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Review:

Introduction of All-Around 3D Modeling Methods for Investigation of Plants

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Digital image phenotyping has become popular in plant research. Plants are complex in shape, and occlusion can often occur. Three-dimensional (3D) data are expected to measure the morphological traits of plants with higher accuracy. Plants have organs with flat and/or narrow shapes and similar component structures are repeated. Therefore, it is difficult to construct an accurate 3D model by applying methods developed for industrial materials and architecture. Here, we review noncontact and all-around 3D modeling and configuration of camera systems to measure the morphological traits of plants in terms of system composition, accuracy, cost, and usability. Typical noncontact 3D measurement methods can be roughly classified into active and passive methods. We describe their advantages and disadvantages. Structure-from-motion/multi-view stereo (SfM/MVS), a passive method, is the most frequently used measurement method for plants. It is described in terms of "forward intersection" and "backward resection." We recently developed a novel SfM/MVS approach by mixing the forward and backward methods, and we provide a brief overview of our approach in this paper. While various fields are adopting 3D model construction, nonexpert users struggle to use them and end up selecting inadequate methods, which lead to model failure. We hope that this review will help users who are considering starting to construct and measure 3D models.

Keywords: three-dimensional modeling, plant, photogrammetry, SfM/MVS, active and passive methods

1. Background

Digital image phenotyping has become popular in plant research over the past decade owing to the use of engineering approaches, including remote sensing, photogrammetry, computer vision, and robot vision. Images are used to investigate morphological traits in automatic, noncontact, and nondestructive methods. These approaches aim to enable accurate and efficient crop production and breeding in plant factories, greenhouses, and fields by evaluating and recording plant growth from germination to yield [1, 2]. In addition, machine learning is expected to eventually predict plant growth by collecting various types of "big data" [3]. Plants are complex in shape, and occlusion can often occur because of shielding by leaves and other organs. Hence, it is expected that three-dimensional (3D) data will be used to measure the complex morphological traits of plants with higher accuracy.

Plants consist of organs with flat and/or narrow shapes, such as leaves and stems, with relatively uniform color in most cases. In addition, similar component structures, such as leaves, are often observed throughout the body. Therefore, it is difficult to construct an accurate 3D model by applying the methods developed for industrial materials and architectures without alterations. Recently, several studies have reported the development of 3D modeling for plants [4, 5]. We review the methods for all-around 3D modeling of plants that can be used to measure plant morphological traits during the growth period with target sizes ranging from a few centimeters to several meters.

In this paper, we target methods for plant 3D modeling using images captured from as many directions as possible. Current typical noncontact 3D measurement methods can be roughly classified into passive and active methods. The former includes measurement methods based on received light, whereas the latter performs measurement using illuminated light. We describe the principles and characteristics of both and introduce the pertinent equipment. The most popular passive method currently used is the structure-from-motion/multi-view stereo (SfM/MVS) method. We describe the SfM/MVS method in detail by dividing the "forward intersection" and "backward resection" methods based on the principle of photogrammetry with the characteristics of camera system configurations.

To enhance the practice of 3D modeling, we outline the measurement equipment used in each method in terms

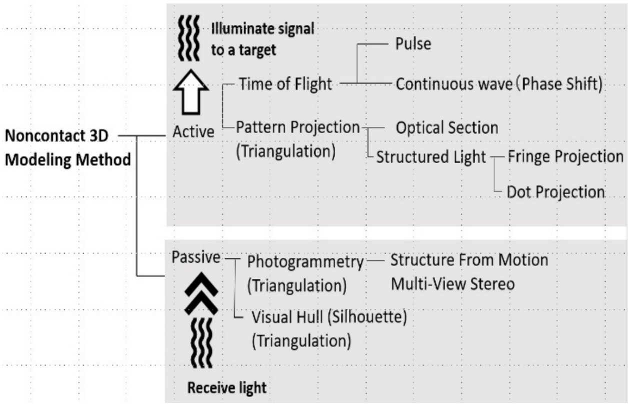

Fig. 1. Practical noncontact 3D modeling methods for plants.

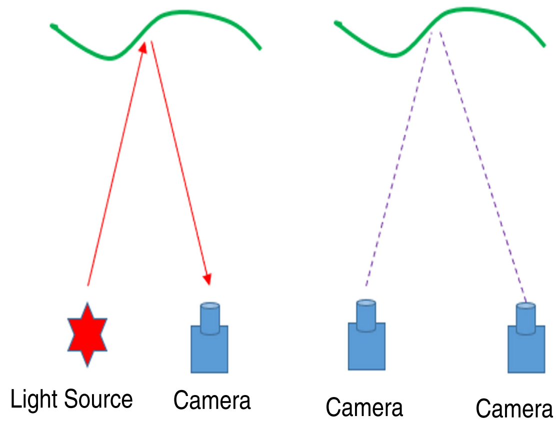

Fig. 2. Schematic representations of the active (left) and passive (right) methods.

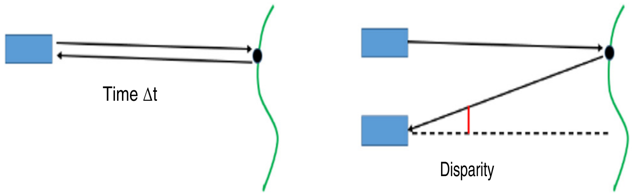

Fig. 3. Time of flight (left) and triangulation (right).

of principles, components, ease of assembly, availability, cost to achieve practical use, and further technical development, such as automation. This guide is intended for plant scientists or developers who are planning to set up a 3D modeling system by themselves [6–8]. We recently developed a 3D modeling system for strawberries composed of commercial products. The accuracy of the constructed model was ∓ 1 mm [9]. The system can also be applied to model larger plants ($\sim$2.4 m). We expect this paper to serve as a guide for plant scientists who are planning to set up a 3D modeling system by themselves using commercial products.

Accuracy is an important factor in 3D modeling. However, the required accuracy in 3D modeling depends on the target size and purpose. Although it is difficult to assume, in this study, we set the required accuracy to less than 5% of the target size in reference to a case where the required accuracy is less than 1 mm when a few centimeters of plants or fruits are measured with a ruler.

Although we focus here on the application to plant 3D modeling, the descriptions could help with 3D modeling of non-plant products when the target size and accuracy are close to those of herbaceous plants (a few centimeters to a few meters). Three-dimensional model construction is now being used in various fields. Nonexpert users who do not understand the principles of such models, however, often run into some problems, such as failing to build a model or selecting an inadequate method. Another major problem is that nonexpert users are sometimes satisfied with merely constructing a "likely 3D model" and do not pay attention to its accuracy. We hope that this review will help users who are considering performing 3D reconstruction and measurement using 3D modeling.

