Tarım Makinaları Bilimi Dergisi (Journal of Agricultural Machinery Science)
2011, 7 (2), 153-158

A Three-Dimensional Imaging Approach for Plant Feature Measurement Using Stereo Vision

Ta-Te LIN, Tsung-Cheng LAI, Chang-Chih LIU, Yu-Che CHENG
Department of Bio-Industrial Mechatronics Engineering, National Taiwan University,
10617, Taipei-TAIWAN (R.O.C.)
m456@ntu.edu.tw

Received (Geliş Tarihi): 09.05.2011 Accepted (Kabul Tarihi): 09.07.2011

Abstract: The information related to plant geometric features is useful for its applications in weed and pest control, growth modeling, quality evaluation, and environmental control in greenhouses, etc. However, plant feature measurement is a challenging task due to irregular plant structure. To efficiently measure plant features, this research proposes an imaging approach to non-destructively measure the 2D and 3D geometric features of selected vegetable seedlings and plants. The imaging method utilizes a stereo vision system which is composed of two off-the-shelf CCD cameras with parallel optical axes. A software program was implemented and image processing algorithms were designed for acquiring the depth images of the plant. The depth images of the plant from different angles are merged to form a complete point cloud of the plant which was further computed to measure the 2D and 3D geometric features such as projected leaf area, plant height, plant volume, equivalent diameters, etc. The results obtained from the image processing algorithm may also be used to reconstruct 3-dimensional model for structural analysis and visualization. The relationship of 2D and 3D plant features were analyzed and discussed for different vegetable seedlings and plants with different geometric structures. The estimation errors of plant measurement were also assessed and compared with the traditional method using single plant image. The proposed 3D measurements system combined with plant growth models, with the capability of computer graphic visualization, forms an integrated system for plant measurement and growth analyses that may be used in many areas both in horticultural research or practical plant production processes.
Key words: Stereo vision, plant growth measurement, background segmentation

INTRODUCTION

The measurement and observation of plant features are fundamental elements of plant science research and its related applications. Plant growth is monitored and determined by measuring a plant's geometric features, such as number of leaves, plant height, leaf area, and leaf weight, etc. Many methods have been applied in plant growth measurement (Hashimoto et al., 1990; Hendry and Grime, 1993). Three approaches to plant feature measurements, direct, semi-direct, and indirect, are employed in most research. Traditional direct measurement methods are generally simple and reliable, but they are also tedious, destructive, time consuming and laborious. Thus, non-destructive plant feature measurement methods were developed. Brenner et al. (1995) compared the measured area of individual *Retama sphaerocarpa* bushes with three commerically available instruments for indirect measurements (DEMON, LAI-2000, and Sunfleck Ceptometer), and the results showed that the surface areas estimated by these three instruments were not significantly different from those established by direct measurement. Thus, it was feasible to measure plant features using an indirect non-destructive method.

Machine vision is a non-destructive method for describing and recording exterior plant features. Many researchers have implemented digital image processing methods for non-destructive measurement of plant growth (Sestak et al., 1991; Hashimoto et al., 1990; Suzuki, 1995; Orbovic and Kieu, 1996; Chien and Lin, 2005). However, most research has reported on the measurement of plant leaf area. İt's necessary to develop a simple and convenient system to measure more plant features.

He et al. (2003) developed a binocular stereo vision system to analyze the aggregate growth variables of a plug tray of transplants. Three-dimensional (3D) color images of the transplant population were reconstructed from pairs of digital two-dimensional (2D) color images. Average height, leaf area, projected leaf area, and mass volume were estimated by extracting user-selected colors, and the results of the digital image analysis correlated closely with those of the destructive measurements. Therefore, stereo vision is a feasible tool to measure the plant features non-destructively.

In this study, the application of an image processing technique to measure projected leaf area, plant height, plant volume, and equivalent diameters was implemented and assessed with the aim of developing a non-destructive measurement system for the growth of selected vegetables.

