

Research on Three Dimensional Reconstruction of Plant Root Based on spatial Geometry Structure and Morphology Architecture Parameters

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Abstract

The root plays an important role in the ecosystem of plants. In order to solve the problem that to measure the root is difficult, this article proposes the three dimensional morphology model of plant root based on spatial geometry structure and morphology architecture parameters, and realize the three dimensional visualization of root. First, constructing three dimensional display model including root axis growing model, branch geometry model and root axis curve model; then combining topological structure of root, we confirm corresponding pixel, using morphology characteristic parameters outputted by root morphology to conduct the three dimensional reconstruction of root. Finally, we realize the visualization expression of plant root, basing on the VTK simulation software. The result of simulation, for establishing the whole visualization plant growing root further, lays technical foundation.

Keywords: *plant root; geometry structure; morphology architecture parameters; three dimensional reconstruction*

Introduction

The root plays an important role in the ecosystem of plants. The roots are not only the main organ used by plants to absorb nutrient and water, but also play the important role in supporting the over-ground part[1]. More and more facts prove that root architecture is the important factor that affects the plants[2]. Additionally, the root's contribution for the carbon cycle is indispensable, approximately occupying 20 percent to 40 percent biomass of forest. At the same time, the root still is the main impetus[3] of soil respiration in rhizosphere environment. So knowing the parameters related to the root, such as the size of root, biomass, distribution range and three dimensional structure, has important meaning in understand root ecological functions exactly[4][5].

Lots of scholars at home and abroad spread much work on the research of root reconstruction. Rose[6] uses algebraic expression of time parameters to describe the growth and branch of root. Borg and Grimes[7] give the statistics function expression based on the maximum growth degree and growth regular of the crop root in the fields, of relative root length and relative time in the growth of root. This model describes the growth regular of root, but don't describe the branch condition of root. Hoogenboom and Huck[8] propose the Rootsimu4.0 model. This model researches root growth on the crop entire characteristic, basing on root distribution ratio for the plant body biomass aboveground to confirm the growth ratio of root, but this model is built by using traditional mathematical knowledge, giving the quantitative distribution rather than the content of morphology distribution, then it can't reflect roundly reality distribution of root. Diggle[9] builds the first three dimensional geometry model which simulates the root structure, but this model don't consider the morphology parameters, such as the radius and growth of the root section. Pages[10] gets the dynamic feature of root structure, using the rules of geometry and movement to simulate the

spread of root, proposing the three dimensional model used to simulate corn root architecture. Clausnitzer and Hopmans [11] propose the method which uses finite element, used to simulate the dynamic growth of root in three dimensional space. But, the root model considers seldom the morphology characteristic of root segment, and morphology descriptive model lays emphasis on simulating the branch habit, growth regular and distribution characteristic of root. Lynch[12] established a new root architecture geometry model in 1997, this model uses data structure of so called spanning tree to record topology, shape and growth data of root architecture, but this model still can't reflect the effect, interaction and competition with adjacent root, of soil local condition.

Feng Bin [13] uses fractal theory to build computer model of fractal metrics of plant root, realizing the computer simulation of development morphology of growth process of plant root. But these models can't combine the structure with function of root. Wang Mei-li and He Dong-jian[14] build computer model of root fractal metrics based on L system, realizing the simulation of growth process of the root of wheat, but the root generated by using L system is rule without true sense. Xiong Hai-qiao[15] proposes a plant root modeling approach based on constraint and particle system, and combines Bezier curve, realizing the optimizing of graphic display, which is very good to simulate the growth process of wheat. The method with constrained control has good universality, applicability and controllability. Luo Xue-wen and Zhou Xue-cheng [16] propose visualization research method of root origin morphology on the base of summarizing research evolution of observation technology of plant root, which is based on multilayer CT technology, and conduct the research.

This article uses the plant root as the object, to construct the three dimensional model of plant root axis, based on spatial geometry structure and morphology architecture parameters of root combining root topology regular, providing theory base for three dimensional reconstruction of plant root.

