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Development of Water Quality Control and Monitoring System for Hydroponic Plants with a Cloud-Based System

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Abstract: The research aimed to develop software and hardware to control the water quality of hydroponic plants; create custom software for the ESP8266, turning it into an IoT client capable of seamless integration with AWS IoT cloud-based system; initiate targets integrating and enhancing AWS IoT modules, facilitating automated water quality control functions and building intuitive dashboards for real-time water quality monitoring. The research started with the preparation of hardware and software focusing on aspects of hydroponics, including monitoring water quality, plant response, and the hydroponic system as a whole. Apart from that, TCP/IP networks were built by using Wi-Fi routers, LAN networks, and access to the internet. Then, System development involving hardware modules, software development, and user interface design were conducted. The final research result is the development of an integrated system to control and monitor water quality which is vital for the growth of hydroponic plants. Finally, by developing a hydroponic planting system supporting device that is integrated into a cloud-based system, it is expected to create a digital system that can work automatically to regulate water quality in maintaining the growth of hydroponic plants which is equipped with easy access at any time remotely and from anywhere.

Keywords: Remote Monitoring, Automatic Remote Control, Internet of Things, Cloud-Based System, Hydroponic Water Quality

Introduction

Imagine a lush garden that thrives without soil, where plants thrive on water and nutrients a modern agricultural marvel known as hydroponics. In the heart of a busy city or in a limited home garden, this innovative farming method using water as a medium has revolutionized traditional farming. Here, water enriched with essential minerals flows to fertilize plant roots, a 24/7 hydroponic system. However, in this complex ecosystem, there is a critical need for precision monitoring of water temperature, nutrient balance, and pH levels to ensure hydroponics thrives to its full potential. Coming into the Internet of Things (IoT), a world where cloud-based systems are intertwined with sensor modules, it changes the way people cultivate the plants in gardens of the future. In this digital world, water quality control and continuous monitoring of hydroponic systems transcend physical boundaries, offering not only nutrition but also a seamless monitoring experience that can be accessed anytime, anywhere via the vast internet.

In the research, the integration of an Amazon Web Service (AWS) cloud-based system revolves around several pivotal hardware modules, each playing a strategic role. The core components include an Arduino open hardware single-board microcontroller, the versatile ESP8266, alongside specialized sensors for water pH, Electrical Conductivity (EC), water temperature, and environmental temperature. The Arduino microcontroller serves as a foundational platform, equipped with a microcontroller enabling the development of application programs crucial for data retrieval from sensors and overseeing pH/EC dosing-pump control. In parallel, the ESP8266 assumes the role of an IoT client, acting as the gateway linking the hydroponic system to AWS IoT CORE via the MQTT protocol.

Objectives and Benefits

The aims of the research include three interconnected and important objectives for advancing hydroponic systems and ultimately strengthening food security. First, the research focuses on pioneering software and hardware development by utilizing Arduino open software and hardware as the main module to control hardware functions and collect essential materials data regarding the water quality of hydroponic plants from the sensor module. Second, the research creates custom software for the ESP8266, turning it into an IoT client capable of seamless integration with AWS IoT cloud-based systems. The ultimate goal here is seamless connectivity between hydroponic systems and cloud infrastructure.

Additionally, the research also initiatives target integrating and enhancing AWS IoT modules, facilitating automated water quality control functions, and building intuitive dashboards for real-time water quality monitoring. By leveraging this integration in a cloud-based system, the goal is to create a digital framework capable of autonomously managing water quality, thereby maintaining optimal growing conditions for hydroponic plants. This digital infrastructure, which can be accessed remotely from any location, embodies the essence of accessibility and convenience.

The next phase of the research roadmap aims to improve automated control systems by combining edge computing and advanced analytics. This augmentation aims to improve water quality maintenance for hydroponic planting, in order to increase precision and accuracy.

Ultimately, by improving hydroponic systems through digitalization and automation, the research benefit indicates democratized access to sustainable food sources, offering a pathway to greater self-sufficiency and resilience in local food production. Especially, this digitalized and automated hydroponic systems are able to develop family food security in which the harvested vegetables can be both consumed and sold in the market.

Hydroponic Technology

With a hydroponic system, plants can grow without using soil media. Water that has been mixed with mineral nutrients needed by plants is placed in a reservoir, then the water is drained to the plant roots with the help of a water pump. By utilizing the force of gravity, this water will flow by itself to the water reservoir through a predetermined pipeline. In addition to maintaining the height, flow, and temperature of water, pH and EC of water are very important to always be observed and controlled, plants will lose the ability to absorb the nutrients needed if the pH value of the water does not match the characteristics of the plant (Rajaseger, 2023).

Hydroponic technology has been around for centuries, but it has only recently become widely adopted in commercial agriculture. This is due in part to recent advancements in hydroponic technology, such as the development of new nutrient solutions and the use of automated systems. These advancements have made hydroponics a more viable and profitable option for growers (Rajaseger, 2023).

The following are some of the hydroponic system techniques currently available (Grigas *et al.*, 2020; HydroPros, 2019): Deep water culture, nutrient film technique, Aeroponic, EBB, and flow and drip system.

Farming using a hydroponic system will have many advantages. With good water management, the plants will grow bigger and faster than the planting system using soil media. The utilization of water also becomes more efficient by using a rotating system. Thus the hydroponic system is more environmentally friendly, cleaner, and healthier in an effort to increase food security.

Arduino Minimum System

Arduino is defined as a minimum system that is open source for hardware or software (Arduino, 2020). The Arduino board can read input from analog or digital sensors, and press buttons, to receive information via a computer network, which is then processed into an output with the support of a microprocessor on the board. Arduino also provides supporting software to make software applications easier, namely by providing the Arduino programming IDE and the Arduino software library (Arduino Project Hub, 2020).

In this study, the minimum system module "MEGA + Wi-Fi R3 ATmega2560+ ESP8266" is used, which is an Arduino Compatible Board with an ATmega2560 microcontroller designed for minimum system development purposes equipped with capabilities as a WEB server (RobotDyn, 2020), WEB client and Wireless Access. Point by using the ESP8266 module (DFRobot, 2020; Espressif Systems, 2020).

Sensor Module

To measure water pH, a pH sensor is used which is a low-cost probe with SKU: SEN0161, while measuring water conductivity using the DFRobot gravity analog electrical conductivity sensor EC meter. These two sensors are connected to the Analog input pin on the microcontroller while measuring water temperature using the DS18B20 waterproof temperature sensor, which is connected to the digital pin on the ATmega2560 microcontroller module. Measurement data from these three sensors will be sent to AWS IoT CORE via the ESP8266 module using the MQTT protocol (Espressif Systems, 2020).

The DS18B20 waterproof temperature sensor is used to measure the water temperature in the water reservoir in the hydroponic system, as well as measure the environmental temperature around the hydroponic system. It is said that "This sensor is capable of operating in a temperature range of up to 125°C Celsius and produces digital output with a resolution of 9-12 bits" (Espruino, 2020; Maxim Integrated, 2019).

The DS18B20 operates over a wide voltage range, typically 3.0-5.5 V, and has a conversion time of 750 ms. The DS18B20 features high and low-temperature alarm outputs, which can be programmed by the user, is compatible with various microcontrollers, and can be easily integrated into different digital systems.

