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Research paper

Nondestructive measurement method for greenhouse cucumber parameters based on machine vision

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ABSTRACT

The use of machine vision technology for nondestructive online measurements of cucumber parameters was investigated. This technology was first used to capture images of a cucumber canopy. Next, a segmentation algorithm (excess green minus excess red (ExG-ExR)) was used to extract the cucumber canopy area and image parameters (i.e., coverage ratio, canopy length and canopy width). These parameters were combined with those obtained by manual measurements (i.e., stem height, stem diameter, leaf number, and fruit number) to generate five inversion models for four cucumber growth parameters. The results showed that the ExG-ExR segmentation method yielded a 99.5% contact ratio and a 98.2% recognition rate in the extraction of the cucumber canopy region. The inversion models were validated with new images using the following three different cultivation modes: 4 × 2, 4 × 3 and 4 × 4. The inversion results showed that the coefficients of determination (R^2) between the measured values and inversion values of stem height, stem diameter, leaf number, and fruit number exceeded 0.921, 0.899, 0.95 and 0.908, respectively. Thus, the inversion method can provide nondestructive online measurements of cucumber parameters.

1. Introduction

Growth parameters are important decision-making tools for modern, intelligent, and accurate system control in cucumber horticulture facilities. Cucumber growth and development is a very complicated process that is affected by genetic factors as well as various environmental and random factors. The dynamic coupling and interaction of the physiological processes of cucumber growth and ecological processes has numerous external controls and internal state variables (Sun et al., 2006). Traditional plant parameter measurement methods cannot be integrated into intelligent real-time control systems. There are currently several nondestructive online methods of testing plant parameters, including techniques based on machine vision (Li et al., 2003, Liu and Chen, 2003), laser vision for reconstructing the space parameters of plants (Feng et al., 2013), remote sensing (Liang et al., 2013), spectroscopy (Lin et al., 2013), and the reconstruction of plant parameters based on a morphological structure model (Ding et al., 2008). These methods can achieve the nondestructive testing or refactoring of plant parameters for individual plants or large areas. Because cucumber parameters vary under identical growing conditions, individual plant parameters are not representative and cannot be used as a suitable basis for decision-making in control systems in horticultural facilities. Additionally, large-scale remote sensing technology is not suitable for the environments of horticultural facilities. Thus, there is an urgent need to develop nondestructive online testing methods for cucumber parameters.

Many detection studies have been confined to identifying plant type, nutrition and moisture state, etc., and have focused on flora segmentation algorithms, such as color vegetation indices that have been proposed to separate plants from soil and the background residue of images. One such index is the normalized difference vegetation index (NDI) (Perez et al., 2000). Hunt used a similar index, the normalized green-red difference index (NGRDI) (Hunt et al., 2005), while Meyer used an improved vegetation index, the excess green minus excess red (ExG-ExR) index (Meyer and Joao, 2008).

All these methods provide a large reference database for this

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study. At present, few reports regarding online nondestructive testing methods for cucumber parameters suitable for horticultural facility environments are available. Machine vision technology was adopted in this study, and images of the cucumbers canopy were captured in a greenhouse environment. Using image segmentation algorithms to extract the area and features of the cucumber canopy and combining these data with the manually measured parameters of the cucumber canopy, inversion models for cucumber parameters were constructed. New cucumber figures were produced and used to validate the performances of the inversion models and to identify the online nondestructive testing parameters that provide a representative and valuable decision basis for intelligent control systems in horticultural facilities.

2. Materials and methods

2.1. Experimental design

The experiments were carried out in a Venlo-type greenhouse at Nanjing Agriculture University in Nanjing, Jiangsu Province, China, using the 'Jinchun No. 3' cucumber variety. The flora information detecting system consisted of a webcam, a computer and flora information detecting software. A 3-megapixel half-sphere wide-angle webcam (manufactured by Hikvision, China, DS-2CD7254F-E) was installed above the flora canopy. The focal length range of the lens was 2.7–9 mm, and the viewing angle ranged from 101° to 30.4°. The camera also featured an RJ45 10 M/100 M adaptive Ethernet communication interface. The camera was installed on top of the greenhouse beam at 3.75 m above the flora canopy. The lens was angled straight downwards, as shown in Fig. 1. The camera and monitoring computer were connected to the control room router via a cable. Images were captured for 16 cucumber strains using the flora information detecting software, as shown in Fig. 1. Images were captured from May 12 to June 29, 2014. Based on the local sunrise time in Nanjing, Jiangsu Province, 6:00 AM was determined to be the time at which the sun's rays had the least influence on image color. Therefore, image capture was conducted at 6:00 AM to ensure convenient and accurate post-processing.

