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Description	

Modeling Trees with Rugged Surfaces

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***Abstract*—In this study, a method for modeling trees with rugged surfaces by simulating tree growth is proposed. The phenomena of cell division is considered for simulating tree growth. There are two types of cells that affect the growth of trees, namely, the apical meristem cells and the cambium cells. The former cells lie at the apex of a branch and are responsible for the extension of the branch. The latter cells cover the surface of the tree and are responsible for its lateral growth. Further, knots are generated by unusual and uneven growth of the cambium cells. To simulate these phenomena, a tree is modeled as a polygon mesh which grows by displacing the vertices of the mesh. Each vertex acts as an apical meristem cell or a cambium cell. The tree growth is defined by an L-System. Subsequently, tree models with rugged surfaces, such as those including knots, are generated.**

***Keywords*-Computer Graphics; Natural Phenomena; Trees Growth Model;**

I. INTRODUCTION

Trees are found to grow everywhere such as in forests, gardens, or at the sides of streets. In other words, a large number of trees are found all over the world. To make a computer-generated image including trees, it is indispensable to generate tree shapes procedurally by a computer.

Though it is important to take into account the contribution of knots to the appearance of a tree surface, previous work did not focus on the appearance of a tree surface. In this study, a method for generating a tree with a rugged surface having many knots is proposed. To generate such a rugged tree, we simulate the tree growth by taking the cell division of tree into account.

Trees grow by the phenomenon of cell division. Further, trees have two types of cells that affect their growth, namely, the apical meristem cells and the cambium cells [1]. The former cells lie at the apex of a branch, and are responsible for the extension of the branch. The latter cells cover the tree surface, and are responsible for the lateral growth of the tree. The shape of a tree is generated on a computer by simulating the above mentioned phenomena associated with cell division.

Viruses, buds or inhomogeneities in the degree of nutrition over a tree surface affect the growth rate of the cambium cells and are responsible for the formation of knots. It should be noted that trees with rugged surfaces can be generated by simulating the generation of knots.

II. RELATED WORKS

The concept of modeling tree shapes was first proposed by Ulam [2] and Honda [3]. Lindenmayer proposed L-System based on a character rewriting system [4], and Prusinkiewicz and Lindenmayer proposed a method to describe the branching structures of plants using the L-System [5].

Many methods use the L-System for modeling branching structures of trees. Méch and Prusinkiewicz proposed a method to generate branching structures by taking into account an interaction between trees and environments [6]. Palubicki et al. proposed a method to model interactions among branching structures of trees [7].

There are studies, tree models have been generated with measured data. Livny et al. [8], Hui et al. [9], and Linvy et al. [10] generated tree models with measured point clouds obtained by a laser scanner. Cheng et al. [11] and Tan et al. [12] generated tree models with single picture. On the other hand, Shlyakhter et al. [13], Neubert et al. [14], and Tan et al. [15] generated tree models with multiple pictures.

Previous researches dealing with branching structures converted a branching structure into a polygon mesh. To convert a branching structure into a polygon mesh, Bloomenthal used generalized cylinders along the skeleton of a branching structure [16]. Weber and Penn modeled polygon meshes of trunks and branches using near-conical tubes [17]. Hammel et al. modeled polygon meshes of leaves by calculating an implicit contour around the skeleton of a branching structure [18]. These methods generate surface polygon meshes, which have simple shapes, around the skeletons of branching structures. Trees, in general, have complex and rugged surfaces owing to the presence of knots; however, previous methods do not consider the presence of knots on a tree surface. We propose a method to generate tree models that have rugged surfaces for improving the visual quality.

III. SIMULATION OVERVIEW

We propose a method that involves the simulation of tree growth for generating tree models. A tree is modeled as a polygon mesh, and each vertex of the polygon mesh acts as

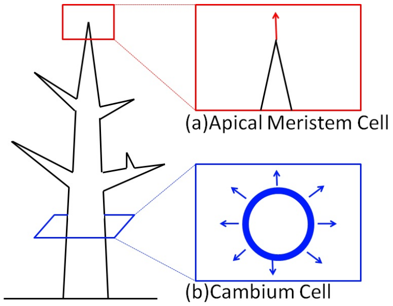

Figure 1. Growth model of tree

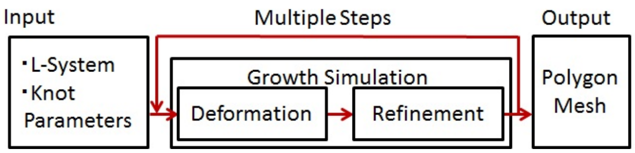

Figure 2. Schematic of tree growth simulation

an apical meristem cell or a cambium cell. Apical meristem cells lie at the apex of a branch and are responsible for he extension of the branch, as shown in Figure 1a. Cambium cells cover a tree surface and are responsible for the lateral growth of the tree, as shown in Figure 1b [1]. Figure 2 shows the schematic of our method for simulating tree growth. An L-System describes the branching structure of a tree, and some parameters specify the growth of knots. For the successful generation of a tree model, the simulation of tree growth involves the displacement of the vertices and mesh refinement processes.

