Proceedings of the 2025 SICE Festival with Annual Conference
September 9-12, 2025, Chiang Mai, Thailand

VPD Estimation Using Spatio-Temporal Kriging

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Abstract: Controlling vapor pressure deficit (VPD) is essential for optimizing plant growth in sunlight-type plant factories. While previous studies have demonstrated the effectiveness of VPD control using fine mist systems, the spatial resolution of VPD monitoring has been limited. This study developed an IoT-based VPD measurement system with 27 sensors placed at different heights to capture three-dimensional environmental data. To evaluate the interpolation accuracy, the VPD values of the measured and estimated values were compared, and the mean squared error ranged from 8.58×10^{-4} to 1.42×10^{-3} kPa. The results show that variogram model parameters remained consistent during mist operation but varied significantly at night or under uncontrolled environments. These findings suggest that VPD control status and environmental conditions should be considered when applying spatial interpolation.

Keywords: plant factory, vapor pressure deficit, kriging

1. INTRODUCTION

When growing plants, controlling the vapor pressure deficit (VPD) at an appropriate level is an important factor in maximizing photosynthesis. Watanabe et al. proposed a VPD control system using fine mist cooling to maintain appropriate VPD values in a sunlight-type plant factory[1]. In this system, VPD values were detected only at the center of the plant factory. However, VPD has various distributions in sunlight-type plant factories. Accurate detection of environmental information such as temperature, humidity, and VPD is important for plant growth. Tobisawa et al. increased the number of measurement points to eight and expanded the system[2]. The expanded system was used to perform real-time measurement and visualization of the internal environment[3]. Koga et al. detected two-dimensional planar distribution data of VPD in a plant factory by interpolating data obtained from a system consisting of mobile and fixed sensors using kriging interpolation and evaluated the interpolated values[4]. In the sunlight-type plant factory, kriging interpolation was performed in spring, autumn, and winter, and the maximum error was within the tolerance range (±0.1 kPa). However, the data used for interpolation was obtained from sensors installed parallel to the ground, and data obtained from sensors installed perpendicular to the ground has not been examined. Furthermore, the usefulness of kriging interpolation when fine mist cooling is operated and when it is not operated in an environment without plants has not yet been clarified.

The purpose of this study was to clarify the distribution characteristics of VPD data in a plant factory. In a sunlight-type plant factory, we will construct an IoT system capable of acquiring temperature, humidity, and VPD data by installing 27 sensors. We will also perform kriging interpolation under environmental conditions with and without fine mist cooling in operation to investigate errors.

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2. VPD MEASUREMENT IOT SYSTEM

VPD is the difference between the saturated vapor pressure at a given temperature and the actual vapor pressure, and serves as an indicator of the potential transpiration rate of leaves at that temperature. The SHT31-DIS sensor manufactured by SENSIRION is used to measure VPD. This sensor can measure with an accuracy of ±0.3°C for temperature and ±2% for humidity, and supports I2C digital communication. Table 1 shows the measurable range and accuracy. The Buck's Eq. (1) is used

Table 1 Specifications for VPD measurement sensor.

	Range	Accuracy
Temperature [°C]	-40 - 125	±0.3
Humidity [%]	0 - 100	±2

to calculate VPD[5]. Here, T_d is the dry-bulb temperature [°C], e_{td} is the saturated vapor pressure of dry air [kPa], RH is the relative humidity [%], and D is VPD [kPa].

$$e_{td}(T_d) = 0.61365\mathrm{e}^{\frac{17.502T_d}{240.97+T_d}}. \quad (1)$$

$$D = e_{td}(T_d)(1 - \frac{RH}{100}). \quad (2)$$

Equation (1) coefficients were determined to minimize the error from the measured values. It is also designed for easy use with computers and is used in international standard dew point generators.

