Temperature Monitoring and Airflow Control System for Balancing the Greenhouse Environment Using IEEE 1451 Standards

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Abstract— It is vital to establish a suitable thermal environment for greenhouses to improve production quality for crop cultivation. However, in greenhouse environments, uneven temperature, caused by the influence of outside temperature, leads to unevenness in air conditioning and results in sub-optimized crop quality and yield. This paper introduces a real-time temperature monitoring and airflow controlling system using IEEE P1451.0 and P1451.1.6 standards to balance and improve greenhouse environments. The controlling system consists of three components: an infrared array of smart temperature sensors (STS) placed inside and outside the greenhouse, a smart airflow controller (SAC), and a temperature monitoring and airflow control application (TMACA). The network communications among STS, TMACA, and SAC are based on IEEE P1451.0 and P1451.1.6 standard network services using the message queuing telemetry transport (MQTT) protocol. In the system, the TMACA can monitor the temperatures inside and outside the greenhouse using two STS, process and estimate the temperature differences inside the greenhouse, and then control and equalize the temperature of the greenhouse using the SAC based on the temperature differences to balance and improve the greenhouse environment.

Keywords—IEEE 1451 Standard, IEEE P1451.0, IEEE P1451.1.6, IoT, Green Houses, MQTT, Smart Airflow Controller, Smart Temperature Sensor, Smart Transducer.

I. INTRODUCTION

A greenhouse is an enclosed structure, in which climatic conditions, such as temperature and humidity can be controlled. In greenhouse cultivation, it is important to achieve an optimal thermal environment to grow crops with uniform quality and the highest yield. However, conventional greenhouse temperature control generally uses a single air temperature as a representative value for temperature control, making it difficult to control air conditioning in consideration of temperature irregularities or differences that may occur inside the greenhouse. This can result in differences in growth environments for different crops within the same greenhouse, which can lead to differences in crop quality and yield. With these in consideration, there is a need for improvements to maintain optimal and uniform temperatures inside greenhouses to limit temperature irregularities. Internet of Things (IoT) applications with edge computing provided promising results to solve such problems [1, 2].

There have been issues in the past concerning the improvement of temperature irregularities from two perspectives. Many environmental sensors must be installed in the greenhouse to observe temperature irregularities. The installation and operation costs are high, and thus temperature distribution data readily available for a research study are sporadic [3]. In the past, to regulate the temperature in large-scale greenhouse designs, an approach by changing the method of laying air ducts has been used; however, this method has a high implementation cost and is difficult to adapt to disturbances such as those caused by the variation of outside temperatures. It is essential to resolve the issues of ease of functional expansion and cost of implementation, including inter-device communication and coordination.

The Institute of Electrical and Electronics Engineers (IEEE) 1451 family of standards for smart transducer interfaces for sensors and actuators defines specifications for device and network-level communication interfaces for sensor networks. The device-level interfaces cover mixed-mode transducers interface (P1451.4), serial wireline (P1451.2), wireless interfaces (P1451.5), and RFID-to-sensor interface (P1451.7) as shown in Fig. 1, where “P” in front of the designated standard means either it is being developed or updated. At the network level, the family consists of standards for P1451.1.4 (or P21451-1-4, extensible messaging and presence protocol (XMPP)), P1451.1.5 (or P21451-1-5, simple network management protocol (SNMP)), and P1451.1.6 (or P21451-1-6, message queue telemetry transport (MQTT)) network interfaces, as well as the P1451.99 network interface acting like a bridge for the harmonization of 1451-based sensor networks with other non-1451 IoT verticals.

The P1451.0 standard outlines the functions and characteristics of a network-capable application processor (NCAP) working as a server or gateway for IEEE P1451.0-based sensor networks. It includes network service application programming interfaces (APIs) for IoT applications to access sensors, actuators, and transducer electronic datasheet (TEDS) data from the NCAP. The standard also defines common functions and characteristics for transducer interface modules (TIMs) and a set of transducer services to facilitate the setup and control of TIMs, as well as the reading and writing of data. The defined APIs are used for communication between applications, NCAPs, and TIMs. Additionally, the standard defines security and time synchronization TEDS for IEEE 1451-based sensor networks [4]. P1451.1.6 defines a method for transporting P1451.0 network service messages over an MQTT network to establish a lightweight, simplified protocol structure to handle IEEE 1451 communications [5].