In the following sections, we describe each process in detail.

IV. Growth Simulation with Polygon Mesh

In this study, a tree is modeled as a polygon mesh, and its growth is simulated by displacing the vertices of the polygon mesh. Each vertex of the polygon mesh acts as a cell of the tree. Merks et al. proposed the same method to simulate coral growth [19]. Their method approximates the coral as a polygon mesh, and each vertex of the polygon mesh acts as a polyp of the coral.

A. Growth

Each vertex of a polygon mesh has a growth vector that defines the displacement for each simulation step. Each vertex is displaced according to the growth vector in multiple steps, and then, a tree model is generated. Equation (1) describes the displacement of a vertex.

$$P_i^{n+1} = P_i^n + \vec{v_i}^n \tag{1}$$

Where n is the number of the current step. P_i^{n+1} and P_i^n are the positions of vertices at the $(n+1)$-th step and n-th step, respectively, and $\vec{v_i}^n$ is a growth vector at the n-th step (Figure 3).

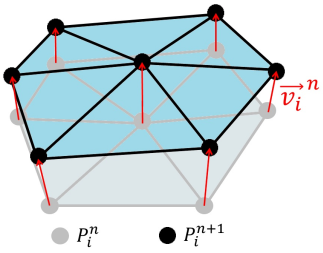

Figure 3. Tree growth simulation with polygon mesh

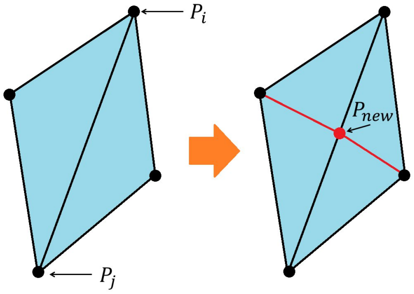

Figure 4. Splitting of polygon

B. Mesh Refinement

After the vertex positions are displaced, the sizes of the polygon become non-uniform. Here, a "uniform polygon" is one in which the lengths of the polygon edges are within the user-specified range. By ensuring uniformity in the polygon sizes, the growth simulation of all over the tree surfaces can be calculated and we find that the growth directions can be calculated accurately. The method of calculating the growth direction is described in Section V-B. To ensure uniformity in the polygon sizes, the polygons are refined by either splitting them or merging them together. It should be noted that carrying out mesh refinement at each step ensure uniformity in the polygon sizes.

Figure 4 shows schematic of mesh refinement splitting of large polygons. As shown in this figure, if an edge length between connected vertices that involve P_i and P_j is longer than a user-specified threshold value T_s, polygons that contain P_i and P_j will split and a new vertex P_{new} will be inserted at the mean position between P_i and P_j.

Figure 5 shows the schematic of mesh refinement merging of small polygons. As shown in this figure, if an edge length between connected vertices P_i and P_j is shorter than a user-specified threshold value T_m, P_i and P_j will merge into a new vertex P_{new}, and P_i and P_j will be deleted. P_{new} is located at the mean position between P_i and P_j.

The operation of merging vertices is performed when an edge length between P_i and P_j is shorter than that in the

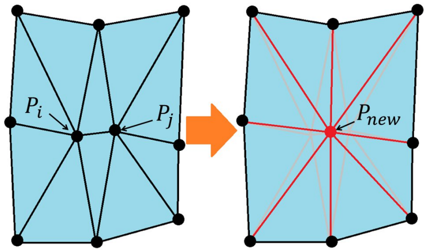

Figure 5. Merging of polygon

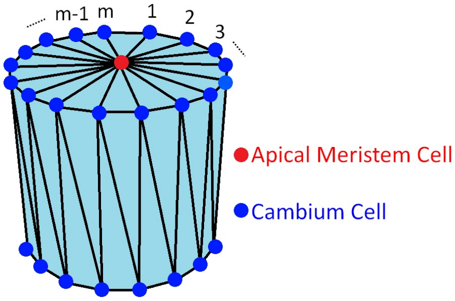

Figure 6. Initial condition

previous step, as given by Equation (2).

$$| P_i^n - P_j^n | < | P_i^{n-1} - P_j^{n-1} | \tag{2}$$

If this rule is not applied, the apex of a branch will break, because the edge length between neighboring vertices around the apex of a branch tends to be shorter than the threshold value T_m.

