Kriging Interpolation Evaluation of Vapor Pressure Deficit in Plant Factory with Solar Light

Takashi KOGA *, Ken’ichi YAMAGUCHI *, Hiroshi IWATA *, and Ikusaburo KURIMOTO **

Abstract: To maximize the growth of plants, controlling VPD is applied by fog cooling in a plant factory with solar light. The spatial data of environmental information cannot be obtained without interpolation among the detected values by the allocated sensors. In this paper, we evaluated the errors between the interpolated values with Kriging and the detected values in the spring, autumn, and winter, respectively, in the plant factory with solar light. The experimental results show that the maximum error of the interpolated values using Kriging are within the acceptable error range, ±0.1 kPa. Therefore, Kriging is useful for interpolation in the plant factory with solar light.

Key Words: plant factory with solar light, vapor pressure deficit, interpolation, kriging.

1. Introduction

It is an important element for growing plants to control vapor pressure deficit (VPD) to a suitable value [1,2]. The fog cooling system has been widely used to control the VPD value [3,4]. Lu et al. [3] demonstrated that the application of fogging systems based on VPD regulation is an effective strategy to regulate greenhouse environment. Watanabe et al. [4] proposed the VPD controlling system with fog cooling to keep a suitable value in a plant factory with solar light. In order to improve the control efficiency of the VPD value, not only the cooling system but also mobile shading [5] and fan ventilation [6] are effective. The existing controlling system detects the VPD value only at the center position of the plant factory with solar light [3,4]. However, the VPD values have various distributions in the plant factory with solar light [7]. Therefore, it is important for the plant growth to detect the data of accurate environmental information (temperature, relative humidity, VPD, and so on). To detect the two-dimensional data of environmental information, we proposed an active sensing platform which consists of mobile and fixed-type sensor nodes [7]. The spatial data of environmental information cannot be obtained without interpolation among the detected values detected by the platform. To the best of our knowledge, the VPD values on two-dimension have never controlled before, and there are no researches discussing how to interpolate the VPD values on two-dimension in the plant factory with solar light. In this paper, we interpolated and evaluated the VPD values on two-dimension in the plant factory with solar light. In order to improve the control efficiency of the VPD value, not only the cooling system but also mobile shading and fan ventilation are effective. The existing controlling system detects the VPD value only at the center position of the plant factory with solar light. Therefore, Kriging is useful for interpolation in the plant factory with solar light.

The detected and interpolated VPD values by the Kriging method [8] used in geostatistics. In this study, the detected and interpolated VPD values are compared by the Kriging and linear methods with the color maps of the error values and root mean squared error (RMSE).

2. Active Sensing System

Figure 1 shows an overview of the experimental area in the plant factory with solar light. The VPD controlling system uses the existing sensor node (marked with a triangle) located on the center of the experimental area. The mobile sensor node (marked with a dotted circle) actively detects the data of environmental information for each 2 m detecting position between plant raised floor style growing beds (marked with a black rectangle) in the whole experimental area.

Figure 2 shows the picture of the mobile sensor node in the experimental area. The mobile sensor node uses Vaisala HMP155 as a temperature/humidity/VPD sensor. HMP155 is assembled in a solar light shield and over 5 m/s forced ventilation is maintained by a waterproof 12 V fan. About 1 minute was needed to detect on every 2 m of a line (32 m) with the mobile sensor node.

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3. Kriging

The spatial data of environmental information cannot be obtained without interpolation among the distributed values detected by the platform. Kriging deals with a local outlier [9], and the accuracy of the environmental data interpolated by Kriging is higher than linear and IDW [10],[11]. Moreover, Pesquer et al. proposed a method of decreasing the computational time of Kriging [12]. This paper evaluates the interpolated VPD values by the Kriging method [8],[9] used in geostatistics. The interpolated values are calculated by (1) where \( \hat{Z}(x_i) \), \( n \), \( Z(x_i) \), and \( \omega_i \) are the interpolated value at the position \( x_i \), the number of the detected positions, the detected value at the position \( x_i \), and the weight of the detected value \( Z(x_i) \), respectively.

\[
\hat{Z}(x_0) = \sum_{i=1}^{n} \omega_i Z(x_i).
\]

Variogram is a function of the distance between \( x_i \) and \( x_j \) as the variance of the detected values. Variogram \( \gamma(h) \) is defined as (2) where \( N(h) \) is the set of \( (i, j) \) whose distance is \( h \).