2. Overview of 3D Modeling Methods

Noncontact 3D modeling methods can be roughly classified into active methods, which require illumination, and passive methods, which use received light. **Fig. 1** shows representative and practical noncontact 3D modeling methods for plants. The active method consists of a light source and a camera, whereas the passive method consists of two cameras without a light source. **Fig. 2** shows examples of typical active and passive illumination.

The active method includes time-of-flight (ToF) methods, which measure the time it takes for light to travel between the pulse and the received signal, and a pattern projection method based on triangulation (**Fig. 3**). There are several methods for projecting patterns, such as with an optical section method, which projects slit light, and a fringe projection method with structured light projection [10]. In terms of passive methods, there is the structure-from-motion (SfM) method, which uses the multi-view stereo method in photogrammetry, and the silhouette (visual hull) method. These methods are also based on triangulation.

Both active and passive methods require either a mechanism for moving a target plant or a measuring equipment when all-around measurement is performed. **Table 1** summarizes the advantages and disadvantages of the active and passive methods described in this paper under conditions where the target sizes range from several centimeters to several meters for all-around 3D modeling of a plant and where there is a possibility of automation. The advantages and disadvantages of each method are summarized in the sections below, along with the introduction of the necessary equipment.

Although any method can be used to reconstruct a 3D model, a passive method is more suitable for 3D modeling in which the target size is a few centimeters to a few meters because active methods require the system to

Table 1. Characteristics of the active and passive methods.

	Active method					Passive method	
Method	Optical section method	Pattern projection	Depth camera (triangulation)	TOF camera LiDAR camera	Terrestrial laser scanner	Silhouette method	SfM/MVS
Compactness of system size	Fair	Fair	Very good	Fair	Poor	Very good	Very good
All-around system	Fair	Poor	Fair	Fair	Poor	Excellent	Excellent
Measured area	Small ∼ Middle	Small	Small	Small ∼ Middle	Large	Small ∼ Middle	Small ∼ Large
Resolution	Submillimeter	Micron ∼ Submillimeter	about 5 millimeter ∼	about 5 millimeter ∼	Millimeter	Submillimeter	Submillimeter
Rapidness of data capture time	Poor	Excellent	Excellent	Excellent	Poor	Very good	Very good
Rapidness of calculation time	Fair	Fair	Excellent	Excellent	Fair	Fair	Fair
Hardware price	Fair	Poor	Excellent	Fair	Unacceptable	Very good	Very good
Flexibility of system	Poor	Poor	Excellent	Fair	Poor	Fair	Excellent
Availability of outdoor measurement	Poor	Unacceptable	Poor	Very good	Excellent	Poor	Excellent
System structure	Line laser, Light-receiving unit, Software	Devices, Software	Devices, Software	Devices, Software	Devices, Software	Camera, Screen, Software	Camera, Software
Advantage	Small system size, High accuracy, Measurable complex structure (with movable parts or manual measurement), Availability of automation	Rapid measuring, High accuracy	Small system size, Rapid measuring, Available low cost devices (e.g., Kinect, RealSense) Simultaneous capture of RGB images and depth images	Rapid measuring, Simultaneous capture of RGB images and depth images, Available TOF sensor	Large objects, Wide-range measuring	Low cost (3DSOM), High accuracy, Available single camera system, Easy all-around measuring	Low cost, High accuracy, Available single camera system, Easy all-around measuring
Disadvantage	Long measuring time, Non-availability of automation when a handheld device is used	Limited measured area, Large devices are required for large area measurement	Low accuracy, Rapid discontinuation of available systems	Low accuracy, Rapid discontinuation of available systems	High cost, Low accuracy for a small object	Long calculation time, Requires a screen, Need to carefully consider camera position, Requires calibration	Long calculation time, Need to carefully consider camera position

make large movements, and, hence, cost increases. Wang et al. [11] compared the performance of measurement methods for plants using laser scanning, MVS, 3D digitization, and manual measurements. They concluded that a combination of the SfM and MVS methods was the most cost-effective, flexible, and productive approach. However, recent technological developments in the field of automated driving systems have started to achieve miniaturization or price reduction of depth and ToF cameras, on which the active methods are based. Therefore, keeping up with the technological development trends in active methods is also important for plant 3D modeling.

The minimum required equipment for passive methods is only a camera and a computer program; therefore, passive methods can lead to flexible systems consisting of commercial products. Among the passive methods, the silhouette method can only be used indoors, whereas a combination of the SfM and MVS methods can be used in the field. We therefore concluded that the combination of the SfM and MVS methods has the most flexibility and convenience in plant 3D modeling. The SfM and MVS methods are based on photogrammetry, which can be applied in various situations such as terrain measurement, civil engineering, industrial measurement, and large-structure measurement [12]. The number of practical applications would make it easier to introduce 3D modeling with this method than with other methods. Those who want to try the 3D reconstruction method can simply download the free version of the software (e.g., VisualSFM) or the trial version of the commercial software (see Section 4.2).

There are several other methods for 3D modeling. However, from the viewpoint of practical 3D modeling for plants, we focus on ToF and pattern projection with a depth camera as the active methods and photogrammetry and silhouette (visual hull) as the passive methods.

3. Active Methods

As mentioned above, pattern projection and ToF are typical approaches to 3D modeling in active methods. In the pattern projection method, patterned light is illuminated in a 3D space and the position of the pattern is measured by sensors. The position of each pattern element is measured by its association with the pattern and light source. Meanwhile, ToF identifies the 3D coordinates of a target by measuring the direction of light and the round-trip time-of-light flight between the sensor and the target. In this section, we describe pattern projection and ToF in more detail.

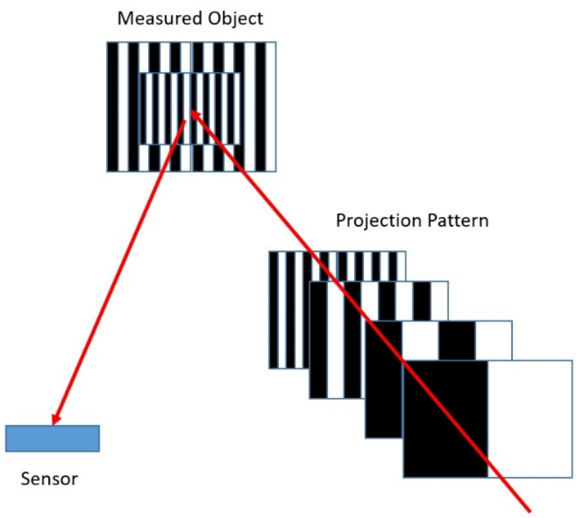

Fig. 4. Pattern projection.

3.1. Pattern Projection

The pattern projection method creates a 3D surface profile of the target surface by projecting patterned light onto the target and measuring (picturing and analyzing) the changes in the pattern. Each distance is measured on the basis of the triangulation. Various types of patterns can be used, including lines, fringes, grids, colors, checkerboard, and corded (**Fig. 4**). Here, we describe slit ray projection, structured light projection, fringe projection, and dot projection in practical use.