1 Root Geometric Composition and Topology Structure Description

1.1. The Definition of Constitutional Unit of Root

The plant root is a complex system formed by lots of root units. In order to describe effectively very component of root, we often use the similar section unit concept of over-ground part of plant. Defining the base unit of growth development of root as root element, which is consisted by root segment and root tip meristem on it and adnation primordium. The adnation primordium of root element and root tip meristem will form new root element. So, lots of root elements generated by the same root tip meristem construct one root axis, then one or some root axis construct one whole plant root system.

1.2. Root Model Structure Description

This article according to the model assumption of document[18], in the model the length of root axis base non-lateral root is L_B , the top length of non-lateral root is L_A , when the root axis length is greater than the value that is L_A plus L_B , then it starts to divide roots, as seen in Figure.1. The root division region spread to the top with the growth of main root, but it keep the distance with the top. L_{BC} express the length gap of conducting twice division root. The root axis has generated division root in someplace, when after the last division root, the length of growth is greater than L_{BC} then generate the new division root.

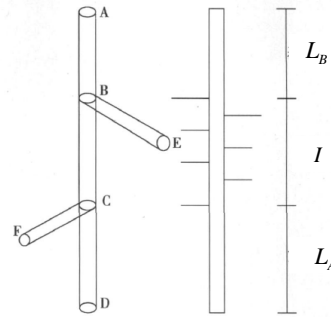


Figure.1 The Root Division Position Of Root Axis

1.3. Root Model Modeling of Geometry Structure Model

Through the conceptual analysis of root model structure description and dynamic variation rule, the morphology structure of root and growth development is complex, but there is still regular in this. They take the main root as the origin derivative points, when the main root grows to some degree, then it will generate one first-order lateral root every time. The first-order lateral is similar to the main root, conducting the meristem of secondary lateral root. In this way themselves constantly root derivatives, forming underground root net of complex distribution. At the same time the research shows that root axis meristem ability of the same type of some plant root is no difference, and they generates daughter roots grow and develop at basic similar ratio. Synthesizing these basic theory, we can use the root morphology characteristic parameters that is described in above, to set every typological root axis consisted of a series of linear root segment that has different growth direction. These root segments represent growth situation in unit time step length, and have certain root division grade. When they reach root division condition as is described in above with the increase of time step length, they put forth new root axis, which is modeling thought of assembly architecture model. This article uses this modeling theory to construct universal three dimensional root model.

1.4. Topology Structure Description

When describing the topology structure of plant root, we use the axis direction tree in graph theory to do some analyzing [19]. It is consisted of root, trunk and outgrowth, every part with tab, and obey certain order. A axis direction tree forms path from root initial node to every terminal node, at least there being one subsequent edge node as the internal node. The termination edge is called top, and trunk, outgrowth is divided into 0 grade, 1 grade, 2 grade in turn[20]. In Figure.2, the topology structure of plant root has several segment with mark and certain direction. The segment sequence is the path from special node to every terminal. In the term of biology, these segments are “shaft segment”. If one segment has other segment behind it in certain path at least, it is called the middle segment. If it hasn't subsequent termination segment, it is called the top. The branch is called lateral segment. Taking the segment sequence call the axis, it meets the follow condition: (1) the first segment of this sequence starts with the initial point, or as one branch of certain node; (2) every subsequent segment is a straight segment; (3) the last segment don't generate any segment any more.