MATERIALS and METHOD

The image acquisition system is depicted in Fig. 1. Two cameras (Logitech® HD Pro Webcam C910) in parallel with a baseline distance of 35.5 mm in between were installed at a height of 515 mm from the bottom surface. The axes of the two lenses were adjusted vertical to the bottom surface. The vegetable sample was placed on a white plate and its images were captured by the two cameras for later image processing.

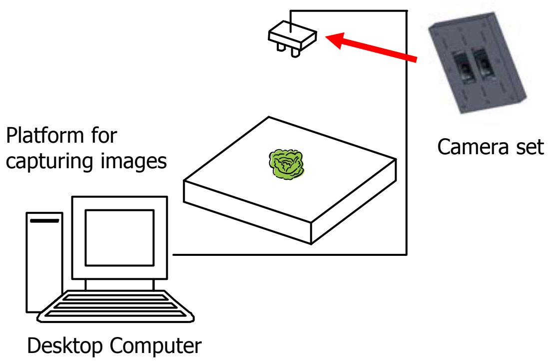


Figure 1. The image acquisition system

The images were digitized into 24-bit (RGB) with a resolution of 640x480, and processed by a desktop computer (Intel® Core™ i5 2.8GHz CPU). An image processing software for plant features measurement was developed using Microsoft® Visual C++ 2010 under the Microsoft® Windows operating system.

To compare the estimated plant volume with the actual plant volume, a total of 9 lettuces (*Lactuca sativa* L.) were sampled for image acquisition and measurement. The actual plant volume was determined by the water displacement method.

The algorithm of the measurement system was developed using the Intel® openCV library, and the procedure includes 4 main steps as shown in Fig. 2: 1) implementing camera calibration to reduce distortion from camera lens; 2) segmenting the plant from the background; 3) calculating the disparity and the range image of each image pair; and 4) calculating the estimated plant features from single image and the range image from stereo vision.

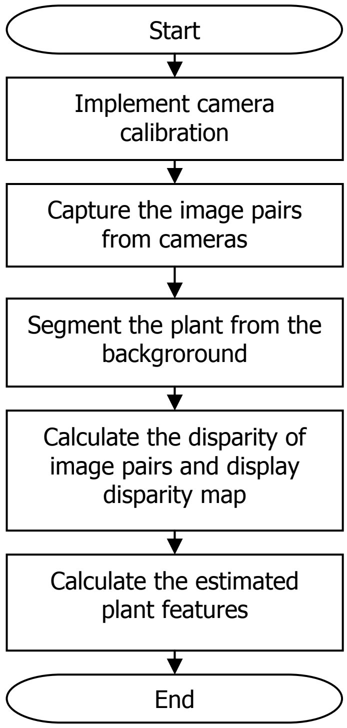


Figure 2. Procedure of 3D feature calculation

The 3D reconstruction algorithm was built from using a pinhole camera model, but radial distortion and tangential distortion from camera lens could result in errors in calculation of plant features. To prevent such influences from image distortion, it is important to calibrate the image captured from the camera. The transfer function for distortion correction is as follows:

$$\begin{bmatrix} x_p \\ y_p \end{bmatrix} = \left(1 + k_1 r^2 + k_2 r^4 + k_3 r^6\right) \begin{bmatrix} x_d \\ y_d \end{bmatrix} + \begin{bmatrix} 2p_1 x_d y_d + p_2\left(r^2 + 2x_d^2\right) \\ p_1\left(r^2 + 2y_d^2\right) + 2p_2 x_d y_d \end{bmatrix} \quad (1)$$

In Eq. (1), x_p and y_p are the coordinates of a pixel in an image after camera calibration; x_d and y_d are the coordinates of a pixel in an image before camera calibration; k_1, k_2 and k_3 are radial distortion coefficients; p_1 and p_2 are tangential distortion coefficients; and r^2 is the sum of the squares of x_p and y_p. In order to calibrate the cameras, a chessboard was prepared. After rotating and shifting the chessboard when capturing the images from the two cameras, the radial distortion and tangential distortion coefficients were estimated from the feature points on the chessboard, and the calibration function in the cameras was then used for the subsequent plant feature measurement experiments.