3. SPATIO-TEMPORAL KRIGING

Kriging interpolation performs interpolation by modeling spatial correlations between data points. The interpolated values are calculated using Eq. (3).

$$\hat{Z}(x_0) = \sum_{i=1}^{n} \omega_i Z(x_i). \tag{3}$$

$\hat{Z}(x_0)$ is the interpolated value at x_0, n is the number of measurements, $Z(x_i)$ is the measured value at x_i, and ω_i is the weight of the measured value $Z(x_i)$.

To estimate interpolated values, a variogram is obtained that represents the relationship between the distances between data points and the differences between their values. The variogram is shown in Eq. (4).

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (Z(x_i) - Z(x_i + h))^2. \tag{4}$$

$\gamma(h)$ is the variogram, and $N(h)$ is the number of measurement pairs at distance h. The weights are obtained using Eqs. (5) and (6) below. Here, μ is the Lagrange multiplier.

$$\begin{pmatrix} \omega_1 \\ \vdots \\ \omega_n \\ \mu \end{pmatrix} = A^{-1} \times \begin{pmatrix} \gamma(x_1 - x_0) \\ \vdots \\ \gamma(x_n - x_0) \\ 1 \end{pmatrix}. \tag{5}$$

$$A = \begin{pmatrix} \gamma(x_1 - x_1) & \dots & \gamma(x_1 - x_n) & 1 \\ \vdots & \ddots & \vdots & \vdots \\ \gamma(x_n - x_1) & \dots & \gamma(x_n - x_n) & 1 \\ 1 & \dots & 1 & 0 \end{pmatrix}. \tag{6}$$

In this study, we use a method called spatio-temporal kriging, which performs interpolation by considering not only coordinates but also time information, to interpolate VPDs spatially in a time series[6]. For each point x_i, the variance between that point and another measurement point at a distance h is calculated, and the temporal difference u is considered. Equation (7) shows the spatio-temporal variogram. A gaussian model is used as the fitted model.

$$\gamma(h, u) = \frac{1}{2N(h,u)} \sum_{i=1}^{N(h,u)} (Z(x_i, t_i) - Z(x_i + h, t_i + u))^2. \tag{7}$$

4. MEASUREMENT AREA

The experiment was conducted at the sunlight-type plant factory No. 5 building Center for Environmenr, Health and Field Science, Chiba University Kashiwanoha Campus. Figure 1 shows the sensor and interpolated estimated positions when looking down on the experimental section of the plant factory. The sensors are placed at nine locations as shown in Fig. 1, with three sensors placed at different heights at each location, for a total of 27 sensors used for kriging interpolation. The sensors are suspended

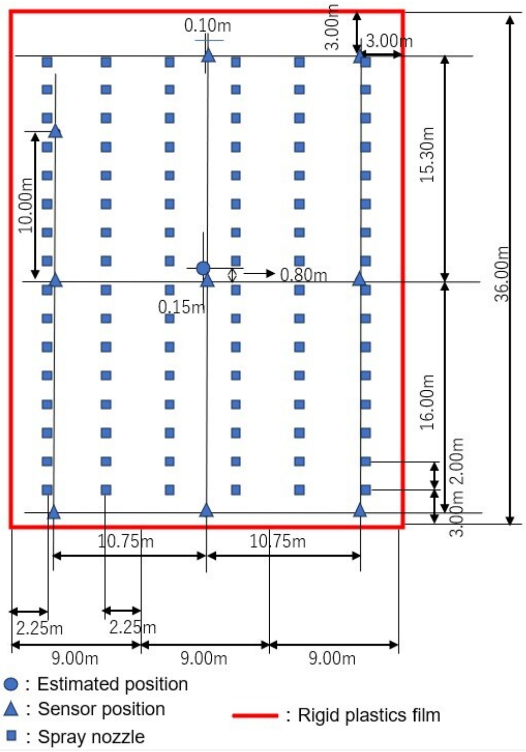

Fig. 1 Sensor placement and estimated positions in the experimental area.