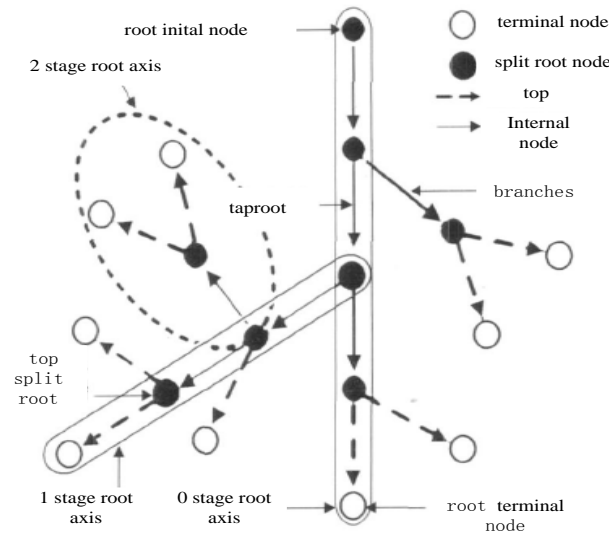


Figure 2. The Topology Structure of Root

2. Geometry Morphology Modeling of Plant Root

Geometry morphology model describes the three dimensional information of the entirety or part organ of plant. Confirming the geometry morphology parameters of root: the number of root, the length of root, the space growth ratio of root, direction of the continuing growth root, the position of root division, the growth direction of subordinate root division.

2.1. The Length of Main Root and the Length of Total Root Length

Because the space position distance of the skeleton point of base root and lateral root is less, we use the sum of European style distance of three dimensional space skeleton point to calculate the length of every root. Having the reconstruction image and skeleton, we can calculate the length of main root and the length of total root length exactly and easily. Assuming data point of the skeleton of certain root R_k is $V_i(x_i, y_i, z_i)$ where $i = \{1, 2, \dots, n\}$, then the length of every root is :

$$D_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \quad (1)$$

Where $i = \{1, 2, \dots, n-1\}$, so the length of the root is $L_k = \sum_{i=1}^{n-1} D_i$. If a root system has m

root, so the total length of the root system is $L = \sum_{i=1}^m L_i$.

2.2. The Growth Rate of Root Axis

This article uses fitting method to simulate the growth rate of every main root axis in different growth period^[21]:

$$V(\text{GDD}) = \begin{cases} -7 \times 10^{-6}(\text{GDD})^2 + 0.0375(\text{GDD}) - 17.334 & 2(a) \\ -1 \times 10^{-6}(\text{GDD})^2 + 0.0564(\text{GDD}) - 47.294 & 2(b) \end{cases} \quad (2)$$

Where GDD is the growth accumulated temperature of branch root, the unit is cm/day. The formulation 2(a) is growth rate of seminal root or first lateral root. Formulation 2(b) is second lateral growth rate.

2.3. The Growth Direction of Root Axis

Through net frame experiment of root, confirming growth direction of horizontal axis. According to the model of reference^[10], under the homogeneity soil condition, the growth direction D of root axis in present growth cycle depends on: the growth direction D_{-1} of the last growth cycle, the tropism influence D_T got by root axis growth, random factor influence D_R got by root axis growth. Where tropism factor includes water, nutrient, genetic nature and geotropism growth trend.

Direction cosine of Descartes space root axis can be express as follow:

$$D_{-1} = (\cos(\alpha_{-1}), \cos(\beta_{-1}), \cos(\gamma_{-1})) \quad (3)$$

The final position of transforming to space coordinates system root axis can be express as follow:

$$X_2 = X_1 + L \cos \alpha, Y_2 = Y_1 + L \cos \beta, Z_2 = Z_1 + L \cos \gamma \quad (4)$$

Where, (X_1, Y_1, Z_1) is the initial position of root axis in this growth cycle; (X_2, Y_2, Z_2) is the final position of root axis in this growth cycle; L is the initial position of root axis in this growth cycle; $(\cos \alpha, \cos \beta, \cos \gamma)$ is direction cosine of root axis vector, root axis vector is decided by formulation D

$$D = D_{-1} + D_T + D_R \quad (5)$$

2.4. The Branch of Root Axis

The root growth leads to branch at last, generating new lateral root. In order to confirm the direction of branch root, using spin transformation tensor method^[22]. We use the relation between space position vector around every root axis to calculate the direction of branch root. First, through a series of spin, taking space structure of root axis branch to translate to coordinate system, then we conduct new branch calculation, getting the new branch direction in coordinate. At last, through reverse direction spin translating to space initial position, confirming the direction of space branch.

