IoT Environmental Monitoring System Using LoRaWAN, MQTT and Node-RED

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Abstract*—The usage of Internet-of-Things (IoT) related technologies in smart farming is increasing. However, previous studies on IoT environmental monitoring systems have only been conducted in a relatively small area of farmland suitable for city farming or greenhouse farming. Recent drastic changes in climate are having a serious impact on large-scale farming, emphasizing the need for an environmental monitoring system for large-scale farmland. Therefore, this paper describes the implementation of an environmental monitoring system that works even in the vast tract of farmland. The environmental monitoring station will collect and process environmental data from various sensors and send the processed data to the Node-RED-based cloud platform through LoRaWAN and MQTT. A LoRaWAN gateway and LoRaWAN network server provide LoRaWAN infrastructure, enabling the station to connect to the internet. The infrastructure exposes an MQTT broker for the cloud platform to connect to and get streams of data from the station. Details of sensors and communication methods are described in this paper. The Node-RED-based cloud platform decodes data from the station, visualizes real-time environmental data through its dashboard interface and stores received data into a database so the historic data can be retrieved and shown to the user later. The platform also sends a notification email to the users if abnormal data is detected. Potential future development of this project includes filtering abnormal sensor data, improving battery capacity, and increasing the intuitiveness of data representation.

***Keywords*—environmental monitoring, IoT, LoRa, LoRaWAN, solar power, Arduino, sensors, MQTT Protocol, Node-RED platform, The Things Stack, MySQL**

I. Introduction

Today, the agricultural sector depends on data collected from farms [1] and as the weather becomes more unpredictable, the demand for an environmental monitoring system for agricultural usage is increasing [2]. Many prior studies have suggested smart farm systems using IoT technologies. However, smart farm systems proposed by prior studies are limited to confined spaces like greenhouses or urban areas [3]. Instead of these approaches, this project aims to build a system that can be operated in vast land such as American farms. This paper explains how an IoT environmental monitoring system that can collect environmental data, send data over long distances, store and visualize collected data in a user-friendly way is designed and implemented using LoRaWAN, MQTT protocol and Node-RED platform.

LoRaWAN is used for connecting the environmental monitoring station to the internet. LoRa is one of the Low Power Wireless Area Network (LPWAN), which is known for its long communication range, low power consumption and operation at low bit rates [4]. These characteristics make LoRa suitable for IoT applications. In addition, LoRa works on unlicensed sub-GHz ISM frequency bands so anyone who registers can get free access to LoRa [5]. Also, frequency between 500MHz to 1GHz has high resistance to interferences [5]. This will enable the environmental monitoring station built in this project to be installed throughout large farmland at a low cost.

LoRaWAN payload is hand over to an MQTT broker that exposes the data making it available to the outside of the boundary of LoRaWAN. MQTT is a messaging protocol with a lightweight publish and subscribe messaging transmission that enables connecting remote devices with a small code footprint and minimal network bandwidth [6]. Also, this protocol uses TCP for security and a stable connection between the server and the client [7]. MQTT uses a Quality of Service (QoS) level system that divided the way messages are exchanged into three levels to ensure the reliability of messaging [8]. Therefore, MQTT has suitable characteristics for this project: lightness, stability, security and reliability.

The data visualization functionality the environmental monitoring system provides is based on a platform called Node-RED [9]. Node-RED is a programming tool for wiring hardware devices together, APIs and online services. In this project, Node-RED visualizes the data received from the MQTT broker into various charts. It enables the user to view the environmental data easily.

As the environmental monitoring system built in this project is intended to be used in large farms, a power supply issue arises. For users who cannot run cables for all environmental monitoring stations or replace batteries from time to time, the environmental monitoring station will be powered mainly by a solar panel, a semi-permanent and environment-friendly power source.

II. Literature Review

Sunehra *et al*. [10] developed a Smart Urban Farming system with Raspberry Pi, Arduino and Node-RED platform. Three sensors and both Arduino and Raspberry Pi were used. The Node-RED platform was also used to make a user interface. The Arduino Uno board is connected to sensors, and the Raspberry Pi acts as a gateway, which receives the data from the Arduino board and sends the collected data to the application server. However, this study has a limitation that it aims to make a system suitable for smaller scales such as city farming. It uses WiFi and Bluetooth for communication methods. The communication range of Bluetooth is up to 10 meters [11] and the range of WiFi is up to 100 meters [12]. 10-meter or even 100-meter range is too short for large-scale farms. Therefore, this project advances the study by replacing the communication method with LoRa, which is suitable for large farmland.

