International Journal of u- and e- Service, Science and Technology
Vol.8, No. 7 (2015), pp.79-88
http://dx.doi.org/10.14257/ijunesst.2015.8.7.08

Analysis of Multi-Climate Controller Data in Tomato Greenhouses

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Abstract

Most farms in South Korea have not applied the best use of greenhouse controllers. The system is used at a basic level, which is only possible to turn on/off at the facility. Therefore, further data analysis is needed to improve greenhouse management and to develop the future value of the technology. This study tests a growth model of the greenhouse tomato by analyzing a set of data collected from a multi-climate control system. The growth model is used to examine the growth rate of tomatoes depending on the climate variables. The results show that the growth rate of the stem thickness and leaf area is affected by temperature, CO_2 concentration and humidity. Since the variables fluctuate between control points, a nonlinear model would fit the data better than a linear one. The results could be posted up on a dash board or sent via a smartphone to the management decision maker.

Keywords: *multi-climate controller, tomato, greenhouse, TOMGRO*

1. Introduction

The rapid economic growth and gradual improvement in the national income of South Korea after the 1970s have made it possible to supply advanced horticultural facilities to nationwide agricultural businesses for the purpose of a steady supply of fresh crops to increasing social demand. Present controller systems have expanded their capabilities to the agricultural industry. New technologies have received attention as to possible solutions to problems such as population aging in rural areas and increasing labor and operating costs. The farms that have adopted multi-climate control systems for greenhouse technology increased productivity from 25 to 30 percent [1].

However, most farms do not apply the best use of the control systems. For example, there are some limitations of data-based climate control systems. The systems are used at a basic level, which is only possible to control at the facilities. Therefore, more interest in data analysis is needed to improve greenhouse management and to develop the future value of the technology. This study investigates data analysis from a multi-climate controller system and tries to find out the methodologies that will improve productivity by considering different combinations of environmental factors.

Previous studies have optimized linear models of tomato growth rates [2-3], but environmental factors fluctuate between control points. Linear models are less efficient

ISSN: 2005-4246 IJUNESST

than non-linear models. This study will compare both models and a more efficient model will be suggested for data-based controller systems.

Chapter 2 of this paper discusses the analyses of previous studies examining the appropriate level of each environmental factor and the development of greenhouse controllers. In Chapter 3, we explain the characteristics of the datasets and research methodologies in detail. Then, the result of the analysis is given in Chapter 4, after which the values and limitations of this study, and recommendations for future studies are discussed in Chapter 5, which is the conclusion.

2. Literature Review

2.1. Greenhouse Multi-Climate Controller

Some pioneering research on the climate control of greenhouse facilities started in the late 1960s [4, 5], and [6]. However, before then, there were commercialized systems that controlled the atmospheric environment inside greenhouses by pumping artificially-made CO_2 into the greenhouses. The previous research considered many affecting factors, such as temperature, amount of sunshine, CO_2 concentration rate, and water and nutrition supply. In turn, more precise models for growth and climate control systems could be developed. Furthermore, after the 1990s, climate control systems could be applied not only to growing crops, but also to livestock industries [7, 8]. Currently, as new materials have been developed, multi-climate controlling systems take care of sustainability as well. [11] designed an environment simulation system for crop growth using light emitting diode(LED henceforth). The role of the LED in their study was to control the system consuming less energy from fossil fuel. Meanwhile, faulty nodes in wireless sensor networks (WSNs henceforth) cause coverage hole and it deserved to be treated. [13] invented a new algorithm to recover them. Not only their study is meaningful for their explicit implications, but also it implies its capability of reducing missing values in observations over a multi-climate controlling system.

2.2 Effects of Temperature

According to the [3], which recommends the proper range of temperature depending on the growth level of the tomato, it is important to set the temperature at 26 degrees Celsius during the daytime of the period when raising seedlings, and 15 degrees at night for the first half of the period and 10 to 12 degrees at night for the second half. Three or four days right after the temporary planting, it is proper to set the temperature between 27 and 28 degrees Celsius during the daytime and between 24 and 25 at night. After this period, which is after when the union has been successful, it is recommended to manage the temperature at about 25 degrees Celsius during the daytime and about 20 degrees at night. Generally, the temperature should be set to between 25 and 27 degrees during the daytime and about 17 degrees at night during the whole period of the growth. The proper management of the temperature range is most important during the fruit pigmentation period, and it is recommended that the temperature be between 19 and 24 degrees Celsius, which enables the forming of lycopenes, because another pigment, carotene can be formed at between 8 and 35 degrees Celsius. Lastly, they found that the proper germination temperature of the seed was between 25 and 30 degrees Celsius, and 27 degrees during the daytime and 17 degrees at night during the growing period.

