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Design and Installation of Coastal Flood Monitoring Device Using Ultrasonic Sensors and LoRa-Based Technology for Real-Time Data Collection and Storage

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Coastal towns in Bataan are nowadays suffering from coastal flooding. The simultaneous occurrence of land subsidence, high water tides, storm surges, and wave conditions significantly increase the water levels during heavy rains. This research paper aims to address the absence of a community-based flood monitoring device to improve societal preparedness for unpredicted coastal floods in Bataan. The proposed automated device was installed on the shore of Kitang I, Limay Bataan, which comprises sensor nodes that collect the water level and meteorological parameters such as temperature, relative humidity, and atmospheric pressure, and a gateway command center on land that receives data for cloud storage and website monitoring. The LoRa module is used to transmit and receive data remotely. It also includes an inquiry system for individuals in the community via SMS keyword. The system's reliability was assessed by comparing the results of the automated system to those of the conventional method in terms of water level and meteorological variables. The result obtained a high correlation between the two measurement methods and the smallest percentage error of 0.057 % for water level data, indicating that the ultrasonic sensors used in the device are reliable for measuring water levels. The paper also aims to help make data-based policies to reduce climate change's impact by providing data on sea-level changes over time.

1. Introduction

The Philippines is located near the equator and is surrounded by bodies of water. The country is constantly at risk of natural hazards. Coastal flooding is the most common natural hazard that often occurs when high tides, storm surges, and wave conditions significantly increase water levels. The rapid urbanization of areas along the coastline in concurrence with climate change and inadequate coastal protection and appropriate mitigation measures also increased flood risks. Disasters caused by coastal floods significantly disrupt coastal communities and damage the urban environment. The growing number of flood-related impacts demands a cost-effective and reliable flood monitoring device. Abon et al. (2012) developed a community-based monitoring for flood early warning system in Bulacan, Philippines, which focuses only on establishing basin and channel models of flood extents during typhoon events rather than being a standalone monitoring device. The system's effectiveness will be determined mostly by the observer's training knowledge, where biases and inaccuracies during monitoring can happen. Data monitoring and recording will only be conducted during the morning and afternoon, which lacks the purpose of real-time monitoring. The main objective of the present study is to develop a monitoring device that detects coastal floods automatically and sends data using an Internet-of-Things-based system with real-time data collection and storage. This study also comprises the sensor nodes and gateway unit that collect meteorological parameters such as temperature, relative humidity, and atmospheric pressure at regular intervals. Similar to the current study, Natividad and Mendez (2018) established a flood monitoring and early warning system in the province of Isabela, Philippines using ultrasonic sensors. The only difference is that the project employed in Rivers of Isabela used GSM modules as a way of data transmission, while the present study integrates LoRa modules, which is an emerging technology in the field of IoT nowadays.

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The project is designed to assist coastal communities that are directly affected by floods during high tides and storm surges. The device provides real-time monitoring of the water level using the ultrasonic sensing method and warning system via SMS, website, and buzzer alarm. Integrating the prototype into the community provides them with real-time and localized information on the coastal areas' water level, temperature, pressure, and humidity. Local Government Units (LGUs) focused on Disaster Risk Reduction and Management (DRRM) could use the project to monitor tidal and coastal floods and improve risk mitigation.