Yoon *et al*. [13] made a smart farm system based on LoRa & MQTT. This study uses a two-way communication system, where the gateway sends data from sensors to The Things Network cloud, and receives data from the cloud and sends it back to an actuator. They also developed a web page as a user interface. In this project, however, due to time and resource limits, it was decided to use a one-way communication structure, in which only sensors send data to the cloud. Yet, this project advanced the idea of the study by implementing a solar panel as a power source.

III. Environmental Monitoring Station

The environmental monitoring station built for this project consists of a RAK3244 BastWAN breakout board from RAKwireless [14] for processing and transmitting data from sensors, a BME680 gas sensor from Bosch Sensortec [15], a DS18B20 temperature sensor from Maxim Integrated [16], a CMS00810C soil moisture sensor from Elecrow [17] and an ML8511 ultraviolet sensor from LAPIS Semiconductor [18] as shown in Fig. 2 and Fig. 3. The station also includes a lithium polymer battery and a solar panel as its power source. RAK3244 is programmed on the Arduino environment since the board is compatible with it [19] and its ecosystem provides a large number of useful libraries.

Fig. 1. RAK3244 BastWAN breakout board.

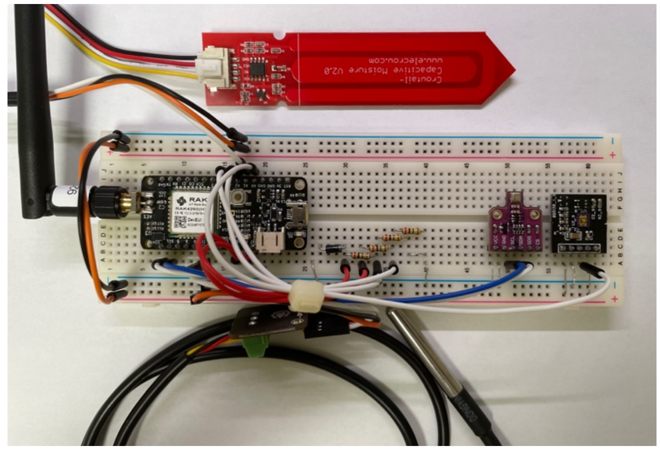

Fig. 2. A RAK3244 (black rectangular PCB with an antenna attached) with a CMS00810 (red PCB), a BME680 (purple PCB), an ML8511 (black square PCB), a DS18B20 (silver probe) connected.

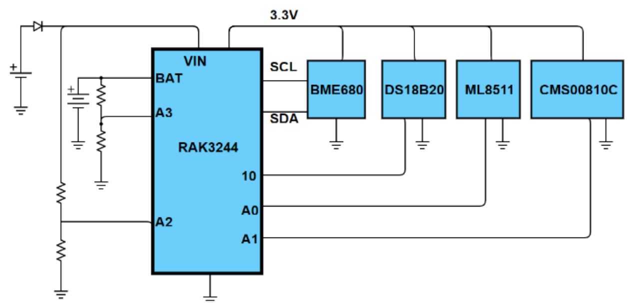

Fig. 3. Schematic of the environmental monitoring station.

A. *Power Sources*

The monitoring station is powered by two power sources: a solar panel that can output 5V 200mA and a 3.7V 350mAh lithium polymer battery. The solar panel provides power to the station and charges the battery during the daytime. The battery will take over the power supply once the output voltage of the solar panel drops significantly due to no sunlight. This setup enables the station to operate in areas where there is no external power available and eliminates the need for frequent maintenance by users such as battery replacement.

B. *Data Gathering*

The processor board communicates with the sensors to measure ambient temperature, ambient relative humidity, barometric pressure, gas resistance, soil temperature, soil moisture level and ultraviolet intensity. Also, the voltage of power sources is measured. The data from sensors is collected every 5 minutes.

1) Ambient Temperature, Ambient Relative Humidity, Barometric Pressure and Gas Resistance

Ambient temperature, ambient relative humidity, barometric pressure, and gas resistance are measured with the BME680 gas sensor. The sensor connects to the processor board using an inter-integrated circuit (I^2C) interface and provides the values in human-readable formats [15].