V. MODELING OF TREE

Trees grow by cell division of the apical meristem cells and the cambium cells. In this study, tree models are generated by simulating cell division. Further, an L-System is used to describe the growth vectors of apical meristem cell vertices and the branching structure of trees.

A. Initial Condition

Initially, a tree polygon mesh is a closed cylindrical polygon mesh, and each vertex acts as an apical meristem cell or a cambium cell, as shown in Figure 6. The center vertex of the top plane of the cylinder acts as an apical meristem cell, and other vertices act as cambium cells. The division number of cylinder m is user defined. The cylinder represents the seed of a tree.

Each vertex that comprises the initial polygon mesh is displaced according to the characteristics of the cells, and the polygon mesh is refined in a step-by-step. As a result, tree models are generated, as shown in Figure 7.

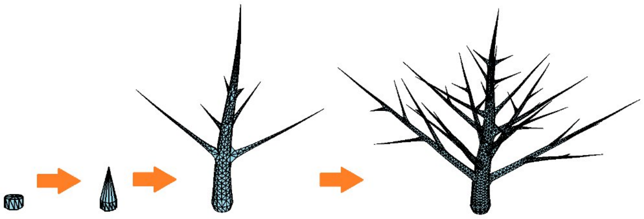

Figure 7. Growth simulation with polygon mesh

B. Growth Vector

The growth vector of the cambium cell vertex is given by Equation (3).

$$\vec{v_i}^n = S_c \, \vec{d_i}^n \tag{3}$$

The growth direction unit vector of a cambium cell vertex, $\vec{d_i}^n$, is given by a vertex normal. The vertex normal is calculated by normalizing the sum of the plane normals of the polygons that contain the vertex. To calculate the normal vectors accurately, it is essential for the polygon sizes to be uniform. The growth rate of the cambium cell vertex, S_c, is user defined.

The growth vector of the apical meristem cell vertex is given by Equation (4).

$$\vec{v_i}^n = S_a \, \vec{d_i}^n \tag{4}$$

The growth direction $\vec{d_i}^n$ and growth rate S_a of the apical meristem cell vertex are given by the L-System, and a polygon mesh that is along the branching structure of a tree is generated.

C. Branch

A new branch is generated by the growth of a bud. The steps involved in the generation of a new branch are described as follows.

1) A bud is generated (Figure 8a): When an apical meristem cell vertex P_i^n is ordered to generate a new bud by the L-System, a new bud vertex P_{bud} is generated at a neighboring vertex on P_i^n, as shown in Figure 9. P_{bud} which minimizes the angle between its normal $\vec{d_j}^n$ and the growth direction of the bud vertex $\vec{d_{bud}}$, is chosen for the new bud vertex to avoid the intersection of the branch on which P_{bud} lies with the shoot of P_{bud}. Further, $\vec{d_{bud}}$ is specified by the L-System.

2) The bud is dormant (Figure 8b): During the number of steps specified by a user, P_{bud} is dormant and grows as a cambium cell vertex.

3) The bud shoots (Figure 8c) and generates a new branch (Figure 8d): After the completion of a certain number of steps, P_{bud} shoots and begins to grow as an apical meristem cell vertex. The new apical meristem cell vertex grows according to the L-System and generates a new branch.

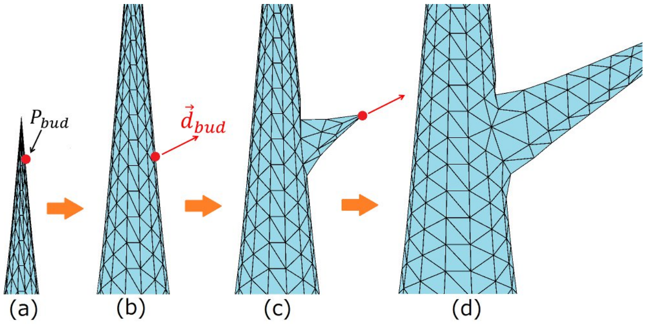

Figure 8. Modeling branch (a) bud (b) dormant bud (c) shoot (d) new branch

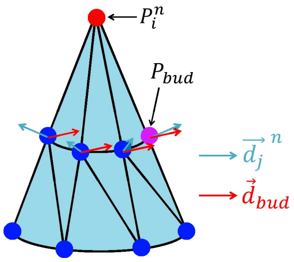

Figure 9. An bud vertex is chosen from The neighboring vertices

D. Fine Branches and Leaves

Fine branches and leaves are given by predefined textured square polygons (Figure 10). The square polygons are randomly placed at cambium cell vertices around the apices of branches.

