Model-based in-situ measurement of pakchoi leaf area

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Abstract: Leaf area measurement is of great significance in plant growth process monitoring. It poses challenges to perform an unattended in-situ measurement, arising from quantifying the 3-dimensional pakchoi leaf surface. Conventional non-destructive measurement techniques, which usually take its projection on the horizon plane of the leaf area, inevitably cause considerable measurement errors. In order to improve the measurement precision for leaf area, the exemplar pakchoi leaf was modeled as a complete or a piecewise spatial plane to approximate the actual leaf surface, and a machine-vision based ad hoc measuring platform was developed to conduct the in-situ measurement. First, the leaf image was captured by a stereo vision system and segmented via a semi-automatic process to obtain its projective area and spatial inclination angle. Second, pakchoi leaves were modeled as spatial surfaces regarding to their projected counterparts. Third, leaf areas were calculated according to the established planar spatial model, acquired inclination angles and projective areas. The experimental comparison among the lattice-based monotype method, projection method, and the model-based method, whose results are denoted as M_A, P_A, and E_A respectively, showed that the proposed framework could simultaneously meet the accuracy and non-destructive measurement requirements. The constructed platform also provided a cost-effective semi-automatic measurement approach for continuously in-situ monitoring of pakchoi growth during its whole cultivation period. It is further suggested from the experimental results that the proposed methodology can offer a generic measurement solution to various kinds of plant physiological and ecological studies in future researches.

Keywords: leaf area, in-situ measurement, non-destructive measurement, stereo vision, image processing

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1 Introduction

Leaves are vital photosynthetic organs and main transpiration access of green-leaf plants and the leaf area is an important index of basic and applied science[1]. Most of previous researches focus on the leaf area index (LAI) in certain territories at a large scale, usually using remote sensing techniques[2-4]. However, more detailed characteristics such as the leaf tilt angle and surface areas have become popular in plant physiology researches, which demands corresponding automatic facilities and methodologies to investigate the morphological trait in millimeter details[5-7]. For example, the pakchoi is extensively cultivated worldwide and the leaf area is the essential index to indicate its growth and productivity, establishing a convenient and accurate method to measure the leaf area has gained much interest from both the academic and production perspectives[8-9].

However, there are three factors that make the leaf area measurement a complex and difficult task; (1) distinguishing leafs from a number of other plant organs, (2) partially or completely shielding and masking found during the measurement and, (3) the geometric complexity of these green leaves such as irregular boundary and distorted surface[10].

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At present, a number of research groups are conducting researches on leaf area measurement, focusing on developing a wide spectrum of facilities and techniques such as desk-top scanner, ultrasound, digital photographic devices, light sensors, and stereo vision[11]. O'neal et al. [12] reported a process using a common desk-top scanner and public domain software for the measurement of both existing leaf area and leaf area removed. In fact this method just measures the projective area rather than the surface area in a spatial case. Nie et al.[13] developed a leaf area measuring instrument by using a poly-Si photoelectric sensor board and a uniform lighting slab with light source systems. The instrument could measure the leaf area with different shapes, thickness and softness, but it is also not vivo measurement with leaves picked off. Lati et al.[14] proposed an approach for 3D plant reconstruction modeling to estimate plant growth parameters. It is complicated to achieve accurate leaf area measurement where the result is affected by illumination. Based on leaf area measurement experiments on six main strawberry cultivars in southern Jiangsu province, China, Qu et al.[15] used a DPS data processing system to analyze the relationship between "leaf length - leaf width - leaf area" and obtained regression equations of six kinds of strawberry, through data aggregation. Kanuma et al.[16] studied leaf area measurement, according to which stereo images of a cabbage crop were taken, 3D coordinates of target points were obtained, and the leaf area of the cabbage crop was calculated as the total trapezoidal parts area. The measurement accuracy was about 10%. There are other traditional or novel methods for leaf area measurement[17-20], however, they have limitations such as implementation complexity, or labor intensive and time consuming.

