

Internet-based temperature monitoring system for hydroponic

N Uddin^{1,3*}, H Hermawan^{1,3}, T M Darajat^{2,3}, S Marwanto⁴

¹⁾ Dept. of Informatics, Universitas Pembangunan Jaya, Tangerang Selatan, Indonesia

²⁾ Dept. of Product Design, Universitas Pembangunan Jaya, Tangerang Selatan, Indonesia

³⁾ Center for Urban Studies, Universitas Pembangunan Jaya, Tangerang Selatan, Indonesia

⁴⁾ Indonesian Soil Research Institute, Bogor, Indonesia

*Email: nur.uddin@upj.ac.id

Abstract. This study presents a monitoring system to provide real-time measurement data of hydroponic that is accessible from anywhere through internet. Temperatures of nutrient solution and ambient air are of concern in the monitoring system. The system is developed through the following steps: design, implementation, and experimental test. The system is built by applying a NodeMCU ESP-12 as the microcontroller and two temperature sensors DS18B20. The NodeMCU ESP-12 is to collect measurement data of both temperature sensors and send the data to a cloud server through a WiFi internet communication. The Google Sheets is applied as the cloud server to store the measurement data and provide the data to users. Using the Google Sheets, the data is presented in a table as in the Microsoft Excel which is very convenience for processing and analyzing the data. Experimental test results show that the system is able to provide real-time and reliable data of the hydroponics temperatures that can be accessed from anywhere through the internet. The monitoring system has a delay about 3 to 6 seconds in presenting the measurement data. This delay is quite small compare to the temperature change period and therefore is negligible. Moreover, the monitoring system is built at cost USD 6.0 which is quite cheap.

1. Introduction

Measurement is a process to collect data of physical object and compare the data to agreed standards [1]. Some examples of the measurement are measuring mass, length, pressure, temperature, and humidity. The measurement is done by using one or more sensors to collect the physical data. The sensor is a device that converts a physical measure into an electric signal that is read by an observer or by an instrument [2]. The sensor signal can be either analog or digital. The advanced digital technology produces computers that are able to process digital data very fast. Sensor that produces digital signals is readily integrated to the computer for processing the signals. However, the sensor with analog signal out needs an analog to digital converter (ADC) to connect to the computer. The ADC is a device that converts analog signal into digital signal [3]. Integrating the sensor with the computer provides many advantages in the measurement, for examples: data processing, filtering, advanced data presentation, and data distribution.

A monitoring system has been developed to help people in observing an object. The monitoring system is an electronics system that automatically works to measure the object parameters, display the measurement data periodically, and store the measurement data in storage device [4–6]. The monitoring system may also provide a warning signal if any of the measured data is indicated beyond a limit. A traditional monitoring system works only for a local area, where the measurement, display, and data storage are done and located in the same area. This traditional monitoring system is only able to cover a small area.

The advance internet technology provides a high-speed internet connection at quite low prices. It results in fast and cheap communication networks around the globe. The communication through internet is not only done by people to people but also by people to devices, devices to people, and devices to devices. The internet is applied in any parts of life such that dependency to the internet is very high. A term to describe the high internet dependency was defined as the internet of things (IoT) [7]. The IoT describes a system that connects everything to internet including human being, computers and things [8].

The emerging internet technology changes the traditional monitoring-system into a modern monitoring system by integrating to internet. The IoT can be applied in the monitoring system and results in an advance monitoring system, where the measured data is not only presented and stored in a local computer but can be presented and distributed around the world in almost real-time. The term of almost real-time is to emphasized that a small delay should be realized due to the data transmission. This advanced monitoring system is called as the IoT-based monitoring system [9–11]. The IoT-based monitoring systems have been studied to be applied in many fields, for examples: environment [9], agriculture [11], transportation [12], and health [13].

Agriculture is very important in human life as producing foods. The agriculture has many planting methods and one of them is hydroponic. The hydroponic is a planting method without soil but using nutrient solution [14]. Plants in the hydroponic can be mechanically supported using an artificial medium, such as: sand, gravel, vermiculite, rock-wool, perlite, peatmoss, coir, or sawdust [15]. Comparing to traditional agriculture, hydroponic provides some advantages [16], for examples: less space requirement, less maintenance, relatively clean, and high productivity. Considering those advantages, the hydroponic is a suitable implemented in urban life. It will support food sustainability and better life environment.