Amazon Web Service (AWS) IoT

Amazon Web Services (AWS) stands as a robust cloud computing platform renowned for its global accessibility, stringent security protocols, user-friendly interface, exceptional flexibility, reliability, scalability, and cost-effectiveness. As hydroponic technology continually evolves, recent advancements, such as those observed in, emphasize the imperative of integrating digital solutions for precision agriculture. Within this landscape, AWS serves as a pivotal tool offering an array of services, including virtual servers, databases, storage, analytics, machine learning, networking, and the Internet of Things (IoT) (AWS, 2022i). This study strategically positions itself within the current hydroponic technology landscape, leveraging the capabilities of AWS to foster innovation in monitoring and controlling hydroponic systems.

Amazon Web Service (AWS) IoT CORE

AWS IoT provides cloud services that can be used to connect Internet of Things (IoT) devices or modules to other IoT devices and to AWS cloud services (AWS, 2022i). As depicted in Fig. 1, AWS IoT facilitates the connection of each registered IoT device to AWS services through various protocols supported by AWS IoT CORE. These protocols include MQTT, MQTT over WSS, HTTPS, and LoRaWAN, enabling a variety of connectivity options for IoT devices operating within the AWS framework (AWS, 2022b-c).

AWS IoT also provides several interfaces, namely: AWS IoT Device SDKs, AWS IoT Core for LoRaWAN, AWS Command Line Interface (AWS CLI), AWS IoT API, and AWS SDKs. In addition, the AWS IoT console is also available which is equipped with a GUI to configure and manage things, certificates, rules, jobs, policies, and other elements as part of an IoT solution.

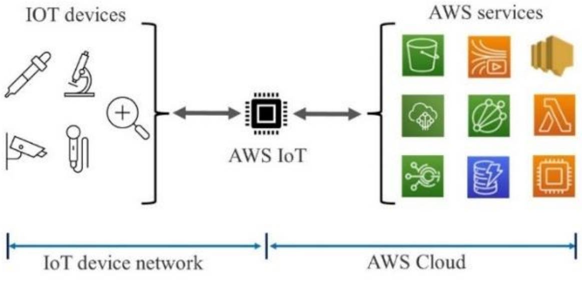


Fig. 1: AWS IoT

Amazon Web Service (AWS) IoT Events

Amazon Web Service (AWS) IoT Events is a service provided by AWS to handle every event from an IoT device by providing responses based on simple “if-then-else” event logic and state. AWS IoT Events can receive input from a variety of sensor device sources and services built into AWS IoT. Each detected event will change the state which is the conditional logic model of the process set stored in the detector model (AWS, 2022e).

Broadly speaking AWS IoT Events can help with several use cases related to remote monitoring and control for IoT devices, automated systems, data telemetry, and notification systems. Meanwhile, action responses that are often used in AWS IoT Events are triggering functions from AWS Lambda, saving data to AWS S3, writing records to AWS DynamoDB, and republishing a message via AWS IoT CORE (AWS, 2022e).

Amazon Web Service (AWS) S3

S3 is a simple cloud object storage service provided by Amazon web service with guaranteed security, data availability, scalability, and high performance. Each data by AWS S3 will be stored as objects in resources called "buckets". The largest size for an object that can be stored in AWS S3 is 5 terabytes (AWS, 2022g).

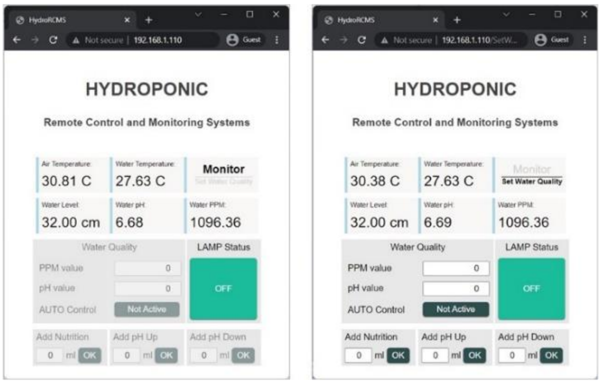
AWS S3 can also be used for static website services by including static content. In simple terms, to activate a static website service is to change the "Static website hosting" attribute in the "properties" menu from one of the "Buckets" to "Enable". HTTPS cannot be implemented on Amazon S3 website endpoints. The solution provided by AWS is to use Amazon CloudFront and Amazon Route 53 for services with custom domains.

The choice of AWS S3 for static website services, coupled with CloudFront and Route 53 for additional functionalities, can be motivated by its scalability, ease of use, integration capabilities, cost-effectiveness, and strong security and reliability features.

Results on Previous Research

In previous research, the pH sensor module can be activated together with the conductivity sensor and runs automatically, but the measurement results are unstable and sensitive to changes in voltage. This causes an error in making the decision to run the motor from a dosing pump so that the process of maintaining water quality takes longer and occurs in several iterations.

The ability to store data in an embedded system is very limited, so additional memory modules are needed. Therefore, to avoid this constraint, a cloud-based system will be implemented in the research. With more sample data, it is hoped that decision-making to maintain water quality stability will be more stable and precise.



Air Temperature: 30.81 C
Water Temperature: 27.63 C
Water Level: 32.00 cm
Water pH: 6.68
Water PPM: 1096.36
PPM value 0
pH value 0
AUTO Control Not Active
Add Nutrition 0 ml
Add pH Up 0 ml
Add pH Down 0 ml

Not secure | 192.168.1.110/SetW...
Air Temperature: 30.38 C
Water Temperature: 27.63 C
Water Level: 32.00 cm
Water pH: 6.69
Water PPM: 1096.36
PPM value 0
pH value 0
AUTO Control Not Active
Add Nutrition 0 ml
Add pH Up 0 ml
Add pH Down 0 ml

Fig. 2: Hydroponic web application

Making an embedded web application to monitor water quality conditions and regulate the pH and conductivity of water remotely via a TCP/IP network can be seen in Fig. 2. In the hydroponic web application.

Monitoring mode is for observing water quality, while set water quality mode is for changing the value of the pH content or nutrient content in water. When the OK button is pressed, the dosing pump will turn on and pump the liquid from the pH or mineral nutrition tube to the water in the hydroponic system pipe.

Automatic mode will make the system always take measurements. If the measurement results are less than the lower limit or exceed the upper limit, then the dosing pump will work to add nutrients or pH-adjusting fluids until it is in the desired range.

Materials and Methods

Materials used in this research:

- MEGA + Wi-Fi R3 ATmega2560+ ESP8266
- DS18B20 waterproof temperature sensor
- HC-SR40 ultrasonic distance sensor
- SEN0161 pH sensor
- Electric conductivity sensor
- Dosing pump

The research applies an experimental method. Data collection involves gathering information on water quality, plant response, and overall hydroponic system performance. The experimental procedure follows a structured flow, starting with the preparation of hardware components such as water quality sensors, dosing pump controllers, and Wi-Fi-connected microcontrollers. On the software side, the research utilizes the Arduino IDE, various Arduino libraries, and web programming languages such as HTML and CSS. The research focuses on hydroponics aspects, emphasizing the monitoring of water quality and plant responses.

