Implementation of crop growth monitoring system based on depth perception using stereo camera in plant factory

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Abstract. The plant factory is extensive cultivation to produce a high quality of vegetables under a controllable environment. The concept of Precision Agriculture (PA) was introduced to improve the plant factory production by the implementation of a crop growth monitoring system. Crop growth can be estimated by monitoring of crop height and canopy foliage by the use of computer vision technology. In our previous study, we have introduced a plant height monitoring system based on depth perception using a stereo camera. However, the validity of the various type of leave is necessary to be tested. The objective of this study was to implement the crop growth monitoring system to monitor plant development with various type of leave for system validation and evaluation. The crop growth monitoring system composed of a stereo camera implementing the depth perception for estimating the distance from camera to highest point in the crop. The implementation of the system with various types of leaves and characteristics has been conducted for (a) Samhon, (b) Lettuce, and (c) Pagoda. The developed crop growth monitoring system could perform the time series estimation of crop height with a maximum error of RMSE 0.875 cm on Pagoda, and MAPE of 5.56% on Lettuce. The system demonstrates better estimation on Samhong with minimum error RMSE of 0.408cm and 2.27% of MAPE. Overall validation for the estimated height vs actual measurement indicates that the coefficient of determination higher than 0.7 means that it has substantial features for estimating the plant height.

1. Introduction
Precision agriculture is an integrated approach to farming systems based on information and technology on agricultural management to identify, analyze, and manage information in specific sites to obtain optimum benefits and minimize the impact on the environment. Information and technology make it possible to carry out specific and precise measurements and observations, thus the observation of agricultural activities no longer using assumption and database-based observation is feasible to be applied [1]. Unlike conventional agriculture, precision farming involves more precise variations.
determination by linking the spatial relationships with management actions, thus farmers get the new insight of agriculture, crops and agricultural practices that lead to costs saving, products and quality optimization according to the production capacity of each sector, improvement of resource management principle [2]. Precision agriculture is used in integrated cultivation under controlled environmental conditions using real-time information data and automatic feedback [3]. The Plant Factory is one of the implementations of an integrated farming system. The Plant factory is different from the greenhouse. Greenhouses use direct sunlight as energy for photosynthesis and there is the influence of the uncontrolled environment, while plant factory uses artificial light with LED lights and closed systems, thus environmental influences can be controlled by humans [4]. This artificial assistance can help control and adjust the quality of the plants according to the expected standard using computer vision.

Vision systems are essential for automating tasks such as object recognition, part manipulation, inspection, and measurement. All vision systems are limited by the quality and images they acquire [5]. Stereo vision uses at least two camera images (binocular) to compute the 3D information. Stereo vision with two perspectives cameras, similar to the distance estimation of humans [6]. The Stereo camera built up of two cameras mounted in parallel and separated by the baseline. It captures a synchronized stereo pair consisting of the left camera’s image and the right camera’s image. The challenge of the stereo camera is the reconstruction of 3D information of a scene captured from two different points of view. Each visible scene point is projected on the image planes to correspond to each other used to determine the three-dimensional position of the projected scene point in a defined coordinate system. In more detail, the horizontal displacement, called the disparity is inverse proportional to the scene point depth [7]. Distance measurement through a camera generally uses two cameras, which is similar to the principle of the human eyes. Since the two eyes of a human observe an object at different positions, there is a difference between the vantage point angles, which is called disparity, and this disparity can be used to estimate the distance of the observed object from the ‘eye’ or the camera. Stereo vision is based on this principle [8].

Previous studies related to the use of stereo cameras for monitoring systems have been applied. Lebreton et al., [9] used the computer vision method to determine the depth of an object as a support to the added value of 3D video, Seal et al., [10] used a single stereo camera to observe depth perception with a two-plan mirror planar stereo radiotherapy system. Bendig et al., [11] conducted a research on the Crop Surface Model (CSM) in wheat fields and calculated the average value of harvest time to estimate the height of plants using unmanned vehicles. A study conducted by Okayasu et al., [12,13] developed an affordable field environmental monitoring and plant growth measurement system for smart agriculture. The application of this previous research aimed to improve agricultural production in terms of advancing the knowledge and techniques of farming, reducing production costs and improving the quality of agricultural products [14]. Related to plant growth, Rizkiana et al. [15] measures and develop the crop growth for vegetative phase in plant factory that can be used for reference.