Nutrient solution is one of the main factors for the growth of hydroponic plants. The nutrient solution is a mix of water and fertilizer that is distributed to the plants through pipelines. Maintenance of the hydroponics needs to periodically observe the quantity and quality of nutrient solution. Quantity of the nutrient solution is represented by a volume, where it can be easily observed by using human eyes. However, monitoring quality of the nutrient solution is more difficult. The quality is represented by several parameters, for examples: temperature, acidity, and concentration [17]. These parameters are observed through measurement process using some sensors. The temperature is measured using a temperature sensor, the acidity is measured by a pH sensor, and the concentration is measured using a total dissolved solids (TDS) sensor. Since observation of the nutrient solution needs to be done frequently, it becomes a tedious job and cumulatively spent a lot of time.

An IoT-based monitoring system is suitably applied in the hydroponic maintenance. The system is able to measure the quantity and quality of nutrient solution every time, while the measured data is stored and accessed from anywhere through internet. Several works on developing the IoT-based monitoring system for hydroponic have been presented. An IoT-based monitoring system presented in [17] was to monitor the volume, temperature, pH, and concentration of the nutrient solution. The monitoring system applied Arduino Uno as the microcontroller, a WiFi module ESP8266 as the connecting bridge to the internet, and a Raspberry Pi 2B as the webserver. The values of monitored parameters were presented in a webpage. Another IoT-based monitoring system was presented in [18] and named the iHydroIoT. The system used Arduino Uno as the microcontroller unit to collect measurement data from sensors, where the sensors communicated to the microcontroller through a Bluetooth Low Energy (BLE) module. A Raspberry Pi 2 was applied as a webserver that received the

measurement data from the Arduino Uno and then sent the data to the Plotly cloud service for visualization. This monitoring system was to monitor light intensity, air humidity, and several parameters of the nutrient that include temperature, CO₂, acidity, concentration, and volume. An advanced IoT-based monitoring system for hydroponic was presented in [19]. This monitoring system is not only to perform monitoring but also applying the measurement data for advanced data analysis using artificial intelligence. The monitoring system is equipped with a quite complex sensors set that includes temperature, pressure, altitude, humidity, lux, ultraviolet, CO₂, water temperature, pH, dissolved oxygen, electricity conductivity (EC), and total dissolved solid (TDS). The monitoring system is also collected vision data using two cameras. An Arduino Mega is applied in the monitoring system to collect the measurement data from the sensors but not the cameras. A Raspberry Pi 3B+ is applied in the monitoring system to collect the vision data from both cameras. The Raspberry Pi 3B+ is also assigned to send the measurement data and the vision data to a database through WiFi communication. The vision data are further analyzed using deep learning for predicting the harvest time.

The previous research works show that the IoT-based monitoring system provides flexibility to monitor the hydroponics. This flexibility means that the condition of hydroponic plant can be monitor anytime from anywhere. The measurement data is not only applied to trigger a warning signal but also to build an artificial-intelligence model. The model can be used to make classification and prediction to improve quality and quantity of the hydroponics production. Applying the artificial intelligent in agriculture is a part of the technology of precision agriculture. Therefore, the monitoring system should be developed to provide data that supports the artificial intelligence.

The temperature is a crucial parameter for determining evapotranspiration of crops, cell metabolism, crops growth, and crops physiological cycles; while, each crops has a specific range of suitable temperature [20–22]. Crop requirement on suitable temperature condition is different at different growth stages and light condition [23–25]. Understanding crop-temperature interaction in precision manner is a one of important keys in managing sustainable greenhouse production.

This study is to develop an IoT-based monitoring system of hydroponic temperatures. This monitoring system will be used to observe nutrient-solution temperature and ambient-air temperature of hydroponic plant. Moreover, the monitoring system will record the temperatures data that is being used in advanced analysis such as finding the optimal temperature for the plant growth and temperature prediction. This monitoring system is built using a NodeMCU ESP-12 and two temperature sensors. Measurement data of the temperature sensors are collected by the NodeMCU and sent to a cloud server via WiFi communication. The data is stored in the cloud server and accessible by authorized users from anywhere through internet. This will provide flexibility in monitoring the hydroponic temperatures. Presentation of this paper is organized as follows. Section I provides background and motivation of the work to develop IoT-based monitoring system with a study case on monitoring hydroponic temperatures. Section II presents the detail of IoT-based monitoring system for hydroponic temperatures. It described the concept, the hardware specification, the hardware design, and the software. Section III describes the experimental test and the result in evaluate the developed monitoring system. Finally, the Section IV concludes the work.

