An Image-based Canopy Reconstruction Framework for Field Maize

Weiliang Wen, Chuanyu Wang, Xinyu Guo*, Xianju Lu and Tingting Qian

ABSTRACT

Plant canopy reconstruction is the fundamental and central problem of functional-structural plant modeling. In order to reconstruct geometric models of plant canopy by real-time image driving, this paper proposes a framework of image-based maize canopy modeling. The framework builds field image and meteorological data acquisition system to acquire real-time information of plant canopy, then extracts plant growth position and plant azimuthal plane of each plant in the canopy. Morphological parameters of plants are generated using crop model. Finally, geometric model of target canopies are reconstructed by parametric modeling and self-regulating from the image extracted coverage parameter. Experimental results shows that the average coverage error of five treatment maize canopies is 2.57% and LAI errors are smaller than ±1%. Light distribution verification average error of five canopies is 8.02%. This framework will provide technical support for maize field growth analysis and decision making based on Internet of things.

KEYWORDS

Maize Canopy, 3D Reconstruction, Image Segmentation, Light Distribution.

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INTRODUCTION

Crop canopy is the organization system which performs photosynthesis and matter production function. Its morphological structure has important influence on light interception ability, canopy photosynthetic efficiency and crop yields. The morphological characteristics of crop canopy have always been the most basic way for people to recognize, analyze and evaluate crops. However, the morphological structure of crop canopy has the characteristics of high complexity, poor spatial distribution regularity, high organ surface structure variability, and there are a large number of organs with occlusion, intersection and interaction. Therefore, the morphological structure of crop canopy is not a physical process of simple replication. Three-dimensional (3D) modeling of crop canopy is a hot issue for digital plant[1], functional structural plant modeling (FSPM)[2; 3], and plant phenotyping[4]. Therefore, it is of great practical significance to rapidly and accurately model and analyze the morphology and structure of crop canopy.

Morphology study on traditional agriculture for crop canopy were mainly based on experience experiments of manual measurements, image analysis[5], or remote sensing[6], it is difficult to accurately describe the morphological differences caused by crop varieties, planting density, and artificial managements. Constructing accurate 3D models of crop canopy is an effective way for describing the detail positions of each organ in the canopy. However, interactively modeling of plant canopy or plant replication directly is difficult to reflect the agronomy differences[7], while 3D reconstruction using 3D digitization data of plants is time consuming[8]. The main difficulty of constructing 3D canopy model is that it is hard to acquire sufficient morphological data of plants in the canopy.

There are lots of cameras in the field which could provide a large amount of information for 3D canopy modeling, calibration, and verification. So by integrating the technology and methods of image processing, computer graphics, statistics, and agriculture, we proposed an image-based framework for field maize canopy reconstruction.

DESIGN GOALS AND FRAMEWORK REQUIREMENTS

The morphological trait and canopy structure of maize directly affect canopy ventilation, light transmission, biomechanics and other characteristics, which is an important indicator of actual field production of maize. This paper presents a framework for 3D reconstruction of maize canopy in the field. The objectives and requirements of the framework include: (i) The image and meteorological data obtained by field camera and sensor are used as the driving force. (ii) The LAI and coverage error of the reconstructed maize canopy are less than 10%. (iii) Reconstructed canopy model could reflect the morphological differences caused by varieties, planting densities or manual management. (iv) The framework is capable of different growth stages reconstruction. (v) The reconstructed three dimensional
A 3D model of maize canopy has a high sense of reality and can be used for functional structural analysis of maize.

**DESCRIPTION OF THE FRAMEWORK**

**The Framework Architecture**

Figure 1 illustrates the image-based maize canopy reconstruction framework structure. Firstly, the data acquisition environment was set up in the field before planting the maize, including field image and meteorological condition acquisition devices. Using these devices, the maize growth continuous image sequence and meteorological data were obtained. The maize canopy parameters were extracted based on the continuous images, and the plant parameters were generated by using meteorological data combined with crop model. Then the geometric model of maize canopy was generated and was calibrated by the coverage of real-time image. Finally, the reconstructed results were verified by the light distribution calculation.