The flow of research is conducted based on the fishbone diagram presented in Fig. 3. It starts with the preparation of hardware, such as water quality sensors, dosing pump controllers, and microcontrollers connected to Wi-Fi. On the software side, the Arduino IDE, various Arduino libraries, and web programming languages such as HTML and CSS are used. Research focuses on aspects of hydroponics, including monitoring water quality, plant response and the hydroponic system as a whole. Apart from that, TCP/IP networks are an important foundation, through the use of Wi-Fi routers, LAN networks, and access to the internet. Then, system development involves hardware modules, software development, and user interface design. Indicators of the success of this project include a stable TCP/IP connection, optimal water pH control capabilities, and effective system observation functions. The final research result is the development of an integrated system to control and monitor water quality which is vital for the growth of hydroponic plants.

System Design

To build a hydroponic plant observation and control system, several hardware and software modules are needed which are selected for specific reasons to support overall system functions.

The water sensor hardware modules pH, water conductivity, water level, water temperature, and air temperature were selected because of their ability to provide important information regarding the environmental conditions necessary for optimal hydroponic plant growth.

The pH up, pH down, nutrient A, and nutrient B liquid dosage control hardware modules were chosen because of their crucial role in regulating and maintaining the right nutrient balance for hydroponic plants.

Microcontroller hardware module with Wi-Fi module and ESP8266 module as the IoT gateway were selected because of their ability to integrate data from sensors and controllers into the cloud, enabling remote access and control.

The existence of a Local Area Network (LAN), internet router, and internet access provides the network infrastructure needed to connect the system to the cloud and access remotely.

The use of AWS IoT device SDKs, Arduino open software libraries, and Python and node JS software libraries were chosen to support integration between hardware and software modules, ensuring compatibility, as well as the system's ability to process, store, and manage data efficiently.

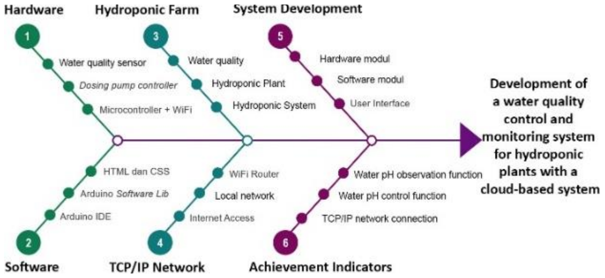


Fig. 3: Research flow based on fishbone diagram

This combination of hardware and software modules was carefully selected to interact synergistically, provide accurate information, and empower the hydroponic plant observation and control system to achieve optimal growing conditions.

Research Stages

In the research, integration is carried out to cloud-based systems, hardware development, and software development which are refinements of the results of previous research, with the following research stages:

- Collection of data and information related to hardware modules and supporting software libraries
- Develop software in a modular way for each hardware module that has been running well functionally
- Integration of hydroponic systems into cloud-based systems via Internet access
- The results of the development of hardware and software modules are then applied to a hydroponic planting trial system in a network

System Development

The waterfall model (Pressman, 2014) was chosen because of its structured and systematic approach to software development, allowing for distinct stages that ensure clarity in each phase of the project. The waterfall model is characterized by a linear and sequential flow, where each phase must be completed before moving on to the next. This methodology is particularly suitable for projects with well-defined and stable requirements, as it provides a clear framework for planning, execution, and control. The application of the research can be seen in Fig. 4.

Figure 4 clarifies the initial stages, requirements gathering involves outlining the specific needs of the hydroponic technology system, with a focus on water quality measurement and control. This phase defines the scope of the research and lays the foundation for further development.

The design phase continues, where the system architecture and functionality are carefully planned. This involves envisioning the integration of water quality sensors into an IoT-based cloud system, ensuring seamless data communication and reporting.

The implementation phase looks at the practical application of the planned design. Here, integration of the water quality measurement system into AWS IoT, Static web development on AWS for monitoring, and incorporation of AWS IoT Events for automated control functions are executed. Deviations from the waterfall model occur during this phase to accommodate the dynamic nature of IoT technology. Adjustments are made iteratively to improve integration and ensure compatibility with evolving IoT protocols.

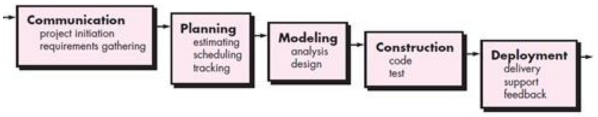


Fig. 4: Waterfall model

After implementation, rigorous testing and evaluation are carried out. This involves assessing the efficiency of AWS IoT Events for automated control functions, the accuracy of data reported from water quality sensors, and overall system performance. Any deviations from the initial design or implementation are documented, allowing for corrective action to be taken.

The final deployment and maintenance phase aims to roll out the system and ensure its continued functionality. Although the waterfall model typically follows a linear sequence, deviations occur primarily during the implementation and testing phases due to the need for iterative adjustments inherent in IoT integration. This deviation is necessary to accommodate the evolving nature of IoT technology and to ensure the system's adaptability and efficiency in real-world applications.

Achievement Indicators

The achievement indicators outlined in the research are an integral part of assessing the alignment between research objectives and the results achieved. The successful integration of the hydroponic system into the AWS IoT cloud-based infrastructure is an important milestone that ensures the realization of the research objectives.

Additionally, regular monitoring and storage of water pH and conductivity data in the AWS IoT cloud-based system indicates the system's efficacy in capturing and maintaining important water quality metrics. This achievement directly correlates with the research objective of improving control and monitoring capabilities.

The ability to maintain water quality, particularly in terms of pH levels and conductivity, according to predetermined values via the AWS IoT cloud-based system, underlines the effectiveness of the system in maintaining optimal growing conditions for hydroponic plants, which is directly in line with targeted research results.

In addition, the success of controlling and monitoring water quality remotely via the internet highlights the system's functionality beyond local boundaries, enabling accessibility and control from anywhere, which is the main goal in enabling remote monitoring.

Lastly, the smooth operation of dashboards connected to AWS IoT indicates successful visualization and representation of data, thereby facilitating informed decision-making. Each of these indicators serves as a tangible measure of how the research results align with the overall goal of improving hydroponic technology through IoT integration.

Results and Discussion

Hardware Development

In the research, more related software has been developed from previous research to improve the overall system function. In order for IoT devices to connect to AWS IoT CORE and other AWS services, it is necessary to add software modules related to MQTT and security access. Changes to the layout and arrangement of the LED growing light along with the installation of power cables to the hydroponic system are also needed to maximize lighting.

