RESEARCH ARTICLE

Visual modeling of *Phyllostachys pubescens* based on measured parameter control

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With the development of computer virtual technology, visualization of plant morphological structure plays an important role in agricultural production and scientific research. The application of computer 3D visualization of plant morphology has been attracted more and more attention. The current research on trees' 3D models is quite common. However, it cannot meet the principal requirements of botany. For the purpose to cover the shortage of 3D visualization of trees, a tree modeling method based on the measured parameter data and intelligent control of variables was developed in this study to analyze Bamboo (*Phyllostachys pubescens*). Based on the cubic Bezier curve fitting and the leaf color grading fine rendering method, it effectively solved the problems of natural bending and seamless connection of bamboo trunk modeling, high realistic rendering of leaf texture, and intelligent control simulation of variables. The experimental results showed that the designed method was fast and intelligent, and the constructed bamboo model was realistic, and had good modeling of flexibility and interactivity. The method improved the existing tree trunk and leaf modeling algorithms and combined with the natural morphological characteristics of bamboo. The methods designed in this study could simulate the 3D visualization model of tree structure with more details and made the modeling efficiently.

Keywords: cubic Bezier curve; multi-image color grading refinement; parameter intelligent control; random parameter difference; *Phyllostachys pubescens*.

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Introduction

Bamboo (*Phyllostachys pubescens*) has characteristics of fast growth, short cycle, wide use, and high economic value, which make the simulating of bamboo more important to predict the growth and morphological characteristics. With the development of 3D visualization, tree modeling has been mainly divided into four different methods which include parameter-based modeling method, image-based modeling method [1], sketch-based geometric modeling method [2], and 3D data point-based modeling method [3]. The advantage of parameter-based modeling method is that it can simulate the shape and topology of each branch. However, the rendering speed is slow. The tree mode has great commonality but has no individual differences [4]. The image-based method has high construction efficiency. However, the process of image processing is difficult due to the accuracy and validity of the constructed model are difficult to control, which causes that the realism of model is not strong. The sketching modeling method can improve the modeling speed, but the modeling accuracy is not high and the differences between models are insignificant [5]. The 3D-data points-based modeling method has high modeling accuracy. However, the data sampling requirements are high. All above mentioned methods have certain shortcomings in describing the real morphological structure of trees, and the models established by each method are also different from the real trees [6].

Currently, many achievements have been made in the application of computer virtual technology to the modeling of trees and shrubs such as Chinese fir and larch. However, the work on modeling of bamboo is less involved. This study was the first analysis of the morphological and structural characteristics of bamboo, which based on the measured structure data by optimizing the modeling algorithms to realize the highly efficient 3D visualized reconstruction and modeling of bamboo. Further, this study applied the stochastic parameter difference modeling method to realize 3D modeling of bamboo stand and, therefore, accurately predicted the bamboo stand growth based on the bamboo stand growth data. The modeling method developed in this study filled the shortage of the visualization and simulation of bamboo plants in domestic three-dimensional visualization research and could effectively guide the adjustment of bamboo stand management.

Materials and methods

Sampling area

The measured parameters of bamboos were obtained from bambush wood species in Sifang mountain State Forest Farm, which is located in the southeast of Hengdong County, Hunan Province. The landform of the forest area is dominated by middle and low mountains. The geographical coordinates are 113°02' to 113° 04’E and 26°57' to 27° 00’N. The lowest elevation is 60 m, while the highest elevation is 700 m. The forest farm is located in the subtropical monsoon humid climate zone with an average annual temperature of 17.8℃ and an average annual precipitation of 1,410.8 mm. The forest coverage rate of the forest farm is 86.24%. The main tree species for afforestation are *Phyllostachys edulis* (Carr.), H. de Lehaie, *Cunninghamia lanceolata* (Lamb. Hook.), and *Pinus massoniana* Lamb., *etc*.

3D modeling algorithm of tree basic shape

It is difficult and inefficient to take every character of the tree for the measurement of the structural data. Branch length and height are the key structural parameters of the tree. The developed method of high-realistic 3D modeling on *Phyllostachys pubescens* used intelligent method to control and adjust the data of topological structure and spatial information of branches and leaves.

