Three-dimensional (3D) reconstruction for non-destructive plant growth observation system using close-range photogrammetry method

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Abstract. Agriculture in Indonesia has recently experienced challenges, especially in terms of meeting market demand that tends to increase. Precision agriculture is an effort to increase productivity through optimizing agricultural production processes by minimizing inputs, maximizing output, and reducing the impact on the environment through the use of information and communication technology. Implementation of the concept of precision agriculture is in observing plant growth and development to estimate plant volume and mass. So far, conventional plant measurements by direct measurement can pose destructive risks to plants. Therefore, a non-destructive system for observing and measuring plants is needed. The purpose of this study was to develop a plant growth observation system based on three-dimensional modelling with non-destructive measurements using the Close-Range Photogrammetry (CRP) method. This system has a 360 orbital scanner component that consists of a frame, camera arm, NEMA 17 stepper motor, Logitech C270 web-camera, Raspberry Pi 3 B +, Adafruit motor driver, and LED strip lights. The stage of image processing using 3DF Zephyr Pro software for generating the 3D sparse point cloud and cropping the unused point. For the validation purposes and its functionality for modelling and estimating volumetric objects, a plant model with three sizes (small, medium, and large) variations were used. As the result, the developed system could observe and model the plant shape in a three-dimensional manner resemble the actual plant model.

1. Introduction

Precision farming is based on information and technology in agricultural management systems that aim to identify, analyze, and manage information on spatial and temporal diversity in the land to obtain optimum, sustainable benefits, and protect the environment [1,2]. Currently, various information and communication technology systems have been developed to support and improve agricultural practices, with a focus on estimating growth and movement of crops, environmental measurement and control, and recording of agricultural work [3].
At present precision agriculture, especially for small areas such as plant factories, focuses on developing data management systems, the efficiency of various types of image analysis and optical sensing, equipment design and sensor efficiency, and related technologies in it [4]. In the application in the Plant factory, to monitor the growth of each plant, a lot of cameras are needed which will be used to support precise measurements [5]. One of the fundamental implementations in terms of precision agriculture is that accurate measurement of plants are needed to observe the rate of growth. Plant growth is one important thing to be able to evaluate the environmental field and also improve agricultural production systems [6]. So far, direct measurements in the field using conventional measuring instruments have become a way to be able to measure plants. The measurement of plants destructively by destroying parts of plants is more detrimental than non-destructive measurements which are proven to be able to provide more data in one sampling [7]. Non-destructive observations and measurements on plants are more beneficial because they can be more flexible to do repeated testing without damaging the plants [8].

One solution for measuring non-destructive measurements of plants is to use laser scanner technology. However, to implement this technology for agricultural purposes requires high costs. The price for one unit of laser scanner sold in several online marketplaces ranges from tens to hundreds of millions of rupiah depending on the features and quality. Advanced sensors, such as cameras, in the future of agricultural automation, will play an important role that can create spatial and color information from natural objects [9]. Therefore, to address those problems, in this study, a method called the Close-Range Photogrammetry (CRP) method is used as a cheaper alternative to laser scanner technology to be able to scan plants and produce three-dimensional objects so that non-destructive plant measurements can be carried out. The Close-Range Photogrammetry method uses the basic principle of overlapping measurements between photos with different points of view and measurements of camera orientation [10].

The purpose of this study was to develop a plant growth observation system based on three-dimensional modeling with non-destructive measurements using the Close-Range Photogrammetry (CRP) method and validate its performance for volume estimation in plant models.

2. Materials and Methods
This research was conducted from January to April 2020 at the Smart Agriculture Research Group, Agro-Informatics Sub-Laboratory, Laboratory of Energy and Agricultural Machinery, Department of Agricultural and Biosystems Engineering, Faculty of Agricultural Technology, Universitas Gadjah Mada, Yogyakarta.

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**Figure 1.** Schematic design of the scanner and 3D reconstruction system.
2.1. System development

Figure 1 shows the schematic design of the scanner and 3D reconstruction system. The scanner consists of a frame that is installed with several components such as the NEMA 17 stepper motor, the Logitech C270 web-camera, the Raspberry Pi 3 B+ microcomputer; the Adafruit motor driver; and Light Emitting Diode (LED) Strips. The scanner will carry out the process of acquiring images of plant objects in a 360° rotation. The image data obtained will then be imported into Zephyr Pro's 3DF photogrammetric processing software to be reconstructed into a three-dimensional object. After obtaining three-dimensional plant objects, the volumetric measurement process is carried out as a representation of the process of growth and development of plants. The detailed procedure for this three-dimensional reconstruction system can be seen in Figure 2.