2.3 Effects of Light

After analyzing the results of the preceding research studies, [2] examined the effects of the intensity of light and the photoperiod on the growth of tomatoes, According to almost every research study, the tomato has 1400μmol/m^2/s of light saturation point, and 580~950μmol/m^2/s of light compensation point. Some other research studies examined the supplemental lighting during the sowing period in December and found that it could increase above-ground seedling dry weights by about 6.6 percent, decrease the falling of blossoms, and increase the total yield by about 10 percent according to [9]. Also, it was found that the intensity of light is highly related to the number of blossoms, the rate of fruit setting and the number of fruits according to [10]. Moreover, [3] suggested setting the light saturation levels of tomatoes at 70,000 lux (70 klux), and managing the intensity of light to that level during the growing period. This level is converted into 1393.747μmol/m^2/s through the conversion formula with the unit of measure from Photosynthetically Active Radiation (PAR), which is close enough to 1400μmol/m^2/s. [1] also suggested the light saturation point of 1400μmol/m^2/s and light compensation point of 20μmol/m^2/s, and further said that low light intensity had a negative effect on the florescence.

2.4 Effect of CO_2 Concentration

[2] analyzed the effects of CO_2 concentration in the interior atmosphere to the growth of tomatoes based on preceding research studies. It was determined that the proper concentration was between 800 and 1000 ppm (parts per million), regardless of the specific level of the growth. Meanwhile, when the interior CO_2 concentration is set to 600 ppm, while that of the exterior is 340 ppm to form the controlled environment, interior tomato growth showed an 8 percent decrease in leaf area, and 10 percent increase in fruit weight according to [11]. [3] also suggests 1,000 ppm as a suitable CO_2 concentration regardless of the growth level. [1] recommended managing the interior CO_2 concentration to be between 700 and 1,000 ppm, also regardless of the growth level.

2.5 Growth Model

The TOMGRO model of [12] was applied in this study to measure the amount of tomato growth. First, the dry weight and the number of leaves are set in the model as dependent variables and indicators of tomato growth. The general equation of the model is represented as:

$$\mathrm{W} = \mathrm{E}\left[P_g(T, S_{PAR}, CO_2) - R_m(T)W\right], \quad N = r_m r(T), \tag{1}$$

Where W and N are dependent variables that represent the total dry weight of the crop and the number of leaves, respectively. For the explanatory variables, T denotes temperature measured in Celsius, S_{PAR} indicates the photosynthetically active radiation, and $CO_2$is the concentration of carbon dioxide in parts per million (ppm). In addition, r(T) is an interval linear temperature that is applied by the TOMGRO model, while $R_m(T)$ is the respiration rate of the leaves. The function Pg (T, SPAR, CO_2) is the canopy gross photosynthesis rate. E is the conversion efficiency of formaldehyde (CH_2O) to plant tissue and coefficient r_m is the maximum rate of leaf appearance per hour [10].

However, this study applies a simplified version of the TOMGRO model instead of applying the full model. We define the dependent variable as the growth rate of stem thickness and leaf area to efficiently measure the relation between growth and other climate factors.

3. Method

3.1. Data collection

For this study, we used data collected from a climate controller in a tomato greenhouse. The data was recorded from July 2013 to June 2014. The greenhouse is at Hwasun-gun in South Korea. Observed and accumulated items are divided into five categories: outside weather conditions, inside greenhouse climate, facility control, irrigation, and growth status. Data is saved on a weekly basis. Detailed information about individual measurement items are provided in Table 1.