Implementation of a crop growth monitoring system based on depth perception in plant factory uses a stereo camera that is placed on the top side of the plant was conducted. Using the disparity technology which is a combination of two image rectifying results in a difference of the corresponding point at both the left and the right images. Disparity map in the stereo vision represents the depth of an object. The disparity is inversely proportional to depth. Higher disparity means that the object is closer to the baseline of the camera. Inversely, lower disparity indicates that the object is farther from the camera baseline [16,17]. In this research, crop growth was monitored and determined in real-time. The process of the crop growth determination enables the system to estimate upward growth by applying the concept of depth perception, thus the three-dimensional visualization and disparity map to measure the distance an object. Plant development will be measured using one camera lens (right or left lens).

The objective of this study was to implement the crop growth monitoring system to monitor plant development, especially the plant height, with various types of leave for system validation and evaluation in a plant factory.
2. Materials and Method
This research was conducted at the Smart Agriculture Research, Laboratory of Agricultural Energy and Machinery, Department of Agricultural and Biosystems Engineering, Faculty of Agricultural Technology, Universitas Gadjah Mada in April - July 2019.

2.1. Monitoring System
Figure 1 shows the schematic application of crop growth monitoring systems based on depth perception in a plant factory. The observation was conducted on plants in a plant factory by installing a stereo camera above the plants. The computer vision module consists of a stereo camera ELP-1MP2CAM001 USB stereo camera, a Raspberry Pi B+ as a microcomputer, and a network device to provide data transmission from the local monitoring chamber to the cloud system. USB stereo camera can be seen in Fig. 2(a). Moreover, the detail specifications are listed in Table 1.

![Schematic application of crop growth monitoring system based on depth perception using stereo camera](image)

**Figure 1.** Schematic application of crop growth monitoring system based on depth perception using stereo camera

| Aspect                  | Information                                      |
|-------------------------|--------------------------------------------------|
| Model                   | ELP-1MP2CAM001-HOV90                            |
| Sensor                  | OV9712                                           |
| Lens Size               | 1/4 inch                                         |
| Pixel Size              | 3.0 µm x 3.0 µm                                  |
| Image Area              | 3888 µm x 2430 µm                                |
| Max. Resolution         | 1280 (H) x 720 (V)                               |
| Resolution & Frame      | 1280 x 720 MJPEG@ 30 fps YUY2@10 fps             |
|                         | 640 x 360 MJPEG@ 60 fps YUY2@30 fps              |
| Dynamic Range           | 69 dB                                            |
| Sensitivity             | 3.7 V/lux-sec@550 nm                             |
| Adjustable Parameters   | Brightness, Contrast, Saturation, Hue, Sharpness, Gamma, Gain, White balance, Backlight Contrast, Exposure |
2.2. Depth perception for height estimation
Depth Perception is the result obtained from image processing using a stereo camera. A stereo camera, Figure 2(a) has two lenses to take pictures at the same time that works like the human eye (binocular vision). The vision cameras that use a single lens can only depict images in 2D while using a stereo camera the resulting image can be obtained in the 3D model due to differences in angles. The approach that is used based on depth perception for estimating plant height is the triangulation method described as displayed in Figure 2(b). P is the position of the taken image, T is the distance between two cameras, Z is the distance between points measured with the camera, f is the focal length and x is the distance of the P point formed at the focal length.

Research procedure can be seen in Figure 3, consists of (a) stereo camera calibration, (b) stereo capture, and (c) crop height estimation which runs the function for disparity estimation, depth map generation, and plant height estimation. The stereo system was developed using Python 3.7 equipped with OpenCV Library 3.4.5.20.

Figure 2. (a) Stereo camera device and (b) distance estimation using triangulation method
2.3. Experimental setup

Figure 4 shows the scenario of measurement of crop height using a stereo camera (a) and plant sample for observations: (b) Samhong, (c) Lettuce, and (d) Pagoda. The program uses the distance between the plant (peak) and the camera so that the equation formed can estimate the height of the plant. The equation for plant height \( h_p \) is the distance between the camera and the base or gully/height camera \( H_c \) minus the distance between the camera and the highest plant height \( h_d \) which is done by measuring at the certain time interval. The general equation for time series data of plant height can be expressed as (2.1) where, \( h_{p[t]} \) is the estimated height at time \( t \) (cm), and \( h_{p[n]} \) is the estimated height at time \( n \).

\[
\begin{align*}
\Box p_{[t]} &= H_c - \Box d_{[t]} \\
\vdots \\
\Box p_{[n]} &= H_c - \Box d_{[n]} 
\end{align*}
\]  

(2.1)
2.4. System performance evaluation

This study was evaluated by comparing the actual and estimated height to find out the error values. Estimation is obtained from linear equations of the models that have been made. Validation evaluation is done using the Root Mean Squared Error (RMSE), and Mean Absolute Percentages of Error (MAPE) where \( p \) is the estimated value, and \( o \) is the actual value. The RMSE and MAPE equation are expressed in (2.2)