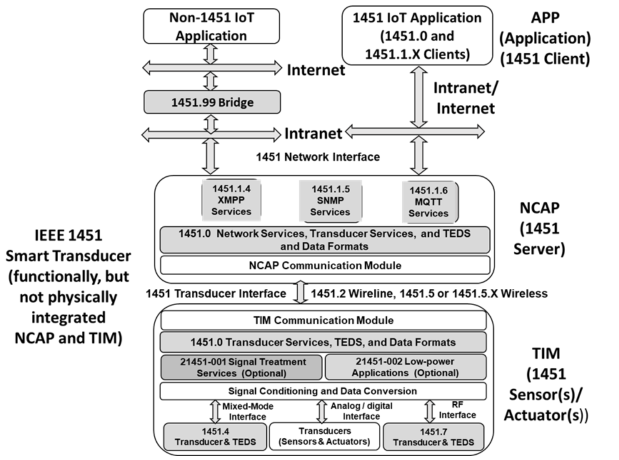

Fig. 1. The Communication architecture of IEEE 1451 family of standards [4].

This study introduces a real-time temperature monitoring and airflow controlling system using IEEE P1451.0 and P1451.1.6 standards to improve and balance the greenhouse environments. Also, this study is conducted to test the system using greenhouses with different characteristics, such as the crops grown and the method of laying ducts, and by using IEEE 1451 standard protocols.

II. Related Works

As for greenhouse management, all the required signals for its remote control are generally focused on the cloud computing system. However, in some cases, cloud computing systems are avoided because they tend to cause the leakage of farming know-how and some proprietary information. Therefore, the use of edge computing, in which only limited information is exchanged with the outside world, and much control is performed locally, may be considered. There are various studies conducted on edge computing in Greenhouse environments [1]. Yang et al. presented an anomaly detection of the sensor data in Greenhouse environments using edge computing [2]. The authors found that there are anomalies in the data generated over time due to various reasons. Hence, they proposed to use online anomaly detection using edge computing in the greenhouses.

Considering the temperature control area, Bayu et al. used image processing interpolation techniques to estimate air temperature and control air temperature and humidity at arbitrary points in a hydroponic greenhouse. Bicubic interpolation was used to estimate the temperature, and interpolation was performed in two-dimensional space. Based on estimated temperatures, the fuzzy theory was used to control sprinklers installed in the hydroponic field to control the temperature and humidity in the greenhouse [6].

For greenhouse design and installation, Lee et al. installed 20 environmental sensors along the width and length of a greenhouse to determine the microclimate throughout the greenhouse. In addition, the temperature in the greenhouse was controlled by utilizing a hot water heating system to reduce temperature irregularities. The high cost of installing a new system for hot water heating and its location-specific control makes it difficult for many ordinary farmers to apply the system [7].

To address standard communication protocols, Nishi et al. introduced time synchronization of IEEE P1451.0 and P1451.1.6 standard-base sensor networks [8]. In addition, Nishi et al. introduced an implementation of IEEE P1451.0 and P1451.1.6 sensor networks to validate some standard services and functions, such as read sensor data and read sensor TEDS [9].

In the past, most sensors deployed in greenhouses were not based on standardized communication interfaces and protocols; therefore, they were not interoperable with each other. As time goes on, many sensors produced by different vendors will be used in modern greenhouse designs. In those cases, these sensors must be designed and deployed based on standards to achieve sensor interoperability. Thus, this present paper focuses on the IoT application of real-time temperature monitoring and control of a greenhouse based on the IEEE P1451.0 and P1451.1.6 standards.