2. Materials and methods

Hydroponic is a planting method by using nutrient solution instead of soil [11]. The nutrient solution is distributed and circulated to all of the plants through lines. Temperature is one of the important parameters for the plant's growth. In the hydroponic, it can be identified at least two types of temperatures: 1) temperature of nutrient solution and 2) ambient temperature. The ambient temperature is the air temperature surrounding the plants. Both temperatures may not be equal due to heat isolation of the pipeline and the different heat capacity of the nutrient solution and the ambient air. The pipelines applied in the hydroponics are commonly made from PVC material. The PVC material is a heat insulator material that prevents heat transfer from the ambient air to the nutrient solution and vice versa. This insulator makes both temperatures may not be equal. Moreover, the nutrient solution has higher heat capacity than the ambient air. The higher heat capacity makes the temperature of nutrient solution more

inert than the temperature of ambient air. Temperature change of the nutrient-solution should be slower than the ambient air.

2.1. Concept of Monitoring System

An IoT-based monitoring system to observe the temperatures of nutrient solution and ambient air is developed. A concept of the monitoring system is explained based on a model in Figure 1 as follows. Two temperature sensors are applied in the monitoring system, where one of the sensors is dipped in nutrient solution in the pipeline and another sensor is place above the pipeline and beside the plant. The measured temperature data of the sensors are collected and sent to a could server by a microcontroller. The measurement data is stored in the cloud server and can be accessed by permitted user from anywhere through internet. Realization of the concept needs to specify, design, and implement the required hardware and software.

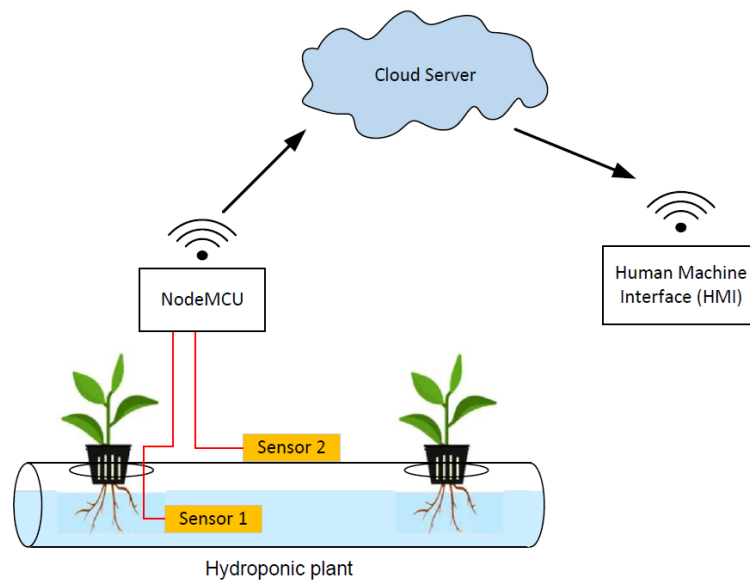


Figure 1. A model of IoT-based temperature monitoring system of hydroponic plant.

2.2. Hardware Specification

According to the concept of monitoring system shown in the Figure 1, the monitoring system consists of four main parts: sensor, microcontroller, cloud server, and HMI. Since the cloud server is a service provided a provider and the HMI is located in the user side, the required hardware for the monitoring system are only the sensor and microcontroller.

This study is concerned in monitoring temperatures of hydroponic that include the nutrient-solution temperature and ambient-air temperature. Therefore, two temperature sensors are required. The first temperature sensor is to measure the nutrient-solution temperature (NST) and called as the NST sensor. The second temperature sensor is to measure the ambient-air temperature (AAT) and called as the AAT sensor. The NST sensor is placed by sinking into the nutrient solution in the hydroponic pipeline. The NST sensor needs to be a waterproof temperature sensor. For this requirement, the Dallas temperature sensor DS18B20 is applied. The DS18B20 is a water-proof and low-cost temperature sensor that can be used to measure temperature from -10°C to $+85^{\circ}\text{C}$ with accuracy $\pm 0.5^{\circ}\text{C}$. Meanwhile, the AAT sensor is not dipped in liquid but for anticipating water contamination on the sensor due to rain and dew, the AAT sensor applies the DS18B20 temperature sensor.

The temperature sensor DS18B20 is shown in Figure 2. The sensor has three pins, where the pin 1 is the ground, the pin 2 is the data, and the pin 3 is the VDD [26]. The sensor works by a power supply 3.0 to 5.5 Volts direct current (DC), where the positive voltage is connected to the pin 3 and the

negative voltage is connected to the pin 1. The pin 2 is the sensor output that provide the measurement data. For operating the sensor, the pin 2 and the pin 3 have to be connected by using a resistor 4.7 k Ω . More detail specification and operation of the DS18B20 sensor can be found in the datasheet [27].