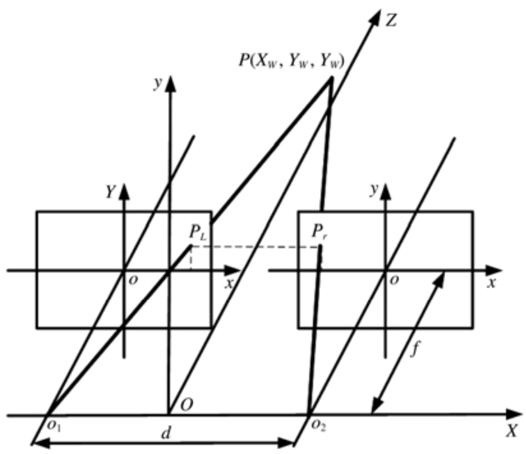
Since conventional leaf area measurement methods do not possess cost-efficiency, user-friendliness and reliability, this research aims to develop a non-destructive measuring system based on stereo vision and digital image processing techniques to perform an in-situ estimation of pakchoi leaf area. The proposed method might contribute to the in-situ leaf growth monitoring automation in plant production or research activities.

2 Theory and measurement modeling

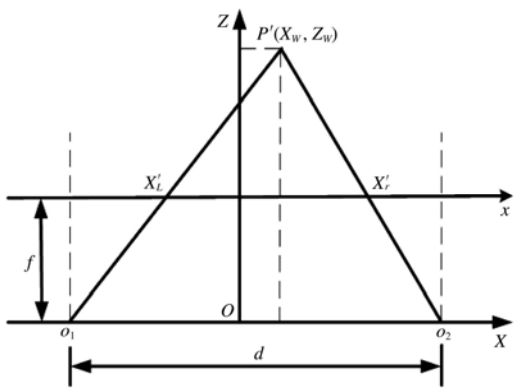
2.1 Principle of a binocular stereo vision measurement

Binocular stereo vision is based on the principle of parallax to obtain 3D geometric information from multiple images[21]. In order to measure the area of an object using binocular stereo vision, it is necessary to know the intrinsic parameters of the camera and distances to the objects. The latter can be obtained through camera calibration and triangular geometry[22].

Camera calibration builds relationships between the world coordinate, the camera coordinate and the image; connecting pixels and physical units. Figure 1 shows a typical stereo vision system. The distance between the two camera centers, which is called the baseline distance, is denoted as d. Two cameras capture object at point P at the same time, obtaining the images of P on the left image and the right image respectively.



a. Binocular stereo imaging



b. The X-Z plane projection

Figure 1 Schematic diagram of a stereo vision system

Assume the coordinate of P on the left image be $P_L=(x_L, y_L)$, and the right image be $P_r=(x_r, y_r)$. If the two cameras are on the same plane, P has the same Y

coordinate on each image. Let $y_L=(y_r, y)$, according to the triangular geometry, the coordinate of P in the camera coordinate system can be written as follows:

$$X_W = \frac{d \cdot x_L}{Disparity} \quad (1)$$

$$Y_W = \frac{d \cdot y}{Disparity} \quad (2)$$

$$Z_W = \frac{d \cdot f}{Disparity} \quad (3)$$

where, $Disparity=x_L-x_r$ and f is the focal length of the camera whose unit is in pixels.

According to the pinhole camera imaging model[23], the parameter that would be calibrated is f. Then, the following relationship is employed

$$W = \frac{1}{f} \cdot H \quad (4)$$

where, W is the real value of the width of the pixel in physical unit in the plane whose distance from the object is H, which is actually Z_W. If the area in pixel unit is N, the real area of the object will be

$$A = N \cdot W^2 \quad (5)$$

2.2 The model-based measuring algorithm

Based on the measurement principles, we can determine the spatial coordinate of a leaf surface point and estimate the leaf area according to the scalar point coordinates. In this research, the leaf is approximated with a complete or piecewise plane model. Figure 2 shows the model of the projective area and the real area.