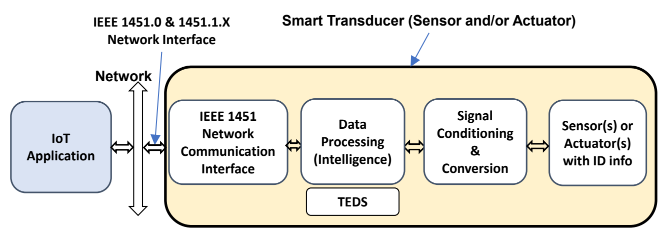

Fig. 2. IEEE 1451 smart transducer (sensor and/or actuator)

III. Monitoring and Airflow Control System using IEEE 1451 Standard

A. *IEEE 1451 Smart Transducer (Sensor and/or Actuator)*

As shown in Fig. 2, an IEEE 1451 smart transducer is a smart sensor and/or actuator that can identify (ID) and describe itself. The smart transducer system consists of a TEDS, data processing capability to present sensor data or actuation values, network communication capability, and plug-and-play features. Furthermore, the IEEE 1451 smart transducer is a combination of NCAP and TIM, which can communicate with IoT applications via the IEEE 1451 network interface.

The IEEE 1451 network communication interface shown in Fig. 2 consists of the P1451.0 network services and the

1451.1.X network interface (e.g., here X = 4, 5, or 6). The IEEE P1451.0 defines common functions, network services, transducer services, and TEDS for members of the IEEE 1451 family for standards to be interoperable for both network and transducer interfaces [4]. The IEEE P1451.1.X network interface includes P1451.1.4 XMPP, P1451.1.5 SNMP, and P1415.1.6 MQTT, where IEEE P1451.1.6 defines a method for transporting IEEE P1451.0 network service messages using MQTT to establish a lightweight, simplified protocol structure to handle IEEE 1451 communications [5] [9].

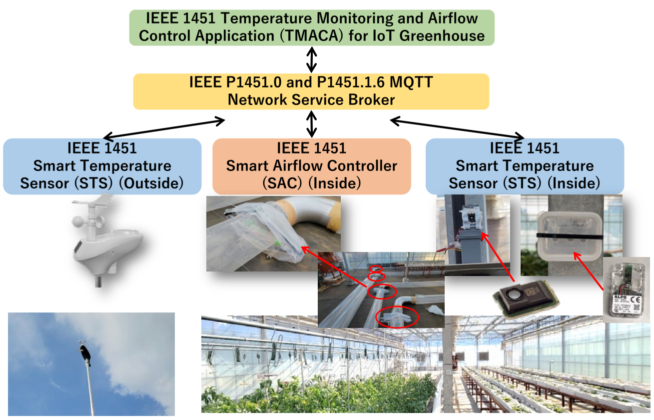

Fig. 3. The architecture of temperature monitoring and airflow control system based on IEEE 1451.0 and 1451.1.6.

B. *Temperature Monitoring and Airflow Control System for IoT Greenhouse Application based on IEEE P1451.0 and P1451.1.6 Standards*

Fig. 3 shows the system architecture for the temperature monitoring and airflow control system for the IoT greenhouse application using IEEE P1451.0 and P1451.1.6 standard-based network interface. This system consists of three components: two smart temperature sensors (STS) inside and outside the greenhouse, a smart airflow controller (SAC), and a temperature monitoring and airflow control (TMACA). In this system, the TMACA can monitor the temperature inside and outside the greenhouse using two STS, process, and estimate the greenhouse temperature differences, and then control or equalize the greenhouse temperature using a SAC to balance and improve the greenhouse environment. The communications among STS, TMACA, and SAC are based on IEEE P1451.0 and P1451.1.6 standard network services using MQTT protocol through the MQTT broker.

IEEE P1451.0 network services consist of a set of services for network communications between APPs and NCAPs. The NCAPs communicate with sensor data and TEDS information to and from a WAN via various network communication protocols, such as, but not limited to, IEEE P1451.1.6 MQTT services. The P1451.0 network services can be classified into four network service types including discovery services, transducer access services, TEDS access services, and event notification services. Each network service type has a set of sub-services with different network service Ids that depends on the network service type. Transducer access services are used to access sensor and actuator data, which are subdivided into synchronous and asynchronous services. Synchronous client-server communication is a blocking communication process, while asynchronous client-server communication is non-blocking. Both services are used to access sensor and actuator data and the TEDS of the TIM via the NCAP.

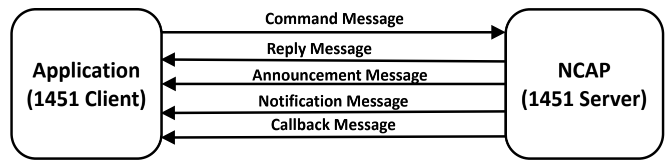

Fig. 4. Network service message types.