The specific process for investigating inversion flora parameters based on machine vision technology is shown in Fig. 2. The flora canopy image was preprocessed after calibrating the camera, and the image parameters were then extracted via image segmentation. Next, inversion models of the detected and manually measured flora parameters were constructed, and their performance was verified and analyzed. The image segmentation methods included ExG + Otsu, NDI + Otsu and ExG-ExR, which were used to extract the mean values of three image characteristic parameters: the flora canopy coverage ratio, canopy width and canopy length. The flora parameters obtained by manual measurements included stem height, stem diameter, leaf number, and fruit number for each of the 16 strains of cucumber. For consistency with the image capture time, the manual measurements were performed at 6:00 AM twice a week (on Monday and Thursday) from May 12 to June 29, 2014 (for a total of 14 times).

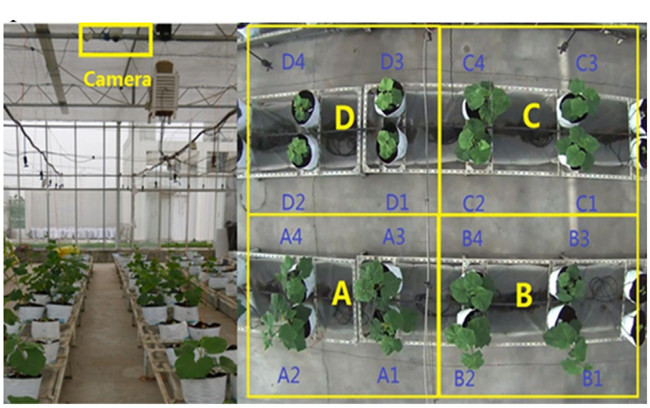

Fig. 1. Testing scenario.

2.2. Camera calibration and image correction

To capture the canopies of the greatest number of plants in the image and obtain the clearest possible image considering the limited imaging distance and the cultivation density, the focal length of the wide-angle camera was set at 2.7 mm, and the focus was manually controlled. The other camera parameters remained unchanged. To correct the barrel distortion exhibited by these images, a 16 × 16 checkerboard calibration board and the camera calibration toolbox in MATLAB were used. Twenty images were captured at different angles and distances for calibration. The camera parameters were calibrated using the image corner. The detailed calibration and correction procedures can be found on the MATLAB website (Camera Calibration Toolbox for Matlab, 2014).

2.3. Flora canopy segmentation

This process was conducted to extract the flora characteristic parameters, accurately identify the flora canopy area, and remove extraneous background information. The ExG, ExG-ExR and NDI methods were investigated, and their performances were compared.

$$\mathrm{ExG} = 2G - R - B \quad (1)$$

$$\mathrm{ExR} = 1.4R - G \quad (2)$$

$$\mathrm{NDI} = (G - R)/(G + R) \quad (3)$$

In Eqs. (1)–(3), R is the red channel value of the image, G is the green channel value of the image, B is the blue channel value of the image, ExG is the excess green segmentation method, ExR is the excess red segmentation method, and NDI is the normalized difference vegetation index.

Fig. 3 a is an example of an original flora canopy image captured by the camera after preprocessing and pre-partition. Fig. 3b shows the images after applying the excess green ExG segmentation method followed by image binarization using the Otsu threshold method (Otsu, 1979). Logic AND was used for the binary figure and the original Fig. 3a to obtain the flora canopy true color partition, as shown in Fig. 3c. Fig. 3d shows the recognition of the flora canopy, where the black area is the identified flora canopy. As observed, this method could not identify parts of the canopy accurately. ExR was subtracted from ExG with a zero threshold to create the ExG-ExR image shown in Fig. 3f, and the corresponding binary image is shown in Fig. 3i. Logic AND between Fig. 3i and a provides the flora canopy true color partition, as shown in Fig. 3g. Fig. 3h shows the recognition of the flora canopy, where the black area is the identified flora canopy. As observed, this method could identify the flora canopy accurately. The image segmentation effect using the NDI method is shown in Fig. 3j, and binarization by the Otsu threshold method is shown in Fig. 3k. Fig. 3l presents the segmentation of the flora figure using the NDI method, which had a large number of false identifications in the noise areas.

To investigate the performance of the flora canopy segmentation methods, two indices were established to evaluate the contact ratio and recognition rate (Eqs. (4) and (5), respectively). Ten flora