The value of \( \gamma(h) \) is called semivariance.

\[
\gamma(h) = \frac{1}{2N(h)} \sum_{(i,j) \in N(h)} (Z(x_i) - Z(x_j))^2.
\]

The approximate curve is created by minimizing the error in the variogram and the following fitting model (spherical model), where \( a \), \( b \), and \( c \) are arbitrary constants:

\[
\gamma(h) = a + b \left[ \frac{3h}{2c} - \frac{1}{2} \left( \frac{h}{c} \right)^3 \right].
\]

The weight \( \omega_i \) is obtained by the following equations, where \( \mu \) is the Lagrange multiplier:

\[
\begin{pmatrix}
\omega_1 \\
\vdots \\
\omega_n \\
\mu
\end{pmatrix} = A^{-1} \times \begin{pmatrix}
\gamma(x_1 - x_0) \\
\vdots \\
\gamma(x_n - x_0) \\
1
\end{pmatrix},
\]

4. Kriging Evaluation with Mobile Sensor Node

This section evaluates the error of interpolated values calculated with the Kriging and linear methods. The experiments were conducted at Daisei Chiba Farm in the Center for Environment, Health and Field Sciences, Chiba University in the spring (February 4, 2018, 14:28 to 14:50, the weather was cloudy). Figure 3 shows the color map of VPD detected by the active sensing system for the whole experimental area. The number of the detected positions is 196. The color map consists of the spline interpolation algorithm by using gnuplot software (version 5.2). The experiments show that the values of VPD have a range of 0.6 kPa to 1.1 kPa. To compare interpolation accuracies between Kriging and linear, the error (\( Z(x_i) - \hat{Z}(x_i) \)) in the detected value (\( Z(x_i) \)) and the interpolated value (\( \hat{Z}(x_i) \)) is used. The interpolated value (\( \hat{Z}(x_i) \)) is calculated by using the detected values of the others (which eliminates the value of its position).

4.1 Interpolation Algorithm

Figure 4 shows the algorithm that calculates the interpolated value. For Kriging interpolation, the interpolated values are calculated from all detected positions except the interpolated positions. Also, we assume the isotropic in the experimental area. For linear interpolation, the interpolated values are calculated by the average of the detected values around the positions.

4.2 Evaluation of Interpolated Values

Due to the measurement error of Vaisala HMP155 [13], the VPD value has the maximum error of about \( \pm 0.05 \) kPa. In order to evaluate the interpolated values, the VPD value is measured twice by the sensor (the first measurement is to calculate the interpolation value, and the second measurement is to compare the VPD value with the “true” value). Therefore the cumulative error of up to about \( \pm 0.1 \) kPa occurs. In this paper, the acceptable error range is \( \pm 0.1 \) kPa.

Figures 5 and 6 show the color maps of the errors in the detected values and interpolated values calculated by the Kriging and linear methods, respectively. These color maps show that there exist \( \pm 0.1 \) kPa errors on lines such as \( x = 11 \) m, \( x = 17 \) m, and so on. The reason why the skewed distribution exists on the lines is the negative effects of the detected values on the next lines.

Figures 7 and 8 show the variogram fitting curves created to interpolate (17, 8) and (7, 0), respectively. The erroneous position (17, 8) includes 0.1 kPa error which is the maximum in the interpolation. On the other hand, the successful position (7, 0) includes about 0.0 kPa error which is the minimum in the interpolation. This result means that variogram can be shared since the characteristics of these curves are almost the same.

4.3 Interpolation-by-Line Algorithm

Since both linear and Kriging methods also used the VPD values of the next lines for the interpolation, the errors increase if the VPD value differs for each line. To decrease the errors, we interpolated using only values detected by the
Fig. 3 The color map of VPD (kPa) at A1-C5 raised floor style growing beds on February 4, 2018.

Fig. 4 Each interpolation algorithm using around detecting positions.

Fig. 5 The color map of the errors of Kriging interpolation using around the detecting position.

Fig. 6 The color map of the errors of linear interpolation using around the detecting position.

Fig. 7 Variogram fitting of the erroneous position (17, 8).

Fig. 8 Variogram fitting of the successful position (7, 0).

Fig. 9 Each interpolation algorithm using the detecting positions on the same line.

same line as the position of the interpolation. Figure 9 shows the algorithm that calculates the interpolated value. For Kriging interpolation, the value used for interpolation consists of the detected values on the same line as the position. For linear interpolation, the interpolated value is calculated by the average of the detected values on the positions of the upper and lower sides.

4.4 Result of Interpolation-by-Line

Figures 10 and 11 show the color maps of the errors in the detected values and interpolated values calculated by the proposed Kriging and linear interpolation methods, respectively. From these results, it can be seen that there is no error in both Kriging interpolation and linear interpolation.

4.5 Quantitative Evaluation with RMSE

For quantification of errors, root mean squared error (RMSE) is used as a basis for evaluation. RMSE is calculated by (6), where $Z(x_i)$ is a detected value, and $\hat{Z}(x_i)$ is an interpolated value by the interpolation algorithm.
Table 1: RMSE of VPD using only the mobile sensor.

| Interpolation method | Kriging (kPa) | Linear (kPa) |
|----------------------|--------------|--------------|
| Whole                | 0.0480       | 0.0413       |
| Line                 | 0.0082       | 0.0091       |

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=0}^{n-1} (Z(x_i) - \hat{Z}(x_i))^2}.
\] (6)

Table 1 shows the values of RMSE calculated by each algorithm. The error in Kriging interpolation is less than the one of linear interpolation when only the detected values on the same line as the interpolated position are used.