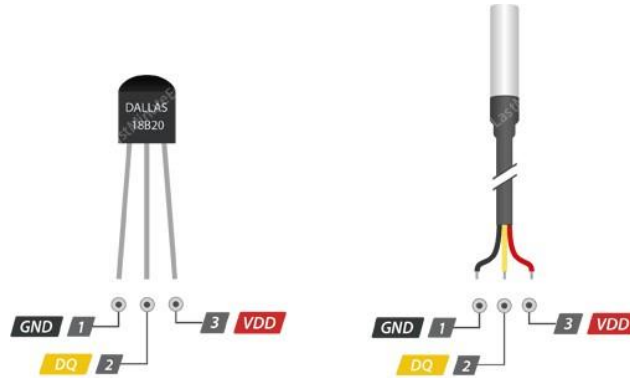


Figure 2. Temperature sensor DS18B20 and the pins wiring [26].

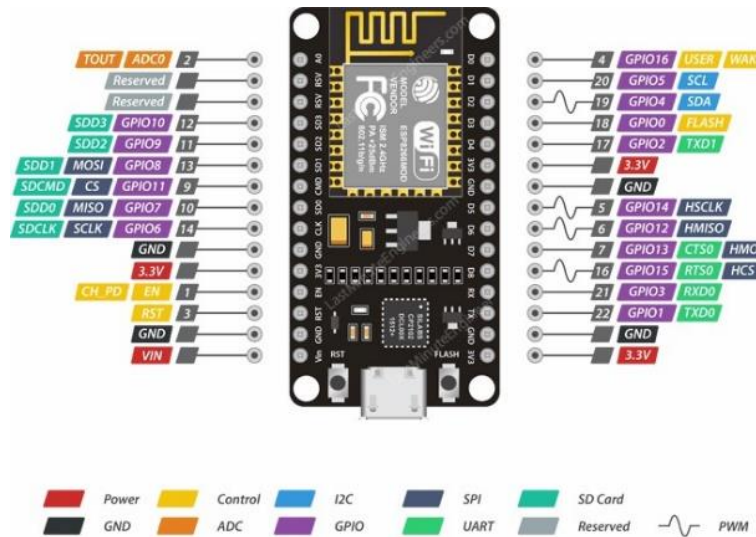


Figure 3. NodeMCU ESP 12 and the pins configuration [26].

Another required hardware in the IoT-based monitoring system is the microcontroller. The microcontroller is used to collect the measurement data resulted by the sensors and sent the data to a web server. Communication between the microcontroller and the web server can be done through wire communication or wireless communication. The wire communication transmits the measurement data to the web server via local area networks (LAN) cable, while the wireless communication does it via WiFi. Compared to the wire communication, the wireless communication provides more advantages, for examples less installation, less cost, but tidier. Developing such kind of the IoT-based monitoring system requires a microcontroller that has an ability to communicate via WiFi. There are several types of microcontrollers that can be applied, for example: Raspberry Pi and NodeMCU ESP-12. Both microcontrollers have facility for WiFi communication. Arduino UNO which is one of most famous microcontrollers does not have facility for the WiFi communication. The Arduino UNO can be applied but requires a WiFi communication module that is available separately. Since the developed monitoring system in this study uses only two sensors, the NodeMCU ESP-12 is best choice by considering the

budget. The NodeMCU ESP-12 is a low-cost microcontroller equipped with a WiFi communication module that can be obtained at price less than USD 4.0. Figure 3 shows the NodeMCU ESP-12 and the pin configuration. The NodeMCU ESP-12 has thirteen pins of general-purpose input output (GPIO). It can be used in a monitoring system by handling up to thirteen measurement data. The NodeMCU ESP-12 is a C programmed microcontroller. It can be programmed by using the Arduino integrated development environment (IDE).

2.3. Hardware Design

The specified hardware for the monitoring system needs to be designed and integrated in an electronic-circuit setup. Figure 4 shows a diagram of the electronic-circuit setup. The NodeMCU ESP-12 is powered by a 5 Volt external power supply that is given through the micro-USB port. The NodeMCU ESP-12 is not only consuming the power for operation but also distributing the power. The NodeMCU has a power regulator and power distribution system to distribute the power in two voltages, 5.0 Volts and 3.3 Volts. The 5 Volt power supply is available at the pin Vin, while the 3.3 Volts power supply is available at the pins 3V3. These distributed powers are available at the pin Vin for 5 Volts and the pins 3V3 for the 3.3 Volts.

The distributed power can be used to supply sensors and actuators but for a limited number due to the power capacity. For an application that utilizes several sensors and actuators, it is very recommended to use an external power supply for the sensors and the actuators and not using the distributed power from the NodeMCU ESP-12. The developed IoT-based monitoring system for hydroponic is utilizing only two DS18B20 temperature sensors which are low-power consumption sensors. Therefore, power for both sensors is supplied by the distributed power of NodeMCU ESP12. In this case, both sensors are powered by 3.3 Volts.