We used the GrabCut algorithm from the openCV library to segment the plant from the background (Rother et al., 2004). Texture color information and edge (contrast) information were employed for the segmentation. Since the colors of the background and the plant were white and green respectively, the plant (foreground) could be distinguished easily with the GrabCut algorithm.

The algorithm used to calculate disparity was SGBM (semi-global block matching) from the openCV library. This is a modified algorithm from the SGM (semi-global matching) method (Hirschmüller, 2005) which matches blocks instead of individual pixels, and uses a simpler sub-pixel metric instead of a mutual information cost function. The modification decreases the computation time required in matching two images.

Calibration of the relationship between the intensity of disparity map and the height of the plant was an important step in this study. The function to estimate the depth (Z) between sample and camera lens was as follows:

$$Z = f\frac{T}{d} \quad (2)$$

In Eq. (2), f is the focal length of the cameras, T is the baseline distance between the center of the two camera sensors, and d is the estimated disparity. After the conversion, the estimated height of the plant could be calculated. Experiments were performed to test the calibration process. In the experiment, a sample was placed in the range of 70 ~ 460 mm below the camera and the distance of the sample from the cameras was estimated. Fig. 3 shows the results of the estimated and the real depth. A linear relationship existed, with a high coefficient of determination (R^2=0.9996) between the real and the estimated depth. Therefore, the real depth could be calculated from the intensity of disparity map.

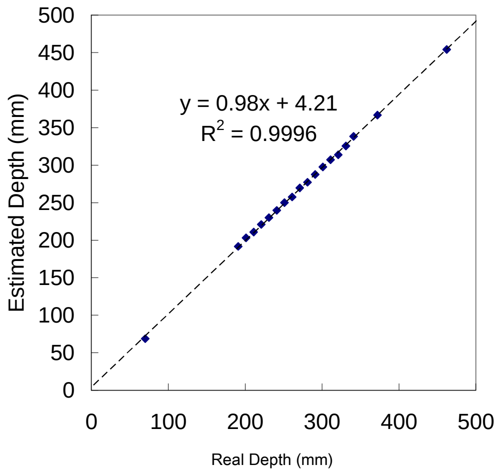


Figure 3. Comparison between the estimated and real depth.

After calculating the real metric from the captured images, the plant features could be calculated from the metric. The equations for the plant features calculation are listed in Table 1.

Table 1. Equations for plant feature calculation

Plant Features	Function
Plant volume	$V_{total} = \sum\left[(\text{stage height} - Z_i) \times K(Z_i)\right]$
Plant height	$H = \max(\text{stage height} - Z_i \times K(Z_i))$
Width	$W = \max\left(\lvert p_{ix} - p_{cx}\rvert\right) \times L(p_i)$
Length	$Len = \max\left(\lvert p_{iy} - p_{cy}\rvert\right) \times L(p_i)$
Maximum diameter	$D_{\max} = 2 \times \max\left(\lvert p_i - p_c\rvert\right) \times L(p_i)$
Minimum diameter	$D_{\min} = 2 \times \min\left(\lvert p_i - p_c\rvert\right) \times L(p_i)$
Equivalent diameter	$D_{eq} = 2 \times \frac{\sum\left[\lvert p_i - p_c\rvert \times L(p_i)\right]}{C}$
Leaf area	$A_{total} = \sum\left[p_i \times F(p_i)\right]$

Where, p_i: is the position of a pixel of the plant

p_c: the position of the centroid of the plant

V_{total}: the estimated volume of the plant

Z_i: the estimated depth of p_i

$K(Z_i)$: voxel size of Z_i

H: maximum plant height

W: width of the plant

p_{ix}, p_{iy}: the coordinates of p_i

p_{cx}, p_{cy}: the coordinates of p_c

$L(p_i)$: length of pixel corresponding to p_i

Len: length of the plant

D_{max}: maximum diameter of the plant

D_{min}: minimum diameter of the plant

D_{eq}: equivalent diameter

C: the total pixel number of the plant

A_{total}: total projected leaf area of the plant

$F(p_i)$: pixel size of p_i

Since the original plant features were estimated from the images, the results of each plant feature obtained from the equations in Table 1 are based on the number of pixels. It is necessary to convert the units of pixels to real spatial dimensions by calibration.

