CONSTRUCTION OF MAIZE VISUALIZATION MODEL BASED ON BIOMASS
/
基于生物量的玉米可视化模型构建

Lili SUN [1], Yuzhi WANG [2)], Yaoyu LI [2)], Xiaoying ZHANG [3)], Wuping ZHANG [2)], Fuzhong LI [2,*)]

[1)] College of Agricultural Engineering, Shanxi Agricultural University, Taigu, Shanxi / China
[2)] College of Software, Shanxi Agricultural University, Taigu, Shanxi / China
[3)] Department of Basic, Shanxi Agricultural University, Taigu, Shanxi / China
Tel: +8603546287093; E-mail: lifuzhong@sxau.edu.cn
Corresponding author: Li Fuzhong
DOI: https://doi.org/10.35633/inmateh-70-05

***Keywords:** biomass, maize, visualization, NURBS surface, OpenGL*

ABSTRACT
Maize is one of the characteristic species in Shanxi Province. It has strong drought and cold tolerance. The study of maize growth and development law through the construction of the model is helpful to accurately understand the growth characteristics of maize, improve the yield, and further provide an important theoretical basis for the realization of precision agriculture. In this paper, "Xianyu 335" maize was taken as the research object. The data of leaf length, leaf width, stem length, stem number and tassel length, as well as leaf, stem, tassel, ear, cob and root organ morphology and biomass of maize during the whole growth period were obtained by field experiment. The maize geometric form structure module was constructed. The dynamic simulation of maize growing process was realized by object-oriented programming in Visual Studio software platform. With the help of 3D OpenGL graphic library Nurbs (Non-Uniform Rational B-Splines) curve and surface simulation technology, the growth visualization of maize organs was realized based on the idea of curve and surface control point selection parameter modeling.

摘要
玉米是山西特色物种之一，具有很强的耐旱性与耐寒性等特点。通过构建模型对玉米生长发育规律研究有助于精准了解玉米生长特性，提高产量，进一步为实现精准农业提供重要的理论依据。本文以“先玉 335”玉米为研究对象，采用田间试验获取玉米全生育期叶片数、叶长、叶宽、节间长、节间数、果穗长，以及叶片、节间、果穗、根器官形态与生物量试验数据，构建玉米几何形态结构模块。采用面向对象的程序设计，在 Visual Studio 软件平台实现玉米生长过程动态模拟。基于曲线曲面控制点选取参数建模思想，借助 3D OpenGL 图形库 Nurbs（非均匀有理 B 样条曲线，Non-Uniform Rational B-Splines)曲线曲面模拟技术，实现玉米各器官生长的可视化。

INTRODUCTION
Global climate changes have threatened the agricultural production in yield stability and increased productivity, along with the increasing population of the world, and have caused great challenges to food security (*Henry E.J. and Eviatar H., 2014*). The widely accepted strategy is to produce more agricultural products on the original arable land, that is, to improve agricultural productivity (*Foley et al., 2011*). The increases in agricultural productivity depend largely on the optimized agronomic management measures and the use of superior varieties of crops (*Henry E.J. and Eviatar H., 2014*). Studies have shown that global climate change will have a significant impact on biodiversity in the 21st century, which, to some extent, also foresees greater uncertainty and difficulties in cultivation of crop varieties with high and stable yields (*Dawson et al., 2011*). So, new technical means are needed to overcome this major challenge in agricultural production systems. In a number of technical solutions, the FSPMs (*Functional-Structural Plant Model*) are a potential to solve or partially solve these problems (*Yan, et al., 2004; Henke et al., 2016; Evers and Bastiaans, 2016*).

[1] *Lili SUN, Ph.D. Eng.; Yuzhi WANG, M.S. Stud. Eng.; Yaoyu LI, M.S. Stud. Eng.; Xiaoying ZHANG, Prof. Ph.D. Eng.; Wuping ZHANG, Prof. Ph.D. Eng.; Fuzhong LI, Prof. Ph.D. Eng..*

The research of crop visualization is helpful to improve the digitalization and visualization level of agricultural growth system expression and lay a foundation for the development of virtual agriculture (*Liu et al., 2009; Yang et al., 2017; Li et al., 2022*) Maize production and planting is of great significance to the development of organic dry farming. The dynamic growth mechanism of maize was studied, the growth process of maize was quantified and digitized, and the relationship model was established (*Guo et al.,2007; Chen et al., 2009; Liu et al.,2021*). It is helpful to optimize decisions, to make predictions through phenotypes, and to overcome the influence of traditional agronomic experiments on weather.