2) Soil Temperature

Soil temperature is measured with the DS18B20 temperature sensor. The sensor communicates with the processor board using a 1-wire interface and provides the value in a human-readable format [16].

3) Soil Moisture Level

The soil moisture level is measured with the CMS00810C soil moisture sensor. The sensor outputs analog voltage [17]. The processor board reads the ADC value and sends the ADC value to a server as-is. This is because the manufacturer doesn't provide the characteristics of the CMS00810C soil moisture sensor. However, it is possible to map the value of soil moisture to soil tension using a tensiometer during future development.

4) Ultraviolet Intensity

Ultraviolet intensity is measured with the ML8511 ultraviolet sensor. The sensor outputs analog voltage relative to the ultraviolet intensity it is sensing. The processor board reads this voltage (ν) and converts it to a human-readable format using (1) which is based on a characteristic graph provided in [18].

$$15(\nu - 0.99) / 1.81 \qquad (1)$$

5) Power Source Voltage

The station has two power sources: a solar panel and a lithium polymer battery. The voltage of each power source is monitored through a voltage divider to halve the original voltage since both battery voltage and solar panel voltage can exceed the maximum logic input voltage of RAK3244 (3.3V) [14].

C. Data Encoding

As LoRa and LoRaWAN are designed to provide long-range wireless communication while consuming less power compared to other wireless technologies by compromising data transfer rate, it is important to keep data payload as compact as possible to transfer data successfully and to minimize power draw [20]. To achieve the compactness required by this limitation, collected values are manipulated by multiplying and/or subtracting constants to eliminate decimal points in them and to adjust the values to fit into 8-bit or 16-bit, signed or unsigned integers depending on data as shown in Table 1. As a result, the station generates a 16-byte data payload after every data collection.

TABLE I. DATA ENCODING

Byte Index	Data	Data Manipulation[a]	Data Type
0	Battery voltage	100v – 320	8-bit unsigned integer
1	VIN voltage	10v	8-bit unsigned integer
2, 3	Ambient temperature	100v	16-bit signed integer[b]
4, 5	Ambient humidity	100v	16-bit unsigned integer[b]
6, 7	Barometric pressure	10v	16-bit unsigned integer[b]
8, 9	Gas resistance	100v	16-bit unsigned integer[b]
10, 11	Soil temperature	100v	16-bit signed integer[b]
12, 13	Soil moisture	v (unmodified)	16-bit unsigned integer[b]
14, 15	Ultraviolet intensity	100v	16-bit unsigned integer[b]

a. 'v' denotes value from the data gathering stage.

b. Big-endian (MSB first) byte order.

D. Data Transmission

Data transmission by the environmental monitoring station is handled by the Beelan-LoRaWAN library [21] which is used in example code written by the manufacturer of RAK3244 [19]. However, this library doesn't support KR920-230 (KR920 for short), the frequency band that all LoRaWAN devices should be operating on in South Korea [22]. As the environmental monitoring station was going to be deployed in South Korea for testing purposes, adding KR920 support to this library was required. This was done by adding constants that state frequencies and data rates that are specified in [22]. Channel selection logic for KR920 is also added so that the library can choose an appropriate channel to transmit and/or receive data according to the KR920 specifications.

The station joins a LoRaWAN network by Over the Air Activation (OTAA) [23] join procedure at boot-up. Several keys to encrypt the LoRaWAN packet is negotiated between the station and the LoRaWAN network server during the device activation procedure [24]. This ensures data transfer between the environmental monitoring station and the application server to be safe and secure.

After each data collection and encoding, the station sends generated data packet to a LoRaWAN gateway. The station chooses a random channel for each data transmission to minimize interference with other LoRa devices in its vicinity. The data rate used by the station is fixed to SF8BW125 (spreading factor of 8, bandwidth of 125kHz). Since the station only sends out upstream data, it is set to be a class A LoRaWAN device. Hence, it will not receive any downstream data except when performing the OTAA process.

E. Deployment

The hardware of the environmental monitoring station is built on a breadboard to accommodate any changes during this project if needed. Assembled parts were put into a water-resistant plastic enclosure. The enclosure has a transparent window for an ultraviolet sensor and holes for ventilation and for the cables to go through with a hood or sealant applied to prevent water from getting into the enclosure and damaging the electronics.