(1) Intelligent modeling of *Phyllostachys pubescens* branch and stem

The geometric modeling of branches and stems is an important part of 3D modeling of trees. The conventional method of stem modeling is to establish three-dimensional circular planes and set and splice circular planes according to certain rules, which can obtain the overall model of branches. To realize 3D modeling of bending branches, the circular planes modeling method needs to rotate each plane to realize the branch bending, which may cause the gap of each plane and reduce authenticity of the modeling. Chang, *et al*. developed methods such as polygon mesh algorithm and fan-shaped filling gap to solve the gap of bending branch. However, it could not meet the intelligent interaction of modeling. This study developed a method based on cubic Bezier curve fitting to realize the natural bending of branches according to the existing methods. The data of the length (D), base radius (R), top radius (r) of a branch were collected according to the real measurement of the real branch. Parameter T and V were made to represent the bending of the branch, while V > 0 represented upward bending branch, V < 0 represented downward bending branch, and T represented the bending degree of the branch. The relationship model of branch length, base radius, and top radius were fitted by using cubic Bezier curve to realize the natural bending of the branch by adjusting the control point of Bezier curve intelligently.

$$Q(t,V)=\sum_{k=0}^{3}B_k(t)V_k \quad (1)$$

where $B_k(t)=C_k^3 t^k(1-t)^{3-k}$, t ∈ [0, 1], V_k was the set of control points, K = 0, 1, 2. A tree-dimensional data point sets was set as $P_i=\{p_0, p_1, \mathrm{L}\ , p_n\}$ and used cubic Bezier curve to fit the point sets, which minimized the distance between the data points and the curve.

Equation (2) was the offset of the data point to the curve.

$$V_0 = p_0,\ V_5 = p_n$$

$$d_i=[Q(t_i,V)-P_i]^{\mathrm{T}}\cdot[Q(t_i,V)-P_i] \quad (2)$$

Equation (3) was the total offset from the space point to the curve.

$$D(t,V)=\sum_{i=1}^{n-1}d_i=\sum_{i=1}^{n-1}[Q(t_i,V)-P_i]^{\mathrm{T}}\cdot[Q(t_i,V)-P_i] \quad (3)$$

In order to minimize the distance between the data points and the curve, the control point V1 and V2 of the curve were acquired by calculating the minimal value of Equation (3). The calculate process was as follow. First, the partial derivatives of point V1 and V2 were calculated by equation (3) and the partial derivatives were set to 0.

$$\begin{cases}\dfrac{\partial D(t,V)}{\partial V_1}=2\sum_{i=1}^{n-1}\dfrac{\partial D(t_i,V)}{\partial V_1}[Q(t_i,V)-P_i]=0\\ \dfrac{\partial D(t,V)}{\partial V_2}=2\sum_{i=1}^{n-1}\dfrac{\partial D(t_i,V)}{\partial V_2}[Q(t_i,V)-P_i]=0\end{cases}$$

$$\Rightarrow\begin{cases}2\sum_{i=1}^{n-1}B_1(t_i)[Q(t_i,V)-P_i]=0\\ 2\sum_{i=1}^{n-1}B_2(t_i)[Q(t_i,V)-P_i]=0\end{cases}$$

$$\Rightarrow\begin{bmatrix}\sum_{i=1}^{n-1}[B_1(t_i)]^2 & \sum_{i=1}^{n-1}B_1(t_i)B_2(t_i)\\ \sum_{i=1}^{n-1}B_1(t_i)B_2(t_i) & \sum_{i=1}^{n-1}[B_2(t_i)]^2\end{bmatrix}\begin{bmatrix}V_1\\ V_2\end{bmatrix}$$

$$=\begin{bmatrix}\sum_{i=1}^{n-1}B_1(t_i)[P_i-B_0(t_i)V_0-B_3(t_i)V_3]\\ \sum_{i=1}^{n-1}B_2(t_i)[P_i-B_0(t_i)V_0-B_3(t_i)V_3]\end{bmatrix}$$

Then, equation (4) could be used to calculate control points of cubic Bezier curve equations.

$$A_k=\sum_{i=1}^{n-1}[B_k(t_i)]^2,\quad A_{1,2}=\sum_{i=1}^{n-1}B_1(t_i)B_2(t_i)$$

$$C_k=\sum_{i=1}^{n-1}B_k(t_i)[P_i-B_0(t_i)V_0-B_3(t_i)V_3]$$

$$\Rightarrow\begin{bmatrix}A_1 & A_{1,2}\\ A_{1,2} & A_2\end{bmatrix}\begin{bmatrix}V_1\\ V_2\end{bmatrix}=\begin{bmatrix}C_1\\ C_2\end{bmatrix}\Rightarrow\begin{cases}V_1=\dfrac{A_2C_1-A_{1,2}C_2}{A_1A_2-A_{1,2}^2}\\ V_2=\dfrac{A_1C_2-A_{1,2}C_1}{A_1A_2-A_{1,2}^2}\end{cases} \quad (4)$$

According to the principle of plant morphology, the positive and negative directions of V1 and V2 represented the bending direction, and their sizes represented the bending degree of the branches. This method could solve the gap problem and enhance the authenticity of the modeling. The arbitrary curvature of the branch could be controlled by changing the control points of Bezier curve (Figure 1).