MATERIALS AND METHODS

Experimental design

The maize variety used in the experiment was Xianyu 335, which showed outstanding lodging resistance and drought resistance. The growth period was 98 days, the plant height was 286 cm, the tassel height was 103 cm, and the number of leaves was about 19.

The experimental area is located in Mengjiazhuang (112°30'E, 37°26'N) in Taigu District. The average annual precipitation in Taigu District is 397.1 mm, the average annual sunshine duration is 2527.5 hours, and the frost-free period is 179 days. The soil texture is clay, organic matter is 14.11 g/kg, total nitrogen is 1.19 g/kg, available nitrogen, phosphorus and potassium are 50.49, 33.63 and 206.41 mg/kg, respectively, pH is about 8, field water capacity is 18.5%.

Data Collection

Destructive sampling was carried out after jointing, and 6 maize plants were randomly selected as test subjects every week. Leaf length, leaf width, leaf area, stem volume, tassel length and root number were obtained, and the dry matter mass (biomass) was weighed in the oven.

Model Construction

In the absence of tillering, the upper part of the maize field contains only independent main stems. There are internode, node, node distribution of maize leaves, in the composition structure of the stem. In the later stage of growth, there are female spikes on part of the stem and male spikes on the top of the stem. This paper discusses how to simulate and analyse maize morphology from the biomass of stem, leaf and leaf sheath.

Leaf is one of the key organs of maize photosynthesis, and leaf morphology is closely related to canopy light interception efficiency.

At the Growth Cycle (GC) i, the area $S_b(i,j)$ of the meta-leaf of section j can be obtained according to its cumulative biomass:

$$S_b(i,j) = \frac{q_b(i,j)}{\varepsilon_b}[\text{cm}^2] \quad (1)$$

where, $q_b(i,j)$ is the cumulative biomass of the leaves at the stem j at the GCi, and ε_b is the specific leaf weight. The relationship between leaf length l_b and cumulative biomass can be expressed by the following formula:

$$l_b(i,j) = k_b \cdot q_b(i,j)^{\gamma}[\text{cm}] \quad (2)$$

In the above formula, $k_b$and γ describe the fitting coefficients.

The calculation of blade area is mainly related to length, width and fitting coefficient λ. After the simulation of blade area and length, the expression of blade width can be obtained as follows:

$$w_b(i,j) = \frac{s_b(i,j)}{\lambda \cdot l_b(i,j)}[\text{cm}] \quad (3)$$

where W_b is the width of the leaves, λ is the fitting coefficient.

The position of internode is directly related to the elongation pattern. The position factor should be considered when describing the internode morphology. Internode can be regarded as a similar cylinder, then the stem volume v_e of the stem j at the GC i can be expressed as follows:

$$v_e(i,j) = \frac{q_e(i,j)}{\rho_e(i,j)} = l_e(i,j) \cdot s_e(i,j)[\text{cm}^3] \quad (4)$$

where:

$q_e(i,j)$ describes the cumulative biomass between stems, and $\rho_e(i,j)$ describes the density between stems. $l_e(i,j)$ describes the length of the internodes and $s_e(i,j)$ describes the cross-sectional area of the stems.

The relationship between the two can be expressed as:

$$l_e(i,j) = k_e \cdot s_e(i,j)^{\alpha}[\text{cm}] \tag{5}$$

In the above formula, k_e and α describe the empirical coefficients, and the coefficients k_e and α between stems have obvious differences. The calculation and simulation of internode morphology are mainly related to coefficients β and b_e, as shown below:

$$\begin{cases} \beta = \dfrac{\alpha - 1}{\alpha + 1} \\ b_e = k_e^{1-\beta} \end{cases} \tag{6}$$

Then the length and cross-sectional area between the stem j at the GC i can be calculated:

$$\begin{cases} l_e(i,j) = \sqrt{b_e} \cdot \left(\dfrac{q_e(i,j)}{p_e(i,j)}\right)^{\frac{1+\beta}{2}} [\text{cm}] \\ s_e(i,j) = \sqrt{\dfrac{1}{b_e}} \cdot \left(\dfrac{q_e(i,j)}{p_e(i,j)}\right)^{\frac{1-\beta}{2}} [\text{cm}^2] \end{cases} \tag{7}$$