Minimum Systems Module

The research uses the minimum system module "MEGA + Wi-Fi R3 ATmega2560+ ESP8266", Fig. 5. It is an Arduino-compatible board with an ATmega2560 microcontroller designed for the purposes of developing a minimum system with a Wi-Fi connection that can connect to a TCP/IP-based network (RobotDyn, 2020). Web client and Wireless Access Point using the ESP8266 module (DFRobot, 2020; Espressif Systems, 2020). The following are the specifications of the main hardware module used in the research:

Microcontroller : ATmega2560
IC Wi-Fi : ESP8266
USB-TTL converter : CH340G
Power Out : 5V-800 mA
Power IN. USB : 5V (500 mA max.)
Power IN. VIN/DC Jack : 9-24V
Power consumption : 5V 800 mA
Wi-Fi : Wi-Fi 802.11 b/g/n 2.4GHz
Clock frequency : 16MHz
Digital I/O : 54
Analog I/O : 16
Memory size : 256 kb
Data RAM type/size : 8 kb
Data ROM type/size : 4 kb
Interface type : serial\OTA
Operating temperature : -40/+125°C
Length × width : 53.361×101.86 mm
Antenna : Build-in\external antenna

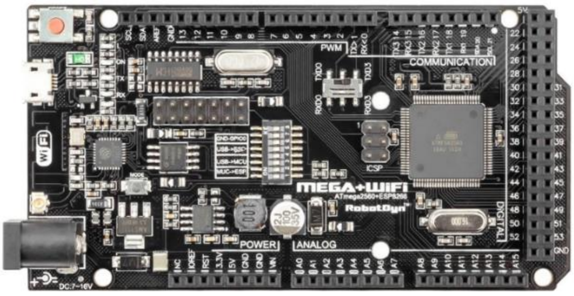


Fig. 5: MEGA + Wi-Fi R3 ATmega2560+ ESP8266 minimum system

Sensor Module

For measuring water pH and water Electric Conductivity (EC), two sensors are needed which are connected to the Analog input pin, while the water temperature measurement is connected to the Digital pin of the ATmega2560 microcontroller module. The results of the sensor measurements will be sent to the ESP8266 module via the internal serial interface to then be forwarded to AWS IoT CORE using the MQTT protocol (Espressif Systems, 2020).

The DS18B20 waterproof temperature sensor is used to measure the temperature of the water in the water reservoir of a hydroponic system. This sensor can be used in environments up to a temperature of 125°C and has a digital output (9-12bit) (Maxim Integrated, 2019).

The water level sensor is needed to determine the water reserves in the water storage area of the hydroponic system. The workings of the HC-SR40 ultrasonic distance sensor by measuring the travel time required for sound to bounce off objects in front of the sensor (Elijah, 2014).

System Architecture Design

Figure 6 clarifies the architecture of implementing IoT devices in a hydroponic system using the minimum system "MEGA + Wi-Fi R3 ATmega2560+ ESP8266". Input data to determine the state of water quality can be obtained from the temperature, pH, and EC sensor modules. The entire data are processed by the ATmega2560 module and forwarded to the ESP8266 via internal serial communication in the minimum system as input data to be forwarded to AWS IoT CORE by the ESP8266 module using the MQTT protocol via a Wi-Fi network connected to the internet. The function of automatic control over the pH value and water nutrition is performed by the AWS IoT Events service. Responses from each event received by AWS IoT Events will be forwarded (republished) to AWS IoT core an order to maintain water quality. The command is received by the ESP8266 using the MQTT protocol via the Wi-Fi network, then forwarded via internal serial communication to the ATmega2650 module to drive the dosing pump pH-up, pH-down, A-mix nutrition, and B-mix nutrition motors via the digital interface I/O.

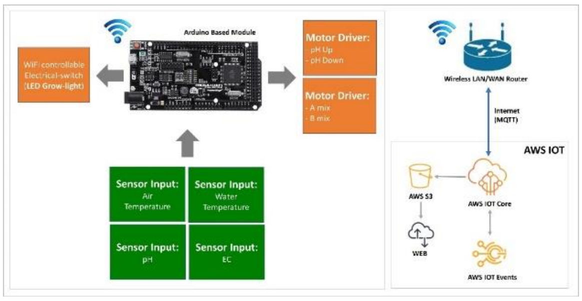


Fig. 6: IoT hydroponic system architecture

Hydroponic IoT devices are connected online to AWS IoT CORE where measurement results are stored in AWS S3. Through the static web available on the AWS S3 service, water quality monitoring can be done using a web browser connected to the internet network. Thus, the hydroponic system can be accessed at any time by client computers from the TCP/IP network connected to the internet.

Hardware Implementation

In previous research, the pH sensor module and conductivity sensor (EC) worked well. In the research, the water pH sensor module was replaced with a newer module in Fig. 7. By replacing the water pH sensor module, measurement results can be more accurate and faster. Automatic control to keep the water pH value more stable and reduce the occurrence of oscillations.

Software Implementation

Following are some of the software configurations that need to be prepared in AWS IoT CORE, namely: IoT device registration, IoT device certificates, and policy settings. Figure 8, after successfully registering an IoT device, you can see it in the AWS IoT service menu, then enter the "manage" menu and select the "things" menu. The IoT device in the research study is named "WaterQualityCM".

To get more detailed information about the configuration that has been done, click "WaterQualityCM". It can be seen in Fig. 9 that "WaterQualityCM" already has Amazon Resource Names (ARN) as a unique identity for AWS resources (AWS, 2022a). In addition, there is also Certificate-ID information that is actively used to ensure security in using AWS cloud services (AWS, 2022h).

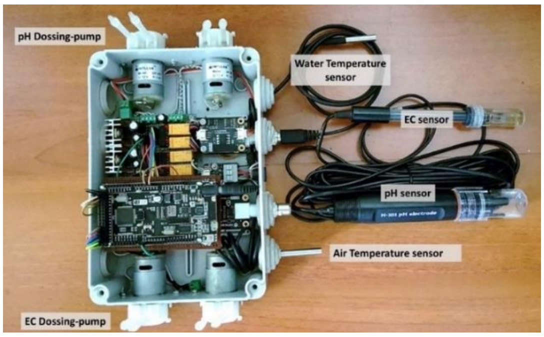
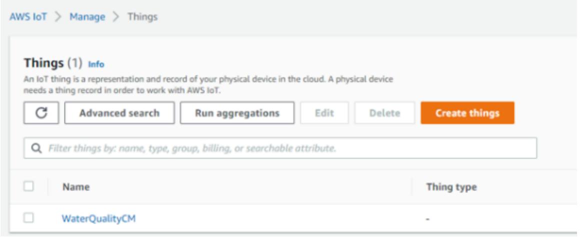


Fig. 7: Hydroponic minimum system

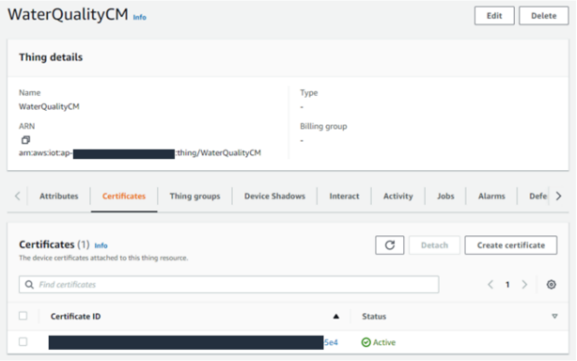


Things (1)

An IoT thing is a representation and record of your physical device in the cloud. A physical device needs a thing record in order to work with AWS IoT.