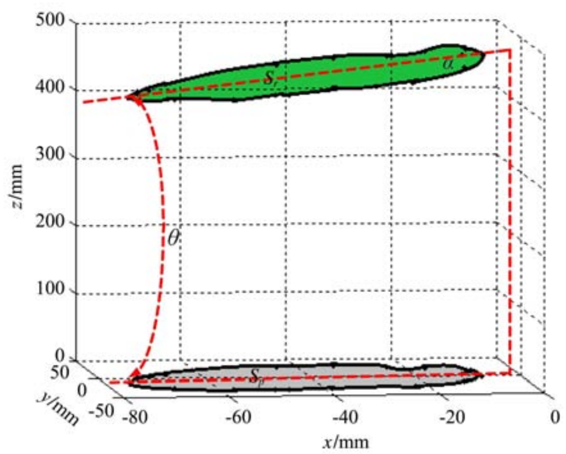


Figure 2 Model of the projective area and the real area

As shown in Figure 2, there is an angle θ between the plane α and the XOY plane. Let S_p be the projected area and S_r be the real area. Clearly, the relationship between S_p and S_r can be given by

$$S_r = \frac{S_p}{\cos\theta} \quad (6)$$

Furthermore, the implementation of the algorithm is shown as a flow chart in Figure 3.

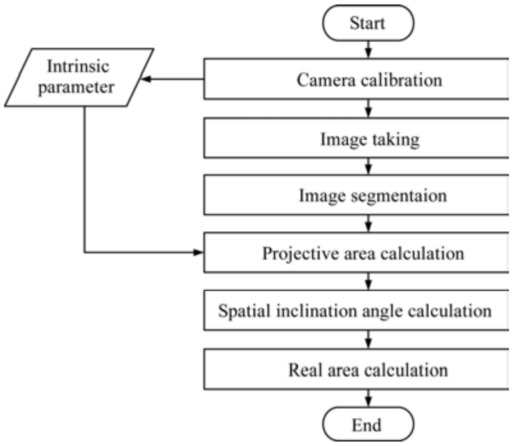


Figure 3 The algorithm flow chart

2.3 Image segmentation

In order to calculate the leaf area, the leaf needs to be segmented from its background. Fully automatic segmentation algorithms usually fail to adapt themselves to demanding conditions such as varying illumination and low distinctions between objects and their background. Manual image segmentation is still an effective alternative in most image segmentation procedures. In this research, the semi-automatic image segmentation strategy was employed to select the leaf for measurement by encircling it in the image via a polygon due to the fact that there might be multiple leaves in an image. Subsequently, a fixed-threshold segmentation algorithm is performed to automatically obtain the binary image in the encircled area. In this way the segmentation accuracy can be increased.

Segmentation algorithms are generally based on the RGB color magnitudes that are conveniently obtained from the acquired image data. However, RGB-based approaches are not always capable of providing satisfactory results under varying conditions[24]. In order to reduce the effect of illumination, the HSI color space is adopted to perform robust segmentation since its independent intensity (I) component can be removed to reduce the dependency with illumination. Then only the remaining two components hue (H) and saturation (S), which are similar to the human visual system, are utilized to implement the segmentation. The transformation from RGB to HIS[25] is given by:

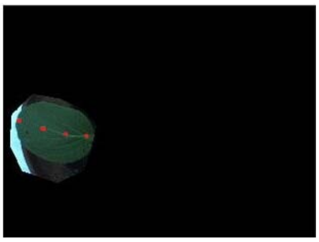
$$I=\frac{1}{3}(R+G+B) \tag{7}$$

$$H=\cos^{-1}\left[\frac{0.5[(R-G)+(R-B)]}{\sqrt{(R-G)^2+(R-B)(G-B)}}\right] \tag{8}$$

$$S=1-\frac{3}{R+G+B}[\min(R,G,B)] \tag{9}$$

According to the values of H and S, a threshold in normalized form is determined to produce binary images of the target regions. Morphological operations[26] are optionally executed if there are holes and glitches in the binary images. The segmentation procedure is shown in Figure 4.

a. Original image with a polygon



b. Aegmented image

c. Binary image

Figure 4 Image segment procedure

2.4 Measurement modeling

To fulfill a precise measurement, two methods are offered in this research. The pakchoi leaf is modeled as a complete or a piecewise spatial plane that approximates the actual leaf surface, and spatial inclination angle of the leaf or of each section is calculated. The estimated leaf area is obtained according to Equation (6).