Since the shape of maize leaves is different, this paper uses Nurbs surface to simulate maize leaves. Nurbs refers to the uniform rational B-spline curve drawing technique, which is a widely used 3D surface model in related fields. It can accurately describe the bending degree of the surface of the target and show the vivid object modeling. In terms of Nurbs theoretical model, it is simple to operate, has high computational efficiency, and can ensure good computational accuracy, which is of great value for the interpretation and presentation of the geometric meaning of objects. This leads to the formula:

$$p(v) = \frac{\sum_{i=0}^{n} \omega_i N_{i,k}(v)\, p(i)}{\sum_{i=0}^{n} \omega_i N_{i,k}(v)} \tag{8}$$

In the above formula: $p(v)$ is different control points, $p_i, i = 0,1 \cdots n$; $\omega_i$is the weight of different control points;

$N_{i,k}$ describe B-spline basis functions generated in different directions.

During the first cycle of maize growth, a growth unit is produced, which is considered to be an approximate cylinder. The geometric dimensions of the organs, such as the radius of the low and top surfaces, and the length of the organs, were obtained according to the allometric growth law. In this study, formula (9) can be used to obtain the spatial coordinate information of the top surface. Assuming that the position and direction of the underside remain fixed, the biomass obtained by plant organs will increase significantly, which can be demonstrated by the dynamic change of growth. The dynamic changes of maize plants include geometric shape and size, which can be reflected by the changes in the radius of the bottom and top surface, as well as the dynamic changes in length extension. The gluCylinder () function in OpenGL can be used to realize visual processing and simulation analysis.

$$\begin{cases} x_2 = x_1 + L \cdot \cos\alpha \\ y_2 = y_1 + L \cdot \cos\beta \\ z_2 = z_1 + L \cdot \cos\gamma \end{cases} \tag{9}$$

where: (x_1, y_1, z_1) are the initial position coordinates; (x_2, y_2, z_2) is the end position coordinate at the end; L is the length of growth and development; $(\cos\alpha, \cos\beta, \cos\gamma)$ refers to the cosine of the function in different directions.

RESULTS AND ANALYSIS

Results of geometric model

The relationship between leaf length, leaf width, leaf area and biomass of maize was obtained through measured data. The power exponential equations were obtained as $l_b = 0.0494e^{0.0504}q_b$, $w_b = 0.1058e^{0.357} \cdot q_b$ and $s_b = 0.0018{q_b}^{1.1435}$. The determination coefficients of the equations were 0.87, 0.79 and 0.91, respectively. Stem volume was linearly correlated with internode biomass, whose equation was $v_e = 0.0018{q_b}^{1.1435}$ and coefficient of determination R^2 was 0.86. There was a power exponential relationship between root number and root biomass.

The equation was $y = 0.0005x^{2.6652}$, and the coefficient of determination R^2 was 0.72. The difference was significant (P<0.01), and the fitting effect was good. Figs. 1 to 5 show the fitting effect.

The morphological structure of maize organs in each period was simulated according to the geometric morphological model, and the simulation results were in good agreement with the experimental results.