As seen in Figure.3a, the final branch direction P_2P_3 is decided by the previous P_0P_1 and P_1P_2 together. Taking the known coordinate to transform to standard orthogonality coordinate system XOY . Corresponding coordinate position transforms to XY plane by spin, being the P'_0, P'_1 and P'_2 respectively. The requested branch direction becomes $P'_2P'_3$, expressed by vector v which is decomposed as (v_1, v_2, v_3) , as seen in Figure. 3(b).

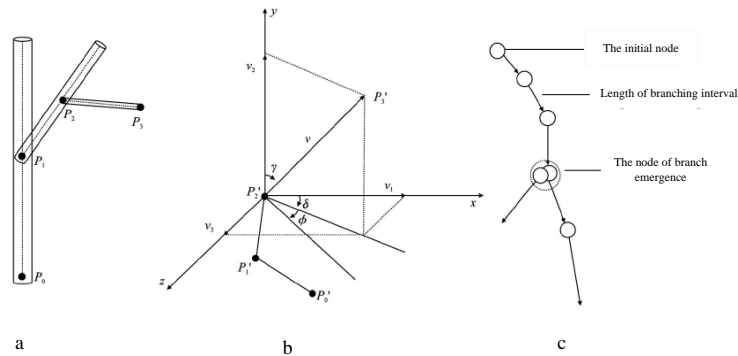


Figure 3. Branching Direction of Root

$$\begin{cases} v_1 = |v| \sin \gamma \cos \delta \\ v_2 = |v| \cos \delta \\ v_3 = |v| \sin \gamma \sin \delta \end{cases} \quad (6)$$

Where $|v| = \sqrt{v_1^2 + v_2^2 + v_3^2}$, spinning to orthogonal coordinate system, we get this:

$$\begin{cases} a_1 = \frac{(x_1 - x_0)}{|v|} \\ b_1 = \frac{(y_1 - y_0)}{|v|} \\ c_1 = \frac{(z_1 - z_0)}{|v|} \end{cases} \quad (7)$$

Where x unitized to $\bar{x} = (a_1, b_1, c_1)$. Then we can get $\bar{y}' = (a_2, b_2, c_2)$, $\bar{z}' = (a_3, b_3, c_3)$, $\bar{x}' = (a_4, b_4, c_4)$. at last, we get three unit vector \bar{x}' , \bar{y}' and \bar{z}' which composes the matrix.

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} a_4 & b_4 & c_4 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{pmatrix} = R \quad (8)$$

Through the calculation of matrix we can get the direction of P_2P_3 , *i.e.* the growth direction of new branch root.

2.5. The Construction of Root Axis Curve

The growth of root axis takes the certain time interval as step length, and go forward one by one by the way of segment, going forward one segment every time. When the growth process need branching, branching by the branch rule, generating new growth node. So it composes one sequence of growth node. We connect these growth node, getting one root axis curve, as seen in 3(c).

3. Three Dimensional Reconstruction of Plant Root

Because the hook face of actual root axis is similar to circular section, so on the basis of three model construction of plant root axis curve, thinking the curve of root axis consists of myriad circular truncated cone circling the axis. But the whole architecture of root consists of certain amount root axis depending on the topology structure.

3.1. The Confirmation of Model Parameter

According to the three dimensional modeling process described in above, the three dimensional morphology of root axis is decided by rooting time, rooting part, growth direction of root axis, direction of branching, there parameters can be simulated to put out through conducting the specific experiment in the different period of root morphology modeling. The parameters are seen in chart 1.

Chart 1 Morphological character parameters and definition of root

Parameter	Implication	Unit
Initial position	The initial position of root	cm
Initial rate	The initial rate of root	mm/GDD
Initial direction	The initial direction of root	TYPE
Axial angle	Angle rotating along the root axial	rad
Radial angle	Angle rotating along the root radial	rad
Radius	Radius of principal axis and other types of root	cm
Bend time	The emergence time of root	TYPE
Branch time	The emergence time of root	TYPE
Branch time	The emergence time of branch	TYPE
Type of root	Types of root	TYPE
Growing degree days	Accumulated temperature for root growth	cm/day

3.2. The Introduction of Random Parameters

When constructing the three dimensional model of plant root, the root of certain plant has different growth development condition in different nature environment, so is the morphology structure characteristic. In order to make it fit to nature growth regular, this article introduces the following random parameters.