☐	Name	Thing type
☐	WaterQualityCM	-

Fig. 8: AWS IoT CORE things



WaterQualityCM

Thing details

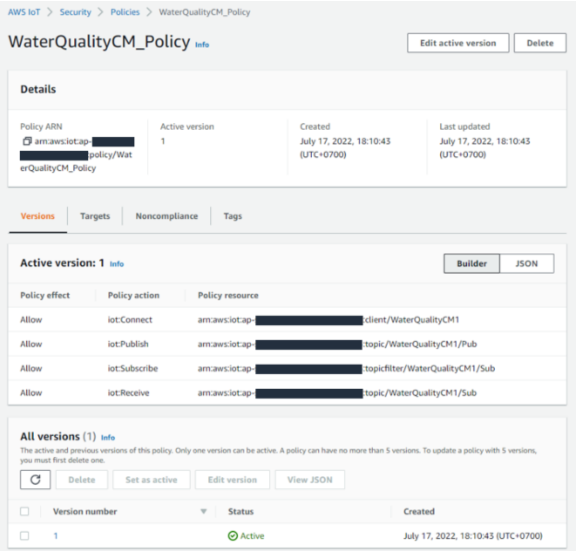
Name: WaterQualityCM
ARN: arn:aws:iot:ap-[redacted]:thing/WaterQualityCM
Type: -
Billing group: -

Certificates (1)

The device certificates attached to this thing resource.

☐	Certificate ID	Status
☐	[redacted]5e4	Active

Fig. 9: AWS IoT CORE certificate



WaterQualityCM_Policy

Details

Policy ARN: arn:aws:iot:ap-[redacted]:policy/WaterQualityCM_Policy
Active version: 1
Created: July 17, 2022, 18:10:43 (UTC+0700)
Last updated: July 17, 2022, 18:10:43 (UTC+0700)

Active version: 1

Policy effect	Policy action	Policy resource
Allow	iot:Connect	arn:aws:iot:ap-[redacted]:client/WaterQualityCM1
Allow	iot:Publish	arn:aws:iot:ap-[redacted]:topic/WaterQualityCM1/Pub
Allow	iot:Subscribe	arn:aws:iot:ap-[redacted]:topicfilter/WaterQualityCM1/Sub
Allow	iot:Receive	arn:aws:iot:ap-[redacted]:topic/WaterQualityCM1/Sub

All versions (1)

The active and previous versions of this policy. Only one version can be active. A policy can have no more than 5 versions. To update a policy with 5 versions, you must first delete one.

☐	Version number	Status	Created
☐	1	Active	July 17, 2022, 18:10:43 (UTC+0700)

Fig. 10: AWS IoT CORE policy

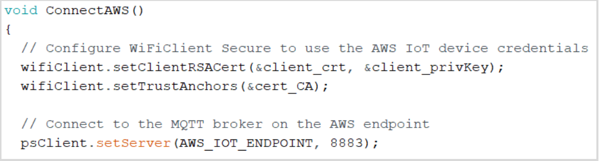
Policy configurations that have been successfully created can be seen in the AWS IoT CORE service by selecting the "security" menu then selecting the "policy" sub-menu and clicking one of the policy lists that have been made. In the research a policy has been successfully created with the name "WaterQualityCM_policy" for several actions in Fig. 10, namely: IoT: Connect, IoT: Publish, IoT: Subscribe, and IoT: Receive (AWS, 2022d).

On the ESP8266 hardware, it is necessary to add some libraries and coding so that hydroponic IoT devices can connect to AWS IoT CORE properly. There are three security certificates that need to be embedded in ESP8266, namely private Certificate Authority (CA), AWS device certificate, and AWS device private key. An example of application in the research can be seen in Fig. 11.

Figure 12 shows a fragment of the program to connect to AWS IoT CORE. The initial step is to apply the certificate required during the authentication process to build encrypted TLS communication channels between IoT devices and AWS IoT CORE. To be able to connect to AWS services, an endpoint is needed in the form of a URL to port 8883 (AWS, 2022f).

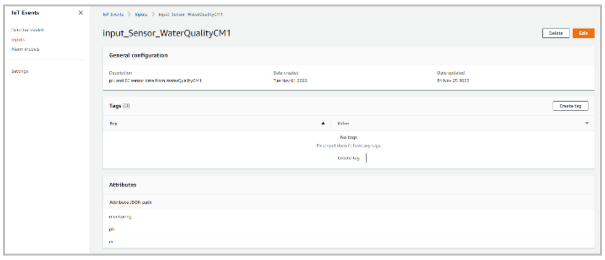
```
// AWS IOT CORE TOPIC
#define AWS_IOT_PUBLISH_TOPIC   "WaterQualityCM1/Pub"
#define AWS_IOT_SUBSCRIBE_TOPIC "WaterQualityCM1/Sub"


WiFiClientSecure wifiClient = WiFiClientSecure();

BearSSL::X509List cert_CA(AWS_CERT_CA);                        //CAPemCertificate
BearSSL::X509List client_crt(AWS_DEVICE_CERT);                 //CertificatePemKey
BearSSL::PrivateKey client_privKey(AWS_DEVICE_PRIVATE);        //PrivatePemKey

PubSubClient psClient(wifiClient);
```

Fig. 11: IoT device certificate



```
void ConnectAWS()
{
  // Configure WiFiClient Secure to use the AWS IoT device credentials
  wifiClient.setClientRSACert(&client_crt, &client_privKey);
  wifiClient.setTrustAnchors(&cert_CA);

  // Connect to the MQTT broker on the AWS endpoint
  psClient.setServer(AWS_IOT_ENDPOINT, 8883);
```

Fig. 12: AWS IoT CORE client



input_Sensor_WaterQualityCM1

General configuration

Description: pH and EC sensor data from WaterQualityCM1
Date created: Tue Nov 01 2022
Date updated: Fri Nov 25 2022

Tags (0)

Key	Value

No tags
This input doesn't have any tags.

Attributes

Attribute JSON path
monitoring
ph
ec

Fig. 13: AWS IoT events inputs

The following is part of implementing AWS IoT events using JSON format as input. There are two attributes that serve as input for the automatic control function of water quality: The pH value of the water and the Nutrient concentration of the water (EC). Every event data sent by the IoT device will be received by the IoT CORE AWS control service to be forwarded to the IoT event AWS data service in the detector models section which can be seen in Fig. 13.

State machines for automatic control of the water quality of hydroponic plants are built into detector models which are part of the AWS IoT events data services. Every input data that comes in is immediately processed and analyzed automatically to determine decision-making regarding the water quality control function of hydroponic plants. The output of this control function is an order to drive the dosing pump to add pH-up, pH-down, or AB-mix solutions as needed to maintain water quality. Overall the state machine can be seen in Fig. 14.

The implementation of the monitoring function for water quality is by using static WEB which is part of IoT CORE S3. The index.html file is an HTML file that is the main page. Meanwhile, the main.js file is a Javascript-based support file that has a function to process incoming data input in JSON format. The two files are placed into the S3 folder which has public mode. Figure 15, the public address of "static web hosting" refers to the index.html file which is the website endpoint bucket.

