components and sensors whereas the second design provide the optimal height and placement of the solar panel, anemometer and ultrasonic sensor. The advantages based on the two designs were applied to the final design and can be seen in the actual fabricated prototype of the weather station shown in Figure 2 below.

3D printing technology was employed in the development of complex and customized components of the weather station. Most parts of the enclosures used in the weather station and including the rain gauge, wind vane, wind anemometer, and other components were 3D printed which is shown on Figure 3 below. The material used in the process is acrylonitrile styrene acrylate (ASA). ASA is highly resistant to ultraviolet radiation and can withstand prolonged exposure to sunlight without significant degradation and it has excellent weatherability making it suitable for outdoor applications. Furthermore, ASA filament possesses high tensile strength and impact resistance and is available is easy to source and to print. These properties of ASA make it ideal for the fabrication of the weather station.

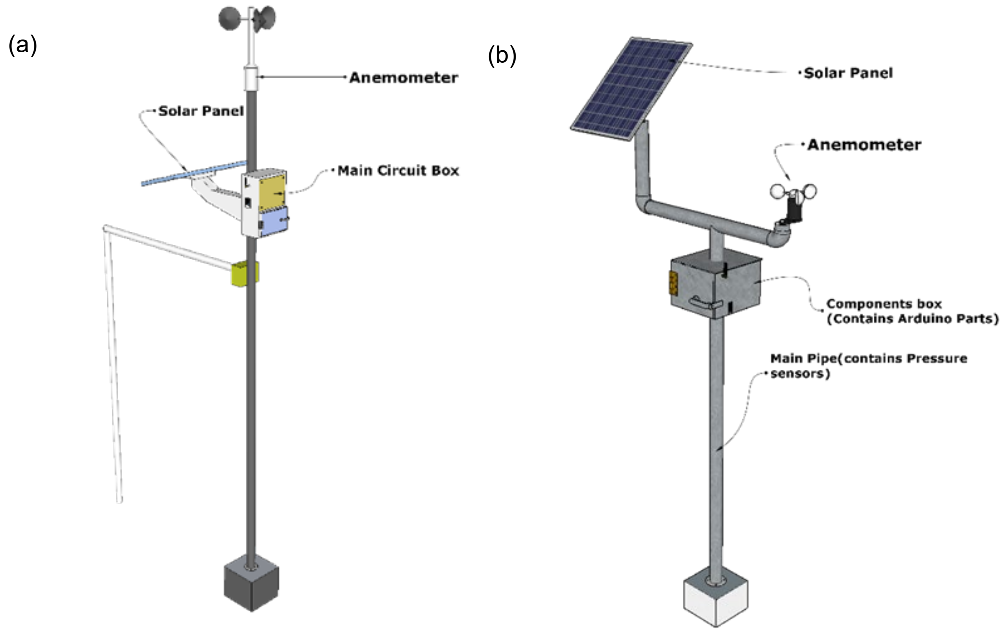

Figure 1: Two structural design options of the weather monitoring station (a) 7-foot pole with series of water level sensor (b) 10-foot pole integrated with ultrasonic sensor.

Figure 2: Actual fabricated prototype of the weather station

(a) (b)