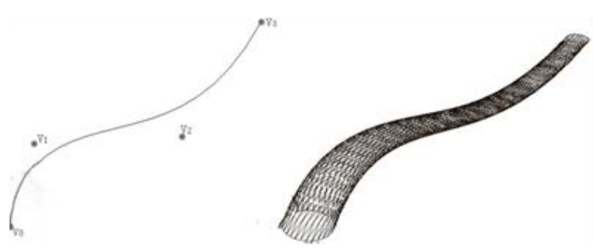

Figure 1. Diagram of natural bending stems controlled by cubic Bezier curves.

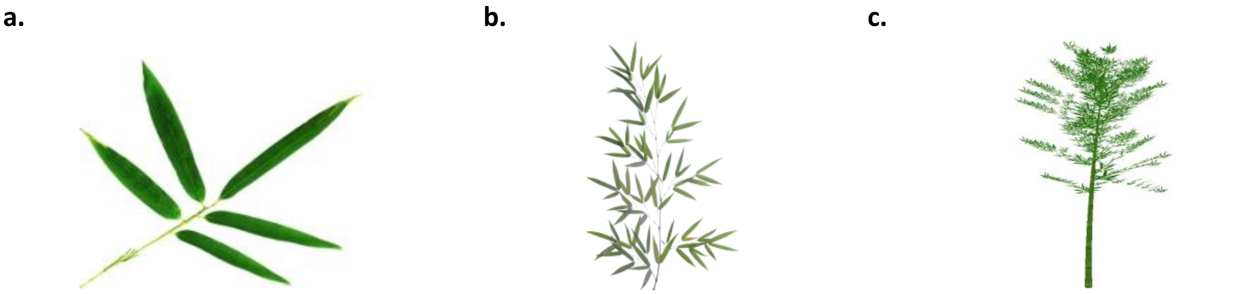

Figure 2. Multi-image color classification refined effect drawing. **a.** texture picture of bamboo first - level branches. **b.** texture image of bamboo secondary branches. **c.** a model of bamboos with two bamboo leaves.

(2) Adaptive intelligent geometric modeling for color classification of bamboo leaves

As the most important morphological organ of bamboo, the accuracy of bamboo leaf modeling directly affects the overall modeling effect of bamboo, and bamboo leaves of bamboo are unique. Bamboo leaves on the first branch are quite different from those on the second branch, but all leaves on each level have high self-similarity. A multi-graph grading method to model bamboo leaves was developed in this study based on the principle of visual self-similarity [7]. The image vectorization of leaf rendering method was applied to construct the basic morphological framework of bamboo leaves. The size, inclination, and azimuth of bamboo leaves were controlled by curve and surface parameters. Billboard technology was used to model leaf texture hierarchically. This algorithm could determine the corresponding position of the bamboo leaf in modeling according to the bamboo leaves classified based on the stratification of branches and their growth state. The steps of the specific algorithm were listed below:

Step 1: selecting a number of bamboo leaf photos with different forms (the number of photos was determined by the configuration of the graphics workstation, generally, not more than 10). Two photos were selected in this study for illustration (Figure 2a and 2b). The photos were converted into PNG format with Alpha channel.

Step 2: the selected images were imported into the system image library sequence, and the color weights of the selected images were calculated by using equation (5) according to the R, G, and B values of each image. The images then were sorted according to the value size.

$$N_i = \sqrt{R_i^{\ 2} + G_i^{\ 2} + B_i^{\ 2}} \qquad (5)$$

where N_i was the color weight of the image, R_i, G_i, B_i were the color pixel value of the image. The higher value of N_i the brighter the color of the corresponding picture, and vice versa. The algorithm could judge the leaf position based on the value of N_i.

Step 3: Billboard technology was used to make the rectangular plane facing the observer, which avoided the disadvantage of only seeing one line when the observer rotated 90 degrees.