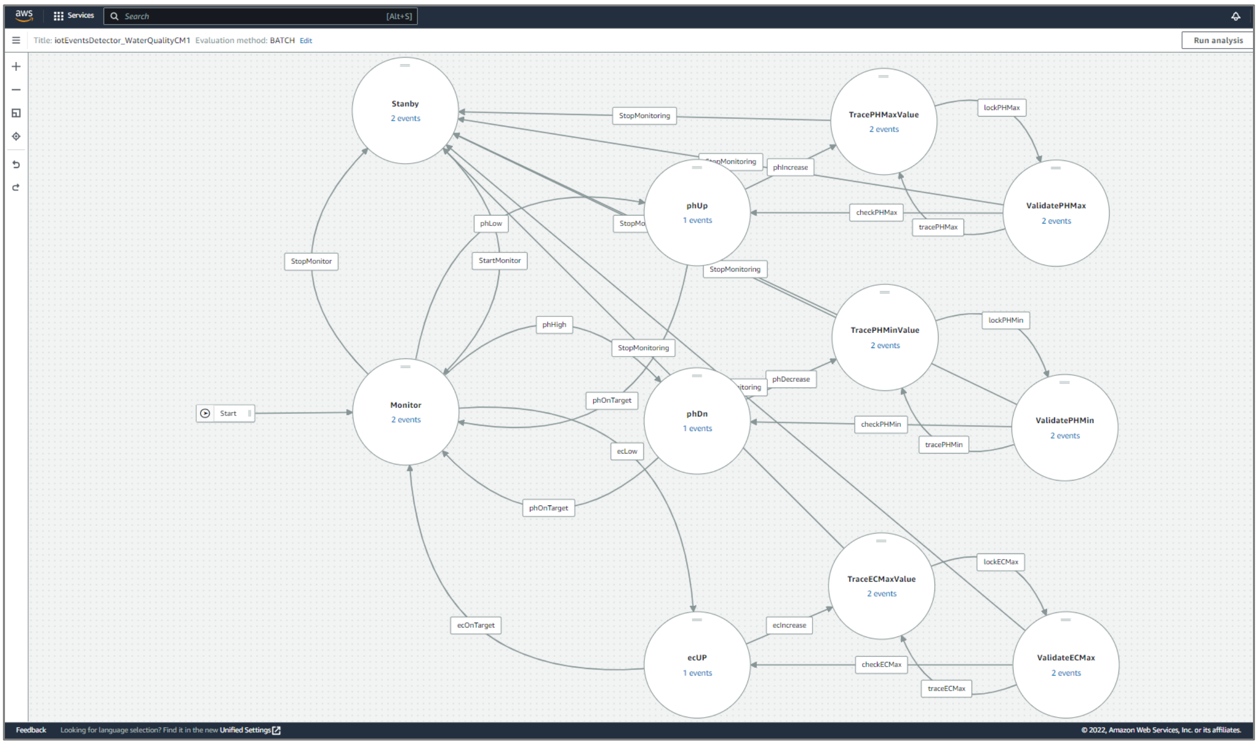
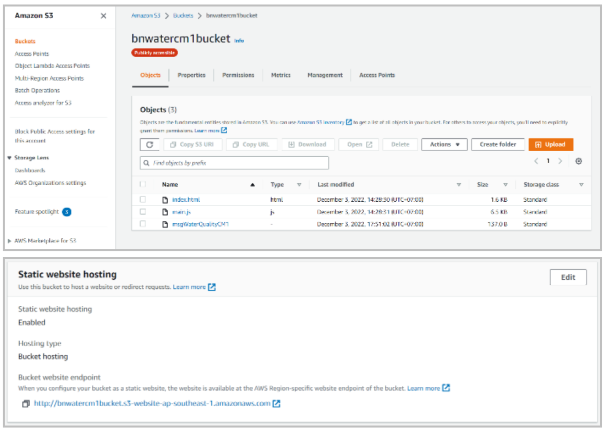


Fig. 14: Detector models for water quality automatic control



bnwatercm1bucket

Objects (3)

Objects are the fundamental entities stored in Amazon S3. You can use Amazon S3 inventory to get a list of all objects in your bucket. For others to access your objects, you'll need to explicitly grant them permissions. Learn more

Name	Type	Last modified	Size	Storage class
index.html	html	December 3, 2022, 14:28:30 (UTC+07:00)	1.6 KB	Standard
main.js	js	December 3, 2022, 14:28:31 (UTC+07:00)	6.5 KB	Standard
msgWaterQualityCM1	-	December 3, 2022, 17:51:02 (UTC+07:00)	137.0 B	Standard

Static website hosting

Use this bucket to host a website or redirect requests. Learn more

Static website hosting
Enabled

Hosting type
Bucket hosting

Bucket website endpoint
When you configure your bucket as a static website, the website is available at the AWS Region-specific website endpoint of the bucket. Learn more
http://bnwatercm1bucket.s3-website-ap-southeast-1.amazonaws.com

Fig. 15: AWS IoT static web

Test Results

Following, the results of the connectivity test, observation, and control functions of pH and EC values between hydroponic IoT devices and AWS IoT CORE will be explained. Adjustment of the pH value and nutrition of water can be determined by moving the dosing pump for pH up, pH down, and AB mix solutions.

AWS IoT CORE Dashboard

When the hydroponic IoT device is able to connect to AWS IoT CORE, a monitoring dashboard is automatically provided in the AWS IoT CORE service to view several attributes in Fig. 16. To enter the monitoring dashboard, you can select the "AWS IoT" menu then select the "monitor" sub-menu. The test results show that there are a maximum of six connection events with a maximum total of 506 outbound messages, 251 inbound messages, and 244 rules executed. Overall 91.77% use the MQTT protocol with 59.24% being Outbound messages and 40.76% being inbound messages.

Hydroponic IoT Device

Before hydroponic IoT devices can be accessed through AWS IoT CORE on the internet, the Wi-Fi module on the ESP8266 hardware module needs to be activated first. After the boot-up process and access to the WLAN network is successful, the ESP8266 will get a local IP address from the wireless router that has access to the internet via the WAN port. The next process is to synchronize time to the internet NTP Server which will be useful for the certificate authentication process when hydroponic IoT devices access AWS IoT CORE. After all these processes are successful, the next step is to detect all installed sensor modules. Figure 17, it can be seen that the machine log output reads “AWS IoT connected” which indicates that the hydroponic IoT device is already connected to the AWS IoT CORE service.