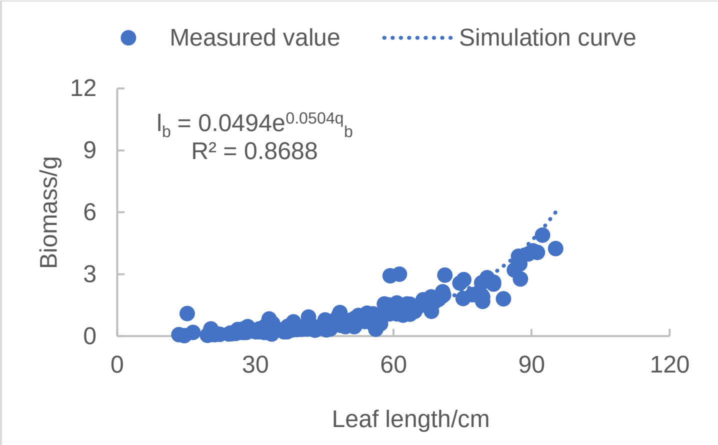


Fig. 1 – Relationship between maize leaf length and biomass

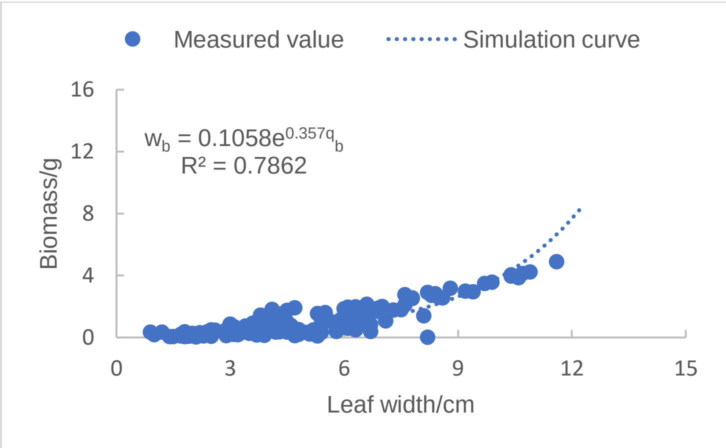


Fig. 2 – Relationship between maize leaf width and biomass

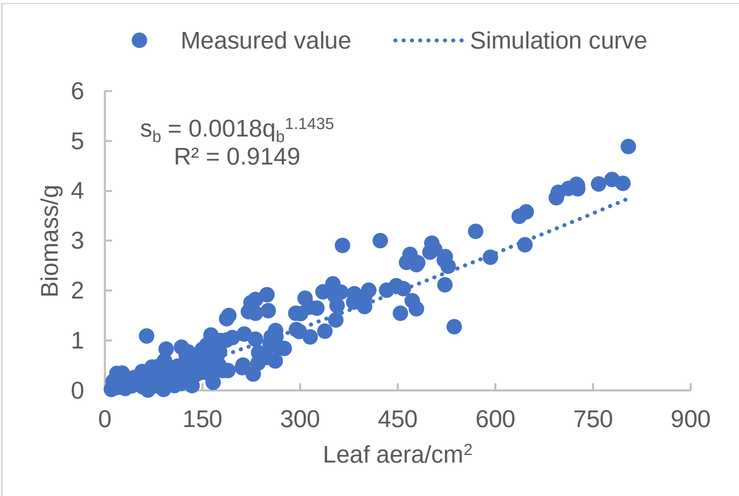


Fig. 3 – Relationship between maize leaf area and biomass

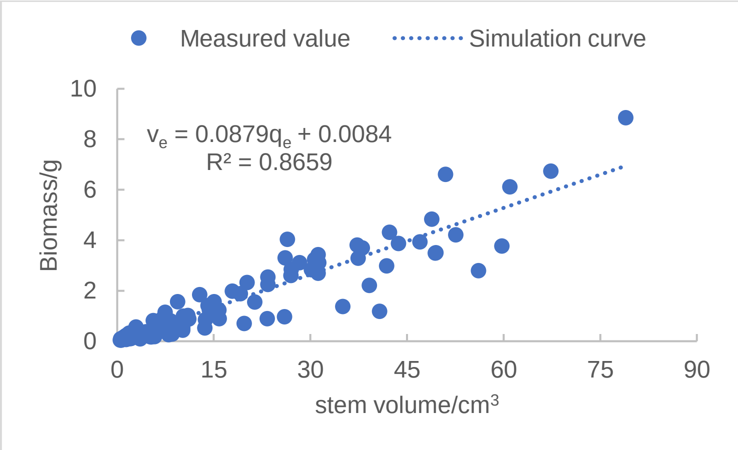


Fig. 4 – Relationship between stem volume and biomass

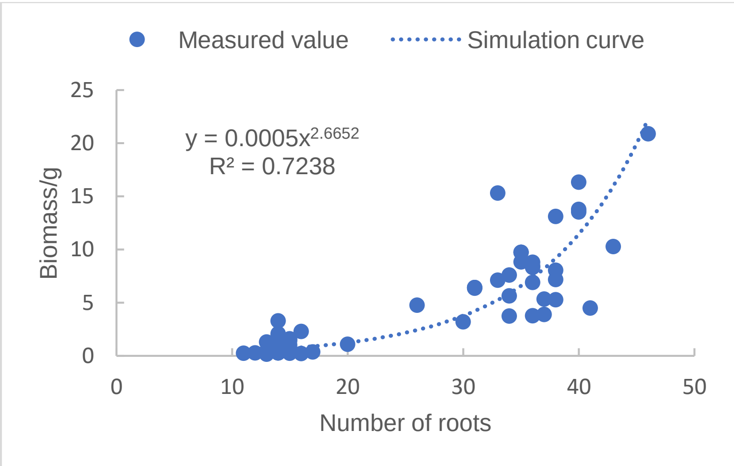


Fig. 5 – The relationship between the number of roots and biomass

Visualization of leaf

Based on the maize morphological data collected in the field experiment and combined with the maize geometric morphological growth simulation model, the maize morphological characteristic parameters were obtained. The surface mesh model of maize leaves was constructed by NURBS surface, and 3D visualization of leaf growth process under different periods was realized based on OpenGL graphic library. The results are shown in Fig. 6.

Fig. 6 – Visualization of maize leaf

Stem visualization

Maize nodes have various forms of internode, and a single internode can be described by columns of different spatial forms. The gluCylinder() library function in OpenGL is used to accurately describe the internode structure morphology and geometric characteristics of maize. The parameters involved include the following: GLU quadric Obj *qobj, which refers to the cylinder drawn by the graphics library; GL double base Radius, which refers to the base radius of the cylinder drawn by the graphics library; GL double top Radius, which refers to the radius of the top surface of a cylinder drawn by the graphics library; Glint stacks refer to the weft lines drawn by the graphics library that surround the Z-axis; GLdouble height, which is the height of the cylinder drawn by the graphics library. After obtaining the simulated values of the bottom surface, top surface and length of internode, a complete maize stem structure can be formed, and the results are shown in Fig.7.