Table 1. Data Collection Description

Category	*Items*	*Measurements*
Weather Condition	4	Temperature, Rainwater, Wind Direction, Wind Velocity
Greenhouse climate	5	Temperature, Humidity, CO_2 Concentration, Insolation, Soil Temperature, Soil Humidity
Facility Control	15	Ventilation Temperature, Double-Ventilation Temperature, Heating Temperature, Skylights, Side Windows, Curtains, CO_2 Operation
Irrigation	10	Supply Frequency, Supply Amount, Total Capacity, Drainage Rate, G-EC Supply, G-pH Supply, Slab-EC Medium, Slab-pH Medium, Medium Water Containment, Medium Temperature
Growth Status	12	Growth Length, Leaf Length, Leaf Width, Leaves Number, Stem Thickness, Flower Cluster Height, Blooming, Fruiting, Harvesting, Fruits Number, Harvesting Amount, Average Fruit Weight

We only used a subset of environmental factors and growth levels over the whole data to compare with the results of Jones [12]: day/nighttime average indoor temperature, amount of solar radiation, CO2 concentration, day/nighttime average humidity, amount of water uptake, and EC/pH of culture medium as the environmental factors. While the speed of leaf area spread and thickness of stems are regarded as the crop's growth levels.

3.2. Model

First, we consider the dependent variables to be the expanding rates of leaf area and thickness, and then the set of environmental factors that are elements of the growth function. The model equations are as shown in (2) and (3):

$$LAX_t = f(ADT_t, ANT_t, SRD_t, CDC_t, ADH_t, ANH_t, AUW_t, ECM_t, PCM_t) \quad (2)$$

$$STX_t = g(ADT_t, ANT_t, SRD_t, CDC_t, ADH_t, ANH_t, AUW_t, ECM_t, PCM_t) \quad (3)$$

Where:

LAX_t : $Leaf\ Area\ eXpanding\ rate$
STX_t : $Stem\ Thickness\ eXpanding\ rate$
ADT_t : $Average\ Daytime\ Temperature$
ANT_t : $Average\ Nighttime\ Temperature$
SRD_t : $Solar\ RaDiation$
CDC_t : $Carbon\ Dioxide\ Concentration$
ADH_t : $Average\ Daytime\ Humidity$
ANH_t : $Average\ Nighttime\ Humidity$
AUW_t : $Amount\ of\ Uptake\ Water$
ECM_t : $Electrical\ conductivity\ of\ Culture\ Medium$
PCM_t : $pH(acidity)\ of\ Culture\ Medium$

If there were any non-linear correlations between a pair among the variables listed above, they would have hardly been discovered by conducting a naive linear regression analysis. Under the assumption that such non-linear interrelationships exist, we surveyed how co-instantaneous observations between a pair of variables appear as Figure 1 shows.