5. Kriging Evaluation with Multi-Point Real-Time Sensor Nodes

This section shows the comparison results between detected and interpolated VPD values using the mobile sensor node and using the multi-point sensor nodes [13], respectively. The multi-point sensor nodes achieved real-time VPD measurement on nine positions in the plant factory with solar light. In this paper, an interpolated value is calculated with the nine detected values where the interpolation position is on the position of the mobile sensor node at the time. Figure 12 shows the way of the mobile sensor and the positions of the multi-point sensor nodes. The experiments were conducted at Daisen Chiba Farm in the Center for Environment, Health and Field Sciences, Chiba University in the autumn (October 19, 2019, 14:30 to 15:17, the weather was cloudy) and the winter (December 27, 2019, 16:15 to 17:18, the weather was cloudy). The mobile sensor node actively detected the VPD values at the position of 4 m intervals for one plant raised floor style growing beds. Figures 13 and 14 show the color maps of the VPD values detected by the active sensing system for the whole experimental area in the autumn and winter, respectively. The numbers of the detected positions are 96 and 78 in the autumn and winter, respectively. These color maps consist of the spline interpolation algorithm by using gnuplot software (version 5.2). Experiments show that the values of VPD have ranges of 0.3 kPa to 0.65 kPa and 0.07 kPa to 0.15 kPa in the autumn and winter, respectively.

5.1 Interpolation Algorithm with Multi-Point Real-Time Sensor Nodes

The multi-point real-time sensor nodes synchronously detect VPD values every 30 seconds. In the experiment, we evaluate the errors between detected and interpolated VPD values using the mobile sensor node and using the multi-point real-time
sensor nodes, respectively. Likewise, the mobile sensor node detects a VPD value at the position to be interpolated every 30 seconds as the true (detected) value. Figure 15 shows an example of interpolation of the VPD value at the position (3, 20) at 14:36:00. The right graph shows the temporal transition of the VPD values detected with nine multi-point real-time sensor nodes located in the positions (named A1-C3) described by the left top view. The VPD value of the position (3, 20) is interpolated from the nine VPD values detected with the multi-point real-time sensor nodes at 14:36:00. On the other hand, the true VPD value is detected when the mobile sensor node exists at the position (3, 20) (the corresponding time is 14:36:00). Therefore, the error at each position (on the way of the mobile sensor node) can be available by the difference between the interpolated and detected values.

5.2 Experimental Results

Figures 16 and 17 show the color maps of the errors between the detected values and interpolated values calculated as discussed above (Section 5.1). The interpolation results show that all the interpolated values in the autumn and winter are smaller than the acceptable error range, the position (22, 19) includes the maximum error, 0.07 kPa, in the autumn, and the position (2, 7) includes the maximum error, 0.08 kPa, in the winter.

Figures 18 and 19 show the variogram fitting curves used to interpolate the erroneous position (22, 19) and the successful position (20, 31) in the autumn, respectively. The interpolated VPD value of the position (22, 19) includes 0.07 kPa error, which is a very small error although the maximum value in this experiment. On the other hand, the interpolated VPD value of the position (20, 31) includes about 0.0 kPa error, which is the minimum in this experiment. The gradient of the variogram at any point in the latter is larger than the former. In other words, Fig. 18 indicates that the weight of the detected value, which is far away from the interpolated position, is large. Therefore, the error of interpolated value was caused by the determination method of the weight coefficient ($\omega_i$). In the experiment in the winter, the relationship between the variogram and the distance with respect to the errors of interpolated VPD values was the same as the experiments in the autumn.

Table 2 shows the value of RMSE calculated by the algorithm with multi-point real-time sensor nodes. The value of RMSE is practically small, and all the interpolated values are within the acceptable error range though the RMSE of the interpolation-by-line algorithm (discussed in Section 4.3) is smaller than the one. Therefore, the algorithm with multi-point real-time sensor nodes is useful for interpolation without the need for additional consideration such as the interpolation-by-line algorithm.
6. Conclusion

Controlling VPD as a suitable value is an essential element for growing plants. It is necessary to detect and interpolate the accurate VPD value for optimally controlling. In this paper, we evaluated the errors between the interpolated values with Kriging and the detected values, at 196 positions in the spring, 96 positions in the autumn, and 78 in the winter, respectively, in the plant factory with solar light. The experimental results show that the maximum error of the interpolated values in the spring, autumn, and winter using Kriging are within the acceptable error range, ±0.1 kPa, and Kriging is useful for interpolation in the plant factory with solar light. This method can be applied to 60 percent of plant factories with solar light without any changes. In other cases, this method can be applied by changing some environment variables.

For future work, Kriging’s future prediction will be achieved by using the characteristics of variogram identity, and therefore more accurate VPD control will be available for maximizing the growth of plants.

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