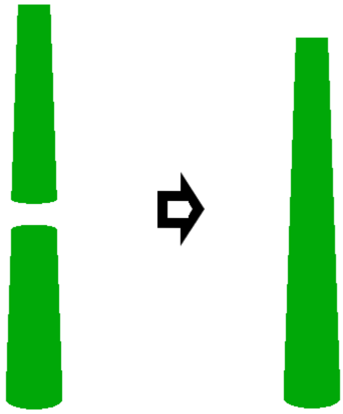


Fig. 7 – Visualization of Maize Stem Nodes

Visualization of ear

The approximate conical shape of the ear can be simulated by a table with different upper and lower surface areas. The experiment is based on the gluSphere() function in the OpenGL graphics library to draw the ear of maize, which mainly includes the following parameters: GLdouble radius, which refers to the radius of the sphere; GLUquadricObj *qob, refers to an instance of an object; Glint stacks refer to the warp lines that surround the Z axis; GLint slices, those are the weft slices that surround the Z axis. After the parameters of gluSphere() function are given, the dynamic simulation of ears in different periods can be realized (Fig. 8).

Fig. 8 – Visualization of Maize Ear

Tassel visualization

Maize tassels are mainly composed of spines, branches and spikelets. The topological structure (number and spatial position of branches) and morphological structure of maize tassels can be programmed to realize visualization. Let the tassel main axis be vertical and overlap with the Z-axis of the coordinate system. The topological parameters of tassel are as follows: length of tassel gh, number of branches i, Angle between branches and main axis θ, and azimuth of branches ϕ.

The tassel morphological structure is composed of two cylinders. The experiment is based on OpenGL graphic library to improve the function required to draw the cylinder, which mainly includes the following parameters: gluCylinder() represents the spatial position and shape size of the cylinder; GLint stacks refer to the warp lines that surround the Z axis; GLint slices, those are the weft slices that surround the Z axis. After the parameters of the gluCylinder() function are given, the dynamic simulation of maize tassels can be realized.