2.4.1 The complete plane model

The first measurement approach was the using of a complete plane model. From the binary image in Figure 4c, the number of white pixels which is the leaf region can be calculated. This is the value of N in Equation (5). Therefore, area A can be calculated as:

$$P_A=A \tag{10}$$

where, P_A is the projective leaf area; A is the variable calculated in Equation (5).

The description of the orientation of a leaf surface requires specification of three parameters[27], namely the azimuth angle on the midrib points, the angle of elevation of the midrib above the horizontal, and the axial rotation or twisting angle. In this research, the axial rotation or twisting of a pakchoi leaf was experimentally verified to be negligible. To reduce the complexity of identifying the leaf midrib, four points along it were marked in red to form a spatial line, including one on the tip, one at the end, and the other two trisection points. These four markers were detected and positioned in the image using color screening. The angle between the line and the horizontal plane was defined as the angle of elevation of the leaf, i.e. θ of the spatial inclination angle as given in Equation (6). To obtain the leaf spatial inclination angle, two different images of the same leaf taken by multiple cameras in different directions simultaneously were provided, as shown in Figure 5.

a. Image taken by left camera

b. Image taken by right camera

Figure 5 Leaf images with markers

The four red markers were extracted from the background and three dimensional coordinates of them were obtained combining the point coordinate information in the two images using Equations (1)-(3). A line was fitted with the four markers, which is shown in Figure 6.

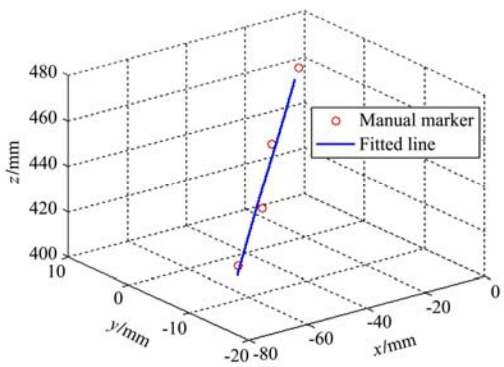


Figure 6 The fitted spatial line

The spatial inclination angle can be found from:

$$\theta = \sin^{-1}\left(\frac{\vec{s}\cdot\vec{n}}{|\vec{s}|\cdot|\vec{n}|}\right) \tag{11}$$

where, θ is the spatial inclination angle; $\vec{s}$ is the direction vector of the fit line, and $\vec{n}$ is the normal vector of the horizontal plane.

Since the actual area value represented by a pixel has been calibrated before the estimation, therefore the leaf area can be estimated using:

$$E_{A1} = P_A / \cos\theta \tag{12}$$

where, E_{A1} is the estimated leaf area, and θ is the spatial inclination angle of the leaf calculated in Equation (11).

2.4.2 The piecewise plane model

The second measurement approach is based on a piecewise plane model, and its main idea is to approximate the whole leaf surface with multiple segmented planes. Four red markers were labeled on the leaf as in the first approach, Marker 1 on the tip of the leaf midrib, Marker 4 on the end of the leaf midrib, and the other two trisection points. The marking scheme is shown in Figure 7.

Figure 7 The leaf with markers

The projective area of the leaf was divided into three parts by the four red marked points, which is shown in Figure 8. Using PA_{01}, PA_{02} and PA_{03} to describe the area of the three sections respectively, the total projective area can be calculated as follows:

$$P_A = PA_{01} + PA_{02} + PA_{03} \tag{13}$$

Then the four red markers were extracted and their three dimensional coordinates were calculated as in the first model. Line 1 - 3 used to link Marker 1 to Marker 4, as shown in Figure 9.