Step 4: according to the plant growth mechanism, the larger the value of N means that the bamboo leaf is located in the sunny side and the growth is good because of the enough sunlight, and vice versa. Therefore, the bamboo leaf photo was mapped to the corresponding plane rectangle as a texture. Two different textures were shown in Figure 2a and 2b. According to the color weight of texture, the system intelligently judged the corresponding bamboo branches corresponding to different bamboo leaves and obtained a complete bamboo with multi-texture (Figure 2c).

Parameter intelligent control modeling algorithm for single bamboo form

According to the botanical principle of bamboo growth and the empirical parameters of bamboo growth, the parameters of random variables conforming to the morphological characteristics of bamboo were adjusted and controlled to generate different morphological models. The parameters could be controlled interactively, and the system could conduct intelligent fine tuning of the imported measured parameters. The main parameters were adjusted as follows.

(1) Adjust the angle of branch's elevation

The angle of branch's elevation was normally distributed in a nearly normal fashion. The elevation of bamboo branch change mainly concentrated in the range from 0 to 70 degree. Approximate normal distribution forest cloud model with the advantage of easier to operate and represent comparing to the normal model was applied to generate random number as the elevation value of bamboo branch.

Step 1: the expectation curve equation of the predicted cloud was obtained by expectation *Ex* and entropy *En*.

$$\theta = e^{-\frac{(x-Ex)^2}{2En^2}} \qquad (6)$$

where the value of *Ex* was 50 according to the universality of the elevation angle size. *x* was the range of elevation angles of all branches on a bamboo. $\theta \in [0,70]$. *En* was the characteristic parameter of branch elevation angle of different tree species. The value of *En* in this study was 2.

Step 2: *Ex*, *En*, and hyper entropy *He* were input to the cloud model and the value of *He* was 1. The cloud model algorithm generated a normal random entropy *En'* with expected value was *En*. The mean squared deviation was *He*.

Step 3: the normal random variable *x* was obtained by *En* and *En'*.

Step 4: θ was obtained by putting *x* into equation (6).

Step 5: step 1 to step 4 was repeated until a predetermined number of 14 predicted branch elevation values were produced. Sequence θ_i (*i* = 1, ..., 14) was generated by Normal Cloud Model referring to the method developed by Chen, *et al*. [8]. θ_i was put into equation (6) to get S_i.

$$s_i = \mathrm{int}\left(\frac{14L_i}{\sum_{i=1}^{14} L_i}\right) \ (i = 1,2,3...14) \qquad (7)$$

S_i was the number of times that θ_i appeared. When the value of S_i was 0, the number of times that θ_i appearance was 0. When $S_i \geq 2$, the number of times that θ_i appearance was more than once. Then the order of θ_i into a one-dimensional array was listed. Finally, random elements were taken from the array as the elevation angle of bamboo branches.

(2) Adjust the azimuth of the branch

Although the azimuth angle was randomly distributed, the conventional random function processing would lead to the same bamboos each time through the system intelligent fine-tuning tree parameters because the different azimuth angle generated different three-dimensional morphology [9]. In order to avoid this situation, the chaotic function was employed instead of ordinary random function. Logistic map was a nonlinear chaotic equation. Although it was simple, it reflected the basic nature of chaotic motion. Its definition was as follow:

$$X_{n+1} = \mu X_n (1 - X_n) \qquad (8)$$

$$x_n \in (0,1) \quad n=0,1,2,3...$$

When $3.56994 \leq \mu \leq 4$, the logistic map was in a chaotic state. Sequence $\{X_0, X_1, X_2, ..., X_n\}$ was pseudorandom and nonperiodic. It was sensitive to the initial value μ and X_0. As long as sequences