Hardware setup of the IoT-based temperature monitoring system for hydroponic is shown in Figure 5. The hardware is built on a PCB and the circuit is quite simple. Both temperature sensors are labeled by numbers 1 and 2. The temperature sensor 1 is connected to the pin D5 of the NodeMCU ESP12, while the temperature sensor 2 to the pin D6. The temperature sensor 1 is the NST sensor that measures temperature of the nutrient solution in the hydroponic pipe, while the temperature sensor 2 is the AAT sensor that measures the air temperature surrounding the plants. This hardware is not ready to operate because the NodeMCU has not been programmed yet. A program that describes an algorithm of the monitoring system need to be embedded into the NodeMCU.

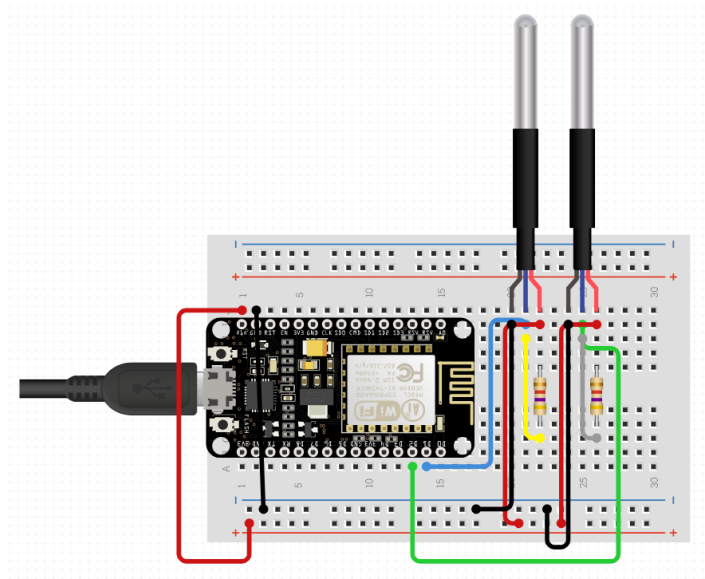


Figure 4. The electronics-circuit diagram of the IoT-based temperature monitoring system.

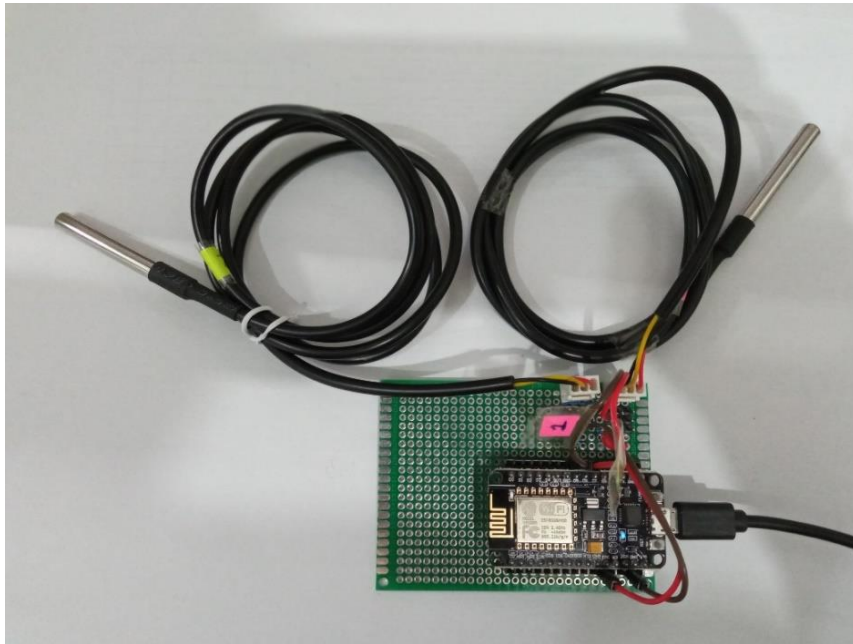


Figure 5. Hardware implementation of the IoT-based temperature monitoring system.