The finished environmental monitoring station was placed in a green area near an apartment building where the gateway was installed as shown in Fig. 4 and Fig. 5. The distance between the station and the gateway is approximately 22 meters and there is a brick wall between them. In this condition, the environmental monitoring station was able to send data without dropping any packets.

Fig. 4. Finished environmental monitoring station deployed in a green area.

Fig. 5. Gateway and the environmental monitoring station installation points marked on a satellite image.

IV. LoRaWAN Infrastructure

The environmental monitoring station connects to the internet via a LoRaWAN network. Data packets generated by the station go through a couple of components before they can be consumed by an application server for data storage and analysis: a LoRa gateway and a LoRaWAN network server.

A. LoRaWAN Gateway

A LoRaWAN gateway receives LoRaWAN messages from end devices and relays these messages to a LoRaWAN network server using its backhaul connection such as Ethernet, Wi-Fi or LTE [24]. In this project, a RAK7258 WisGate Edge Lite LoRaWAN gateway from RAKwireless [25] is used. It is configured to use Wi-Fi as its backhaul connection and relays LoRaWAN messages to a LoRaWAN network server using packet forwarder mode.

Fig. 6. RAK7258 WisGate Edge Lite LoRaWAN gateway.

B. LoRaWAN Network Server

This project uses The Things Stack developed by The Things Industries [26] for a LoRaWAN network server. It performs various backend tasks such as end-device management and also handles message decryption and payload conversion that are normally handled by an application server for convenience [27]. The results of these operations are exposed through an integrated MQTT broker of The Things Stack. An application server can connect to this MQTT broker and subscribe to topics to receive streams of data.

V. Node-RED

Node-RED is a flow-based programming tool built on Node.js, which is well known for its easy-to-use, intuitive UI and its reusability of built-in libraries [9]. It is widely used for IoT development, from wiring hardware devices to developing a simple user interface. In this project, three functionalities of Node-RED are used.

A. MQTT Connection

Data from the station goes into the Node-RED platform through the MQTT broker of The Things Stack. Node-RED supports a convenient MQTT connection from its built-in library (node-red v2.0.3), receiving data from the MQTT broker can be performed with ease [28].

Connecting Node-RED platform and MQTT broker from The Things Stack requires the public address of the MQTT broker, its port number, username and password. The Things Stack generates an API key as a password. Entering QoS settings and the topic to subscribe or publish is also needed. After a deployment, Node-RED can receive or send data to the MQTT broker.

B. Database Connection

Node-RED supports various kinds of database connections such as MySQL, MongoDB, Firebase, SQLite, OracleDB and PostgreSQL. MySQL is selected for the database of this project, so Node-RED library node-red-node-mysql v0.2.1 [29] is used. This library allows Node-RED basic access to MySQL database such as sending queries to the database and retrieving selected data from the database.

C. User Interface Development

Node-RED provides libraries that contain sets of nodes that enable the developer to make a simple user interface. One of these libraries (node-red-dashboard v2.30.0) [30] provides nodes to create a live data dashboard. It supports features like sidebar, layout, site, theme, widgets, and icons. In this project, widgets like linear chart, gauge, date picker and text input are used to visualize data and facilitate user-interactive functionality.

In addition, a library that supports email connection is also used (node-red-node-email v1.12.3) [31]. This library needs valid email credentials for the email server. It sends the payload of the message object and fetches emails from an IMAP or POP3 server. This project includes an e-mail notification system according to certain measurement values using the library.

VI. Database

Just by receiving sensor data directly from the sensors, Node-RED can already show the tendency of weather data for a short period. However, farming is not a work for few days, it lasts for months and even years. Therefore persisting data for a longer period is essential for statistical purposes.

To achieve this, storage for environmental data was needed. In this project, the MySQL database system is used. Data fields are defined as shown in Table 2.