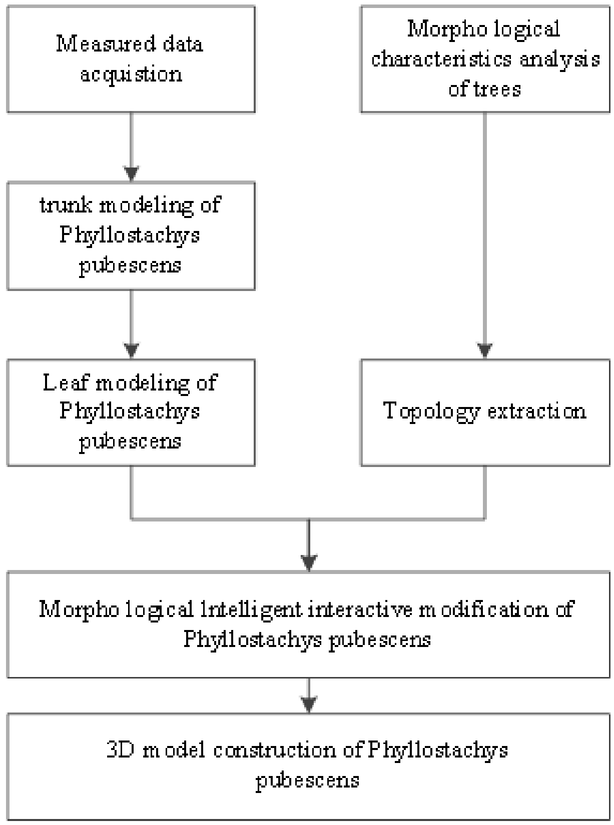

Figure 3. The experimental process to test the developed method.

had the same initial values, the sequence were the same. All the random sequences were multiplied by 360 to get the randomly generated azimuth.

(3) Adjustment of the first and second branches of bamboo leaves

The number of leaves on the primary and secondary branches, the size of leaves, and the rotation angle of leaves around the branch were adjusted by parameters. The bamboo leaves on the first and second levels were controlled by the program intelligently, and the corresponding bamboo leaf texture was added at the corresponding position. In order to verify the improved algorithm of bamboo three-dimensional model and the visual simulation of bamboo stand growth developed in this study, the Visual Studio 2008 (Microsoft, Redmond, WA, USA) combined with Direct 3D (Microsoft, Redmond, WA, USA) was used to develop the bamboo single wood modeling visual simulation system. The bamboo three-dimensional modeling and bamboo forest visual simulation were implemented on the Windows operating system platform. After the analysis of the measured data of bamboos, the naturally curved bamboos were fitted by three Bezier curves, and the color grading maps of multiple bamboos were mapped. Through the intelligent control of the reference variables, the system automatically generated the three-dimensional model of bamboos with high authenticity. The system exported the model of bamboos into the three-dimensional scene and realized the dynamic growth of the forest stand.

Test experimental process

The developed method was applied to the test experiments by using the real measurements of a bamboo. The experimental process was listed in Figure 3.

Results and discussion

The morphological measured data of a bamboo in the format of Microsoft Excel table were input into the modeling system. According to the relevant data, the system could intelligently judge the trunk texture required by the tree species and realize automatic mapping (Figure 4).

Figure 4. The system generated shape and texture of bamboo's trunk based on the morphological measured data.

The system was used to adjust the height of the trunk, the radius of the root, and the radius of the top of the trunk. The bending direction and bending degree of the trunk could be selected. The morphological analysis of the bamboo showed that the bamboo had very obvious sunny growth characteristics. Therefore, the trunk would bend to a certain angle in the direction of the sun. Those data were inputted into the equation (1) to (4), and the bend degree of the trunk was calculated (Figure 5).

Figure 5. The system calculated trunk bend degree was 0.3 degree to the right.

According to the excel table of basic morphological data, the methods developed in this study were applied to bend the primary and secondary branches and adjust the angle and azimuth of the branches. Equations (7) and (8) were used to calculate the data of angle and azimuth (Figure 6).

Figure 6. The system calculated rotation and bend of first and second branches of bamboo.

Equation (5) was used to calculate the correct position of the leaf textures according to the measured data. The system was then used to adjust the parameter to improve the realism of the model (Figure 7).

Figure 7. The system calculated positions of the leaf textures of bamboo.

The experimental results showed that the developed method not only satisfied the control of the elevation angle of branches and fitted the actual structure of bamboo, but also facilitated the efficient and intelligent realization of the modeling system.

Conclusion

A bamboo modeling method based on the measured data and intelligent control of parameters was developed in this study. The method of three Bezier curve fitting was used to control the bending of the branches, which not only solved the notch problem in the process of simulating the branches, but also made the method of controlling the bending of the branches more free, simple, and effective. Innovative multi-image hierarchical and refined bamboo leaf modeling method, combined with billboard technology to achieve leaf mapping. The experimental results showed that the developed method had the advantages of fast modeling speed, high accuracy, good effect, high intelligence, and strong user interaction. The complexity of modeling algorithm was greatly reduced, and the modeling efficiency and truthfulness were obviously improved. Finally, according to the growth characteristics of bamboos stand, the difference visual modeling of bamboos growth was carried out by using random parameter variation values, which made the process of visual modeling more refined. The experimental results were in line with the expected forest growth estimation, and could be used to guide the production, management and planning of Bamboos stand.

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