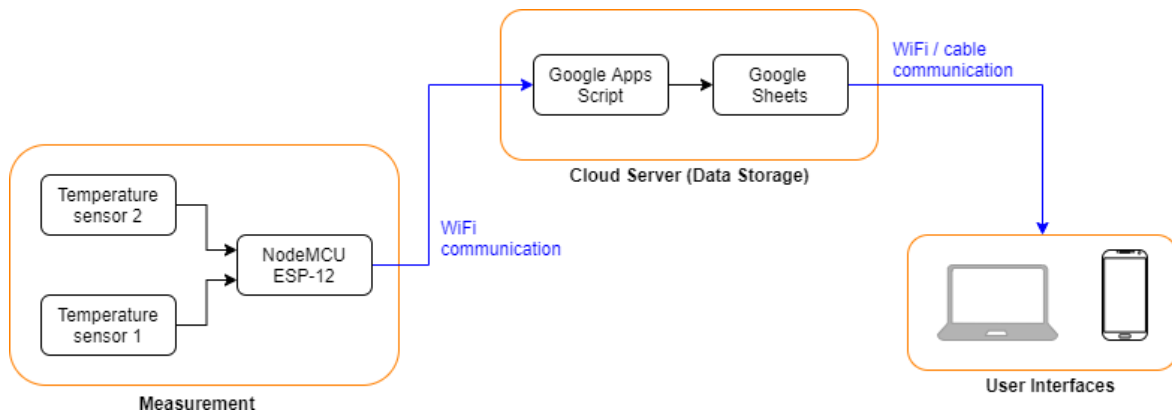


Figure 6. Data flow of the IoT-based hydroponic monitoring system.

2.4. Software

The IoT-based monitoring system consists of three main parts: measurement, cloud server, and user interface. Figure 6 shows a diagram of this monitoring system including the data flow. The measurement is to obtain data using sensors which is done by two temperature sensors and a NodeMCU ESP-12. The NodeMCU is to collect the temperature data and send the data to the cloud server. Communication of the NodeMCU and the cloud server is done through a WiFi communication. The cloud server is to store the data and provide the data to authorized users. The applied cloud server in this study is the Google Sheets. The users do a monitoring of the hydroponic by accessing the Google Sheets on their computer or smartphone.

The NodeMCU is a microcontroller that can be program using the C language. Arduino IDE provides a facility to write a program for the NodeMCU and embed the program into the NodeMCU memory. In this monitoring system, the program declares sequential tasks for the NodeMCU. The tasks include collecting the measurement data of both temperature sensors, connecting to WiFi server, and feeding the measurement data into the Google Sheets. An access of the NodeMCU to the Google Sheets is obtained by defining a code program at the Google Apps Script.

The Google Sheets is a cloud application that can be used to store and process data in cloud. The Google Sheets is very similar to the Microsoft Excel. By storing the temperature measurements data in the Google Sheets, the users can monitor the hydroponic by accessing the Google Sheets on their computer or smartphone. The data can be presented in table as well as in graphs. This provides flexibility in monitoring the hydroponic.

3. Results

The IoT-based temperature monitoring system for hydroponic is built and experimentally tested as shown in Figure 7. The hydroponic is placed in open area without sun protector. This is expected to result in a significant temperature different between noon and night. This experiment test is run to observe the nutrient-solution temperature (T_1) and the ambient-air temperature (T_2). The measurement data is logged every 30 seconds and the experimental test is carried out for 3.5 days. Data of the monitoring system is accessed in the Google Sheets using a computer.



Figure 7. Experimental test setup.

The monitoring results are shown in Figure 8 and Figure 9. The Figure 8 shows a plot of the measured temperatures for the 3.5 days period. The plot was generated in the Google Sheets. The plot shows two temperatures data, the Temperature 1 and Temperature 2. The Temperature 1 is the nutrient solution temperature (NST) measured by the temperature sensor T_1 . Meanwhile, the Temperature 2 is the ambient air temperature (AAT) measured by the temperature sensor T_2 . The plot shows that both temperatures were change during the time. Maximum temperature of the ambient air every day during the three days period was about 32 to 32.5 °C and occur around 3 PM, while the maximum temperature of the nutrient solution was in the range of 28 to 28.8 °C and occur at 5 to 6 PM. The minimum temperatures of the ambient air were in the range of 24.6 to 25.4 °C at 6 AM, while the minimum temperatures of the nutrient solution were 24.8 to 25.2 °C at 8 AM.