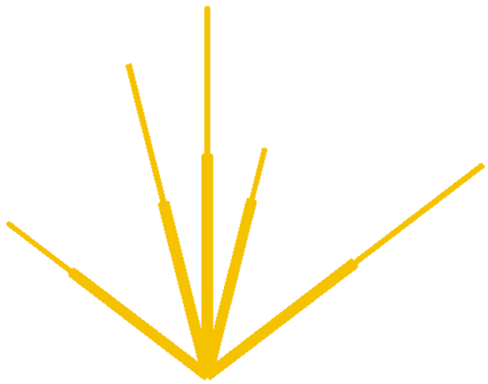
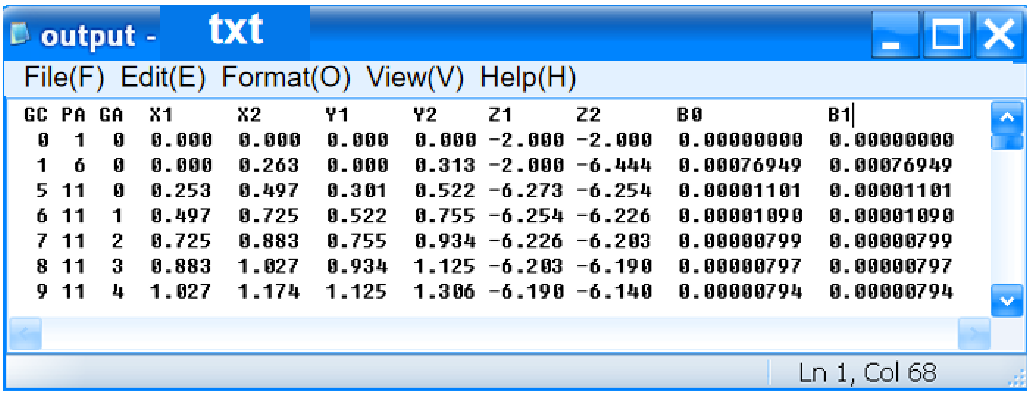


Fig. 9 – Visualization of Maize tassel

Visualization of roots

The visualization of the whole root system can be realized through the visualization of each root element. During each cycle of root growth, all root element individuals are traversed, and each individual is treated as follows. Call the spatial position data of the root element, namely the beginning point and end point of the root element, to carry out spatial translation and rotation. Draw the root by calling the top bottom diameter and the bottom diameter of the root. Realize the visual display of root system in 3D space.



output - txt

File(F) Edit(E) Format(O) View(V) Help(H)

GC	PA	GA	X1	X2	Y1	Y2	Z1	Z2	B0	B1
0	1	0	0.000	0.000	0.000	0.000	-2.000	-2.000	0.00000000	0.00000000
1	6	0	0.000	0.263	0.000	0.313	-2.000	-6.444	0.00076949	0.00076949
5	11	0	0.253	0.497	0.301	0.522	-6.273	-6.254	0.00001101	0.00001101
6	11	1	0.497	0.725	0.522	0.755	-6.254	-6.226	0.00001090	0.00001090
7	11	2	0.725	0.883	0.755	0.934	-6.226	-6.203	0.00000799	0.00000799
8	11	3	0.883	1.027	0.934	1.125	-6.203	-6.190	0.00000797	0.00000797
9	11	4	1.027	1.174	1.125	1.306	-6.190	-6.140	0.00000794	0.00000794

Ln 1, Col 68

Fig. 10 – Data structure for storing the data of BRSU

In the root data, each row represents a root metadata, including the physiological age of the root element, the growth age (the number of root growth cycles minus the number of root generation cycles), the coordinates of the two end points of the root element, the biomass obtained by the axial expansion of the root element, and the accumulative sum of the biomass obtained by the radial expansion of the root element. Call OpenGL graphics library to realize the visualization of root three-dimensional space, as shown in Fig. 11.