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n}(p_i - o_i)^2}{n}}, \quad MAPE = \frac{1}{n} \sum \frac{|p_i - o_i|}{o_i} \times 100\%
\]  

3. Result and Discussion

Figure 5 shows the disparity value vs actual depth or distance measurement for each camera setup and crop types which have different characteristics in their growth. Measurement of the distance estimation was carried out for 16 times at three different types of plants. The results of the disparity are depicted in a disparity chart that contains the difference in color from the farthest to the nearest using a comparison of the basic distance with the camera and the distance of the object to the camera. The disparity relation shows that the closer plant object to the camera the higher disparity value of the disparity obtained. The result is the disparity to depth equation for each plant that can be used for further application.

The time-series measurement of actual and estimated plant height for each sample crop can be seen in Figure 6. The actual measurement of plant height using manual ruler compared with the estimated value using a stereo camera system in time-series manner. Measured plant height tends to fall because the highest tip of the plant is bent because of the increase in leaf mass as it develops. Crop height of Samhong (a) and Lettuce (b) have identical growth patterns between estimated and actual representing the performance of the monitoring system. However, error or underestimated value has measured on Lettuce (b) and Pagoda (c) in early ten days of observation. The underestimate value caused by the leaf type and tip does not have a sharp corner with significant contrast during the stereo-capture step. Accordingly, an error has occurred in the early-stage on Lettuce and Pagoda height estimation.
Further investigation, the performance of crop height estimation error analyzed using RMSE and MAPE. The result of the RMSE for Samhong is 0.408 cm, Lettuce is 0.874 cm and Pagoda is 0.585 cm. The validation result using MAPE shows the error of 2.27% for Samhong, 5.56% for Lettuce and 2.61% for Pagoda. Although the appearance of time series data of Pagoda shows a high error in the early ten days, the RMSE and MAPE indicate lower value than in Lettuce. The Samhong time-series displayed the best fit compared with others with the smallest RMSE and MAPE.

**Figure 5.** Disparity value vs actual depth measurement for estimating the equation for automatic depth calculation for each crop types and camera setup for: (a) Samhong, (b) Lettuce, and (c) Pagoda.

**Figure 6.** Time-series measurement of actual and estimated plant height of (a) Samhong, (b) Lettuce, and (c) Pagoda.

**Figure 7.** Validation result for estimated vs actual measurement of plant height for: (a) Samhong, (b) Lettuce, and (c) Pagoda.
Figure 7 shows the validation result for estimated vs actual measurement for all samples using the coefficient of determination using $R^2$. The value $R^2$ for Samhong has a higher coefficient of determinations, means that the estimated value could represent the actual plant height measurement. Both time-series and error for Samhong show identical and lower value comparing with others. Overall validation for the estimated height vs actual measurement indicates that the Coefficient of Determination higher than 0.7 means that the estimated value could represent the actual one [18]. Accordingly, the estimated height by using stereo camera can be used to estimate plant height. Dealing the decrease of height phenomena, caused by the change in highest point at the plant tip due to the bent of the stem affected by the increase in leaf mass as it develops, it is necessary to measure the structure of the stem and leaf precisely. For recommendation, not only measuring the highest part of plant for estimating the plant growth, but also utilizing precise plant leaf reconstruction.

4. Current Conclusion and Future Works
The implementation of a crop growth monitoring system with various types of leaves and characteristics has been conducted for Samhong (a), Lettuce (b), and Pagoda (c). The developed crop growth monitoring system could perform the time series estimation of crop height with a maximum error of RMSE 0.875 cm on Pagoda, and MAPE of 5.56% on Lettuce. The system demonstrates better estimation on Samhong with minimum error RMSE of 0.408cm and 2.27 % of MAPE. Overall validation for the estimated height vs actual measurement indicates that the coefficient of determination higher than 0.7 means that it has substantial features for estimating the plant height. Minimizing error by precise measurement on leaf tip and reconstruction using stereo camera will be in our future works for better representation of plant growth in a plant factory.

Acknowledgements
Authors wishing to acknowledge financial support from The Ministry of Research, Technology and Higher Education of the Republic of Indonesia by 2018 - 2019 Research Grants of Penelitian Terapan Unggulan Perguruan Tinggi (PTUPT) 2019 (No. 2771/UN1/DITLIT/DIT-LIT/LT/2019), Research Grant of Rekognisi Tugas Akhir (RTA) Scheme from Universitas Gadjah Mada 2019 (No. 3414/UN1/DITLIT/DIT-LIT/LT/2019). Also, the author would like to thanks Smart Agriculture Research group of Agricultural and Biosystems Engineering UGM for the support.

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