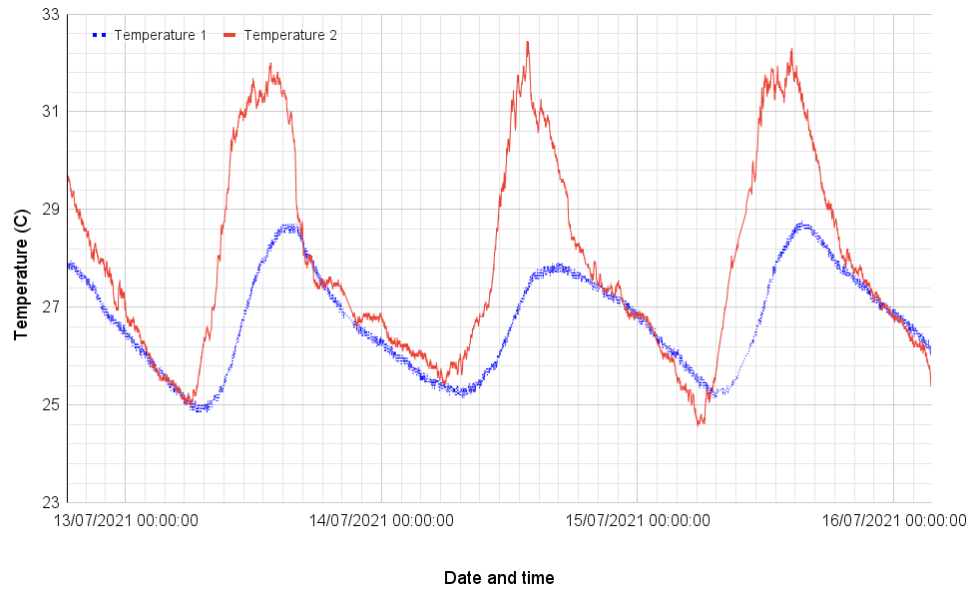


Figure 8. Plot of the hydroponic temperatures.

The Figure 9 presents some measurement data in the Google Sheets table. Time column in the table shows that interval of each data is not exactly 30 seconds but in the range of 33 to 36 seconds. Meanwhile, it was mentioned that the data was logged every 30 seconds. This deviation indicates a delay about 3 to 6 seconds in each transferring data from the NodeMCU to the Google Sheets server. The delay could be caused by the internet connection.

Penelitan_LogData_01 - Google					
docs.google.com/spreadsheets/d/1yIQ0V1NLPNcNp-FoY3rZ_eGuaOnDFEcFyfkQ4nH9f4/edit#gid=0					
Penelitan_LogData_01					
File Edit View Insert Format Data Tools Add-ons Help Last edit was made seconds ago by Penelitan					
125% 123 Default (Arial) 10 B I U A					
H19474	A	B	D	E	F
1	Date	Time	Temperature 1 (C)	Temperature 2 (C)	
21993	14/07/2021	10:56:47	26.02	28.75	
21994	14/07/2021	10:57:20	25.96	28.88	
21995	14/07/2021	10:57:54	26.02	28.88	
21996	14/07/2021	10:58:27	25.96	28.81	
21997	14/07/2021	10:59:01	26.02	28.94	
21998	14/07/2021	10:59:34	26.02	28.94	
21999	14/07/2021	11:00:08	25.96	29	
22000	14/07/2021	11:00:42	26.02	29.06	
22001	14/07/2021	11:01:16	26.02	29.12	
22002	14/07/2021	11:01:49	26.02	29.19	
22003	14/07/2021	11:02:23	26.02	29.06	
22004	14/07/2021	11:02:57	26.02	29.12	
22005	14/07/2021	11:03:31	26.09	29.19	
22006	14/07/2021	11:04:05	26.09	29.25	
22007	14/07/2021	11:04:38	26.09	29.31	
22008	14/07/2021	11:05:15	26.02	29.19	
22009	14/07/2021	11:05:48	26.02	29.06	
22010	14/07/2021	11:06:24	26.02	29.06	
22011	14/07/2021	11:06:57	26.09	29.12	

Figure 9. Presenting the hydroponics temperatures data in the Google Sheets.

4. Discussion

This study has resulted in a prototype of IoT-based monitoring system for hydroponic that is intended to monitor the nutrient solution temperature and the ambient air temperature. The system measures the temperatures every 30 seconds. The measured temperatures data are stored and presented in the Google Sheet. This allows the users to monitor the hydroponics by accessing the Google Sheet using computer of smartphone from anywhere through internet.

The experimental test result in Figure 9 shows a delay on the measurement data up to 6 seconds of each measurement. The Figure 8 shows that both temperatures are look like periodical functions with time period about 24 hours. Therefore, the time interval 30 seconds is actually too short compared and can be increased, for an example the measurements are done every 30 minutes. Performing measurements with longer time interval, such as 30 minutes, will make the delays up to 6 seconds to be insignificant values.

5. Conclusion

A temperature monitoring system for hydroponic plant has been developed. The monitoring system is able to provide reliable and real-time measurement data of the hydroponic temperatures. The measurement data can be accessed in Google Sheets by user form anywhere through internet using a computer or mobile device. Presenting the measurement data in the Google Sheets provides a flexibility for further data processing and analysis to the users. The developed monitoring system was concerned on the hydroponic temperatures only. It can be expended to monitor other parameter by adding more sensors, such as pH sensor, TDS sensor, and nutrient volume. This is considered as a further work of this study.