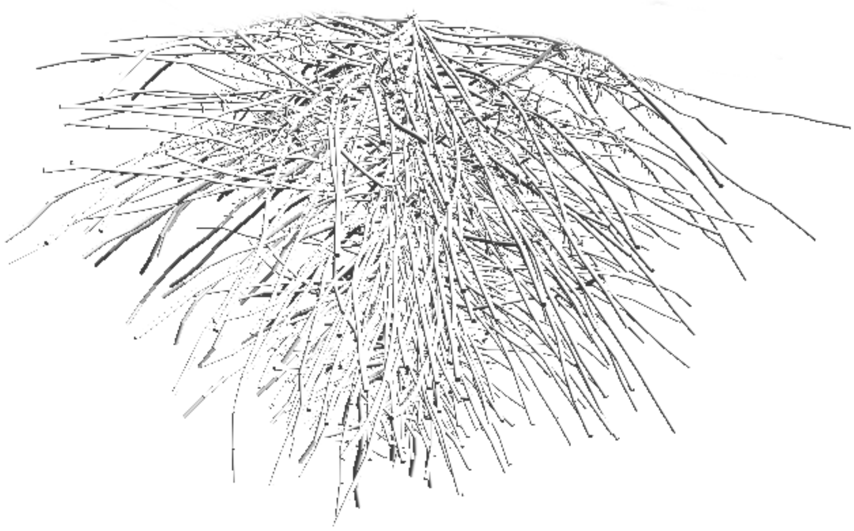


Fig. 11 – Visual simulation to the root of maize based on OpenGL

Visualization processing and simulation analysis of maize growth process

In this experiment, various parameters during the growth and development of maize plants were simulated and analysed, including the number, type and morphological characteristics of organs. After entering the second cycle, the growth and development of two organs of the plant, namely the growth and development of the top and collateral organs, showed specific changes in Fig. 12. Firstly, the corresponding geometric size was simulated according to the degree of organ biomass acquisition. Secondly, the specific spatial location information is determined according to the dynamic linked list. Finally, the visualization and simulation analysis of each vector are carried out by using computer graphics library.

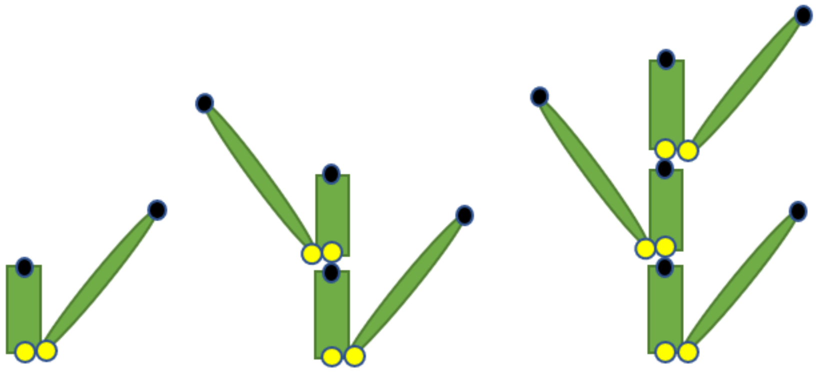


Fig. 12 – Visual processing and simulation diagram of spatial geometric structure changes of various organs during maize plant growth and development

Note: The white circle represents the starting point of growth, while the black circle represents the ending point of growth

Windows, Visual C++ and other tools were used to complete the visual processing and simulation analysis of maize growth. See Figure 13 for details.