2. Review of Related Literature

A study by Tolentino et al. (2022) on real-time flood detection, alarm, and monitoring systems used image processing as a flood detection method. The system is set to capture images that undergo image processing and depth analysis every 15 minutes to give real-time updates and estimate water level by using multiple linear regression. The process requires a complicated process and might result in an error and inaccuracy of readings due to the complex interaction of the variables. In the current study, ultrasonic sensors have been installed in distinct positions which enables the acquisition of water level data from multiple directions, thereby improving the reliability of the readings. Sensor readings are periodically uploaded on the website at three-minute intervals for real-time monitoring. Numerous types of ultrasonic sensors are available, with significant frequency and power consumption variances. Abdul and Zulfaesa (2020) developed an early warning system using HC-SR04 ultrasonic sensor then Lai and Oo (2019) designed a real-time water level monitoring system using JSN-SR04T ultrasonic sensor. Ultrasonic sensors have been put on hundreds of coastal tide gauge platforms to warn of tsunamis and tropical storm surges. Considering the current advancements in ultrasonic sensing, the present study also employed an ultrasonic sensor specifically the JSN-SR04T since it is more reliable and is waterproof. Yumang et al. (2017) developed a standalone flood water level monitoring system using GSM modules to send alerts to the local community in Kahilom Street, Pandacan, Manila. A study by Thekkil and Prabakaran (2017) transmitted and generated the acquired camera images and flood-related warnings through the utilization of Zigbee. Zahir et al. (2019). utilized Wi-Fi modules, which enable the device to send the sensor data to the remote IoT platform using the IoT protocols over the Wi-Fi connection. Hashim et al. (2018) employed a wireless flood monitoring device that transmits data in proximity alert via Bluetooth interface through a smartphone. The transmission modules mentioned in the studies above are just some of the variety of communication devices available for specific needs in the realm of IoT devices. Bluetooth and Wi-Fi are the most popular wireless technologies. The issue with Wi-Fi and Bluetooth innovations is their high energy consumption. They share similar limitations, such as limited reach and narrow paths. The current study utilized the emerging technology that is being used in the field of IoT nowadays, which is LoRaWAN. The novelty of this work falls under the utilization of the LoRa modules that can transmit the data acquired by the sensors gathered from the sensor node and subsequently transmitted to the gateway through LoRa modules located at 50 meters. Lora's long-range capability allows the data to be sent over several kilometers, even in challenging terrain or urban environments compared to the communication technologies mentioned above that only have short-medium range transmission capabilities.

3. Methodology

The procedure, by which the system is developed, consists of defined procedures such as requirements, design and 3D printing of sensor houses, development and coding, system testing, implementation, and field testing.

(a)

(b)

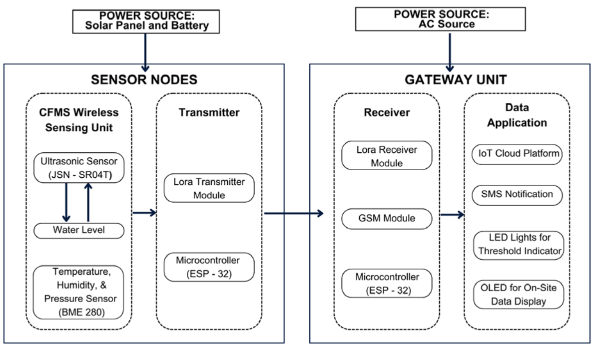

Figure 1: (a) Actual Prototype, and (b) Conceptual Framework

The system is divided into the Sensor Nodes and the Gateway. Figure 1a is the 3-meter pole-type flood monitoring device and Figure 1b shows the conceptual framework of how the whole system works. The sensor nodes, which are solar powered, consist of an ESP-32 microcontroller that will collect and analyze all the sensor's sensed data and the LoRa modules with an antenna that will transmit the data wirelessly to the gateway unit. Figure 1b shows the circuit connections of the hardware components in the gateway unit. The gateway is situated in a location where it can receive data for remote monitoring. A buzzer and LED lights for the alarm system are also connected to the gateway unit. The processed data will be displayed and saved on the ThingSpeak IoT Cloud Platform and KloudTech Coastal Monitoring Website. Figure 2a and 2b is the schematic diagram or circuit connections of the sensor nodes and gateway unit, showing all important electrical components used in the building of the system.