![Figure 1. The frame structure.](image)

**Image Acquisition**

Before the maize is sowed, the camera supporting device is set up in the field, and the image acquisition device is installed on the corresponding cell. The image sensor is 5 meters high above the ground, so as to obtain the image of the whole growth period of the canopy. The image acquisition device is connected to the server through the web bridge, and the acquired images are sent to the server in real time. The image sensors are photographed vertically downward and fixed without rotation, which ensures the continuity of the monitored maize canopy. The image acquisition devices are used to acquire the continuous image of the target cell, and the acquisition interval is set up to 1 hour. Figure 2 shows the image acquisition device and continuous image sequence obtained.
Figure 2. Field image acquisition device and sequential image sequence obtained.

Figure 3. Plant growth position and plant azimuthal plane extraction using image at jointing stage of maize canopy.

**Image-based Canopy Parameter Extraction**

Two maize canopy structure information can be extracted by using the obtained maize image sequences. (i) The growth position of each plant in the field does not change during the whole growth period. In addition, when all the leaves spread, adjacent leaves stay in opposite direction. Studies have shown that most of the maize leaves distributes in the vicinity of a single vertical plane, which is named plant azimuthal plane and has been determined at the jointing stage. The growth position and plant azimuthal plane of each plant in the target maize canopy were extracted by using jointing stage images, and the two sets of parameter information could be used to guide the 3D reconstruction of maize canopy at any growth stage after jointing. Figure 3 is the growth position and plant azimuthal plane of the canopy extracted from the images. (ii) Leaf cross is serious after the closure stage of maize canopy, so it is difficult to segment each plant from the canopy image. However, it is possible to extract coverage of maize canopy from the images. Maize and not maize pixels are segmented by image segmentation method[9] and the proportion of maize pixels to the whole image is calculated as the canopy coverage parameter. Figure 4 is the effect of image segmentation.
Parameter Generation Based on Crop Model

Crop growth is highly correlated with environmental factors, so crop model can be used to generate important plant morphological parameters which are difficult to extract from images. A small meteorological station was set up in the field to obtain the meteorological data such as air temperature, humidity, solar radiation and rainfall during the whole growth period of maize. Using these meteorological data, combined with soil parameters, variety genetic parameters and cultivation management measures, the plant height parameters of different growth stages in target plot were generated by CERES-Maize model[10]. On this basis, the plant morphological parameters of each leaf were obtained through the statistical model of phytomer relationship constraint, including the leaf height, leaf inclination angle and azimuth angle of each unit, which deviated from the plant azimuth plane angle, leaf length and leaf width.

3D Canopy Reconstruction

Geometric model of individual plants in the target canopy was generated by combining the parametric geometric modeling method[11] of maize and defined similarity measurement function to search the maximum similarity of organ template from the 3D template resource database of maize organs[12][13], after the morphological parameters of each plant were obtained. According to the growth position and azimuthal plane of each plant in the maize canopy extracted by image extraction, the plants were placed in the specified position and direction within the canopy by rotation and translation, and the geometric model of maize population was obtained.

Figure 4. Image segmentation of field maize canopy.

The orientation of the leaves on the plants of the reconstructed maize canopy were randomly generated under the constraint of the plant azimuthal plane, which had systematic errors with the actual field conditions. In this framework, the leaf azimuth angles of each plant in the maize population were corrected by the parameters of maize canopy coverage extracted from real time images. By adjusting the coefficient of enhanced azimuthal angle parameter, different geometric models of maize canopy were obtained and corresponding canopy coverage was calculate. If the coverage information and real-time image extraction coverage difference is less
than a predetermined threshold value, the current geometric model was considered to be the final maize canopy model.