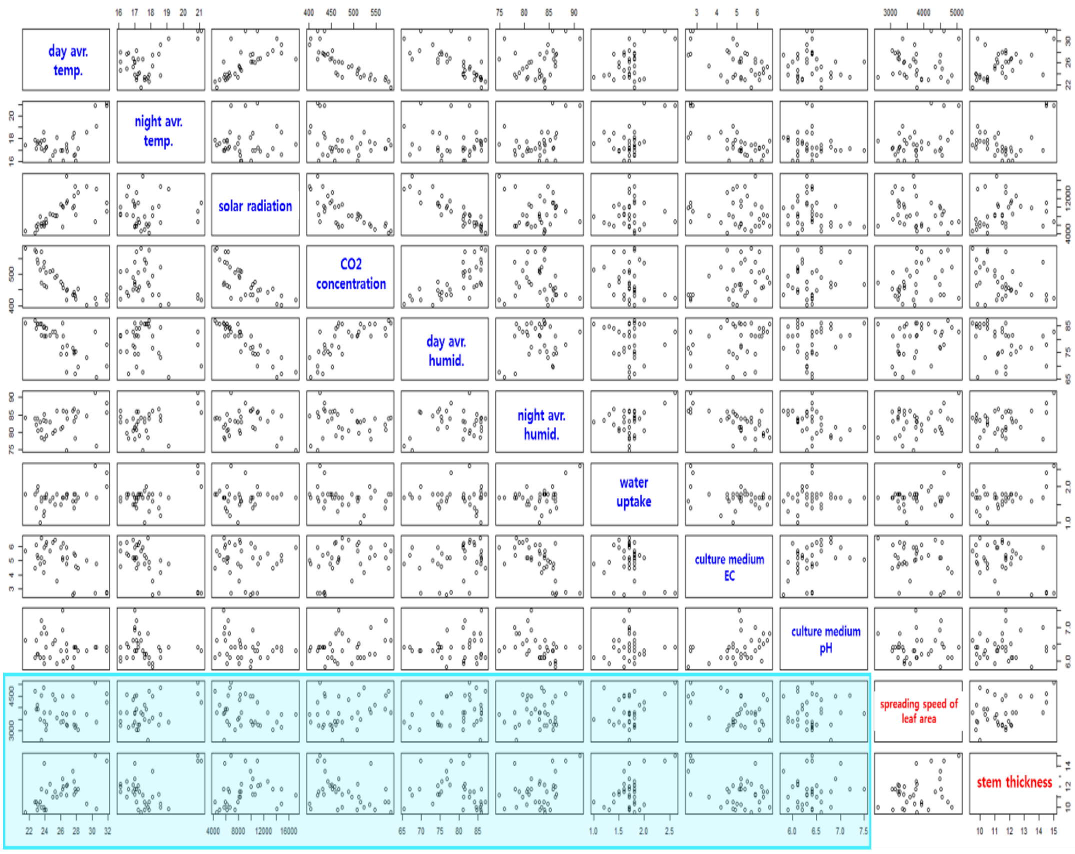

Figure 1. Distributions of Coinstantaneous Observations between Variable Pairs

The set of scatter diagrams inside the bluish rectangle in Figure 1 depicts the effects of environmental factors on growth levels. According to the distributional aspect of those figures, there is no evidence that limits any pair of relationships in a linear equation. Thus, we tried raising each environmental factor variable's degree to 2, and subsequently conducted a regression analysis. For instance, let the environmental factor variable "average daytime temperature" be x_1, let the growth factor variable "stem thickness" be y_1, as mentioned in Table 1, and let the linear regression analysis function be $f(.)$, the non-linear interrelationship between each pair of variables is tested by using $f((x_1 - \alpha_1)^2,\ y_1)$ instead of $f(x_1,\ y_1)$. In this case, α_1 is the critical point of the variable x_1, which is used to maximize the value of y_1 in the quadratic function mentioned above.

4. Results

4.1 Descriptive Statistics

The results show that there are several significant correlations between climate factors and growth, and irrigational factors and growth. For example, the growth length of the crop is positively related to the inside and outside temperatures as well as the supplied amount of irrigation, while negatively related to the Slab-EC and Slab-pH mediums. Also, the lengths of the leaves are negatively related to ventilation temperature, outside temperature, insolation, supply frequency, total capacity, and G-pH supply, while positively related to CO_2 concentration and G-EC supply. The amount of insolation, which is related to leaf condition and fruiting status, is the most relevant climate factor for growth. The second most relevant factor is the outside temperature, which is related to overall length of growth and number of leaves, and stem thickness. For the irrigation factors, supplies of G-EC and G-pH are highly related to the growth factor among other factors that affect the leaves and fruits, which are the opposite of each other. Table 2 shows the climate factor results and Table 3 shows the irrigation factor results.

Table 2. Correlation Analysis between Climate and Growth Factors

	Growth Length	Leaf Length	Leaf Width	Number of Leaves	Stem Thickness	Fruiting	Harvesting	Number of Fruits
Ventilation Temperature	0.2126	-0.2901*	0.01909	0.1101	0.5657**	0.1702	0.5347**	-0.1095
Inside Temperature	0.4421**	-0.2147	-0.01251	0.1173	0.4179**	-0.0468	0.8798**	-0.0026
Outside Temperature	0.3496**	-0.4694**	-0.15644	0.3107*	0.3380**	0.1063	0.9679**	0.2791
CO_2 concentration	-0.2481	0.2977*	0.17832	-0.0102	-0.2813*	-0.1196	-0.31148	-0.1899
Insolation	0.0136	-0.6785**	-0.3583**	0.4988**	0.1352	0.6029**	0.8446**	0.5236**