TABLE II. DATA FIELDS

Field name	Data type
msgID	Varchar(20)
Time	Datetime
Battery_voltage	Decimal(4,2)
VIN_voltage	Decimal(4,2)
Ambient_temperature	Decimal(4,2)
Ambient_humidity	Decimal(4,2)
Barometric_pressure	Decimal(6,2)
Gas_resistance	Decimal(4,2)
Soil_temperature	Decimal(4,2)
Soil_moisture	Int
UV_intensity	Decimal(4,2)

VII. Result and Discussion

All the components mentioned above: the environment monitoring station, the LoRaWAN infrastructure, Node-RED-based cloud platform and database becomes an IoT environmental monitoring system.

A. System Design

Fig. 7 shows the structure of the system that is built in this project. LoRaWAN network server is The Things Network, storage is MySQL, and Node-RED chart is the analytics.

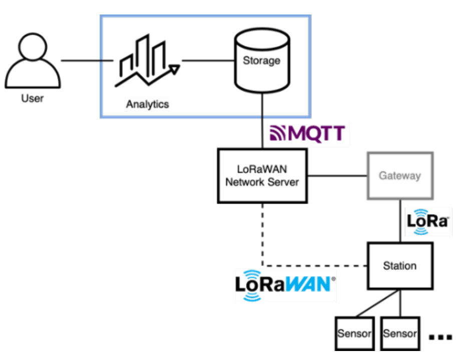

Fig. 7. System structure diagram of the environmental monitoring system.

B. Flowchart

Fig. 8 shows a flowchart of the whole system.

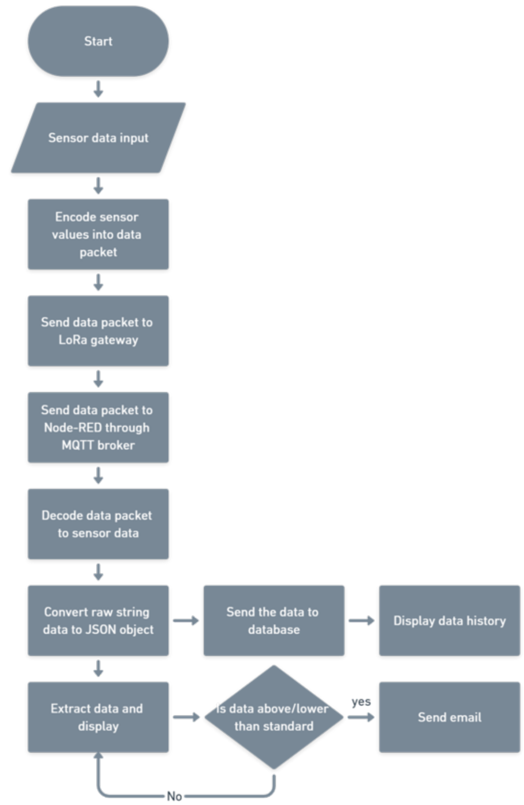

Fig. 8. System flowchart of the environmental monitoring system.

C. Implementation

1) Real-time Sensor Data

Fig. 9 shows the most recently sent environmental data. The linear chart shows data sent within one hour until now. Battery, VIN voltages, Gas Resistance and UV intensity will be shown in the form of gauge charts, and the rest will be shown in the form of linear charts.

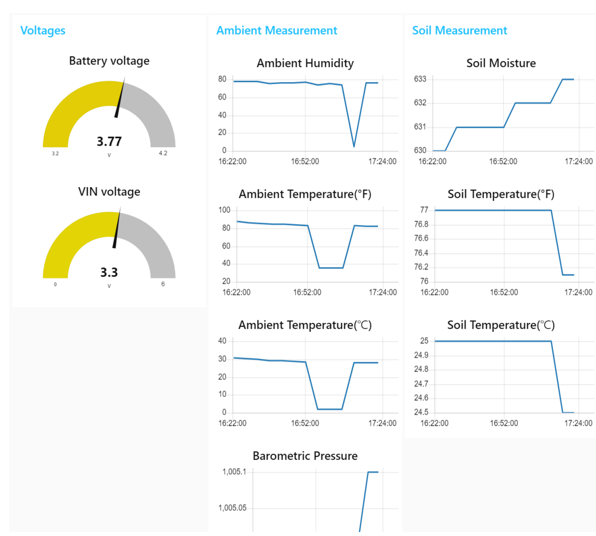

Fig. 9. Screenshot of the real-time data page.