3.1.1. Optical Section Method

The optical section method obtains a linear 3D surface profile by actively projecting a linear light onto the target. In **Fig. 2**, for example, the light source shines the liner light onto the target, and in **Fig. 4**, a linear pattern is used to project a slit light onto the target. The equipment necessary for this method consists of a line laser, which is an illumination unit, a light-receiving unit, and a control software program. This method has been applied to highly accurate 3D model measurement systems [13]. It is also applied to unitize commercial products for plant 3D modeling systems [14] and for plant research with minor improvements [15, 16].

The advantages of this method include the small equipment size and high precision (micrometer scale) [17]. A handheld scanner is often used to investigate complex shapes [18]. The disadvantage of the optical section method is that the measurement time is long because it measures a target body by moving the light source or the target. In fact, measurement accuracy often decreases because of the movement of the target by wind or vibration. In addition, handheld scanners are difficult to use with automated systems because they are premised on a human user. Automation is possible by creating an operating unit. However, when all-around measurement of a plant is performed, multiple operating units are required to capture complex shapes, thus increasing the price of the entire system. Therefore, this method is not suitable for small-scale all-around 3D modeling systems for plants. However, for settings in a larger space, such as plant factories or fields, the method is suitable because the movable part can be set in the space.

3.1.2. Fringe Projection Method in the Structure Light Method

Various patterns are used in the structure light methods, such as fringe, grid, and checker patterns, and random dots. Of the structure light methods, fringe projection uses fringe patterns and photographs taken consecutively at high speed as the fringe pattern changes (**Fig. 4**). Digital light processing (DLP) technology is often used for fringe pattern projection. In DLP technology, small light particles are projected in multiple directions at high speed using a digital mirror device (DMD). In this technology, several hundred to several thousand pattens are projected and the captured patterns are used for 3D modeling and measurement [19, 20].

Devices using DLP technology have been developed and applied to industrial measurement, such as in automobile manufacturing for car bodies and parts [21]. The advantages include high measurement accuracy (micrometer scale) and high-speed shooting, which are less affected by wind and vibration. In addition, automation is easier with this method. The disadvantage is that most of the devices developed for industrial measurement are large and expensive.

Several small, relatively inexpensive devices have been developed [22, 23]. However, the measurement area is limited to approximately 500 mm^2 when a small device is used. Therefore, in the case of a target plant with a complex shape and a size of a few meters, multiple sensors and light projection units are needed to perform all-around measurements. In this case, the equipment becomes expensive. Software for the registration of point clouds is also required in this method.

3.1.3. Dot Projection (Depth Camera) in the Structure Light Method

Grid projection is applied with a depth camera or a distance image camera that projects multiple infrared lights in a grid pattern and receives the light with a camera. Popular commercial products that use this method include Kinect v1 [24] developed by Microsoft (note: Kinect v2 uses ToF) and RealSense [25] by Intel. These devices have lower costs than those of other systems and are popularly used in games, robots, and hobbies. Owing to its easy availability, Kinect is often used in plant 3D modeling research [26–28].

The advantages of a depth camera are the small size, real-time measurement, and simultaneous capture of an image and its depth. For example, Intel's RealSense Depth Camera D435 [29] is small (90 mm $\times$ 25 mm $\times$ 25 mm and 5 g), low cost, and easy to obtain, and has a development environment (software development kit). However, its disadvantage is its lower accuracy, such as a few millimeters to several centimeters. Careful attention to accuracy is required, especially when the distance between the device and the target is more than 50 cm. The devices are suitable for use in plant 3D modeling when accuracy is not a large factor in the measurement. Because these devices are mass produced, models change and are discontinued frequently as new models are brought to the market. Novel products sometimes provide new approaches to plant measurement; thus, it is important to frequently update information.

3.2. ToF Method

There are two methods in TOF: one measures ToF by illuminating the pulse waveform, and the other measures the phase differences of the illuminated continuous waves (**Fig. 1**). The latter has higher accuracy; however, the appropriate distance between the device and the target is shorter.

The typical device applying ToF is a terrestrial laser scanner used in terrain surveys. Recently, various small and low-cost ToF sensors have been developed and applied to cars, drones, mobile robots, and smart phones. These devices are generally called 3D ToF cameras or 3D LiDAR (light detection and ranging) cameras. They are evolved forms of the depth camera, described in Section 3.1.3, with the principal point adjusted to the ToF for improved accuracy and available distance.

3.2.1. Terrestrial Laser Scanner

The terrestrial laser scanner (TLS) is suitable for measuring large objects and topographical maps from a long distance (1–100 m). The pulse method is generally used for long-distance measurements (a few kilometers) in ground surveys [30]. On the other hand, the phase-difference method is often used in short-distance measurements (∼100 m) in construction surveys [31]. Some devices can apply both methods for middle-distance measurements (∼500 m) [32]. To improve mobility, researchers have recently achieved size miniaturization in several devices [33, 34]. It has also been applied for plant measurements [35–38].

The TLS produces a 3D point cloud by moving a laser spotlight up, down, left, and right (**Fig. 5**). Using this system, one can easily obtain point clouds automatically. However, laser scanners of this type have been developed to measure wide-area fields of several to hundreds of meters, and, therefore, they are not applicable to plants. When a TLS is used for all-around plant measurements, the scanner should be moved or multiple scanners should be set around the plant. In addition, target markers and special software are required for the registration of point cloud data. Such equipment is extremely expensive and unsuitable for general use.

3.2.2. ToF Camera

ToF cameras are often called LiDAR or depth cameras. Their accuracy is lower than that of the TLS; however, they are also smaller and less expensive. In addition, they can acquire depth information and images simultaneously. ToF cameras do not scan laser beams mechanically. Size and cost reductions are achieved by eliminating moving parts with the assistance of semiconductors and optical technologies.

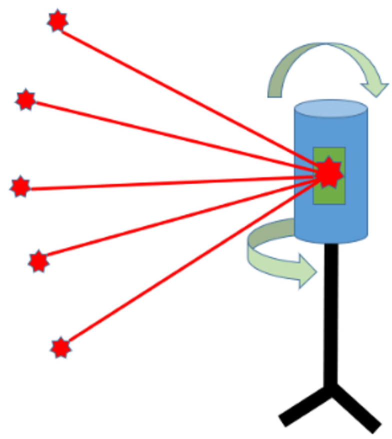

Fig. 5. How a terrestrial laser scanner produces 3D point clouds.

A type of 3D ToF camera that takes depth information with a special two-dimensional (2D) sensor array in the light-receiving section is available [39]. The price of the camera is higher because it uses a special sensor array. However, as it enables miniaturization and weight saving, the 3D ToF camera can be mounted on a car. Sony is developing ToF sensors and applying them to robots, drones, autonomous driving vehicles, and virtual reality/mixed reality for the expanding market [40]. A 3D ToF camera with ToF sensors has also been developed by Lucid [41] and Basler [42].