*p-value < 0.1, **p-value < 0.05

Table 3. Correlation between Irrigation Factors and Growth

	Growth Length	Leaf Length	Leaf Width	Number of Leaves	Stem Thickness	Fruiting	Harvesting	Number of Fruits
Supply Freq.	-0.0396	-0.7220**	-0.4309**	0.7084**	-0.0257	0.6362**	0.8575**	0.5876**
Supply Amount	0.5497**	-0.1688	0.0580	-0.0362	0.6533**	-0.1152	0.2882	-0.1532
Total Capacity	0.2668	-0.5275**	-0.3180**	0.4591**	0.0572	0.2914	0.8497**	0.6556**
Drainage Rate	0.2761	-0.0464	-0.0083	0.05473	-0.1582	-0.2731	0.7325**	0.4333**
G-EC Supply	0.2237	0.7838**	0.5170**	-0.7013**	0.2377	-0.7018**	-0.9360**	-0.7748**
G-pH Supply	-0.3593	-0.5453**	-0.4082**	0.5610**	-0.3035**	0.4563**	0.7123**	0.5326**
Slab-EC Medium	-0.5989**	-0.1497	-0.3103**	0.1866	-0.4386**	0.5371**	-0.6722**	0.1789
Slab-pH Medium	-0.4591**	0.1460	0.1512	-0.1662	0.0509	0.1371	-0.5649	-0.4605**

*p-value < 0.1, **p-value < 0.05

Table 4. Description of Data

	Min.	1st Q.	Median	Mean	3rd Q.	Max.
Average Daytime Temperature (℃)	21.5	23.85	26	25.98	27.7	31.8
Average Nighttime Temperature (℃)	16.1	17	17.3	17.66	18	21.1
Solar Radiation ($\frac{\mu mol}{m^2 \cdot s}$)	4290	6316	8273	8946	10817	17063
CO2 Concentration (ppm)	402	435.5	467	478.8	513	582

Average Daytime Humidity (Pa)	65.6	75.1	81.3	79.22	84.35	87
Average Nighttime Humidity (Pa)	74.9	80.6	83.1	82.85	85.4	91.2
Water Uptake (L)	1	1.6	1.7	1.709	1.8	2.6
EC of Culture Medium (dS/m)	2.6	4.55	5.2	4.989	5.9	6.6
Acidity of Culture Medium (pH)	5.8	6.1	6.4	6.397	6.55	7.5
Leaf Area Expansion Rate (cm)	2615	3312	3755	3794	4277	5063
Stem Thickness Expansion Rate (cm)	9.5	10.41	11.5	11.51	12.1	15

4.2. Estimation Results

Tables 6 and Table 7 describe the results of the analyses briefly. For each dependent variable, at first we conducted a linear regression analysis, and then we modified some of the variables into quadratic ones. Variables such as "leaf area expanding rate", raising the degrees of "average daytime temperature", "average nighttime temperature", "solar radiation", "carbon dioxide concentration", "average daytime humidity", and "amount of uptake water" modified into quadratic variables maximized the goodness of fit for the non-linear model, as shown in (4). Other variables, such as "stem thickness expanding rate", raising degrees of "average daytime temperature", "average nighttime temperature", "solar radiation", "carbon dioxide concentration", "average daytime humidity", "average nighttime humidity", and "acidity of culture medium" modified into quadratic maximized the equivalent value, as shown in (5).

$$LAX_t = f((ADT_t - 30.7)^2, (ANT_t - 17.1)^2, (SRD_t - 11353)^2, (CDC_t - 582)^2, (ADH_t - 70.5)^2, ANH_t, (AUW_t - 1.9)^2, ECM_t, PCM_t) \quad (4)$$

$$STX_t = g((ADT_t - 30.7)^2, (ANT_t - 17.1)^2, (SRD_t - 11353)^2, (CDC_t - 582)^2, (ADH_t - 77.6)^2, (ANH_t - 86.0)^2, AUW_t, ECM_t, (PCM_t - 6.2)^2) \quad (5)$$

For both dependent variables, it was helpful to change the variable quadratic appropriately in order to discover the model with optimal fit. It is remarkable that in both models, the critical points of the first four variables are the same. In the case of "leaf area expanding rate", it is interesting that despite not having modified the variable "average nighttime humidity", its significance had improved as the model into which it had been incorporated was being transformed. The significance of "electrical conductivity of culture medium" is similarly enhanced in the model with "stem thickness expanding rate".