As shown in Fig. 4, IEEE P1451.0 network services include five message types: command message, reply message, announcement message, notification message, and call-back message. Table 1 shows the message structure of P1451.0 network services, consisting of the message header and body. The message header includes network service type, network service Id, message type, and length. The message bodies depend on network service types, service Ids, and message types.

Table 1. P1451.0 network service message structure

	1-Octet							
	7	6	5	4	3	2	1	0
Message Header	Network Service Type (1,2,3, and 4.)							
	Network Service Id (1,2,3,…, N))							
	Message Type (1, 2, 3, 4, and 5)							
	Length (most significant octet)							
	Length (least significant octet)							
Message Body	Message Body fields: ...							

These IEEE P1451.0 network services and messages are implemented using IEEE P1451.1.6 MQTT interfaces for temperature monitoring and airflow control for IoT greenhouse applications.

IV. IMPLEMENTATION OF TEMPERATURE MONITORING AND AIR FLOW CONTROL SYSTEM BASED ON IEEE P1451.0 AND P1451.1.6 STANDARDS

A. *Implementation of Temperature Monitoring and Air Flow control System based on IEEE P1451.0 and P1451.1.6*

As stated, this system consists of two IEEE 1451 STS using an infrared array temperature sensor MelDIR** [10] and a temperature sensor of the weather station inside and outside the greenhouse, an IEEE 1451 SAC or smart actuator using airflow controller shutter, and a real-time TMACA system. Each STS and SAC, IEEE 1451 smart transducer (sensors and/or actuators), is a combination of a network-capable application processor (NCAP) with a transducer interface module (TIM) based on IEEE 1451. In this system, the TMACA can monitor the inside and outside temperature of the greenhouse using two STS, process and estimate the temperature differences inside the greenhouse, and then control and equalize the temperature of the greenhouse using the SAC to balance and improve the greenhouse environment. The communication between STS, TMACA, and SAC is based on IEEE P1451.0 and P1451.1.6 standard network services using the MQTT protocol. The temperature data acquired from each STS is converted to IEEE P1451.0 network service message format and then transmitted to the TMACA through the MQTT broker using the P1451.1.6 standard protocol. After the TMACA receives the temperature sensor data from the STS, it processes and estimates the temperature differences inside the greenhouse, and then sends an angle control command to the SAC to control the airflow. When the SAC receives the angle control command from the TMACA, the SAC controls the airflow volume by adjusting the size of the ducts to equalize the temperature of the greenhouse. Data acquiring frequencies are approximately 1-minute and 30-second intervals for the infrared array sensor, 1-minute intervals for the environmental sensor, and 12-minute intervals for the outdoor environmental sensor.

B. IEEE 1451 Smart Temperature Sensor (STS)

The STS as shown in Fig. 5 can be used to measure the surface temperature of an object to estimate the temperature differences. The STS with a servo motor and a wide viewing angle is used to measure crop temperatures over a wide area in the greenhouse as shown in Fig. 7. The system then divides the crop area in the thermal image according to the actual arrangement of the crops and obtains the temperature distribution among the areas to estimate the temperature differences. The STS in Fig. 5 shows an IEEE 1451 STS with a wide-angle thermal image acquisition system, which consists of a thermal diode infrared array sensor [11]. Mitsubishi MelDIR was used for the thermal imaging system. The MelDIR pedestal was designed to be able to capture images of the entire greenhouse. The pedestal of MelDIR is connected to a servo motor at the bottom, and the servo motor's rotation can change MelDIR's shooting range horizontally. The system also has an IEEE P1451.0 and P1451.1.6 network interface. The binary data of the thermal image is directly packed into synchronous read transducer message of P1451.0 network services.

C. IEEE 1451 Smart Airflow Controller (SAC)

SAC in Fig. 3 shows an IEEE 1451 smart airflow controller (SAC), which consists of an airflow control shutter and two servomotors, and the shutter is opened and closed by controlling the angle of the servomotors. The airflow is controlled in the ducts when the shutters are opened or closed, adjusting the size of the ducts. A SAC with a pantograph-like mechanism is fabricated, the airflow rate of each duct is thus adjusted by controlling the airflow ducts, and the temperature difference in the greenhouse is changed proportionally. The air volume of the ducts is controlled to equalize the temperature of the crops across the area by using the temperature differences of the crops obtained from the thermal image. The control command is packed and encoded into synchronous write transducer message of P1451.0 network services.