In addition, several different types of devices, such as those that scan laser beams with micro-electro-mechanical system (MEMS) mirrors [43, 44] or that change the beam angle by shifting the light phase [45], have been developed. Most of these technologies have been developed for the highly competitive field of autonomous driving.

For plant 3D modeling, Kinect v2, which uses a ToF sensor, is often used and is considered a promising candidate [46–48]. The advantages are the small size, real-time measurement, and simultaneous capture of an image and its depth. Meanwhile, the disadvantage is the lower accuracy, such as a few millimeters to several centimeters (approximately 1% of the distance between the device and the target). The size and price are higher than those of the depth camera described in Section 3.1.3. For example, Intel's RealSense LiDAR Camera L515 is 60 mm × 60 mm × 26 mm [49]. The available distance and accuracy are longer and higher, respectively, than those of a depth camera, and shorter and lower, respectively, than those of a TLS.

Because these devices are mass produced, models change and are discontinued frequently as new models are brought to the market. Novel products sometimes provide new approaches to plant measurement; hence, it is important to frequently update information.

4. Passive Method (Image Measurement Using Commercial Cameras)

For the passive method, which measures a target object by reflected light, a measurement system can be constructed with a minimum of one camera and one turntable; hence, the required cost is generally lower and the system is more flexible than that of the active method. Because commercial-release cameras can be used, it is possible to design flexible layouts with multiple cameras according to the shapes and sizes of the targeted plants. The use of multiple cameras also has the benefit of less impact from wind and vibration. In addition, the passive method has the advantage of capturing 2D images for 3D modeling, and, therefore, 2D images can be used to monitor the growth conditions of plants.

A disadvantage of the passive method is that careful consideration of camera positions and measurement accuracy (resolution) is required according to the target shape and size. Another is that 3D model reconstruction takes more time. Here, the passive method is roughly classified into the silhouette method, which is an image-based visual hull method, and the SfM method, including the MVS method, which is based on photogrammetry. The silhouette and SfM methods operate according to different principles.

Recently, a few novel devices or approaches have been developed. For example, a 3D light field camera with multiple microlenses estimates the depth length by calculating the light directions [50]. A photometric stereo system performs 3D modeling by estimating the light direction with a camera and multiple light-emitting diode sources [51, 52]. These novel approaches are considered promising technologies because of the possibility of reduced cost and size. However, as they remain at the development stage and are currently unavailable for practical use, we do not describe them here.

Both the silhouette method (visual hull method) and photogrammetry use camera pictures, and the configurations of the devices are similar. However, the principles are different. We describe the principles and applications separately below.

4.1. Silhouette Method or Visual Hull Method (Shape from the Silhouette)

The silhouette method reconstructs 3D silhouette images based on the visual hull concept, which calculates the crossover parts of the visual volumes generated by capturing the back-projections of the silhouettes of the targets in a 3D space. It captures images from multiple directions and constructs a 3D model with voxels [53] (**Fig. 6**).

This method is sensitive to errors and requires strict calibration in the illuminant layout and the creation of a target silhouette. Yamazaki et al. [54] developed an

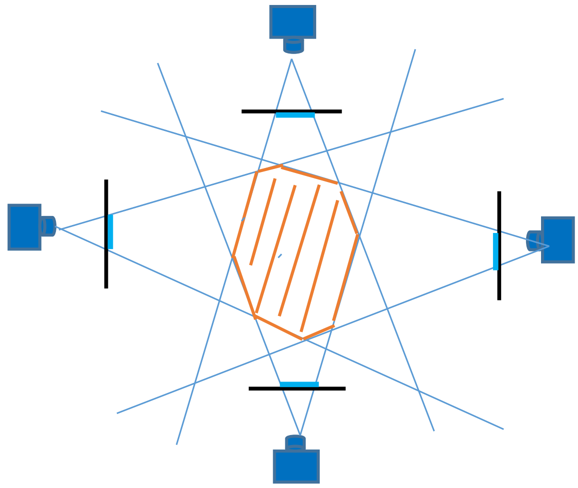

Fig. 6. A conceptual diagram of the silhouette method.

approach to create a precise 3D model of an object with a complex shape using a large number of images. Nguyen et al. [55] reported a methodology for measuring plant organs in a 3D model reconstructed on the basis of 360 images captured by a system with two cameras and a turntable. Golbach et al. [56] captured a silhouette by taking multiple images with 10 cameras. However, these methods require relatively large-scale devices to obtain silhouettes on a screen behind an object.

To overcome this disadvantage, CDSL Limited developed the 3DSOM commercial software for reconstructing a 3D model with small devices by using calibration targets [57, 58]. 3DSOM has been used in plant measurements [59]. In addition, Scharr et al. [60] developed an automatic image-capturing system that applies the silhouette method. These tools are suitable for plant measurement because the device composition is simple (i.e., one or more cameras and a turntable) and the accuracy is high. The disadvantage is that users must construct the systems by themselves because an open-source system is not yet available.

4.2. SfM and MVS Methods

The SfM method, also known as the multi-view geometry (MVG) method, is based on the geometry of photogrammetry for constructing a rough 3D point cloud of an object with the estimation of camera position and attitude. The MVS method creates a dense 3D point cloud by performing dense matching, which is a process of identifying a corresponding point by matching multiple images with the information on camera positions and attitude estimated by the SfM method.

Because the combination of the SfM and MVS methods can reconstruct 3D surface models at a low cost and with a simple device, such as a single commercial camera, it is used in plant phenotyping in both the greenhouse and the field [61–67]. In many studies, camera position and attitude were estimated using open-source image feature descriptors (e.g., SIFT [68]) available in OpenCV [69] with

Table 2. Composition of the camera system.

	Forward intersection method	Backward resection method	Forward intersection and backward resection mixed method
Number of cameras	More than two	One	One or more
Camera fixation	Necessary	Not necessary	Not necessary
Pre-calibration	Necessary	Not always necessary	Not always necessary
Setting control points	Not necessary	Necessary	Not always necessary
Shooting time	Short	Long	Middle
Movable parts	None	Existence	Existence
Maintenance	Whole system	Control points only	Not necessary

the bundle adjustment software Bundler [70] to minimize errors. A free software package, VisualSFM, can also be used to estimate camera position and attitude [71, 72]; it can also be used to perform dense matching with an MVS software program [73]. These software programs can be downloaded at no cost. Liu et al. [74] published an open-source software program that can reconstruct plant 3D models with a single camera and a turntable.

Other available free software programs for the SfM method include Apero [75], OpenMVG [76], Theia [77], OpenSfM [78], and Colmap [79]. OpenMVS is an open-source software program for the MVS method [80], and MicMac is a software program that uses semi-global matching methods [81]. Three-dimensional model reconstruction can be performed using a combination of these programs. There are also commercial packages that combine the SfM and MVS methods, such as Pix4D [82], ContextCapture [83], Reality Capture [84], and Metashape (formerly Photoscan) [85].