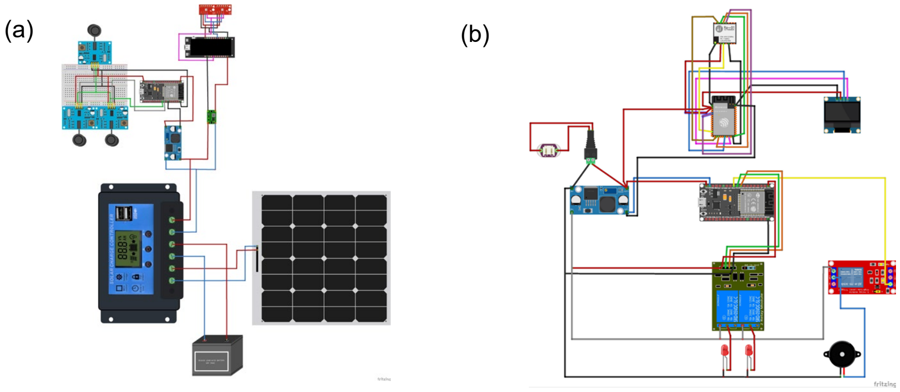

Figure 2: (a) Sensor Nodes, and (b) Gateway Unit

4. Results and Discussion

The project was deployed and tested in a coastal area in Bataan for seven days of monitoring and experimentation. collected from the system, including temperature, humidity, atmospheric pressure, and water level readings, was compared with readings from Extech SD700 and staff gauge using a Bland Altman Plot to show the reliability agreement between the values obtained (Fig. 3-4).

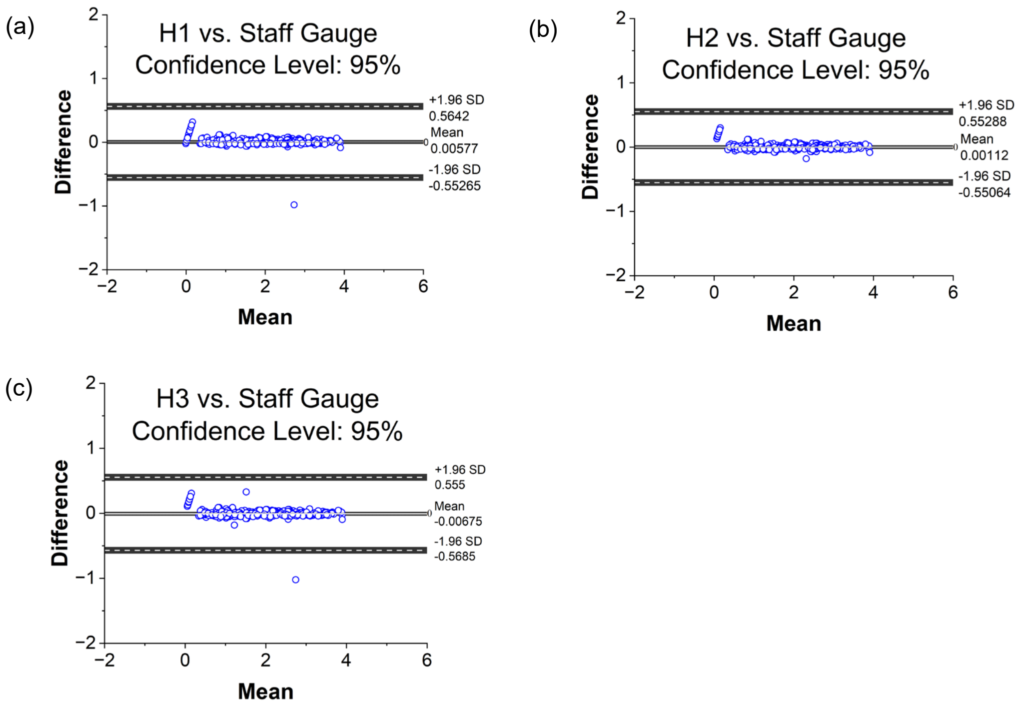

Figure 3: Bland Altman Plot for Water Level Reading (a) H1 vs. Staff gauge, (b) H2 vs. Staff gauge, and (c) H2 vs. Staff gauge.