RESULTS and DISCUSSION

An image pair was captured from the cameras and the disparity map was constructed from the image pair using equation (2). Fig. 4 shows the images acquired from the dual cameras, the pseudo-color disparity map, and the illustrations of the maximum and minimum radii. By comparing the image pair (Figs. 4(A) and 4(B)) and disparity map (Fig. 4(C)), the depth information of the vegetable is clearly revealed and, thus, the features concerning depth information, such as plant height and volume, could be calibrated and estimated from the depth image.

Segmentation of the plant from the image is an important step when measuring the 2D features. Fig. 4(D) shows the result of background segmentation, with the white area representing the plant. The profile of the plant is clearly revealed and the 2D features, such as total projected leaf area of the plant, the maximum, minimum, and equivalent radii could then be estimated from the binary image, as shown in Fig. 4(E).

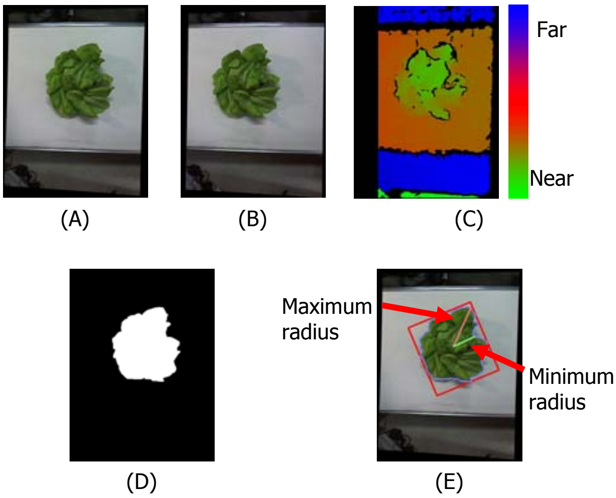
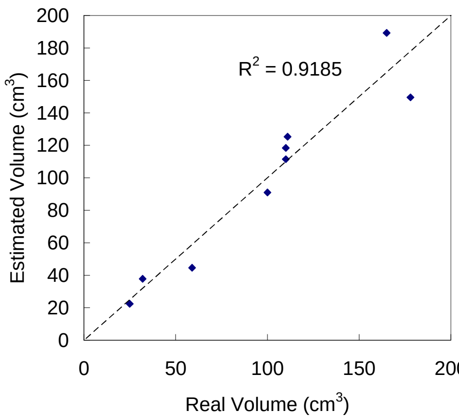


Figure 4. Results of image processing: (A) image from left camera; (B) image from right camera; (C) disparity map and pseudo-color scale; (D) background segmentation; (E) illustration of maximum and minimum radii

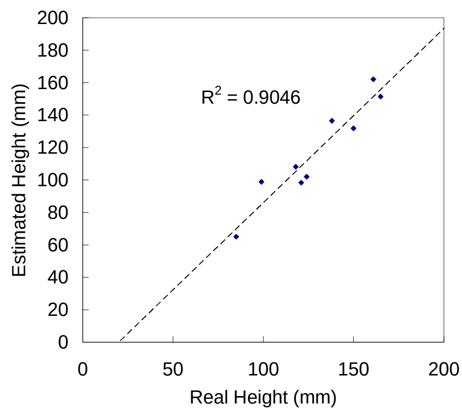
After obtaining the disparity map, the estimated plant volume and height could be measured. Fig. 5 shows the relationships of the estimated and real plant volumes, and the estimated and real plant heights, respectively. Linear relationships exist in the estimated and real plant volumes (R^2=0.9185) and in the estimated and real plant height (R^2=0.9046). Comparing the results of plant volume in Fig. 5(A), the relative estimation error was 13.0±8.7%. The error could have been due to the void space existing in the lettuce plant; thus, the estimated volume from the stereo vision could have been over-estimated.