VisualSLAM, a combination of the SfM and MVS methods, is also used for 3D modeling based on images [86–88]. The difference is that SLAM performs a sequential image input under a running process, whereas the SfM process runs after all the images have been obtained. SLAM is more popular in robot vision.

Both free and commercial software are available for the SfM and MVS methods, and, therefore, it is possible to build a low-cost measuring system. In addition, the precision setting of the camera and the object positions are not required because camera positions are estimated on the basis of the feature points of an object. However, the unstable creation of 3D modeling sometimes occurs owing to errors in estimation. Several approaches have been reported to avoid this fault, such as loop closing [89] and adjusting camera positions using graph theory [61, 90, 91].

5. Composition of Camera Systems in the SfM and MVS Methods

The SfM and MVS methods are most frequently used in plant 3D modeling. Careful consideration and optimization of a camera system are key in 3D modeling with the SfM and MVS methods because they are closely related to measurement accuracy, maintenance, and cost. Having knowledge of the composition of the camera system is essential to success in the construction of 3D modeling. From the perspective of photogrammetric methods, there are two main ways to configure a camera system: a forward intersection method and a backward resection method. In this section, we review the features of these methods and introduce a mixed approach that we are currently developing for guiding appropriate camera system settings in plant 3D modeling. The compositions of the camera system in each method are summarized in **Table 2**.

5.1. Forward Intersection Method (with Fixed Cameras)

In the forward intersection method, the camera position is fixed before the image capture and external orientation parameters (i.e., camera position and attitude) are calculated, as are internal parameters (i.e., the principal point position, principal distance, and lens distortion). This method is suitable for stereo cameras and multicamera configurations. The advantage of this method is the possibility of real-time and automatic measurements. Because image shooting is performed within seconds, it is less susceptible to wind and vibration. In addition, there is no need for markers to calculate camera positions before shooting.

The disadvantage of this method is that it requires multiple cameras and the calibration of internal and external parameters prior to shooting. Once the external calibration (calculation of camera position) is completed, the position of the system must not be changed [92]. Therefore, the preparation of a calibration tool is necessary and, therefore, the maintenance cost becomes high.

5.2. Backward Resection Method (with Moving Cameras or Objects)

Unlike in the forward intersection methods, in the backward resection method, cameras or objects are moved. External parameters (i.e., camera positions and attitudes) are calculated from more than three control points. This method has been in practical use as it is one of the most popular forms of photogrammetry, e.g., for archeological measurements [93]. The method is also commonly used as an SfM method and applied to drones [94].

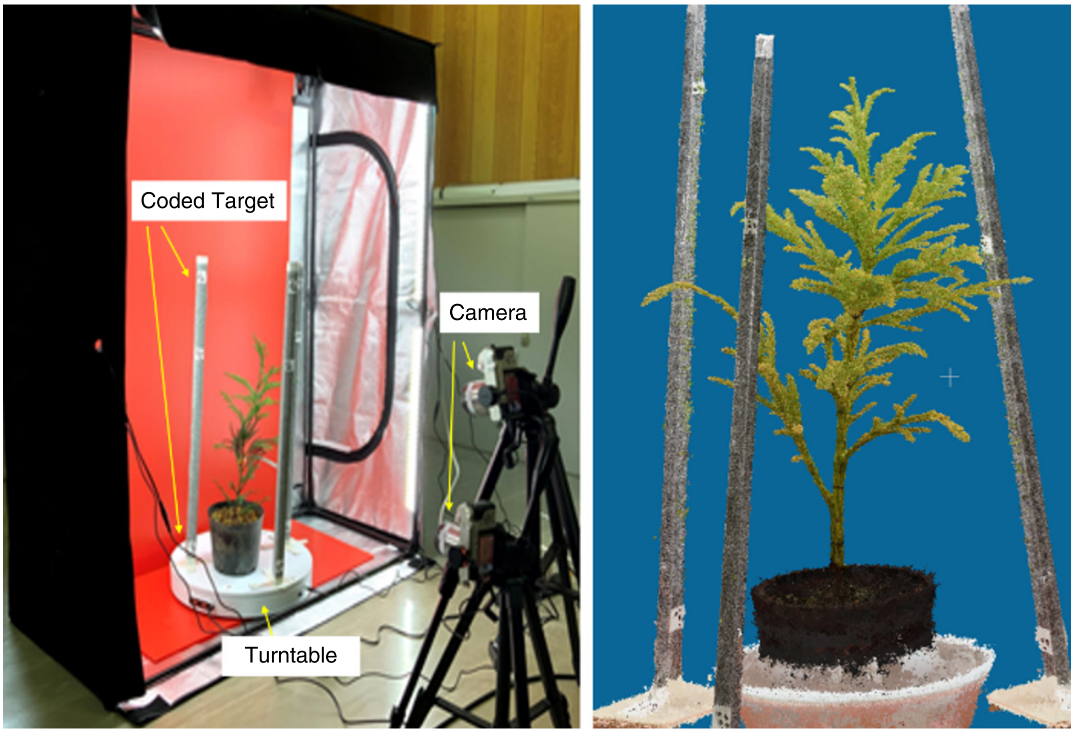

Fig. 7. The developed system with the forward intersection and backward resection methods applied (left), and the resultant 3D model (right).

SfM methods are usually performed using the backward resection method. The internal camera parameters may be calculated before shooting, or self-calibration, i.e., automatic calculation of the internal parameters can be done when there are enough feature points on an object. Because the system can consist of a single camera, it is cost effective and suitable for full automation.

The disadvantage of this system is the need for 3D control points (e.g., a set of target markers) on or near the target object. The 3D control points must be measured by other equipment before images can be obtained. Software for the registration of point clouds is also necessary. The positions of the markers for creating 3D control points should be carefully set because they affect the measurement accuracy [95].

5.3. Forward Intersection and Backward Resection Methods

We are currently developing a method that combines the forward intersection and backward resection methods; that is, it shoots a moving object with multiple cameras or multiple moving cameras. In this method, single or multiple cameras are set up in accordance with the shape (complexity) of an object. Multiple target markers or feature points are also set on or near the object to calculate camera position and attitude. 3D coordinate information is not needed to calculate the positions of these targets. Scales with known lengths are set in the X-, Y-, and Z-directions. The known distances of a set of coded target markers are used as scales to convert arbitrary units to meters [96]. In this approach, models are reconstructed in fixed 3D coordinates by using target markers as anchoring points. In addition, the camera can be moved because the 3D positions of the camera and objects are automatically calculated with every measurement. As a result, more precise 3D point clouds can be constructed in plants with less noise.

The developed system and a sample 3D model are shown in **Fig. 7**. The 3D model was constructed with two cameras, and the plant on the turntable was shot every 5° rotations. The 3D model was constructed with pictures shot from 72 directions.