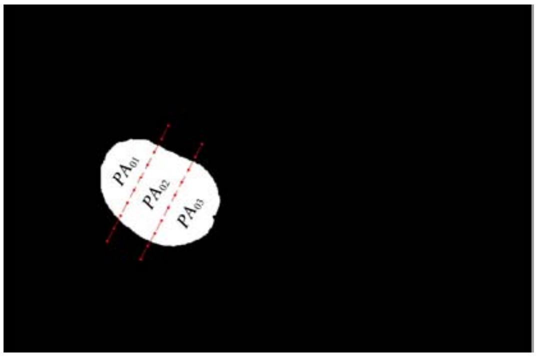


Figure 8 The divided binary image

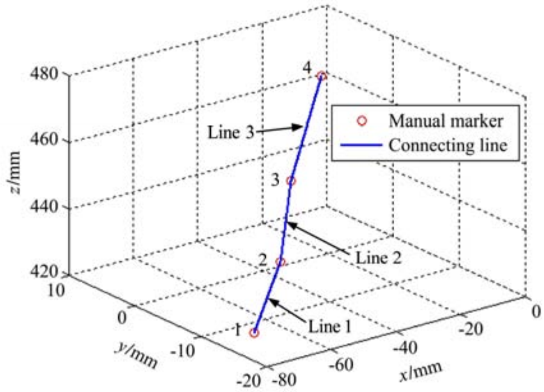


Figure 9 Connecting lines

Each of the spatial angles between the three lines and the horizontal plane was determined, and defined as θ_1, θ_2, and θ_3 respectively. The estimate area of the leaf therefore can be figured out using the following equations:

$$EA_{01} = PA_{01} / \cos\theta_1 \tag{14}$$

$$EA_{02} = PA_{02} / \cos\theta_2 \tag{15}$$

$$EA_{03} = PA_{03} / \cos\theta_3 \tag{16}$$

$$EA2 = EA_{01} + EA_{02} + EA_{03} \tag{17}$$

where, $EA2$ is the estimated leaf area.

3 Experiments and results

3.1 Experimental setup

Figure 10 shows the developed platform which was used to conduct the measurement. The equipment mainly consists of four items, an Industrial Personal Computer (IPC), a computer monitor, two cameras and the lighting system. The IPC is configured with the Intel Atom processor D2550, and Intel® NM10 Chipset. The operating system is Windows XP Professional with Service Pack 2 installed. The programming environment is VC++ 6.0 with Open Source Computer Vision Library (OpenCV). Two cameras with the same intrinsic parameters are fixed to the platform vertically. The cameras connected to the IPC are used to obtain images from the perpendicular position for projective leaf area and spatial leaf angle calculating. The IPC allows the user to control the flash and image acquisition synchronously in dark situations and control the image acquisition only in bright situations. The pictures were saved in the IPC as digital images (in jpg or bmp format) and processed by the developed program for this system.

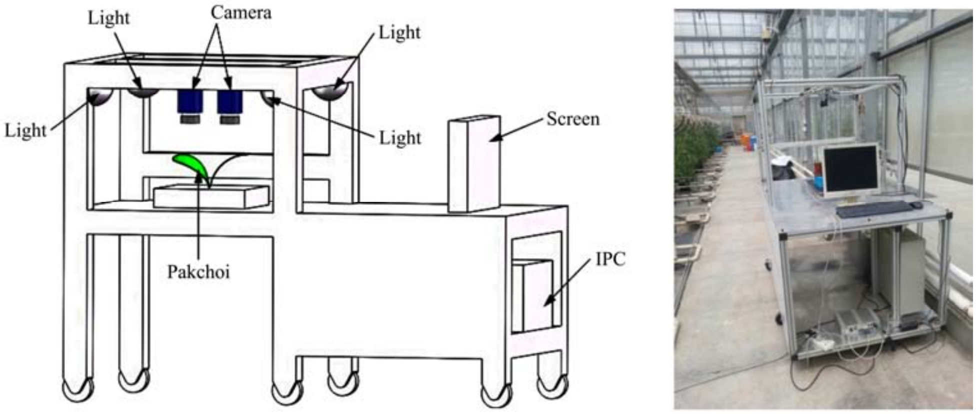


Figure 10 The developed measurement platform

3.2 Experimentation and discussion

With the nursery-pakchoi placed on the platform mentioned in Section 3.1, the two cameras controlled by the IPC took pictures of the pakchoi simultaneously at different directions. Twelve pakchoi images were captured at regular intervals during day and night under natural conditions for 10 d. Then, 240 pairs of left and right images of pakchoi were obtained. The size of each image is 2 592×1 944, and were stored in 24-bit true color in the jpg format.