D. Temperature Monitoring and Airflow Control Application (TMACA)

The TMACA is implemented on Linux-based embedded micro controller (GMKtec NucBox5) as an edge computing node. The TMACA monitors the inside and outside temperatures of the greenhouse using two STS, process and estimate the temperature differences of the greenhouse, and then controls the greenhouse temperature using a SAC to balance and improve the greenhouse environment. However, it was identified that dealing with temperature differences caused by external disturbances such as outside temperature and wind must be addressed. Therefore, an air conditioning control method was developed for estimating and improving temperature differences for the applications.

The temperature differences are estimated by comparing the temperatures of identical crops. First, the temperature of a certain region of a crop is extracted from the thermal image, as shown in Fig. 6. In this case, the crop is considered a fixed heat source, and the crop area is extracted by comparing the thermal image acquired by the STS with a red, green, and blue (RGB) image taken with a similar field of view (Fig. 6).

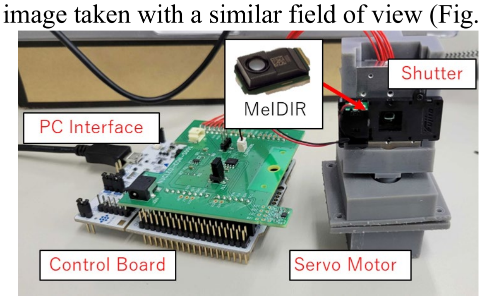

Fig. 5. STS with wide-angle thermal image acquisition system.

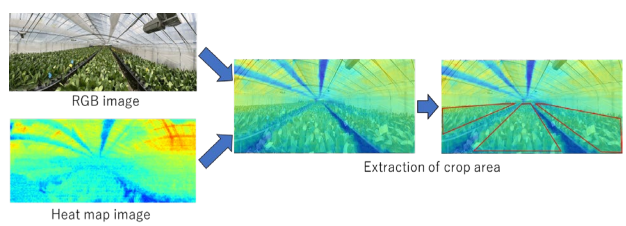

Fig. 6. Extraction of crops area.

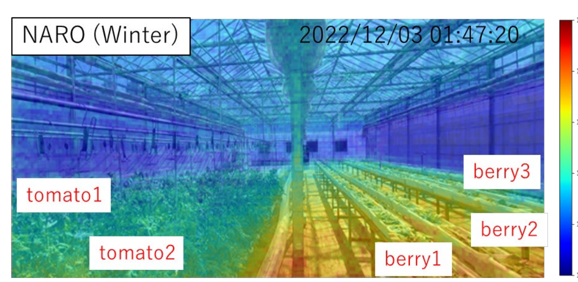

Fig. 7. Crops and temperature differences.

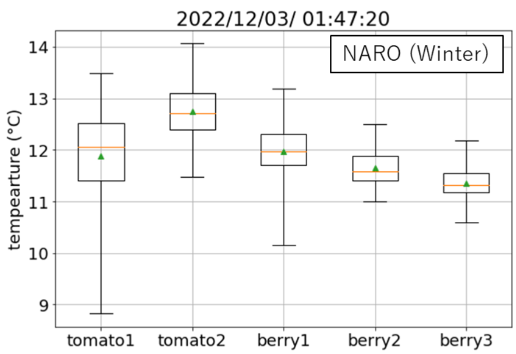

Fig. 8. Example of temperature differences and average in each crop area.

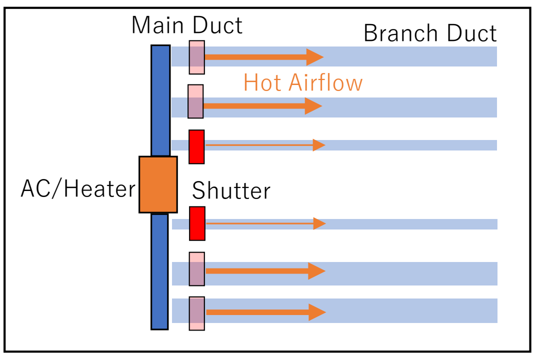

Fig. 9. Schematic diagram of airflow control by adjusting the size of the ducts.