Figure 3 shows the calculated mean difference for the three ultrasonic sensors and the staff gauge for water level reading. Each data point almost lies or is close to zero, indicating good agreement and minimal bias between the two measurement methods. The three ultrasonic sensors stand alone at three different points of the device, and all these measurements are significant in the device's alarm; thus, it must provide at least two almost equal readings. Figure 4 present the high correlation of readings from two BME280 sensors and BPSU's Extech SD700 Data logger in terms of temperature, relative humidity, and atmospheric pressure. The graph also shows that 95% of the data is within the standard absolute accuracy set by the BME 280 manufacturer BOSCH Sensortech (±1.0℃, 1.0 kPa and, 3%). Few outliers are seen in the graph indicating there might be a sudden change in the environment, especially temperature, and humidity in the air or sea breeze during the data-gathering period. Outliers may occur during extreme weather conditions, such as heat waves, cold snaps, or sudden changes in humidity. Redundant sensors enhanced the reliability of measurements by reducing the risk of failures. By comparing the readings from the different sensors, it is possible to identify inconsistencies or deviations that will be potential problems or errors that can be investigated and rectified.

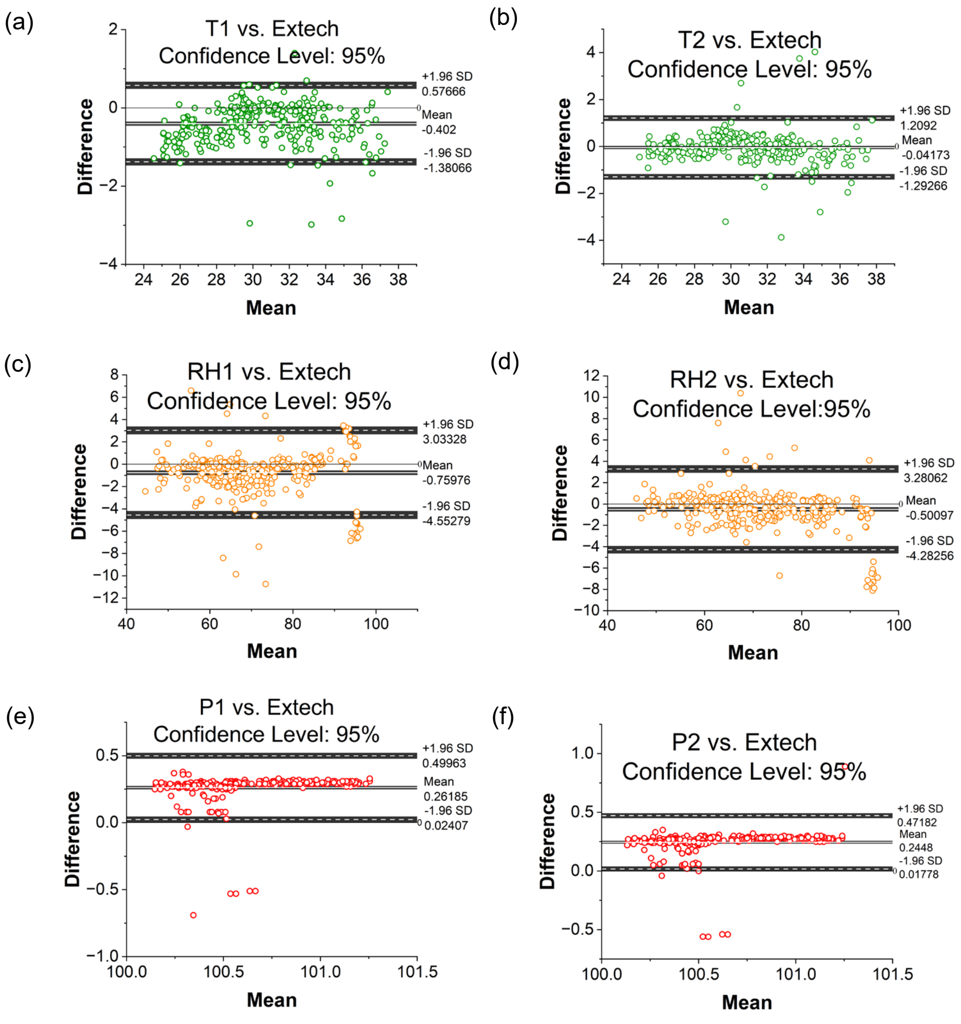

Figure 4: Bland Altman Plot for Temperature (a) T1 vs. BPSU Extech SD700, and (b) T2 vs. BPSU's Extech SD700; Relative Humidity (c) RH1 vs. BPSU Extech SD700, and (d) RH2 vs. BPSU Extech SD700; Atmospheric Pressure (e) P1 vs. BPSU Extech SD700, and (f) P2 vs. BPSU Extech SD700