Values of projected pakchoi leaf area (P_A) in the collected images, estimated area (E_{A1}, E_{A2}) using the models presented in this research, and actual area measured by the method of lattice (M_A) were obtained respectively. Relative errors were calculated to make a comparison based on the following criteria:

$$Relative\ error = \frac{PA - MA}{MA} \times 100\% \qquad (18)$$

$$Relative\ error\ 1 = \frac{EA1 - MA}{MA} \times 100\% \qquad (19)$$

$$Relative\ error\ 2 = \frac{EA2 - MA}{MA} \times 100\% \qquad (20)$$

Part of the sample data is summarized as follows in Table 1.

Observing from Table 1, we can find that the *Relative error* 1 are either positive or negative, while the *Relative error* 2 are all positive, which demonstrates that the estimated areas calculated by the first model contain bilateral deviation. However, the estimated areas calculated by the second model are all greater than the actual areas measured by the method of lattice. Besides the random error, there are many factors that contribute to the overall measurement discrepancy.

Table 1 Part of the sample data

Sample	PA /cm^2	EA 1 /cm^2	EA2 /cm^2	MA /cm^2	Relative error/%	Relative error 1/%	Relative error 2/%
1	6.8781	10.1793	10.7199	10.27	-33.03	-0.88	4.38
2	9.1339	11.1487	11.7475	10.83	-15.66	2.94	8.47
3	10.6373	11.2802	12.6585	10.87	-2.14	3.77	16.45
4	9.8193	11.2596	11.8910	10.92	-10.08	3.11	8.89
5	9.8456	11.3110	11.7374	11.20	-12.09	0.99	4.80
6	17.4151	28.6844	30.6980	28.98	-39.91	-1.02	5.93
7	31.1758	31.9373	35.7212	32.91	-5.27	-2.96	8.54
8	26.6589	34.5918	36.7877	34.39	-22.48	0.59	6.97
9	30.4566	36.5757	38.6604	36.79	-17.22	-0.58	5.08
10	30.4280	38.4958	41.3364	38.35	-20.66	0.38	7.79

I. No matter the pakchoi leaf surface is concave or convex, *EA*1 will be less than *MA*;

II. The axial rotation or twisting of a pakchoi leaf is neglected; nevertheless it does exist in nature, which leads to the result that *EA*1 is less than *MA*;

III. The spatial inclination angle of the leaf applied in this research is between the fitted line and the horizontal plane, which may not be equal to the real inclination. That is, if the measured θ is greater than the real angle, EA1 is greater than MA, and vice versa;

IV. The positive error of EA2 is caused by the fact that the measuring points locate at the valleys of a leaf surface and the measured spatial inclination angles are always greater than those actually exist. Greater inclination angle always leads to the positive bias and the result is that EA2 is greater than MA.

V. EA1 is assumed to be less than MA due to the curved feature of leaves.

VI. Since the inclination angle is determined by the markers and the markers are not in the extremely terminal position, the measured value is greater than the real which introduces positive bias for both EA1 and EA2.

In summary, factors II and III randomly affect the measurement error while factor VI dominates the result with positive bias. As the negative bias of EA1 introduced by factor V alleviates the overall positive bias of the measurement system, the comprehensive error of EA1 is less than that of EA2. Experiment shows that the first proposed measuring method has the absolute relative errors less than 5%, which meets the accuracy requirement of the pakchoi growth monitoring. The absolute values of *Relative error* 2 are greater than those of *Relative error* 1, and most of the values of *Relative error* 2 are beyond 5%. Relatively, the first method is more accurate.

4 Conclusions and future work

Aiming at providing an in-situ non-destructive measurement system for leaf plant growth, a model-based measurement platform and corresponding algorithms are developed. The proposed models generally achieve the measurement accuracy with less than 10% relative errors. Error analysis explores the sources that affect and dominate the measurement biases and errors, which inspires more effective leaf area measurement methodology development in the future. Besides the application of packchoi leaf area measurement, the technology is eligible for reliable leaf area measurements of diverse kinds of herbivory in leaf vegetable growth researches. Note that the leaf area is approximated with a complete plane or a piecewise plane, while the fact is that the leaf is a curved surface in nature. To eliminate the measurement errors, future studies will focus on more precise leaf area measurement by reconstructing the 3-D leaf, measurement setup improvement and more advanced modeling algorithms.

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