Table 5. Leaves Area Expanding Rate

Comparative model	Linear model coefficient	Non-linear model coefficient
Avg. Day Tmpr. (℃)	267.3*	-24.86**
Avg. Night Tmpr. (℃)	-25.8	57.28*
Solar Rdt. (μmol/m^2/s)	0.136	0.000008
CO_2 Conc. (ppm)	12.8***	0.06993***
Avg. Day Hmd. (Pa)	117.7**	-5.666***
Avg. Night Hmd. (Pa)	-70.88	-108.2**
Water uptake (L)	167.6	225.4
EC of Cltr. Md. (dS/m)	-28.98	-228.2*
Acidity of Cltr. Md. (pH)	-23.97	-251.1
R^2	0.4444	0.5757

*p<0.05, **p<0.01, ***p<0.001

Table 6. Stem Thickness Expanding Rate Model

Comparative model	Linear model coefficient	Non-linear model coefficient
Avg. Day Tmpr. (℃)	0.5588*	0.006218
Avg. Night Tmpr. (℃)	-0.5312	3.415***
Solar Rdt. (μmol/m^2/s)	-0.0000005	-0.00000001
CO_2 Conc. (ppm)	0.008302	-0.00004712
Avg. Day Hmd. (Pa)	0.07919	-0.01444**
Avg. Night Hmd. (Pa)	-0.04181	0.02035**
Water uptake (L)	1.312	0.1160
EC of Cltr. Md. (dS/m)	-0.5490	-0.8231***
Acidity of Cltr. Md. (pH)	0.6455	0.9605
R^2	0.4223	0.7434

*p<0.05, **p<0.01, ***p<0.001

By the process we have carried out so far, we were able to notice that the results from our analyses were similar to the results of preceding research studies. With regard to the temperatures, the most appropriate temperatures for daytime and nighttime in this study are 30.7℃ and 17.1℃, respectively. Even though there are 3~5℃ of difference in the daytime temperature between our data and other data, such as those of the [3] and the [1], considering the variety of species that exist, this error is tolerable.

For solar radiation, the most appropriate light intensity was 11353 μmol/m^2/s. However, this level was calculated by accumulating for a week. Therefore, if we normalize the intensity, then it becomes 1621.8 μmol/m^2/s. Considering that the light saturation point of tomato is 1400 μmol/m^2/s, the intensity barely exceeds this level.

For carbon dioxide, the optimal concentration level we derived from our analyses was 582 ppm. Due to the maximum value of the observation over this variable being 582, it cannot be stated that the value denotes the genuine critical point of the carbon dioxide variable over the equation. According to the vast majority of studies, at present 800~1,000 ppm is considered desirable. Other variables have either different critical points or different degrees from those of the dependent variables.

5. Discussion

Tomato plants are responsive to changes in temperature, humidity, CO_2 concentration and light levels. Controllers regulate climate variables based on tomato growth rates in greenhouses. Each variable fluctuates between control points. Therefore, we tested a non-linear model and compared it to a linear model using data collected from a multi-variate controller. The average temperature at night has a positive relationship with leaf area and stem thickness growth rates, while during the day, the average temperature has a negative relationship with leaf area growth rate. High temperature interrupts plant growth, because it increases more than 40 degrees Celsius during the summer. Daytime humidity negatively influences leaf area and stem thickness growth rates, because high humidity inhibits the evaporation of water from the leaves. CO_2 concentration positively affects leaf area growth rate. Finally, in a non-linear model, R^2 is larger than that of a linear model, because the non-linear model better fits the data.

The results of this study can be applied in various ways. A multiple climate control system can be connected to the Internet. Thus, appropriate information, such as weather or prices, from certain databases is easy to obtain. Such a system could centralize and combine data from different channels and sources to form an accumulated "big data" property. If utilized properly, a centralized database can find out the causes of present problems, suggest reliable clues to solve these problems, or provide comprehensive information to farmers to help them develop optimal conditions for growing crops. Also, relevant information and analytical methods can be easily checked or controlled in real-time with personal devices, such as smart phones, and with dash boards.

Acknowledgements

This research was supported by the MSIP (Ministry of Science, ICT and Future Planning), Korea, under the C-ITRC (Convergence Information Technology Research Center) (IITP-2015-H8601-15-1007) and supervised by the IITP (Institute for Information and Communications Technology Promotion).

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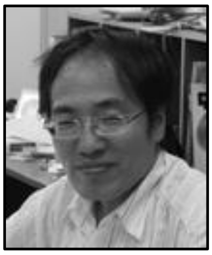

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