6. Conclusion

In this paper, we reviewed the advantages and disadvantages of the methods for noncontact and all-around 3D modeling and configuration of camera systems for the measurement of morphological traits in plants in terms of ease of system composition, accuracy, cost, and usability. Although any of the methods described in this paper can be used to measure plants, 3D modeling methods with images offer the most advantages because of their simple and flexible configuration, i.e., cameras, a turntable, and a software program.

Multiple remodeling of a target plant during the growth period is often considered for recording the growth of precious plants. Although not mentioned in this paper, high-speed 3D modeling will be the next phase in plant 3D modeling. In addition, the extraction of measured values, such as shapes and volumes, remains to be examined. Further discussions are expected along with the expansion of 3D modeling in plant studies.

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References:

[1] R. T. Furbank and M. Tester, "Phenomics-technologies to relieve the phenotyping bottleneck," Trends in Plant Science, Vol.16, pp. 635-644, 2011.

[2] R. Pieruschka and T. Lawson, "Phenotyping in plants," J. of Experimental Botany, Vol.66, pp. 5385-5637, 2015.

[3] F. Tardieu, L. Cabrera-Bosquet, T. Pridmore, and M. Bennett, "Plant phenomics, from sensors to knowledge," Current Biology, Vol.27, pp. R770-R783, 2017.

[4] M. Vázquez-Arellano, H. W. Griepentrog, D. Reiser, and D. S. Paraforos, "3D imaging systems for agricultural applications – a review," Sensors, Vol.16, 618, 2016.

[5] S. Paulus, J. Behmann, A. K. Mahlein, L. Plümer, and H. Kuhlmann, "Low-cost 3D systems: suitable tools for plant phenotyping," Sensors, Vol.14, pp. 3001-3018, 2014.

[6] M. Minervini, M. V. Giuffrida, P. Perata, and S. A. Tsaftaris, "Phenotiki: An open software and hardware platform for affordable and easy image – based phenotyping of rosette – shaped plants," The Plant J., Vol.90, pp. 204-216, 2017.

[7] A. Dobrescu, L. C. Scorza, S. A. Tsaftaris, and A. J. McCormick, "A "Do-It-Yourself" phenotyping system: measuring growth and morphology throughout the diel cycle in rosette shaped plants," Plant Methods, Vol.13, 95, 2017.

[8] T. Tanabata and S. Isobe, "DIY Phenology: Open Source and Affordable Technology Development in Plant Phenotyping," Int. Plant & Animal Genome XXVIII (PAG XXVIII), San Diego, CA, USA, 2020.

[9] N. Kochi, T. Tanabata, A. Hayashi, and S. Isobe, "A 3D Shape-Measuring System for Assessing Strawberry Fruits," Int. J. Automation Technol., Vol.12, No.3, pp. 395-404, 2018.

[10] T. Yoshizawa, "Handbook of optical metrology: Principles and Applications," CRC Press, 2017.

[11] Y. Wang, W. Wen, S. Wu, C. Wang, Z. Yu, X. Guo, and C. Zhao, "Maize Plant Phenotyping: Comparing 3D Laser Scanning, Multi-View Stereo Reconstruction, and 3D Digitizing Estimates," Remote Sensing, Vol.11, No.1, 63, 2019.

[12] N. Kochi, "Photogrammetry," T. Yoshizawa (Ed.), "Handbook of Optical Metrology: Principles and Applications," Taylor and Francis, 2009.

[13] A. Chaudhury, C. Ward, and A. Talasaz, "Machine vision system for 3D plant phenotyping," IEEE/ACM Trans. on Computational Biology and Bioinformatics, Vol.16, pp. 2009-2022, 2018.

[14] QVI OGP. https://www.ogpnet.com/ [Accessed October 30, 2020]

[15] Phenospex. https://phenospex.com/products/plant-phenotyping/planteye-f500-multispectral-3d-laser-scanner/ [Accessed October 30, 2020]

[16] T. Dornbusch, S. Lorrain, and D. Kuznetsov, "Measuring the diurnal pattern of leaf hyponasty and growth in Arabidopsis – a novel phenotyping approach using laser scanning," Functional Plant Biology, Vol.39, pp. 860-869, 2012.

[17] S. Winkelbach, S. Molkenstruck, and F. M. Wahl, "Low-cost laser range scanner and fast surface registration approach," Joint Pattern Recognition Symp., pp. 718-728, 2006.

[18] CREAFORM, "Portable 3D Measurement Solutions." https://www.creaform3d.com/en/portable-3d-scanners [Accessed March 31, 2021]

[19] Texas Instruments. https://www.ti.com/dlp-chip/advanced-light-control/overview.html [Accessed October 30, 2020]

[20] L. Benjamin, "Introduction to ±12 Degree Orthogonal Digital Micromirror Devices (DMDs)," 2018. https://www.tij.co.jp/lit/an/dlpa008b/dlpa008b.pdf [Accessed October 31, 2020]

[21] Zeiss ATOS. https://www.handsonmetrology.com/products/atos-q [Accessed March 31, 2021]

[22] T. Wakayama and T. Yoshizawa, "Compact camera for three-dimensional profilometry incorporating a single MEMS mirror," Optical Engineering, Vol.51, No.1, 013601, 2012

[23] HP 3D Structured Light Scanner. https://support.hp.com/us-en/product/hp-3d-structured-light-scanner/14169438 [Accessed March 31, 2021]

[24] S. Paulus, J. Behmann, A. K. Mahlein, L. Plümer, and H. Kuhlmann, "Low-cost 3D systems: suitable tools for plant phenotyping," Sensors, Vol.14, No.2, pp. 3001-3018, 2014.

[25] L. Keselman, J. Iselin, W. Anders, G. Jepsen, and A. Bhowmik, "Intel(R) RealSense(TM) stereoscopic depth cameras," Proc. of the IEEE Conf. on Computer Vision and Pattern Recognition Workshops, pp. 1267-1276, 2017.

[26] Y. Chéné, D. Rousseau, P. Lucidarme, J. Bertheloot, V. Caffier, P. Morel, and F. Chapeau-Blondeau, "On the use of depth camera for 3D phenotyping of entire plants," Computers and Electronics in Agriculture, Vol.82, pp. 122-127, 2012.

[27] G. Azzari, M. Goulden, and R. Rusu, "Rapid characterization of vegetation structure with a Microsoft Kinect sensor," Sensors, Vol.13, No.2, pp. 2384-2398, 2013.

[28] D. Li, L. Xu, C. Tan, E. Goodman, D. Fu, and L. Xin, "Digitization and visualization of greenhouse tomato plants in indoor environments," Sensors, Vol.15, No.2, pp. 4019-4051, 2015.