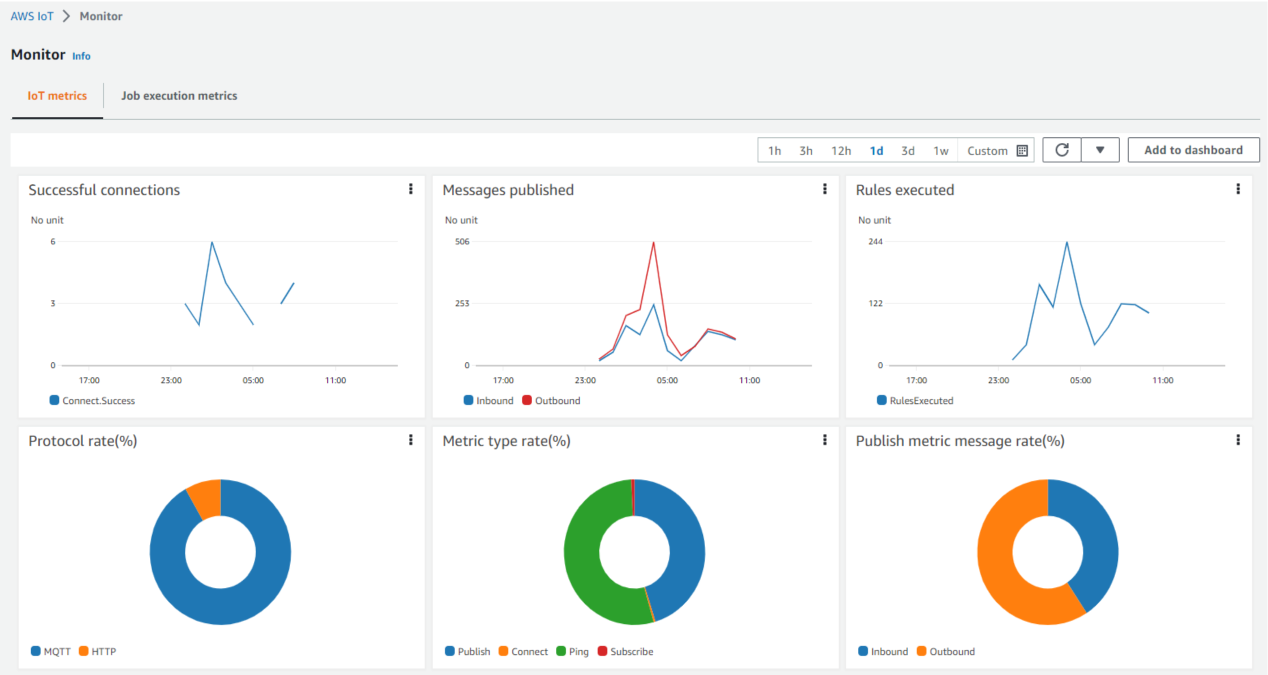
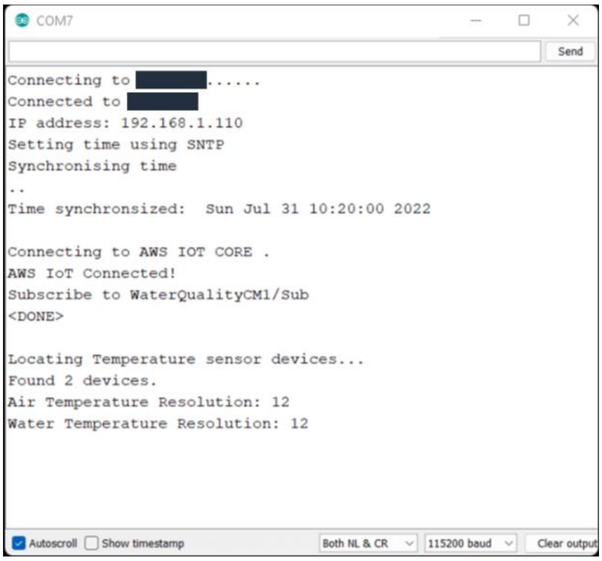
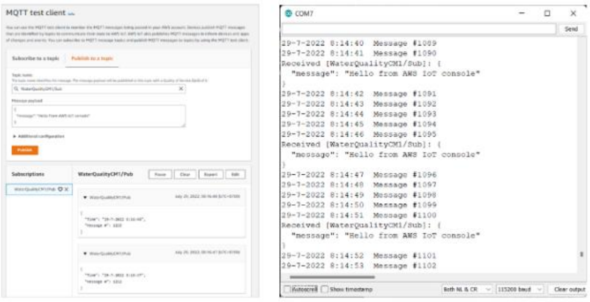


Fig. 16: AWS IoT CORE monitoring dashboard



```
Connecting to [redacted]......
Connected to [redacted]
IP address: 192.168.1.110
Setting time using SNTP
Synchronising time
..
Time synchronized:  Sun Jul 31 10:20:00 2022

Connecting to AWS IOT CORE .
AWS IoT Connected!
Subscribe to WaterQualityCM1/Sub
<DONE>

Locating Temperature sensor devices...
Found 2 devices.
Air Temperature Resolution: 12
Water Temperature Resolution: 12
```

Fig. 17: IoT device initiation



```
29-7-2022 8:14:40  Message #1089
29-7-2022 8:14:41  Message #1090
Received [WaterQualityCM1/Sub]: {
  "message": "Hello from AWS IoT console"
}
29-7-2022 8:14:42  Message #1091
29-7-2022 8:14:43  Message #1092
29-7-2022 8:14:44  Message #1093
29-7-2022 8:14:45  Message #1094
29-7-2022 8:14:46  Message #1095
Received [WaterQualityCM1/Sub]: {
  "message": "Hello from AWS IoT console"
}
29-7-2022 8:14:47  Message #1096
29-7-2022 8:14:48  Message #1097
29-7-2022 8:14:49  Message #1098
29-7-2022 8:14:50  Message #1099
29-7-2022 8:14:51  Message #1100
Received [WaterQualityCM1/Sub]: {
  "message": "Hello from AWS IoT console"
}
29-7-2022 8:14:52  Message #1101
29-7-2022 8:14:53  Message #1102
```

Fig. 18: Connectivity test

Connectivity Test

The quality of network connectivity that is not good can be one of the causes of failure to display measurement results. To see the performance of the Wi-Fi module in the minimum system "MEGA + Wi-Fi R3 ATmega2560+ ESP8266" and internet connection to AWS IoT CORE, a connectivity test is carried out by creating a program to send messages periodically every 1 sec to AWS IoT CORE and several times manually sending data from AWS IoT CORE to hydroponic IoT devices. The implementation of the connectivity test can be seen in Fig. 18, where there are 1102 messages sent to AWS IoT CORE continuously every second. From the observations there are no failed messages and all messages can be sent properly for either the up-link or down-link directions.

Water Quality Observation Function

Observations of pH, nutrition, water temperature, and air temperature are carried out by opening a static web page using a browser application in Fig. 19. By using the AWS static web, the monitoring function can be performed from a remote location as long as there is access to the internet network. From the test results, the observation of water quality through a web browser can run well, according to the results of the log machine from the hydroponic IoT device. The latest data will be displayed periodically every 1 sec.

Automatic Control Function for Water pH and Water Nutrients

To keep hydroponic plants from absorbing nutrients properly, the pH value of the water must be maintained at a certain level according to the characteristics of the plants. The amount of nutrients also needs to be maintained according to their needs so that plants can grow properly. Too high a nutrient concentration (PPM) can kill hydroponic plants. Figure 20, it can be seen that the pH of the water will be maintained at a value of 7, and water nutrition (EC) will be maintained at a value of 1200 ppm. Automatic settings to change the pH value of the water are made by AWS IoT Events to the IoT hydroponics device with the command to move the dosing pump to add a pH-up solution so that the pH value of the water rises when the pH value of the water drops from the lower limit of 3.7 or pH-down to lower the pH water if the pH value of the water exceeds the upper limit of 7.3. Whereas the dosing pump for water nutrition (EC) will actively add AB-mix solution if the EC value is below 1200. The unit for controlling the amount of solution pumped is in multiples of 1 mL.