The relative estimation error for plant height was 10.1±8.6%. The estimated plant height was systematically less than the real plant height judging from the intercept and slope of the regression equation. This could possibly have been due to the block matching algorithm used to calculate the disparity map. The information on the highest point of the vegetable could have been lost with this algorithm during computation.

The software program developed was also capable of computing the 2D plant features from a single image. These features included the estimated projected leaf area and equivalent diameter of the plant, and they were compared with the real volume in this study. Fig. 6(A) shows the comparison of estimated leaf area and real volume. Linear regression analysis revealed that a linear relationship exists between the estimated leaf area and the real volume (R^2 = 0.8544). The result shows that the volume of the plant is related to the projected leaf area of the plant, so the estimated volume could be estimated by using the projected leaf area from a single image after proper calibration.



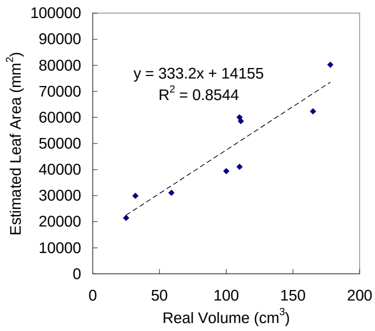
(A)



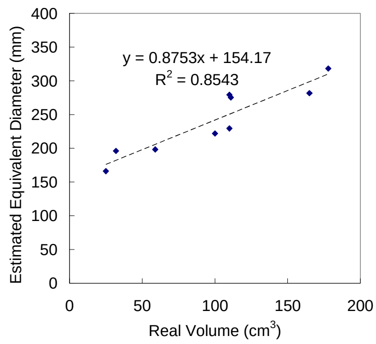
(B)

Figure 5. Relationship of estimated and real 3D features: (A) plant volume; (B) plant height

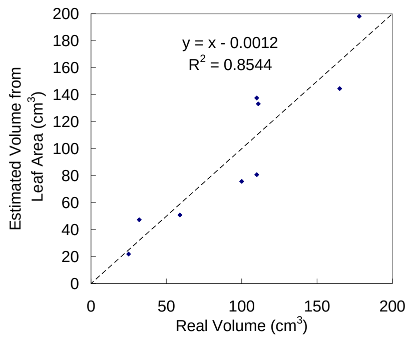
On the other hand, the estimated equivalent diameter was compared with the real volume. The result, as shown in Fig. 6(B), is similar to the result of the estimated projected leaf area, in that a linear relationship exists between the estimated equivalent diameter and the real volume (R^2 = 0.8543). Integrating the results from a comparison of the estimated leaf area, the equivalent diameter, and the real volume, we found that the leaf area and equivalent diameter are related to the plant volume.



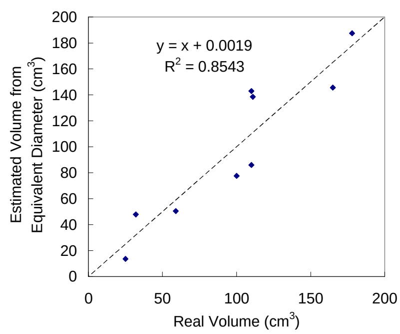
(A)



(B)



(C)



(D)

Figure 6. Relationship of estimated 2D features and real plant volume and plant height: (A) leaf area and real volume; (B) equivalent diameter and real volume; (C) estimated volume from relationship of estimated leaf area and real volume; (D) estimated volume from relationship of estimated equivalent diameter

After determining the linear relationship of the estimated leaf area and real volume, the estimated volume could then be calculated from that relationship. Fig. 6(C) shows the estimated volume calculated from the leaf area, and the result of the linear regression. The slope of the regression line was 1, so the estimated volume from the leaf area is similar to the real volume. On the other hand, the y-intercept of the regression line was -0.0012, and the relative error was 21.6±11.6%. With the linear relationship of the estimated equivalent diameter and the real volume, the estimated volume could be calculated, and the result is shown in Fig. 6(D). The slope of the regression line was 1, so the estimated volume from the equivalent diameter is similar to the real volume. On the other hand, the y-intercept of the regression line was 0.0019, making the relative error 25.1±14.8%. Comparing the relative errors of the estimated volumes from the disparity map, the estimated leaf area and equivalent diameter, the volume using stereo vision is the least. When measuring the volume of lettuce, it's better to choose the stereo vision system.