Acknowledgement

The authors acknowledge a financial support from Universitas Pembangunan Jaya through Internal Grant No. 008/PER-P2M/UPJ/11.20

References

- [1] Webster J G and Eren H 2018 *Measurement, Instrumentation, and Sensors Handbook: Two- Volume Set* (CRC press)
- [2] Chen K Y, Janz K F, Zhu W and Brychta R J 2012 *Medicine and science in sports and exercise* **44** S13
- [3] Zhang Y, Chen C H, He T and Temes G C 2017 *IEEE Journal of Solid-State Circuits* **52** 1066–1076
- [4] Finogeev A, Finogeev Fionova L, Lyapin A and Lychagin K A 2019 *Journal of Industrial Information Integration* **15** 15–20
- [5] Haasnoot M, van't Klooster S and Van Alphen J 2018 *Global Environmental Change* **52** 273–285
- [6] Sun S, Zheng X, Villalba-Díez J and Ordieres-Meré J 2019 *Sensors* **19** 4157
- [7] Ashton K *et al.* 2009 *RFID journal* **22** 97–114
- [8] Suresh P, Daniel J V, Parthasarathy V and Aswathy R 2014 A state of the art review on the internet of things (IoT) history, technology and fields of deployment 2014 *International conference on science engineering and management research (ICSEMR)* (IEEE) pp 1–8
- [9] Shinde S R, Karode A and Suralkar D S 2017 *International Journal of Electronics and Communication Engineering and Technology* **8** 103–108
- [10] Rahaman A, Islam M M, Islam M R, Sadi M S and Nooruddin S 2019 *Revue d'Intelligence Artificielle* **33** 435–440
- [11] Kaburuan E R, Jayadi R *et al.* 2019 *Procedia Computer Science* **157** 459–464
- [12] Mallidi SK R and Vineela V 2018 *International Journal of Advanced Research in Computer Science* **9** 738–741
- [13] Darshan K and Anandakumar K 2015 A comprehensive review on usage of internet of things (IoT) in healthcare system 2015 *International Conference on Emerging Research in Electronics, Computer Science and Technology (ICERECT)* (IEEE) pp 132–136

- [14] Son J E, Kim H J and Ahn T I 2020 Hydroponic systems *Plant factory* (Elsevier) pp 273–283
- [15] Jensen M H 1997 *HortScience* **32** 1018–1021
- [16] Hidayanti F, Rahmah F and Sahro A 2020 *International Journal of Advanced Science and Technology* **29** 5157–5164
- [17] Crisnapati P N, Wardana I N K, Aryanto I K A A and Hermawan A 2017 Hommons: Hydroponic management and monitoring system for an iot based nft farm using web technology 2017 5th *International Conference on Cyber and IT Service Management (CITSM)* (IEEE) pp 1–6
- [18] Marques G, Aleixo D and Pitarma R 2019 Enhanced hydroponic agriculture environmental monitoring: An internet of things approach *International Conference on Computational Science* (Springer) pp 658–669
- [19] Park S and Kim J 2021 *Electronics* **10** 1400
- [20] Jones J 2013 *GroSystems, Anderson, SC, USA* **716**
- [21] Hatfield J L, Boote K J, Kimball B A, Ziska L, Izaurralde R C, Ort D, Thomson A M and Wolfe D 2011
- [22] Al-Rawahy M S, Al-Rawahy S A, Al-Mulla Y A, Nadaf S K *et al.* 2019 *Journal of Agricultural Science* **11** 75–92
- [23] Shamshiri R, Ahmad D, Ismail W I W, Man H C, Zakaria A, Yamin M and van Beveren P 2016 Comparative evaluation of naturally ventilated screenhouse and evaporative cooled greenhouse based on optimal vapor pressure deficit 2016 *ASABE Annual International Meeting* (American Society of Agricultural and Biological Engineers) p 1
- [24] Shamshiri R R, Jones J W, Thorp K R, Ahmad D, Che Man H and Taheri S 2018 *International agrophysics* **32**
- [25] Garcia M, Medrano E, Sanchez-Guerrero M and Lorenzo P 2011 *Biosystems Engineering* **108** 133–143
- [26] Engineers L M 2020 Interfacing ds18b20 1-wire digital temperature sensor with arduino URL <https://lastminuteengineers.com/ds18b20-arduino-tutorial/>
- [27] Semiconductor D 2019 Ds18b20 datasheet