at heights of 0.5 m, 1.5 m, and 2.5 m above the ground. The estimated height is 1.5 m above the ground. Figure 2 shows the positions of sensors at different heights. In

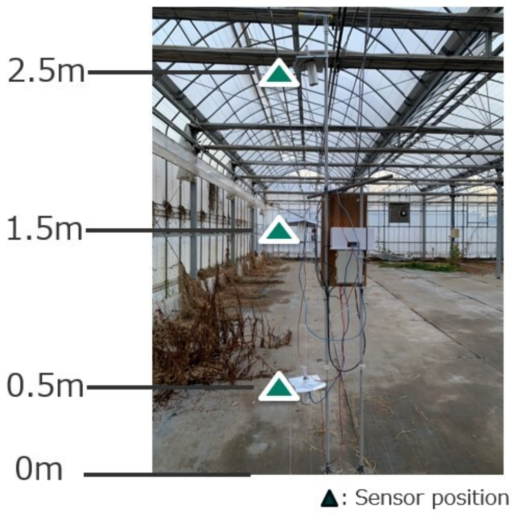

Fig. 2 Positions of sensors at different heights.

the experimental area, the fine mist cooling system was operated on January 11 and 13, and the VPD was kept constant.

5. RESULTS

Figures 3 and 4 show the variogram fitting using daytime data obtained when the fine mist cooling system was operated on January 11 and 13. Figure 5 shows the variogram fitting using data from the night when the system was not operational on January 12. The results of variogram fitting using VPD data when the fine mist cooling system was not operating on January 12 are shown in Fig. 6. Table 2 shows the parameters of the model equations for each variogram. Table 3 shows the mean squared error (MSE) between estimated values obtained by kriging interpolation and measured values.

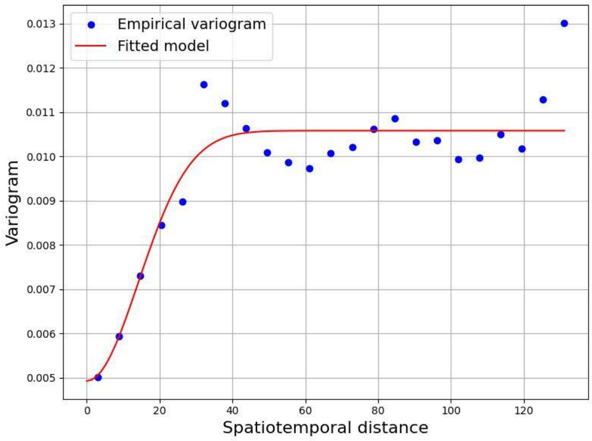

Fig. 3 Variogram using VPD data from 12:00 to 13:00 on January 11 (daytime data under PI control environment).

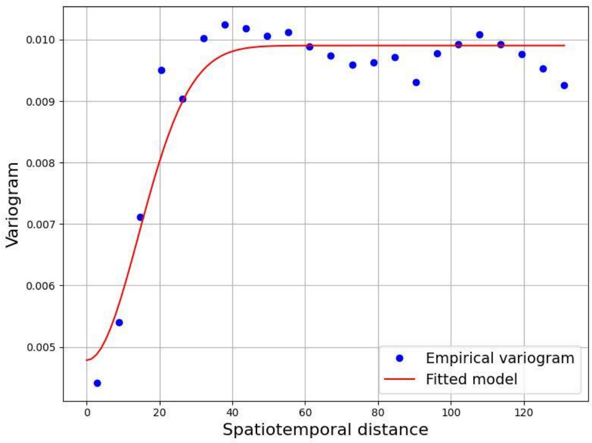

Fig. 4 Variogram using VPD data from 12:00 to 13:00 on January 13 (daytime data under PI control environment).

Table 2 Parameters of the variogram model equation.