2) History

History is the name of a subgroup of pages. It includes *History, Daily history, Weekly history, Monthly history, Yearly history* page. The history page represents the entire data of a specific period stored in the database. Other pages show the data from each period. Fig. 10 shows the Daily history page. For now, the only significant page is the Daily history page since no data is older than one week. However, every history page is working as expected.

Fig. 10. Screenshot of the daily history data page.

3) Email Notification System

As shown in Fig. 11, the user can set threshold values to enable the system to send email notifications when the environmental data value goes beyond or under that. Fig. 12 shows that the notification system is working when the ambient temperature goes under 33, the value set by the user.

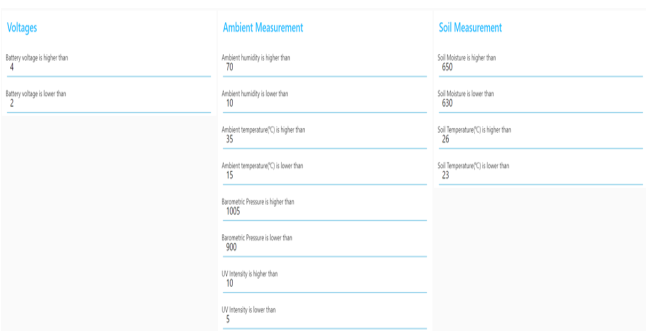

Fig. 11. Screenshot of the Settings page.

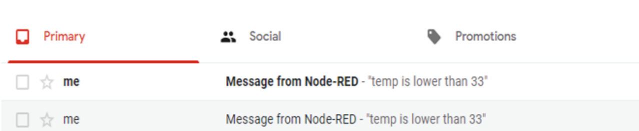

Fig. 12. Email notification from the Node-RED platform.

D. Limitations

This project successfully shows how an IoT environmental monitoring system using LoRaWAN, MQTT and Node-RED. However, some points can be improved in the future.

1) Data Accuracy

Although the best effort was made to measure data as accurately as possible, two unexpected results were seen: abnormally high ambient temperature during daytime and sudden drops of the values.

High temperature value during daytime is caused by direct sunlight exposure to the environment monitoring station. This problem was expected, and a ventilation hole was made to the enclosure to make sure the sensor has direct contact with the air outside the enclosure. However, this wasn't enough, and the sensor is still affected by the heat built up in the enclosure. This can be addressed by using a Stevenson Screen rather than a closed plastic enclosure as the outer case of the station.

Sudden drops of the values were seen randomly throughout this project. Bad connections between the processor board and the sensors due to the poor build quality of the breadboard used in this project are suspected to be the cause of this issue. If this assumption is correct, this problem can be eliminated by using a higher-quality breadboard or a printed circuit board to connect the components. Adding logic to ignore the unexpected can be another solution.

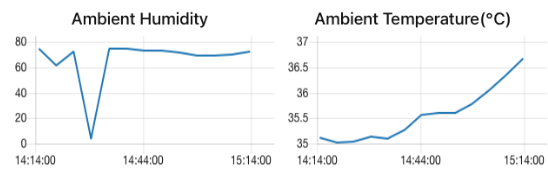

Fig. 13. Example of the sudden drop of value and high temperature reading.

2) Battery Life

The environmental monitoring station runs on a 300mAh lithium polymer battery when there is no sunlight available. This battery is enough to power the weather station during nighttime when it is sunny during the daytime, still, the station experienced a power cut-off on a rainy day. The processor of the station is programmed to go into sleep mode between each data collection and transmission. However, it appears standby power consumption of the sensors is high enough to drain the battery even when they are not used. Adding power control capability to the processor so that it can control the supply of power to the sensors or replacing the battery with the one that has higher capacity can solve this problem.

3) Soil Moisture Data Representation

A capacitive soil moisture sensor, which measures the soil's change in capacitance according to the amount of water contained in the soil is used in this project. In the current setup of the system, the soil moisture value decreases when the moisture content of the soil rises. This can be counter-intuitive to the user.

A device called tensiometer can be used to mitigate this problem. It is a device used in soil science to determine the matric water potential of the area between the surface of the earth and the groundwater [34]. It represents the availability of water to the plant. Its outputs are easier to interpret and suitable for measurement at the same location over an extended period [32]. In [33] the author carried out an experiment to calibrate a soil moisture sensor using a tensiometer. Calibrating the soil moisture sensor using a tensiometer like this in this project can improve user readability and accuracy of the soil moisture data.