[29] https://www.intelrealsense.com/depth-camera-d435/ [Accessed October 31, 2020]

[30] https://leica-geosystems.com/en-us/products/laser-scanners/scanners [Accessed October 31, 2020]

[31] https://www.faro.com/en/Products/Hardware/Focus-Laser-Scanners [Accessed March 31, 2021]

[32] https://www.topcon.co.jp/en/positioning/products/product/3dscanner/GLS-2000_E.html [Accessed March 31, 2021]

[33] https://leica-geosystems.com/en-us/products/laser-scanners/scanners/leica-rtc360 [Accessed October 31, 2020]

[34] https://leica-geosystems.com/en-us/products/laser-scanners/scanners/blk360 [Accessed October 31, 2020]

[35] Y. Lin, "LiDAR: An important tool for next-generation phenotyping technology of high potential for plant phenomics?," Computers and Electronics in Agriculture, Vol.119, pp. 61-73, 2015.

[36] M. Friedli, N. Kirchgessner, C. Grieder, F. Liebisch, M. Mannale, and A. Walter, "Terrestrial 3D laser scanning to track the increase in canopy height of both monocot and dicot crop species under field conditions," Plant Methods, Vol.12, No.1, 9, 2016.

[37] Y. Su, F. Wu, Z. Ao, S. Jin, F. Qin, B. Liu, and Q. Guo, "Evaluating maize phenotype dynamics under drought stress using terrestrial lidar," Plant methods, Vol.15, No.1, 11, 2019.

[38] W. Su, D. Zhu, J. Huang, and H. Guo, "Estimation of the vertical leaf area profile of corn (Zea mays) plants using terrestrial laser scanning (TLS)," Computers and Electronics in Agriculture, Vol.150, pp. 5-13, 2018.

[39] T. Oggier et al., "SwissRanger SR3000 and first experiences based on miniaturized 3D-TOF cameras," Proc. of the First Range Imaging Research Day at ETH Zurich, 2005.

[40] Sony. https://www.sony-depthsensing.com/ [Accessed October 31, 2020]

[41] https://thinklucid.com/helios-time-of-flight-tof-camera/ [Accessed October 31, 2020]

[42] https://www.baslerweb.com/en/products/cameras/3d-cameras/ [Accessed October 31, 2020]

[43] https://www.signal.co.jp/english/products/vbc.html#3d [Accessed October 31, 2020]

[44] http://autonomousdriving.pioneer/en/3d-lidar/ [Accessed October 31, 2020]

[45] https://quanergy.com/products/s3/ [Accessed October 31, 2020]

[46] M. Hämmerle and B. Höfle, "Direct derivation of maize plant and crop height from low-cost time-of-flight camera measurements," Plant Methods, Vol.12, No.1, 50, 2016.

[47] X. Wang, D. Singh, S. Marla, G. Morris, and J. Poland, "Field-based high-throughput phenotyping of plant height in sorghum using different sensing technologies," Plant Methods, Vol.14, No.1, 53, 2018.

[48] R. F. McCormick, S. K. Truong, and J. E. Mullet, "3D sorghum reconstructions from depth images identify QTL regulating shoot architecture," Plant physiology, Vol.172, No.2, pp. 823-834, 2016.

[49] https://www.intelrealsense.com/lidar-camera-l515/ [Accessed October 31, 2020]

[50] G. Polder and J. W. Hofstee, "Phenotyping large tomato plants in the greenhouse using a 3D light-field camera," 2014 ASABE and CSBE/SCGAB Annual Int. Meeting, 2014-07-13/2014-07-16, 2014.

[51] L. N. Smith, W. Zhang, M. F. Hansen, I. J. Hales, and M. L. Smith, "Innovative 3D and 2D machine vision methods for analysis of plants and crops in the field," Computers in Industry, Vol.97, pp. 122-131, 2018.

[52] G. Bernotas, L. C. Scorza, M. F. Hansen, I. J. Hales, K. Halliday, L. N. J. Smith, and A. J. McCormick, "A photometric stereo-based 3D imaging system using computer vision and deep learning for tracking plant growth," GigaScience, Vol.8, No.5, giz056, 2019.

[53] W. Matusik, C. Buehler, R. Raskar, S. J. Gortler, and L. McMillan, "Image-based visual hulls," Proc. of the 27th Annual Conf. on Computer Graphics and Interactive Techniques, pp. 369-374, 2000.

[54] S. Yamazaki, S. G. Narasimhan, S. Baker, and T. Kanade, "The theory and practice of coplanar shadowgram imaging for acquiring visual hulls of intricate objects," Int. J. of Computer Vision, Vol.81, pp. 259-280, 2009.

[55] C. V. Nguyen, J. Fripp, D. R. Lovell, R. Furbank, P. Kuffner, H. Daily, and X. Sirault, "3D scanning system for automatic high-resolution plant phenotyping," Proc. of the 2016 Int. Conf. on Digital Image Computing: Techniques and Applications (DICTA), pp. 1-8, 2016.

[56] F. Golbach, G. Kootstra, S. Damjanovic, G. Otten, and R. van de Zedde, "Validation of plant part measurements using a 3D reconstruction method suitable for high-throughput seedling phenotyping," Machine Vision and Applications, Vol.27, No.5, pp. 663-680, 2016.

[57] A. Baumberg, A. Lyons, and R. Taylor, "3D SOM – A commercial software solution to 3D scanning," Graphical Models, Vol.67, No.6, pp. 476-495, 2005.

[58] 3DSOM. http://www.3dsom.com/ [Accessed October 31, 2020]

[59] A. Paproki, X. Sirault, S. Berry, R. Furbank, and J. Fripp, "A novel mesh processing based technique for 3D plant analysis," BMC plant biology, Vol.12, No.1, 63, 2012.

[60] H. Scharr, C. Briese, P. Embgenbroich, A. Fischbach, F. Fiorani, and M. Müller-Linow, "Fast high resolution volume carving for 3D plant shoot reconstruction," Frontiers in Plant Science, Vol.8, 1680, 2017.

[61] M. P. Pound, A. P. French, E. H. Murchie, and T. P. Pridmore, "Automated recovery of three-dimensional models of plant shoots from multiple color images," Plant Physiol., Vol.166, pp. 1688-1698. 2014.

[62] M. P. Pound, A. P. French, J. A. Fozard, E. H. Murchie, and T. P. Pridmore, "A patch-based approach to 3D plant shoot phenotyping," Machine Vision and Applications, Vol.27, No.5, pp. 767-779, 2016.

[63] L. Lou, Y. Liu, M. Sheng, J. Han, and J. H. Doonan, "A cost-effective automatic 3D reconstruction pipeline for plants using multi-view images," Proc. 15th Conf. Towards Autonomous Robotic Systems, pp. 221-230, 2014.

[64] Z. Ni, T. F. Burks, and W. S. Lee, "3D Reconstruction of Plant/Tree Canopy Using Monocular and Binocular Vision," J. of Imaging, Vol.2, No.4, 28, 2016.

[65] S. Liu, L. Acosta-Gamboa, X. Huang, and A. Lorence, "Novel Low Cost 3D Surface Model Reconstruction System for Plant Phenotyping," J. of Imaging, Vol.3, No.3, 39, 2017.