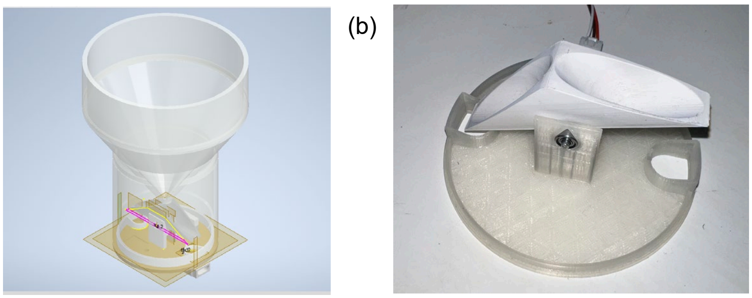

Figure 3: (a) 3D model of the rain gauge and (b) sample 3D printed component

2.2 Programming and web application development

The weather station employed different sensors and controllers to gather weather data and send them to a cloud data service. The data collected by the weather station include temperature in °C, relative humidity in % and atmospheric pressure in hPa using the BME280 sensor along with the DHT22 sensor and the BMP180 sensor as redundancy sensors. The weather station also collects data on light intensity in lux using BH1750 sensor, UV light intensity in nm using GUVA-S12SD sensor, wind speed in m/s using hall effect sensor, wind direction using AS5600 encoder and rainfall intensity in mm/s using hall effect sensor mounted in a 3D-printed rain gauge. The system shown on Figure 4 uses the BME280 sensor for reading the temperature in °C from –40 °C to 85 °C, the atmospheric pressure from 300 to 1,100 hectopascals, and the relative humidity from 0% to 100 %. The sensor has a resolution of 1.5% for temperature, 0.25% on pressure, and 3% on humidity. To ensure the accuracy of the three weather parameters, the system features additional sensors which are the DHT22 sensor that reads the relative humidity and the BMP180 sensor that reads the temperature and atmospheric pressure. The DHT22 sensor has an accuracy of 2% for relative humidity and a 0.5% accuracy for temperature. The data gathered from this sensor is used for data redundancy or validation of the sensed data of the BME280 sensor. The BMP180 sensor also serves as redundancy sensor for validated data readings.

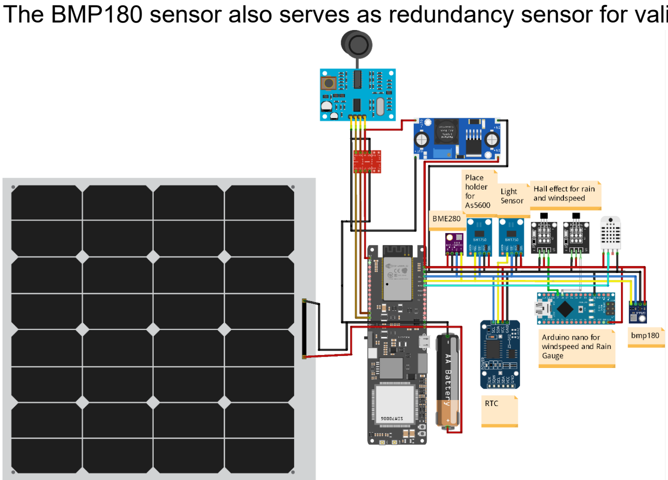

Figure 4: Schematic diagram of the sensors and microcontrollers

To measure light intensity, the system uses the BH1750 sensor with a tolerance of 5 % at a range of 1 to 65,535 lux. The measured value is multiplied by 0.0079 to give the value of solar irradiance. The system also uses the GUVA-S12SD UV sensor to measure the wavelength of UV light from 200 to 370 nm with a tolerance of 1 %.
For wind direction, the AS5600 encoder is used that measures the position of the diametrically polarized magnet. It has a tolerance of 1 % and can measure any wind direction. The remaining sensors for rain fall and wind speed are controlled by the Arduino Nano microcontroller that uses hall effect sensors and a count function for operation. In measuring the amount of rain fall, every one count of the hall effect sensor is equal to 1 mm of rain fall. In measuring the wind speed, one revolution is equal to one count which is then processed to determine the wind speed in m/s. All these sensing processes take place in less than one minute, and the measured data are transmitted and stored in a cloud database. All sensors and controllers are powered by photovoltaic cells.
As the system gathers data from the sensors, it generates a URL-encoded string containing the sensor data. The string is then transmitted to the online server hosted in awardspace.com using GSM through an HTTP

POST request. Upon receiving the data, the server interprets and stores it in the server database. On the dashboard side, the client side initiates an HTTP request to the server every second to detect changes from the database records, specifically requesting the ten most recent rows from the database. Once the client side receives the requested data, it presents the recorded data on the dashboard using Chart.js for visual representation and a table for tabular display shown on Figure 5 below.