VIII. Conclusion

This project proposes an environmental monitoring system for large farmland with LoRaWAN, MQTT, and Node-RED.

The main goal of this project is to advance prior studies to enable long-distance communication and to visualize environmental data in various ways. As mentioned in section I, LoRa is suitable for long-distance communication. Hence, the environmental monitoring station and the Node-RED application server communicate with LoRaWAN and MQTT. The easy-to-use characteristic of Node-RED reduces a significant amount of time and effort to connect to the MQTT broker and construct the user interface. Node-RED receives the collected data from the station and visualizes them in graphs and gauges. Also, it provides the notification system with user-interactive settings.

This shows that on vast farmland, farmers can monitor localized environmental data through the proposed environmental monitoring system. The various ways of providing environmental data and the e-mail notification system provided users a convenient way to ingest the environmental data. Altogether, the system becomes a user-friendly smart farm, not only a high-tech smart farm.

Furthermore, limitations stated in section VII can be improved by: replacing the breadboard or replacing logic to increase data accuracy, adding a power control capability to the processor or replacing the battery to compensate for significant dormant power draw of the station and calibrating the soil moisture sensor using a tensiometer to improve soil moisture data representation.

References

[1] A. Gemert, “The farming of tomorrow is already here: How LoRaWAN® technology supports Smart Agriculture & Precise Animal Production,” LoRa Alliance, Fremont, CA, USA, Nov. 2020. Accessed: Aug. 20, 2021. [Online]. Available: https://lora-alliance.org/wp-content/uploads/2020/12/THE-FARMING-OF-TOMORROW-IS-ALREADY-HERE-HOW-LoRaWAN%C2%AE-TECHNOLOGY-SUPPORTS-SMART-AGRICULTURE-PRECISE-ANIMAL-PRODUCTION.pdf

[2] K. Sivanraju, “IoT in Agriculture: Smart Farming,” *IJSRCSEIT*, vol.3, no.8, pp.181-184, 2018.

[3] N. V. Dharwadkar and R. K. M. Math, “IoT Based Low-cost Weather Station and Monitoring System for Precision Agriculture in India,” *International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud)*, 2018, pp. 81-86

[4] A. J. Onumanyi, A. M. Abu-Mahfouz, and G. P. Hancke, “Low Power Wide Area Network, Cognitive Radio and the Internet of Things: Potentials for Integration,” Sensors, vol. 20, no. 23, p.6837, Nov. 2020.

[5] S.-H. Mah and B.-S. Kim, “LoRa Technology Analysis and LoRa Use Case Analysis By Country,” *The Journal of The Institute of Internet, Broadcasting and Communication*, vol. 19, no. 1, pp. 15-20, Feb. 2019.

[6] “MQTT: The Standard for IoT Messaging”. MQTT. https://mqtt.org/. (accessed Aug. 19, 2021).

[7] O. Deschambault, A. Gherbi, and C. Légaré, “Efficient Implementation of the MQTT Protocol for Embedded Systems,” *Journal of Information Processing Systems*, vol. 13, no. 1, pp. 26-39, Feb. 2017.

[8] S. Lee, H. Kim, D. K. Hong, and H. Ju, “Correlation analysis of MQTT loss and delay according to QoS level,” in *Proc. International Conference on Information Networking (ICOIN)*, 2013, pp. 714-717.

[9] *Node-RED*. (v.2.0.5). OpenJS Foundation. Accessed: Aug. 18, 2021. [Online]. Available: https://nodered.org/

[10] D. Sunehra and M. Srinidhi, "Implementation of Smart Urban Farming using Raspberry Pi, Arduino and Node-RED Platform," In *Proc. IEEE International Conference for Innovation in Technology (INOCON)*, 2020, pp. 1-6.

[11] “What is the maximum communication range of the Bluetooth connection?” SONY. https://www.sony.com/electronics/support/articles/00014085 (accessed Aug. 19, 2021)

[12] B. Mitchell. “What Is The Range of a Typical Wi-Fi Network?” Lifewire. https://www.lifewire.com/range-of-typical-wifi-network-816564 (accessed Aug. 19, 2021)

[13] H. W. Yoon, D. J. Kim, M. Lee, C. Weon and A. Smith, "L & M Farm: A Smart Farm based on LoRa & MQTT," in *Proc. International Conference on Omni-layer Intelligent Systems (COINS)*, 2020, pp. 1-6.