4.1 Interpretation of Results

The data is interpreted by measuring the percentage error of the calculated value and the reference. Eq(1) is the difference between the mean obtained from separate devices and the mean of prototype, over the mean of separate devices.

$$\% \, Error = \frac{X_1 - X_2}{X_1} \, x \, 100 \tag{1}$$

Following field testing, the accuracy of water level, temperature, humidity, and atmospheric pressure was assessed by comparing results to existing technologies for the same parameters that measure the same parameter used in the study. Table 1 displays the average mean of water level, temperature, relative humidity, and atmospheric pressure.

Table 1: Percent Error of Water Level, Temperature, Relative Humidity, and Atmospheric Pressure

Parameters	Mean of Prototype (X_2)			Mean of Separate Device (X_1)
Water Level	H1AVG	H2AVG	H3AVG	StaffAVG
	0.601 m	0.599 m	0.597 m	0.599 m
	BME1AVG	BME2AVG		BPSUExtechAVG
Temperature	30.287 ºC	30.640 ºC		30.677 ºC
Relative Humidity	70.948 %	71.206 %		71.707 %
Atmospheric Pressure	100.723 kPa	100.706 kPa		100.462 kPa

4.2 Validation of Results

The validation approach involves checking the consistency and reliability of the calculated values by comparing them with values reported in previously conducted studies.The acceptability of the study's findings was validated by comparing the results with several established studies as shown in Tables 2 and 3.

Table 2: Validation of Results for Water Level Readings

Parameter	% Error			Comparison of Percent Error to Existing Studies		
	H1	H2	H3	Azid and Sharma (2012)	Andang et al. (2019)	Nuhu et al. (2016)
Water Level	0.297 %	0.057 %	0.344 %	0.998 %	0.750 %	0.999 %

Table 3: Validation of Results for Temperature, Relative Humidity, and Barometric Pressure

Parameters	% Error		Percent Error from Existing Studies	
	BME1	BME2	Warnakulasooriya et al. (2018)	Carranco et al. (2017)
Temperature	1.271 %	0.123 %	2.54 %	4 %
Relative Humidity	1.060 %	0.699 %	13.81 %	5 %
Atmospheric Pressure	0.261 %	0.243 %	1.555 %	0.02 %

Table 2 presents the comparison of the calculated percent error to the cited studies that used conventional methods to test the accuracy of their water level readings. In Table 3, the calculated percent error for temperature, relative humidity, and atmospheric pressure were validated by comparing the results with two studies that employed the same model of the BME 280 sensor. The results of these established studies were compared to a meteorological station in their area. The percentage error of the cited studies yielded greater than the calculated percent error of the study and smaller percentage errors indicate an acceptable value. It is reasonable to conclude that the reading provided by the prototype is accurate.

5. Conclusion

After conducting a comparative analysis of observed data (water level, temperature, relative humidity, and atmospheric pressure), the device used performed effectively and produced reliable outcomes. The project could be a helpful device in monitoring tides and coastal flooding, specifically targeting Local Government Units (LGUs) focused on Disaster Risk Reduction and Management (DRRM). Implementing such coastal monitoring systems allows for more effective risk mitigation. The traditional practice of tide predictions in calendars to determine high and low tides is prone to errors due to differences in reference points compared to actual tide measurements obtained from monitoring devices. As a result, this study offers invaluable insights and guidance to local governments looking to improve their coastal tide and flood monitoring and management capabilities.

Nomenclature

X_1 – Reading from Separate Device
X_2 – Reading from Prototype Device

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