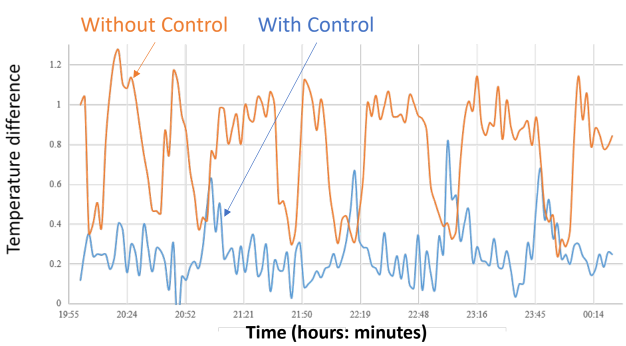

Fig. 10. Temperature difference of tomato field.

E. Estimating Temperature Differences

As shown in Fig. 7, the thermal image of the greenhouse in winter at the National Agricultural and Food Research Organization (NARO) is shown as an example. For simplicity, each crop region was labelled in Fig. 7. It shows the temperature differences information in an aerial manner. Crop temperatures are obtained from the thermal images, and temperature differences or irregularities are estimated by comparing the temperatures of the crops.

Fig. 8 depicts the temperature differences and averages for different crops in the greenhouse. Due to space limitations, the differences between thermal images and temperature sensors are discussed in [12], and the result of the differences are omitted. As a result, the temperature differences estimated using the thermal images were used for temperature control.

V. Case Studies

A. Temperature equalization by air conditioning control

As illustrated in Fig. 9, the airflow was controlled by the SAC. The shutters of the SAC are controlled using a single-input, single-output proportional integral derivative (PID) control algorithm, assuming that only the crop area adjacent to each duct is affected when controlling the airflow from the ducts. It would be desirable to use a control algorithm with other inputs and outputs because each crop area is affected by all the air ducts, but this would increase the complexity of the control and the cost of determining parameters.

Therefore, a single-input, single-output PID control algorithm is used for airflow control to make it easy for farmers to implement. Each air conditioning duct was associated with a crop area and was controlled using the PID control algorithm. The control input is the temperature difference between the temperature of the target crop area measured and the set temperature control value, and the output is the shutter opening degree. The PID control parameters are set to be controlled slowly enough to avoid control oscillations due to the relatively long time constant of the air conditioning control.

This control method has the advantage that it can affect the entire greenhouse by installing simple control devices at several locations and is very cost-effective. To demonstrate the effectiveness of the control method in reducing temperature irregularities or differences, two dates with close outdoor temperature conditions were selected at the National Institute of Agro-Environmental Sciences during the experimental period to compare the time variation of temperature differences with and without airflow control. Fig. 10 compares the temperature difference of tomatoes in the same greenhouse when the outside temperatures are close to each other, and the conditions other than air conditioning are the same as much as possible. The temperature difference is reduced by the airflow control in the proposed method. The same periods were set for without and with airflow control on two consecutive days. For example, the airflow was under controlled from time 20:00 on December 1, 2022, to time 0:00 on December 2, 2022, and was not under control from time 20:00 on December 2, 2022, to time 0:00 on December 3, 2022. By running experiments with and without temperature controls under a relatively constant external environment, the reduction of temperature differences in the tomato field with temperature control was demonstrated, as shown in Fig. 10.

The control method reduced the temperature differences by an average of 46.5 % as shown in Fig. 10 by comparing the area between the minimum and maximum temperature fluctuations. This shows that the proposed system can reduce temperature irregularities even in greenhouses with different conditions, such as duct installation methods and greenhouse geometries. The system reduces the temperature differences, and therefore, it is expected to be more effective in reducing the temperature differences by the same percentage in greenhouses where temperature irregularities are more likely to occur, such as greenhouses that do not have double wall coverings.