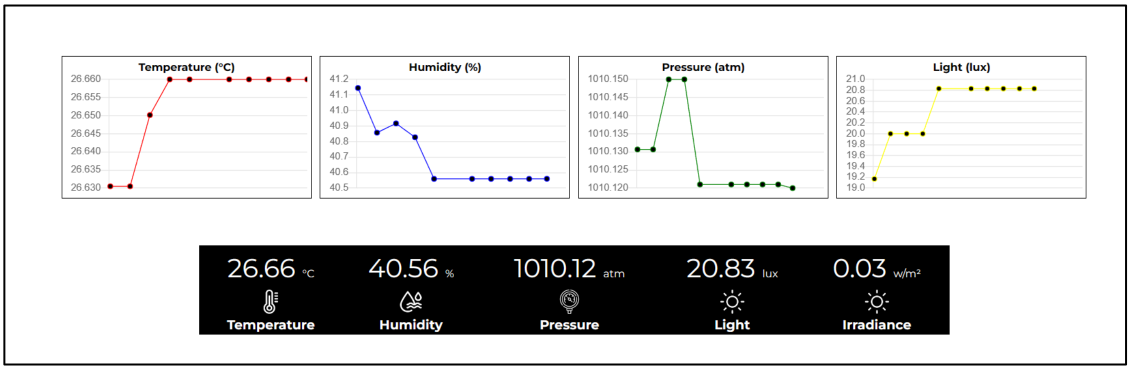

Figure 5: Dashboard of the web application for data visualization

2.3 Accuracy and Precision Testing

The fabricated weather station with all its sensors, controllers and other electronic components was tested based on its precision in reading the different weather parameters. A digital display board was attached to the weather station to check its actual readings of the weather parameters. A calibrated device which is Extech SD700 Barometric Pressure/Humidity/Temperature Datalogger was used to validate the readings on ambient temperature, atmospheric pressure and relative humidity of the weather station and the data displayed in the web application.
A controlled set-up was prepared to determine the accuracy of the water level and wind speed reading. Wind speed accuracy and precision testing involved using a wind blower set a particular wind speed and comparing the measurement of the weather station and the measurement of another calibrated device which is Extech HD300 Thermo-Anemometer. The accuracy and precision of water level reading was tested in two types of water quality, clear and turbid water. A refillable cylindrical container with water level marks was put under the water level sensor, and the readings from the container marks and the device were recorded. The reaction time of the alarm through the siren as the water level increases by 1 foot was also tested. The percent error is computed by comparing the readings of the weather station and the calibrated devices.

3. Results

The average of data readings from day 1 to day 5 of the weather station and the calibrated measuring device as well as the computed percent error are tabulated in the Table 1 and Table 2 below. The percent error for the ambient temperature is 0.92 %, 0.46 % for the relative humidity and 0.29 % for the atmospheric pressure.

Table 1: Measured data from weather station and calibrated device and percent error

Parameters	Weather Station	Calibrated Device (Extech SD700)	Percent Error
Temperature °C	33.428	33.12	0.92 %
Humidity %	61.96	62.24	0.46 %
Pressure (hPa)	1,009.47	1,006.56	0.29 %

A similar calculation was used to calculate the percentage error of the wind speed readings. Table 2 shows the percentage error at 0.5-meter distance of the calibrated device from the weather station at 0.81 % and 1.46 % at 1 m distance between the weather station and the calibrated device.

Table 2: Measured wind speed from weather station and calibrated device and percent error

Distance	Weather Station	Calibrated Device (Extech HD300)	Percent Error
0.5 m	5.72 m/s	5.77 m/s	0.81 %
1 m	3.38 m/s	3.43 m/s	1.46 %

The average reaction time of the siren and the response time of the data display in the web application were also recorded as shown in Table 3. The average reaction time of the siren as the water reaches the predetermined water level of 2 ft is at 0 second indicating that there was no delay. The average response time of data display in the web application in clear water is 2.20 s and 2.06 s in muddy water. The research team employed both muddy water and clear water as simulation media to emulate real-world and ideal conditions, respectively. Furthermore, the study revealed that ultrasonic waves exhibited a higher velocity of propagation in muddy water compared to clear water.

Table 3: Measured data from weather station and calibrated device

Water Quality	Water Level Measured (ft)	Average reaction time delay of siren (s)	Average display time delay of web application (s)
Clear water	2	0	2.20
Turbid water	2	0	2.06

4. Conclusions

In conclusion, this project has explored and examined various aspects related to the development of a localized weather and hydrologic monitoring system with web application. It provides valuable insights into the use of integrated sensors such as DhT11 for temperature and humidity, BMP 180 for air pressure, wind speed sensor, GSM 800l v2 for IoT connectivity, and an ultrasonic sensor for water level detection. The analysis of the measurements of the local weather station compared to calibrated measuring devices proves that the weather station is reliable in accurately monitoring the weather conditions. Comparing the data obtained from the Barometric Pressure and Temperature Data Logger and Thermo-Anemometer Data Logger, the interconnection of sensors DhT11, BMP 180, wind speed sensor, GSM 800l v2, and ultrasonic sensors integrated into the weather station provide accurate measurements of weather conditions. It shows a percent error of 0.29 % being the lowest and 1.46 % being the highest. This result is well within the range of the acceptable tolerance value of 5 %. It becomes evident that a low cost, but accurate localized weather monitoring device can be created using ESP32 hardware and components that are easily obtainable and only requires minimal power consumption.

While this project has made significant results, there are still areas that warrant further investigation. Future research could delve deeper into the development of a localized weather and hydrologic monitoring system with artificial intelligence.

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