CONCLUSIONS

A stereo vision system using two off-the-shelf cameras with parallel optical axes was developed to measure 2D and 3D plant features in this study. A software program was implemented and image processing algorithms were designed to acquire the depth images of the plants, and to calculate plant features.

A linear relationship exists in the estimated and real depth; thus, this system was suitable for measuring the depth of each pixel in the plant, and the 3D features, including plant volume and plant height, could be estimated. After comparing the estimated and real plant volumes and heights of lettuces, linear regressions shows the R^2 values were 0.9185 and 0.9046 for volume and height, respectively. The estimation error for volume was 13.0±8.7%, and the estimation error for plant height was 10.1±8.6%. The experiment results indicated that the method used to determine 3D plant features is feasible.

2D features, including leaf area and equivalent diameter, were compared with real plant volume. Linear relationships were found existed between the 2D features and the real plant volumes. Given the linear relationship of estimated leaf area, equivalent diameter and real volume, it's possible to estimate the volume from the leaf area and the equivalent diameter of a single top-view image. There is a linear relationship when the slopes of the regression lines is 1 and the y-intercepts of the trend lines is -0.0012 from the leaf area and 0.0019 from the equivalent diameter, respectively. After comparing the relative errors of the estimated volume from stereo vision, the estimated leaf area, and the equivalent diameter, they were 13.0±8.7%, 21.6±11.6%, and 25.1±14.8%, respectively. The estimated volume from stereo vision has the least relative error of these three analyses; thus, using the stereo vision system to measure volume is better than using a single top-view image. This study developed a non-destructive stereo vision system to measure plant features from a disparity map and a single top-view image. This system will prove useful in many areas of both in horticultural research and practical plant production processes.

REFERENCES

Brenner A.J., M. Cueto Romero, J. Garcia Haro, M.A. Gilabert, L.D. Incoll, J. Martinez Fernandez, E. Porter, F.I. Pugnaire, M.T. Younis, 1995. A comparison of direct and indirect methods for measuring leaf and surface areas of individual bushes. Plant, Cell & Environment, 18: 1332-1340.

Chien C.F., T.T. Lin, 2005. Non-destructive growth measurement of selected vegetable seedlings using orthogonal images. Transactions of the ASAE, 48: 1953-1961.

Hashimoto Y., P.J. Kramer, H. Nonami, B.R. Strain, 1990. Measurement Techniques in Plant Science. San Diego, California: Academic Press, Inc.

He D.X., Y. Matsuura, T. Kozai, K.C. Ting, 2003. A binocular stereovision system for transplant growth variables analysis. Applied Engineering in Agriculture, 19(5): 611-617.

Hendry G.A.F., J.P. Grime, 1993. Methods in Comparative Plant Ecology: a laboratory manual. London: Chapman & Hall.

Hirschmüller, H., 2005. Accurate and efficient stereo processing by semi-global matching and mutual information. IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 20-26.

Orbovic V., K. Kieu, 1996. A semi-automatic method for measurement of seedling length. Plant Growth Resulation, 20: 303-305.

Rother C., V. Kolmogorov, A. Blake, 2004. GrabCut-Interactive foreground extraction using iterated graph cut. ACM Transactions on Graphics, 23: 309-314.

Sestak Z., J. Catsky, P.G. Jarvis, 1991. Plant Photosynthetic Production: Manual of Methods. The Hague: Junk.

Suzuki T., 1995. Measurement of growth of plug seedlings by image processing in broccoli. Acta Horticulturae, 399: 263-267.