[14] RAKwireless, “RAK3244 BastWAN Breakout Board Datasheet,” RAK3244 datasheet, Jul 2021

[15] Bosch Sensortec, “Low power gas, pressure, temperature & humidity sensor,” BME680 datasheet, Jan. 2021

[16] Maxim Integrated, “Programmable Resolution 1-Wire Digital Thermometer,” DS18B20 datasheet, Jan. 2007 [Revised Jul. 2019]

[17] “Crowtail-Capacitive Moisture V2.0.” Elecrow Wiki. https://www.elecrow.com/wiki/index.php?title=Crowtail-Capacitive_Moisture_V2.0 (accessed: Aug. 16, 2021)

[18] LAPIS Semiconductor, “UV Sensor with Voltage Output,” ML8511 datasheet, Mar. 2013

[19] RAKwireless Technology, Shenzhen, GD, CN. *BastWAN Quick Start Guide* (2021). Accessed: Aug. 19, 2021. [Online]. Available: https://docs.rakwireless.com/Product-Categories/WisDuo/BastWAN/Quickstart/

[20] “Limitations.” The Things Network. https://www.thethingsnetwork.org/docs/lorawan/limitations/ (accessed Aug. 19, 2021)

[21] *Beelan-LoRaWAN*. (ver. 2.0.0). Beelan. Accessed: Aug. 19, 2021. [Online]. Available: https://github.com/BeelanMX/Beelan-LoRaWAN

[22] *LoRaWAN Regional Parameters*, RP002-1.0.2, LoRa Alliance, Fremont, CA, USA, Oct. 8, 2020. [Online]. Available: https://lora-alliance.org/wp-content/uploads/2020/11/RP_2-1.0.2.pdf

[23] “What are LoRa® and LoRaWAN®?”. LoRa DEVELOPER PORTAL. https://lora-developers.semtech.com/library/tech-papers-and-guides/lora-and-lorawan/ (accessed Aug 19, 2021).

[24] “LoRaWAN Architecture.” The Things Network. https://www.thethingsnetwork.org/docs/lorawan/architecture/ (accessed: Aug. 19, 2021)

[25] “Connect to the IoT cloud even indoors with RAK7258 from RAKwireless.” RAKwireless. https://www.rakwireless.com/en-us/products/lpwan-gateways-and-concentrators/rak7258 (accessed: Aug. 19, 2021)

[26] *The Things Stack.* (v3.14.1). The Things Industries. Accessed: Aug. 19, 2021. [Online]. Available: https://www.thethingsindustries.com/stack/

[27] N. Selimović, B. Olayinka and A. Mares. “Application Server”. The Things Stack Documentation. https://www.thethingsindustries.com/docs/reference/components/application-server/ (accessed Aug. 19, 2021)

[28] “Connect to an MQTT Broker,” Node-RED Cookbook. https://cookbook.nodered.org/mqtt/connect-to-broker. (accessed: Aug. 18, 2021)

[29] *node-red-node-mysql*. (v0.2.1). JS Foundation. Accessed: Aug. 18, 2021. [Online]. Available: https://flows.nodered.org/node/node-red-node-mysql

[30] *node-red-dashboard*. (v2.30.0). JS Foundation. Accessed: Aug. 18, 2021. [Online]. Available: https://flows.nodered.org/node/node-red-dashboard

[31] *node-red-node-email*. (v1.12.3). JS Foundation. Accessed: Aug. 18, 2021. [Online]. Available: https://flows.nodered.org/node/node-red-node-email

[32] S.R. Grattan and J. Oster. “Field Use of Tensiometers.” Department of Land, Air and Water Resources – UC Davis.

https://lawr.ucdavis.edu/cooperative-extension/irrigation/drought-tips/field-use-tensiometers (accessed: Aug. 18, 2021)

[33] Ltrium. “Soil Moisture Sensor Calibration.” Instructabales circuits. https://www.instructables.com/Soil-Moisture-Sensor-Calibration/ (accessed: Aug. 18, 2021)

[34] W. J. Rawls and D. R. Maidment, Infiltration and soil water movement. New York: McGraw-Hill, 1993.