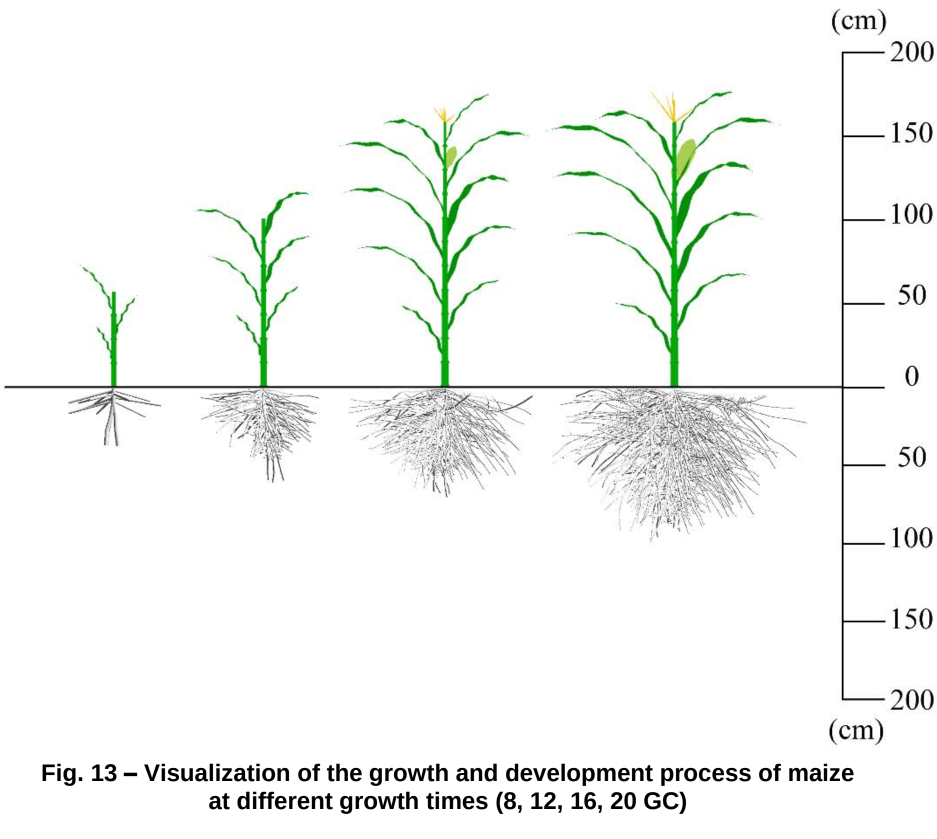


Fig. 13 – Visualization of the growth and development process of maize at different growth times (8, 12, 16, 20 GC)

CONCLUSIONS

In this paper, geometric parameters such as leaf length, leaf width, node length and node diameter of maize were simulated based on the structural function model and the 2019 field experiment data. This model simulated the morphological changes of maize organs during the growth process, and realized the visualization of maize leaves, stems and tassel by using NURBS surface and OpenGL.

ACKNOWLEDGEMENT

The authors were funded for this project by the Major research and development Projects of Shanxi Province, China (2022ZDYF127), and the Basic Research Project of Shanxi Province (202103021224123).

REFERENCES

[1] Chen Guo-qing, Zhang Ji-wang, Dong Shu-ting. (2009). Visualization-Based Growth Simulation System for Super-Maize (基于可视化的超级玉米生长模拟系统). *Scientia Agricultura Sinica*, Vol. 42, pp. 3361-3367, Shandong/China.

[2] Dawson T P, Jackson S T, House J I, et al. (2011). Beyond predictions: biodiversity conservation in a changing climate. *Science,* Vol. 332, pp. 53-58, UK.

[3] Evers J B, Bastiaans L. (2016). Quantifying the effect of crop spatial arrangement on weed suppression using functional-structural plant modelling. *Journal of plant research*, Vol.129, pp. 339-351, Netherlands.

[4] Foley J A, Ramankutty N, Brauman K. A, et al. (2011). Solutions for a cultivated planet. *Nature*, Vol. 478, pp. 337-342, USA.

[5] Guo Xinyu, Zhao Chunjiang, Xiao Boxiang, et al. (2007). Design and implementation of three-dimensional geometric morphological modeling and visualization system for maize（玉米三维重构及可视化系统的设计与实现). *Transactions of the CSAE*, Vol. 23, pp. 144-148, Beijing/China.

[6] Henke M, Kurth W, Buck-Sorlin G H. (2016). FSPM-P: towards a general functional-structural plant model for robust and comprehensive model development. *Frontiers of Computer Science*, Vol.10, pp. 1103-1117, Germany.

[7] Henry R J, Nevo E. (2014). Exploring natural selection to guide breeding for agriculture. *Plant biotechnology journal*, Vol. 12, pp. 655-662, Australia.

[8] Li Dong, Gao Hexuan, He Yuying, et al. (2022). Research on the Visualization Model of Astragalus Growth Based on Open GL. *Tropical agricultural engineering*, Vol. 46, pp. 48-51, Gansu/China.

[9] Liu Hui, Tang Liang, Zhang Wenyu, et al. (2009) Construction and implementation of model-based visual rice growth system. *Transactions of the CSAE*, Vol. 25, pp. 148-154, Jiangsu/China.

[10] LIU Qing, LIU Yang, HU Yang, et al. (2021) Visual Method for Rapid Screening of Transgenic Maize (一种可视化快速筛选转基因玉米的方法研究). *Journal of Maize Sciences*, Vol. 29, pp. 50-59, Jilin/China.

[11] YAN H P, Kang M Z, De Reffye P, et al. (2004). A dynamic, architectural plant model simulating resource‐dependent growth. *Annals of Botany,* Vol. 93, pp. 591-602, China.

[12] Yang Le. (2017). Modeling and Visualization of Rice Root Based on L－System (基于 L 系统的水稻根系模型构建及可视化研究). *Bulletin of science and technology*, Vol. 33, pp. 156-158, Jiangxi/China.