![Flowchart for the 3D reconstruction system](image)

**Figure 2.** Flowchart for the 3D reconstruction system.
3. Results and Discussion

3.1. Three-dimensional scanner design
The design results in this study are a web-camera based scanner. This tool consists of a frame. The frame is box-shaped with size (50 x 50 x 50 cm). The object is placed in the middle of the tool, then a web camera mounted on the camera arm and connected to the stepper motor begins to take the image by rotating the object so that the object image data is obtained from various sides. The image obtained will then be processed in the photogrammetric processing software. The results of the design of a three-dimensional scanner can be seen in Figure 3.

![Figure 3](image)

Figure 3. The results of the design of a three-dimensional scanner.

3.2. Images acquisition results
Plant objects used for image capture in this study are dummy plant models with 3 size variations; small, medium, and large. The selected plant model is also colored off or does not reflect light. This is to avoid coordinate interpretation errors in the photogrammetric processing software so that it has implications for the results of the three-dimensional objects produced. The results of image samples resulting from various variations in plant size can be seen in Figure 3.

3.3. The result of the three-dimensional reconstruction process in 3DF Zephyr Pro software
3DF Zephyr Pro is an image processing software for three-dimensional objects. The first process is the process of matching images and sparse reconstruction. The image matching process is the process of finding the same points between one image and another. When the same points between images are matched, then the software will immediately carry out the process of reconstructing points from two-dimensional image data into points in three-dimensional space. This collection of points is commonly called a point cloud/vertex. The number of point clouds in the initial reconstruction is not large enough so that the object produced is still in the form of sparse points or called sparse point clouds. Sparse point cloud results for the three plant variations can be seen in Figure 4. Furthermore, the sparse point cloud that has been formed is then reprocessed so that the number of point clouds generated increases in the dense reconstruction process. The result of this stage is called a dense point cloud. In this study, the dense point cloud formed can be seen in Figure 5. The shape of an object in the dense point cloud can already be said to resemble an actual object. The final process in this three-dimensional modeling is surface reconstruction. This process connects points between point clouds to create an object surface. The results of surface reconstruction in this study can be seen in Figure 6.
Figure 4. Sparse point cloud image for third crop variation, a) plant 1, b) plant 2, and c) Plant 3.

Figure 5. Dense point cloud for third crop variations, a) plants 1, b) plants 2, and C) Plant 3

Figure 6. Images of three-dimensional object crops after process surface reconstruction, a) plant 1, b) plant 2, and c) plant 3.

| Plant Model | Actual Volume (cm³) | Estimated Volume-CP (cm³) | ΔVolume (cm³) |
|-------------|---------------------|---------------------------|---------------|
| Plant 1 (small) | 166 | 166.643003 | 0.643003 |
| Plant 2 (medium) | 226 | 227.363950 | 1.363950 |
| Plant 3 (large) | 250 | 250.676920 | 0.676920 |

Table 1. Comparison of conventional methods and CRP measurement results.

3.4. Volume measurement results

In this study, volumetric measurements were carried out for each plant variation using the conventional method of volume measurement and measurement of three-dimensional objects in the 3DF Zephyr Pro software. The results of volumetric measurements of plant objects by conventional methods and photogrammetry can be seen in Table 1.

From the results of these comparisons, it can be seen that there are differences in measurement results between the conventional method and Close-Range Photogrammetry even though when seen in the graph Figure 7. The difference is very thin in all three plant variations. The difference in the results of these two methods can occur due to the quality of the image data used by cameras that are not as good as cameras with larger sensors or metric cameras, thus making the three-dimensional objects produced less detailed. Plant objects that should have gaps between leaves, three-dimensional objects appear to
It can be seen from the result data that the measurement of the three objects of the plants using the CRP method has a larger volume than the object measured manually.

**Figure 7.** Comparison of volume measurements in each crop variation.

4. **Conclusions**

The development of a non-destructive plant growth measurement system in this study resulted in a scanner designed to scan plant objects by acquiring 360° rotational images. The image data that has been obtained is reconstructed so that it gets three-dimensional objects from three dummy plants using Zephyr Pro's 3DF photogrammetric processing software. From the results, it can be said that the volumetric measurement of the plant observation system using the Close-Range Photogrammetry method is quite accurate and can be an alternative non-destructive measurement for plants.

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