VI. MODELING OF KNOTS

Knots are generated on the surface of a tree, with aging. These knots are generated because of unusual tree growth or inhomogeneity in the degree of nutrition transported through the phloem. In this study, realistic trees are generated by simulating the generation of the knots on the tree surface.

A. Growth Vector Considering Knots

To simulate the generation of knots, the growth rates of the cambium cell vertices are controlled. The growth vector considering knot $\vec{v'}_i^{\,n}$ is calculated by Equation (5).

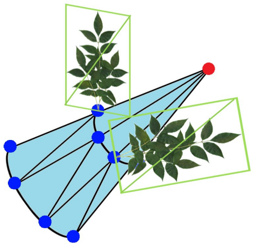

Figure 10. Fine branches and leaves with square polygons

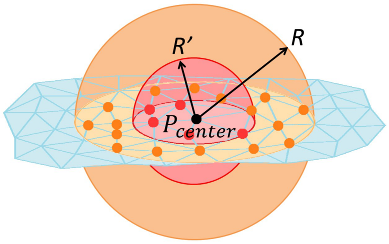

Figure 11. Effect region of a knot

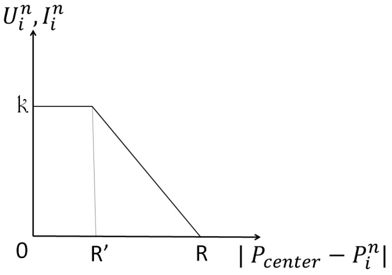

Figure 12. Function that affect growth rate by unusual and inhomogeneity in the degree of nutrition growth

$$\vec{v'}_i^{\,n} = (1 + U_i^n + I_i^n)\vec{v}_i^{\,n} \tag{5}$$

Where U_i^n is the factor of unusual growth and I_i^n is the factor indicating inhomogeneity in the degree of nutrition. U_i^n and I_i^n are controlled to generate several surface shapes with knots.

B. Knot Caused by Unusual Growth

Sometimes unusual tree growth occurs because of viruses or buds buried under the bark of the tree; this unusual tree growth causes the formation of knots. Knots often appear on the surfaces of old trees.

A knot is defined in terms of its center P_{center} and its radius R, as shown in Figure 11. The effect of unusual tree growth U_i^n is calculated using a function, where P_{center}, P_i^n, R, and R' are chosen to be the inputs (Figure 12). Here, P_i^n denotes the vertex position, k denotes the maximum value of U_i^n, R denotes the knot size, and R' denotes the radius of a sphere, where $U_i^n = k$. We assume that U_i^n decreases with an increase in the distance between vertex P_i^n and P_{center}. For carrying out mesh refinement that involve the splitting of a large polygon, It is essential for R' to be greater than a threshold value T_s; otherwise, sharp knots will be generated. If vertex P_i^n appears in multiple spheres, the largest value U_i^n will be chosen for P_i^n.

C. Knot Caused by Inhomogeneity in the Degree of Nutrition

The growth rate of the surface of a tree depends on the amount of nutrition transported through its phloem. To simulate the tree growth depending on nutrition, links of the phloem are generated on the surface of a tree polygon

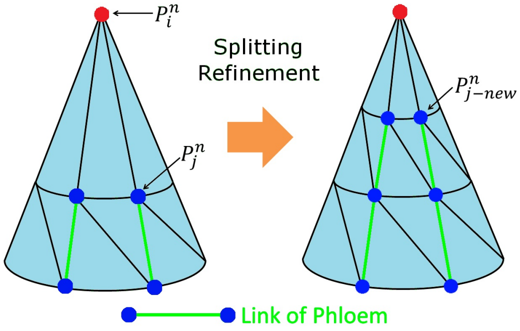

Figure 13. Generation of new vertex between the apical meristem cell vertex and the cambium cell vertex