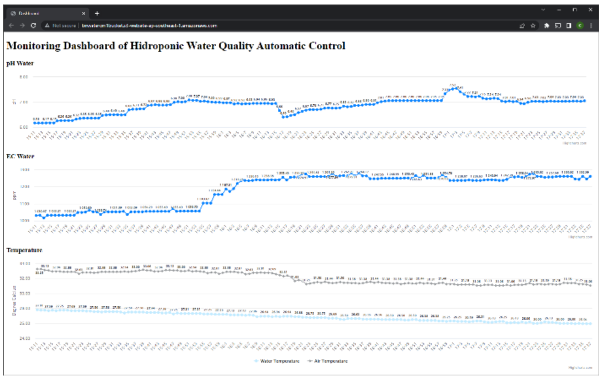
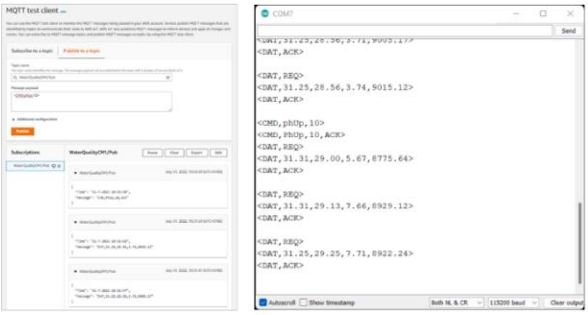
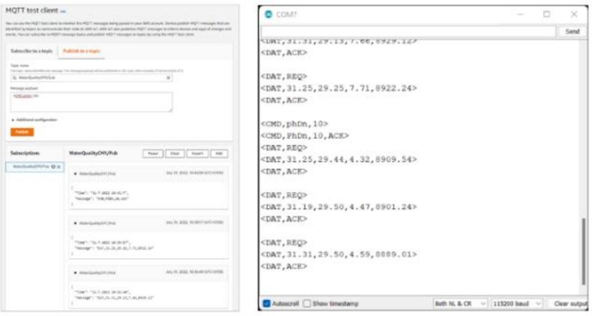


Fig. 19: Dashboard for monitoring water quality



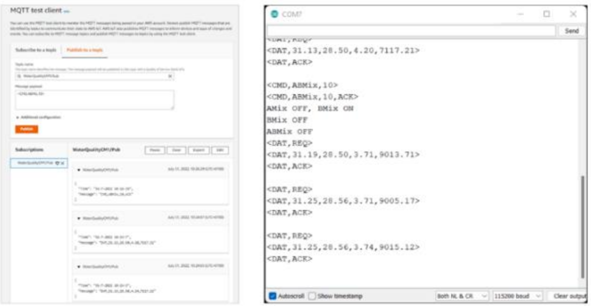
```
<DAT,ACK>

<DAT,REQ>
<DAT,31.25,28.56,3.74,9015.12>
<DAT,ACK>

<CMD,phUp,10>
<CMD,PhUp,10,ACK>
<DAT,REQ>
<DAT,31.31,29.00,5.67,8775.64>
<DAT,ACK>

<DAT,REQ>
<DAT,31.31,29.13,7.66,8929.12>
<DAT,ACK>

<DAT,REQ>
<DAT,31.25,29.25,7.71,8922.24>
<DAT,ACK>
```

Fig. 20: Control of increasing water pH



```
<DAT,ACK>

<DAT,REQ>
<DAT,31.25,29.25,7.71,8922.24>
<DAT,ACK>

<CMD,phDn,10>
<CMD,PhDn,10,ACK>
<DAT,REQ>
<DAT,31.25,29.44,4.32,8909.54>
<DAT,ACK>

<DAT,REQ>
<DAT,31.19,29.50,4.47,8901.24>
<DAT,ACK>

<DAT,REQ>
<DAT,31.31,29.50,4.59,8889.01>
<DAT,ACK>
```

Fig. 21: Control lowering the water pH



```
<DAT,31.13,28.50,4.20,7117.21>
<DAT,ACK>

<CMD,ABMix,10>
<CMD,ABMix,10,ACK>
AMix OFF, BMix ON
BMix OFF
ABMix OFF
<DAT,REQ>
<DAT,31.19,28.50,3.71,9013.71>
<DAT,ACK>

<DAT,REQ>
<DAT,31.25,28.56,3.71,9005.17>
<DAT,ACK>

<DAT,REQ>
<DAT,31.25,28.56,3.74,9015.12>
<DAT,ACK>
```

Fig. 22: Control of increasing water nutrition

Figure 20, after the <CMD, pH-Up, 1> message is sent using the MQTT protocol to the IoT device, the dosing pump will add 1 ml of pH-up solution. It can be seen that the value gradually increased from 6.17-6.23 after 1 minute. Conversely, if the message <CMD, pH-Dn, 1> is given, then 1 mL of pH-Down solution is added so that the pH value of the water changes from 7.30-7.21 Fig. 21.

Figure 22 it can be seen that the water nutrition control function is carried out automatically by AWS IoT Events by giving the message <CMD, ab mix,1> which has the meaning to add 1 mL of A-mix and B-mix nutrient solutions each. The test results show that the EC value increased from 1056-1103 ppm.

Conclusion

Based on the experiment of the research it can be concluded that the software and hardware based on Arduino open software and hardware have been developed as the main module for hardware control functions and data collection for hydroponic plant water quality from sensor modules.

Developing software on ESP8266 as an IoT client device that can connect to the AWS IoT cloud-based system has been conducted to enhance the hydroponic planting system.

The integration and development of AWS IoT modules for automatic water quality control functions and dashboards for monitoring water quality has been done successfully.

Finally, by developing a hydroponic planting system supporting device that is integrated into a cloud-based system, it is expected to create a digital system that can work automatically to regulate water quality in maintaining the growth of hydroponic plants which is equipped with easy access at any time remotely and from anywhere.

The static web provided by AWS allows flexible access for observing the water quality of hydroponic plants. Implementation of automatic control functions using AWS IoT event runs well and can be adjusted relatively quickly if changes are needed. When automatic control is activated, water pH and nutrient levels can be properly maintained according to the desired target.

Recommendation and Further Research

The limitation of the research is the dependency on a 24×7 internet connection for proper reception of commands from state machines in the AWS IoT event service by IoT devices. A 24×7 internet connection is highly needed because the real-time nature of the hydroponic planting system requires continuous monitoring and control. The challenge might be if it is not maintained, interruptions in the internet connection could lead to delays or disruptions in the execution of critical commands, affecting the overall performance and health of the hydroponic plants.

The number of events sent to AWS needs optimization to increase traffic efficiency to AWS IoT services on the Internet. This is essential because excessive or inefficient event transmissions can result in higher data transfer costs and increased latency. Optimizing the number of events ensures a more streamlined communication process, reducing the strain on the network and enhancing the overall responsiveness of the hydroponic system. Implementing techniques such as batching or prioritizing events can contribute to this optimization.

A suggestion for the next research is to explore advanced techniques for ensuring system robustness in scenarios where continuous internet connectivity is challenging. This could involve the development of offline modes or local processing capabilities within the hydroponic system to handle situations where internet connectivity is temporarily lost. Additionally, investigating alternative communication protocols or hybrid solutions that blend cloud-based and edge computing approaches may provide more resilience to intermittent connectivity issues.

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Author's Contributions

Cahya Lukito: Experiments, data analysis, written report.

Rony Baskoro Lukito: Experiments, data analysis, written manuscript.

Endang Ernawati: Written manuscript, proof- readed.

Ethics

All authors have read and agreed to the published version of the manuscript.

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