According to certain standard fits the condition of normal distribution: the distribution of frequency centers on average, the left right sides of distribution curve is symmetry. The frequency approaching to the two sides of average is more, but the two sides that are far away from the average, the corresponding frequency is less. On research, through the fact measure of geometry exponent of plant root, finding that certain relative geometry parameters of root has great change, but most of these parameters are in certain range, ranging at the center of certain average. So, this article assumes the geometry parameters of plant root is approximately match normal distribution condition. So, in the construction of root model, introducing normal distribution model to approximately process the growth factor. Considering the two distribution parameters of normal distribution curve: the average μ and variance σ , when in the range of $\mu \pm 2.58\sigma$, occupying the 99 percent area of normal curve, so we make the following random variable^[23]:

$$N_r = (N_{\max} - N_a) \left| \frac{r_1}{2.58} \right| - (N_a - N_{\min}) \left| \frac{r_2}{2.58} \right| \quad (9)$$

$$N = N_r + N_a \quad (10)$$

Where N is the final value of parameter; N_r is the random variable; N_a is the average of parameter; N_{\max} is the maximum; N_{\min} is the minimum; r_1 and r_2 the random number, which submits to normal distribution $N[0,1]$.

3.4. The Three Dimensional Reconstruction of the Whole Root

After constructing the three dimensional morphology of root axis, according to the topology structure of root, we can realize three dimensional reconstruction of the whole root. First, we complete the geometry structure of single root axis by the morphology characteristic, then according to rooting node and rooting time of different sort decided by morphology model, depending on topology regular of root, realizing the three dimensional reconstruction of root.

4. The Analog Simulation of Root

In order to prove the effectiveness of three dimensional model of plant root constructed by this article, according to three dimensional morphology parameter described in reference [24] and [25], summarizing the regular of morphology distribution characteristic and growth development, then we get morphology structure parameter of plant root.

This article uses the VTK (visualization toolkit) soft and Open GL soft^[26], through recursive algorithm thought and programming, to build the simulation system of plant root. We use VTK and Open GL three dimensional image interface function library, realizing three dimensional simulation of plant root. The reconstruction of the root is shown in Figureure 4.

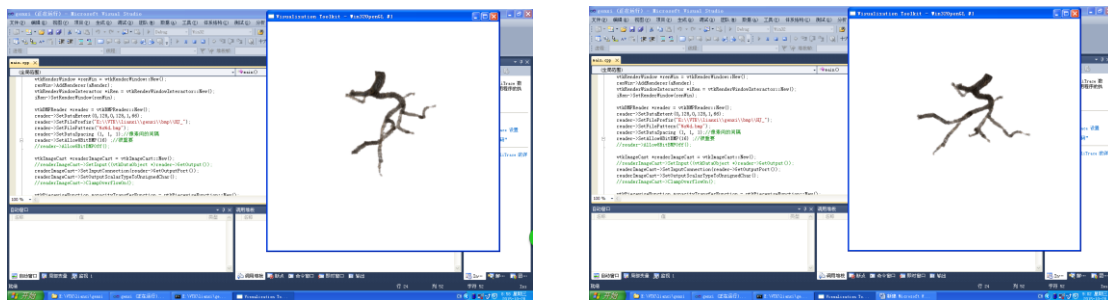


Figure 4. The Reconstruction of Root

The result of experiment shows that the modeling theory described in this article can construct the three dimensional model of plant root vividly.

5. Conclusion

This article constructs three dimensional model of plant root. Through the experiment result showing: according to the requirement of input, through the inputting the model parameter, we can realize the three dimensional visual analog simulation of plant root. This model takes the modeling thought of geometry structure and morphology parameters as theory basic, then it can describe the structure of root effectively. According to model input parameter, introducing random disturbance based on normal distribution, we can make the simulation express the morphology variety of plant root growth.

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