**RESULTS**

In order to evaluate the accuracy of 3D reconstruction of maize canopy, five nitrogen treatments maize canopies were applied to conduct the experiment. The cultivar is Zhengdan 958 with the density of 4000 plant/mu, and was sowed on May 12th in experimental farm of Beijing Academy of Agriculture and Forestry Sciences. The five nitrogen treatment is 0kg ha\(^{-1}\) (N0), 75 kg ha\(^{-1}\) (N1), 150 kg ha\(^{-1}\) (N2), 225 kg ha\(^{-1}\) (N3), and 300 kg ha\(^{-1}\) (N4) respectively. The canopies are irrigated according to requirement during growth period to promise the morphometrics of the canopies are not affected by water stress. The fertilizer is urea and was applied for two times, 50% as starter treatment and 50% at eight leaf stage. Phosphate fertilizer is superphosphate, and the application amount is 85kg ha\(^{-1}\). Potassium fertilizer was potassium chloride, and the amount of application was 67.5kg ha\(^{-1}\). Phosphate and potash were all applied once before planting. Jointing stage maize canopy images of five target canopies in July 12th were selected to extract the plant growth position and plant azimuthal plane. 3D digital data of three silking stage maize plants for each canopy were obtained on August 30th and 31th. On the basis of the digitization data of plants, five maize canopy models formed using replication domain method, and leaf area index (LAI) was calculated which was considered as the actual LAI for verification. The framework also generated five corresponding geometric models, see Figure 5. The verification result of LAI and coverage is shown in Table I. The average coverage error of five treatment canopies is 2.57% and LAI error is smaller than \(\pm 1\%\).

![Figure 5. Visualization of reconstructed geometric models of five treatment maize canopies.](image)

a. N0  
  b. N1  
  c. N2  
  d. N3  
  e. N4
### Table I. LAI and Coverage Verification of Reconstructed Maize Canopies.

<table>
<thead>
<tr>
<th>Canopy treatment</th>
<th>Situ-measured canopy LAI</th>
<th>Reconstructed canopy LAI</th>
<th>LAI error (%)</th>
<th>Image extracted coverage</th>
<th>Reconstructed model coverage</th>
<th>Coverage error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>4.473</td>
<td>4.474</td>
<td>-0.02</td>
<td>0.851</td>
<td>0.8369</td>
<td>1.60</td>
</tr>
<tr>
<td>N1</td>
<td>4.634</td>
<td>4.612</td>
<td>0.47</td>
<td>0.738</td>
<td>0.7007</td>
<td>5.11</td>
</tr>
<tr>
<td>N2</td>
<td>4.694</td>
<td>4.659</td>
<td>0.75</td>
<td>0.806</td>
<td>0.8029</td>
<td>0.41</td>
</tr>
<tr>
<td>N3</td>
<td>4.841</td>
<td>4.887</td>
<td>-0.95</td>
<td>0.745</td>
<td>0.7267</td>
<td>2.47</td>
</tr>
<tr>
<td>N4</td>
<td>4.468</td>
<td>4.47</td>
<td>-0.04</td>
<td>0.785</td>
<td>0.7598</td>
<td>3.24</td>
</tr>
</tbody>
</table>

The reconstructed geometric model of maize canopies were also verified by light distribution method. On September 6th, which is a sunny day, we measured light distribution of each target canopy using AccuPAR along the row direction every 20 cm height. Using the measured light environment and the reconstructed canopy models, and combined with light distribution simulation algorithms, light distribution within the canopy was calculated. The simulation outputs visual photosynthetically active radiation (PAR) of the same measured position. Figure 6 shows the result of measured and simulated light distribution of five treatment canopies. The average error is 8.02%.

### Conclusions

This paper proposed an image-based maize canopy reconstruction framework, which combines image-based feature extraction, meteorological data based crop model, and parameterized geometric modeling method, could realize the 3D maize canopy reconstruction of different maize canopies. Morphological and light distribution validation results show that the systematic error is below 10%, which could meet the needs of further agronomy analysis. The framework is calibrated by real time image data, which is a great improvement to the accuracy of maize population reconstruction. This framework will provide technical support for maize field growth analysis and decision making based on Internet of things.
Figure 6. Validation of light distribution within the reconstructed maize canopies.

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