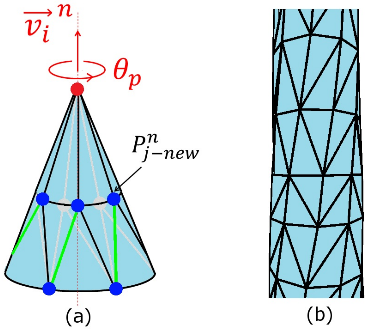

Figure 14. (a) Twisted links of phloem (b) result of twisted phloem

mesh. The links of the phloem are represented as edges of a polygon, as shown in Figure 13. If the length between an apical meristem cell vertex P_i^n and a cambium cell vertex P_j^n is longer than the threshold T_s, a new cambium cell vertex P_{j-new}^n will be generated on the edge between these vertices. P_{j-new}^n is linked with P_j^n, and the new links serves as the phloem. The number of links of the phloem depends on the division number of the initial cylinder m, as shown in Figure 6.

The phloem either grows straight or twists around the axes of a branch. The degree of twist depends on the species of the tree. The mechanism of the twisting of the phloem was proposed by Schulgasser and Witztum [20]. To generate a twisted phloem, the new vertex P_{j-new}^n is twisted around a growth vector $\vec{v_i}^n$ when a phloem link is generated (Figure 14). The twist angle is defined as θ_p, and this angle gives rotation speed as a function of the growth rate.

Each vertex constituting the phloem corresponds to P_{center} (Figure 11), and I_i^n, i.e. the change in the growth rate attributed to uneven growth, is calculated in the same manner as that used for a knot caused by unusual tree growth (Figure 12).

VII. RESULT

Figure 15 shows a photograph of a real ancient cherry tree. This tree has two types of knots, namely, linked knots and block knots. Figure 16 shows the generated rugged tree surface with knots which are caused by unusual tree growth and an inhomogeneity in the degree of nutrition. As shown in this figure, the generated tree surface has knots that are similar to those of the cherry tree shown in Figure 15. A rugged tree surface with knots is generated by simulating the growth of the tree surfaces.

Figure 15. Photograph of a real tree with a rugged surface

Figure 16. Generated rugged tree surface

Figures 17, and Figures 18 show the different types of knots generated by unusual growth and an inhomogeneity in the degree of nutrition, respectively. In these cases, the trees grow straight with parameters $T_s = 150.0mm$, $T_m = 70.0mm$, $S_a = 60.0mm/step$, $S_c = 3.0mm/step$, $R' = 160.0mm$, and $n = 300steps$. The knots shown in Figures 17 can be controlled by U_n, which is calculated with knot size R and k of each knot, and the number of knots. The centers of knots, P_{center}, are given randomly. The knots shown in Figures 18 can be controlled by I_n, which is calculated with knot size R and k of each phloem, the twist angle θ_p, and the division number of the initial cylinder m.

Figures 19 and 20 show the rendering results of the generated trees. The trees have many knots and a realistic surface shape. The branching structure and a uniform surface can be controlled using an L-System, and a rugged surface can be controlled by certain knot parameters. These experimental results are obtained on a Windows PC with Intel Core i7 950 3.07 GHz processor with a single thread. It took less than 120 s to generate one tree.

VIII. CONCLUSION AND FUTURE WORK

In this study, a method for modeling trees with rugged surfaces by simulating tree growth is proposed; here, a tree is modeled as a polygon mesh. Each vertex of polygon mesh grows as an apical meristem cell or a cambium cell. The branching structure is defined by L-System, and knot shape is controlled by certain parameters. The knots are generated by simulating the effects of unusual and uneven tree growth.

Though our method can generate several shapes of tree surfaces, some features of the trees are not considered. Knots are generated by an inhomogeneity in the degree of nutrition, which is caused by leaves; however our method does not consider the amount of nutrition provided by the leaves. When a tree is under high pressure, it stimulates cell division and generates knots to protect its body. For such features of knots, transportation of nutrition and physical simulation should be considered.

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(a) (b) (c) (d) (e)

$k = 0.5$

(a) without knots (b) $R = 500.0mm$ (c) $R = 1000.0mm$ (d) $R = 500.0mm$ (e) photograph

Figure 17. Knots caused by unusual growth

(a) (b) (c) (d)

$k = 1.0$

(a) $R = 300.0mm$, $\theta_p = 0.0rad/mm$, $m = 10$ (b) $R = 300.0mm$, $\theta_p = 0.004rad/mm$, $m = 10$

(c) $R = 600.0mm$, $\theta_p = 0.004rad/mm$, $m = 5$ (d) photograph

Figure 18. Knots caused by inhomogeneity in the degree of nutrition

Figure 19. Result (1)

Figure 20. Result (2)