VI. Conclusion

This paper describes a real-time temperature monitoring and airflow controlling system based on the IEEE P1451.0 and P1451.1.6 standards by using a single infrared array temperature sensor to balance and improve the greenhouse environments. This system consists of three components: smart temperature sensors (STS) using an infrared array sensor and a temperature sensor of the weather station, a smart airflow controller (SAC) using an airflow control shutter, and a temperature monitoring and airflow control application (TMACA). The communications among STS, TMACA, and SAC are based on IEEE P1451.0 and P1451.1.6 standard network services using the MQTT protocol. The system was installed in the experimental greenhouse of NARO during winter, and it was confirmed that there was a difference of up to 1^{o} C in average temperature between the crops located in the center and at the walls of the greenhouses. In this study, a SAC with a pantograph-like mechanism was fabricated, and by controlling the airflow ducts, the airflow rate of each duct was adjusted, and the temperature differences in the greenhouse were changed. The airflow rate of the ducts was controlled to equalize the average temperature of the crop across the area by using the crop temperature obtained from the thermal image. As a result, the temperature fluctuation was reduced by 46.5 % and the average temperature uniformity was improved at the NARO's experimental greenhouse.

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** Certain commercial products or company names are identified here to describe our study adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the products or names identified are necessarily the best available for the purpose.

References

[1] C. Surianarayanan, J. J. Lawrence, P. R. Chelliah, E. Prakash, C. Hewage, “A Survey on Optimization Techniques for Edge Artificial Intelligence (AI)”, *Sensors*, vol. 23, no. 3, pp.1279-132, Jan. 2023.

[2] Y. Yang, S. Ding, Y. Liu, S. Meng, X. Chi, R. Ma, C. Yan, “Fast wireless sensor for anomaly detection based on data stream in an edge-computing-enabled smart greenhouse”, *Digital Communications and Networks*, vol. 8, no. 4, pp. 498-507, Aug. 2022.

[3] R. R. Shamshiri, J. W. Jones, K. R. Thorp, D. Ahmad, H. C. Man, and S. Taheri, "Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: a review," *International Agrophysics*, vol. 32, no. 2, pp. 287-302, Feb. 2018.

[4] IEEE P1451.0 - Standard for a Smart Transducer Interface for Sensors, Actuators, Devices, and Systems - Common Functions, Communication Protocols, and Transducer Electronic Data Sheet (TEDS) Formats, [Online]. Available: https://standards.ieee.org/project/1451_0.html.

[5] IEEE P21451-1-6 - Standard for a Smart Transducer Interface for Sensors, Actuators, and Devices - Message Queue Telemetry Transport (MQTT) for Networked Device Communication, [Online]. Available: https://standards.ieee.org/project/21451-1-6.html.

[6] E. Bayu, R. Andrian, A. Endro, "Micro-climate control for hydroponics in greenhouses", *2020 8th International Conference on Information and Communication Technology (ICoICT),* June 2020. Yogyakarta, Indonesia.

[7] C. K. Lee, C. Mo, S. Ki-yeol, I. Yong-hoon, Y. Si-won, "A study of the effects of enhanced uniformity control of greenhouse environment variables on crop growth", *Energies*, vol. 12, no 9, pp. 1749-1773, May 2019.

[8] H. Nishi, E. Y. Song, K. B. Lee, Y. Nakamura, Y. Liu, and K. F. Tsang, "Time Synchronization of IEEE P1451.0 and P1451.1.6 Standard-based Sensor Networks", IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society, Oct. 2021, Toronto, Canada.

[9] H. Nishi, K. B. Lee, "Implementation of IEEE P1451.0 and P1451.1.6 Sensor Networks, IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Oct. 2022, Brussels, Belgium.

[10] Mitsubishi Electric Corporation, "Infrared Sensors," [Online]. Available: https://www.mitsubishielectric.co.jp/semiconductors/products/icsensor/infraredsensor/index.html. Accessed on 19 10 2022.

[11] M. Kimata, "Trends in small-format infrared array sensors", 2013 IEEE SENSORS, Nov. 2013, Baltimore, MD, USA.

[12] A. Sonoda, Y. Takayama, A. Sugawara and H. Nishi, "Greenhouse heat map generation with deep neural network using limited number of temperature sensors," IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Oct. 2022, Brussels, Belgium.