Date Time	Sill	Range	Nugget
1/11 12:00–13:00	10.05×10^{-3}	20.0	4.93×10^{-3}
1/13 12:00–13:00	9.90×10^{-3}	20.0	4.78×10^{-3}
1/12 2:00–3:00	6.10×10^{-4}	82.0	2.45×10^{-5}
1/12 12:00–13:00	4.43×10^{-3}	24.0	1.06×10^{-3}

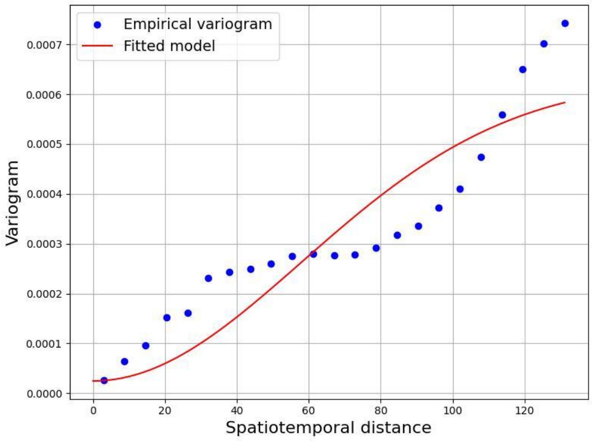

Fig. 5 Variogram using VPD data from 2:00 to 3:00 on January 12 (nighttime data).

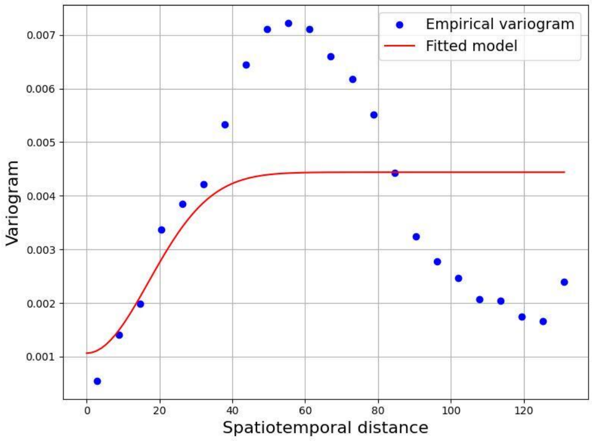

Fig. 6 Variogram using VPD data from 12:00 to 13:00 on January 12 (daytime data in a non-PID control environment).

Table 3 MSE between estimated values obtained by kriging interpolation and measured values.

Date	Time	MSE
1/11	12:00–13:00	1.42×10^{-3}
1/13	12:00–13:00	1.22×10^{-3}
1/12	2:00–3:00	8.58×10^{-4}
1/12	12:00–13:00	1.36×10^{-3}

6. DISCUSSIONS

From the results shown in Fig. 3 and 4 and Table 2, it can be confirmed that the model equations for the variograms during operation of the fine mist cooling system during the day show similar parameters. The parameters are similar because the VPD is controlled at a nearly constant level, creating a consistent environment. On the other hand, Figs. 5 and 6 and Table 2 show that the parameters differ greatly at night and under uncontrolled VPD conditions. When applying interpolation methods to simulators, it is necessary to consider parameters such as VPD control and environmental conditions. Table 3 shows that the difference between the measured values and estimated values was kept to 1 or less in all environments, but the difference was particularly small at night. The difference at night was small because the measured values and estimated values were relatively small to begin with.

7. CONCLUSIONS

In this study, we constructed a 27-point sensor network in a sunlight-type plant factory to measure VPD at different heights and conducted spatial interpolation using spatio-temporal kriging. The results showed that when the fine mist cooling system was operational, the VPD environment remained stable, and the variogram parameters were similar across different days. In contrast, under uncontrolled or nighttime conditions, the VPD distribution varied, resulting in different variogram characteristics. Future works include applying simulations and synchronizing them with real-world data.

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