[66] Y. Zhang, P. Teng, M. Aono, Y. Shimizu, F. Hosoi, and K. Omasa, "3D monitoring for plant growth parameters in field with a single camera by multi-view approach," J. of Agricultural Meteorology, Vol.74, No.4, pp. 129-139, 2018.

[67] S. Wu, W. Wen, Y. Wang, J. Fan, C. Wang, W. Gou, and X. Guo, "MVS-Pheno: A Portable and Low-Cost Phenotyping Platform for Maize Shoots Using Multiview Stereo 3D Reconstruction," Plant Phenomics, Vol.2020, 1848437, 2020.

[68] D. Lowe, "Distinctive Image Features from Scale-invariant keypoints," Int. J. of Computer Vision, Vol.60, No.2, pp. 91-110, 2004.

[69] OpenCV team, OpenCV@CVPR2019. https://opencv.org/ [Accessed October 31, 2020]

[70] N. Snavely, "Bundler: Structure from motion (sfm) for unordered image collections," 2008. https://www.cs.cornell.edu/~snavely/bundler/ [Accessed October 31, 2020]

[71] C. Wu, S. Agarwal, B. Curless, and S. Seitz, "Multicore bundle adjustment," Proc. of Conf. on Computer Vision and Pattern Recognition (CVPR), pp. 3057-3064, 2011.

[72] C. Wu, "Towards Linear-time Incremental Structure from Motion," Proc. of the 2013 Int. Conf. on 3D Vision – 3DV 2013, pp. 127-134, 2013.

[73] Y. Furukawa and J. Ponce, "Accurate, dense, and robust multiview stereopsis," IEEE Trans. on Pattern Analysis and Machine Intelligence, Vol.32, No.8, pp. 1362-1376, 2009.

[74] S. Liu, L. Acosta-Gamboa, X. Huang, and A. Lorence, "Novel Low Cost 3D Surface Model Reconstruction System for Plant Phenotyping," J. of Imaging, Vol.3, No.3, 39, 2017.

[75] M. P. Deseilligny and I. Cléry, "Apero, an open source bundle adjustment software for automatic calibration and orientation of set of images," The Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol.XXXVIII-5/W16, pp. 269-276, 2011.

[76] P. Moulon, P. Monasse, R. Perrot, and R. Marlet, "Openmvg: Open multiple view geometry," Int. Workshop on Reproducible Research in Pattern Recognition, pp. 60-74, 2016.

[77] C. Sweeney, T. Hollerer, and M. Turk, "Theia: A Fast and Scalable Structure-from-Motion Library," Proc. of the 23rd ACM Int. Conf. on Multimedia, pp. 693-696, 2015.

[78] Mapillary, "OpenSfM: Open source Structure from Motion pipeline," 2019. https://github.com/mapillary/OpenSfM [Accessed October 31, 2020]

[79] J. L. Schonberger and J. M. Frahm, "Structure-from-motion revisited," Proc. of the IEEE Conf. on Computer Vision and Pattern Recognition, pp. 4104-4113, 2016.

[80] D. Cernea, "OpenMVS: Open Multiple View Stereovision," 2015. https://github.com/cdcseacave/openMVS/ [Accessed October 31, 2020]

[81] E. Rupnik, M. Daakir, and M. P. Deseilligny, "MicMac – a free, open-source solution for photogrammetry," Open Geospatial Data, Software and Standards, Vol.2, No.1, 14, 2017.

[82] Pix4D. https://www.pix4d.com/ [Accessed October 31, 2020]

[83] Bentley Systems, "ContextCapture." https://www.bentley.com/en/products/brands/contextcapture [Accessed October 31, 2020]

[84] CapturingReality. https://www.capturingreality.com/Product [Accessed March 31, 2021]

[85] Agisoft, "Metashape-Photogrammetric processing of digital images and 3D spatial data generation." https://www.agisoft.com/ [Accessed October 31, 2020]

[86] J. Engel, T. Schöps, and D. Cremers, "LSD-SLAM: Large-Scale Direct Monocular SLAM," Proc. of European Conf. on Computer Vision (ECCV), pp. 834-849, 2014.

[87] R. Mur-Artal, J. M. Montiel, and J. D. Tardos, "ORB-SLAM: a Versatile and Accurate Monocular SLAM System," IEEE Trans. on Robotics, Vol.31, No.5, pp. 1147-1163, 2015.

[88] R. Mur-Artal and J. D. Tardos, "ORB-SLAM2: an Open-Source SLAM System for Monocular, Stereo and RGB-D Cameras," IEEE Trans. on Robotics, Vol.33, No.5, pp. 1255-1262, 2017.

[89] D. Scaramuzza, F. Fraundorfer, and M. Pollefeys, "Closing the loop in appearance-guided omnidirectional visual odometry by using vocabulary trees," Robotics and Autonomous Systems, Vol.58, No.6, pp. 820-827, 2010.

[90] M. Havlena, A. Torii, and T. Pajdla, "Efficient structure from motion by graph optimization," Proc. of the European Conf. on Computer Vision, pp. 100-113, 2010.

[91] C. Sweeney, T. Sattler, T. Hollerer, M. Turk, and M. Pollefeys, "Optimizing the viewing graph for structure-from-motion," Proc. of the IEEE Int. Conf. on Computer Vision, pp. 801-809, 2015.

[92] K. Kitamura, N. Kochi, H. Watanabe, M. Yamada, and S. Kaneko, "Human Body Measurement by Robust Stereo Matching," Proc. of the 9th Conf. on Optical 3-D Measurement Techniques, Vol.2, pp. 254-263, 2009.

[93] N. Kochi, T. Ito, T. Noma, H. Otani, S. Nishimura, and J. Ito, "PC-Based 3D Image Measuring Station with Digital Camera an Example of its Actual Application on a Historical Ruin," Int. Archives of Photogrammetry and Remote Sensing, Vol.XXXIV-5/W12, pp. 195-199, 2003.

[94] T. Anai, N. Kochi, N. Fukaya, and N. D'Apuzzo, "Application of Orientation Code Matching for Structure from Motion," The Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol.34, Part XXX Commission V Symp., Newcastle upon Tyne, pp. 33-38, 2010.

[95] T. Anai et al., "Examination about influence for precision of 3D image measurement from the ground control point measurement and surface matching," The Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol.XL-4/W5, pp. 165-170, 2015.

[96] A. Hayashi, N. Kochi, K. Kodama, T. Tanabata, and S. Isobe, "Automatic Omnidirectional Image Photographing System and 3D Model Construction System for Plant," PAG ASIA 2019, P0019, 2019.

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- A. Nakaya and S. Isobe, "Derivation of Linear Models for Quantitative Traits by Bayesian Estimation with Gibbs Sampling," R. Varshney, M. Roorkiwal, and M. Sorrells (Eds.), "Genomic Selection for Crop Improvement," pp. 23-53, Springer, 2017.

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