PERCEPTUALLY REALISTIC FLOWER GENERATION

Zhaoying Lu
Claire Willis
Derek Paddon

Computing Group
Department of Mathematical Sciences
University of Bath
BATH BA2 7AY, UK
email: {zl,cpw,derek}@maths.bath.ac.uk

ABSTRACT

This paper describes a method for generating flower growth animation in which a petal surface and shape can be changed in real time. Most plant modelling currently animates the plant development process by assuming a time interval and the corresponding growth direction, and cannot easily change the time step or deform the shape. In the model presented here we use a graphical representation for plant growth function, along with a new description of plant growth rate, to enable the user to obtain flexible parameters for surface control. The model generates non-deterministic results which give more realistic and varied petals than can be obtained using pre-defined surfaces or interpolating between given initial and final shapes.

Keywords: surface modelling, growth, animation.

1 INTRODUCTION

When we build virtual environments, it is relatively easy to generate walls, desks, chairs, machines and other man-made objects because their shapes are designed by ourselves. However, it is quite hard to simulate biological processes because they grow and move according to highly complex natural principles, which can be very difficult to model. Of course, if we restrict ourselves to deterministic models of growth, we can find equations which will allow us to generate the final model of an organism. However, this approach will fail to provide the natural growth of organism and miss the infinite perturbation found in nature. In the work we strive to find a non-deterministic method that accounts for natural growth.

Recently, many attempts have been made to simulate the development of plants, trees and botanical structures. Some interesting results have been obtained using branching process constructions [Aono84a], particle systems [Demko85a], ramification matrix of trees [Vienn89a] and structure creation on trees [Holto94a, Weber95a]. A virtual plant system has been generated by parametric L-systems, which is a recursive algorithm, and can model highly complex and irregular structures [Prusi90a]. Mech built a modelling framework to simulate and visualize a wide range of interactions at the level of plant architecture [Mech96a]. Fowler uses spiral phyllotaxis to model flowers [Fowle92a]. However, most of this work has focused on a target structure and ignored the transient stages of plant growth and development. The main problem with these systems is that they do not support level-of-scale simulation. In the main, zooming in would expose poor images. If we assume that the user is in complete control of level-of-scale operation, then we must consider carefully modelling the surface features of the plant and all transient stages during the development of the plant.

This paper focuses on the simulation of flower petals through all transient stages from a bud to the fully developed flower. Thus, we need to develop methodologies that support the simulation, to ensure that we achieve realistic results of time transient behaviours. Flowering, or more precisely, reproductive development, is composed of many independent but highly coordinated processes. Since one cannot precisely determine the exact point at which a flower base is formed, it is necessary to wait for the appearance of true floral structures; this is usually referred to as flower formation.

1.1 Related Work

Recently, Lintermann and Deussen presented a modelling method [Linte99a] that allows easy generation of many-branching objects including flowers, bushes, trees, and even non-botanical structures. A set of components describing structural and geometrical elements of plants, map to a graph that forms the description of a specific plant and generates the plant geometry. Users of their system obtain immediate feedback on what they have created – geometrical parameters, tropisms, and free-form deformations can control the overall shape of a plant. However in their system, a natural leaf or petal must be scanned before creating a single leaf or petal component for the system. Thus this system does not attempt to model growth by evolving the natural stages of plant development, but instead uses stored components to simulate the process.

Manipulation of Bézier patches using L-systems has been described in detail by Hanan in [Hanan92a]. The developmental bicubic surfaces are implemented by using an interactive surface editor to set sixteen control points and defining the initial and final shapes in the sequence. It allows the user to manipulate parameters for petal width, length and bending angles in order to model members of a family of petals. This means that the user must manipulate all these components appropriately to control the bicubic patches. Once the shapes have been chosen, the L-system must be designed to interpolate between the two shapes with a fixed number of steps. However, the user must have some knowledge of the structure and the parameters of the petal to generate the petal shape desired. The structure of the petal surface must be changed if a different shape is required. It is not easy to control when a complicated or asymmetrical petal surface is generated. In our work, a simple patch surface with three base factors for the petal length, width and curvature would allow a non-expert user to control the shape change with minimum effort.

Growth is a continuous process, but simulation models operate in discrete time steps, making it convenient to simulate the discrete addition of structural units. Consequently, the structural unit considered by a model, the time taken for a unit to appear, and the time step used by the model are usually related. A close approximation to continuous growth can be achieved by solving differential equations for very small time steps [Prusi93b]. The disadvantage of L-systems is that the time step and the component shape is a part of the model and cannot be easily changed. Any change related with these parameters will need a restart for the recursion. Furthermore, a proper surface modelling is necessary for the levels of scale, which will allow zooming in or zooming out on the surface and changing the viewing position.

Since it is necessary to obtain a growth surface for representing petals or leaves, it is important to construct a suitable surface model. Guo describes a method for reconstructing an unknown surface [Guo97a] from a set of scattered points. Welch presents a method [Welch92a] for the interactive modelling of free-form surfaces, where the user is free to manipulate the control points to obtain different shapes for the same surface with constraints. Durikovic presents the shape of the organ by a number of ellipsoidal clusters centred at points on the skeleton [Durik98a]. He also introduces several tables with which to store the database of statistical geometry of organs, such as size, growth speed, among others. However, these surface representations are not suitable for petal surfaces, which can be constructed and controlled by some major points for the desired shape.

1.2 Paper Objectives and Overview

The objectives of this paper are to:

- Present a new theory of growth functions, the purpose of which is to give a good description of plant development.
- Develop a graphical representation for plant growth functions.
- Introduce the integral equations for growth measurement based on the specific time interval.
- Illustrate step by step the petal development controls with analysis of the shape changes.
- Describe the shape control by the generations of unique petals with bicubic surface representation.

In this paper, we propose a method for generating flower growth animation in which petal surface and shape can be changed simultaneously in real time. We represent a flower petal as a set of the control points defining a bicubic patch. In addition, we expand growth function theory to enable the growth rate to vary as the petal develops.

2 DESCRIPTION FOR THE MODEL

The animation of plant development remains a challenging problem in computer graphics. The entire growth process and mechanism have not yet been made clear, with many unknown factors remaining which depend on biological principles or environmental variance. However, animation based on the theory of growth functions could make a significant contribution to the field of simulating plant growth.

2.1 Surface Representation

To achieve a realistic result for the development of a bud into a flower, it is inevitable that the petal model must possess some measure of the complexity of a real petal. This presents problems for the construction of the 3D model for our simulation. The model needs to provide satisfactory surface continuity and smoothness. Building a model of this complexity using traditional polygonalization techniques would involve prohibitive storage and processing overheads, therefore alternatives must be used.

2.1.1 Bicubic Surface Patches

Prusinkiewicz and Lindenmayer showed how plant components [Prusi90a], such as stamens, petals, leaves, seeds, can be built out of bicubic patches. A patch is defined by three polynomials with degree three, with respect to parameters s and t. The following equation defines the x coordinate of a point on the patch:

$$\begin{aligned} x(s,t) \;=\;& a_{11}s^3t^3 + a_{12}s^3t^2 + a_{13}s^3t + a_{14}s^3 + \\ & a_{21}s^2t^3 + a_{22}s^2t^2 + a_{23}s^2t + a_{24}s^2 + \\ & a_{31}st^3 + a_{32}st^2 + a_{33}st + a_{34}s + \\ & a_{41}t^3 + a_{42}t^2 + a_{43}t + a_{44} \end{aligned}$$

Analogous equations define $y(s,t)$ and $z(s,t)$. All coefficients are determined by interactively designing the desired shape. Complex surfaces are composed of several patches.

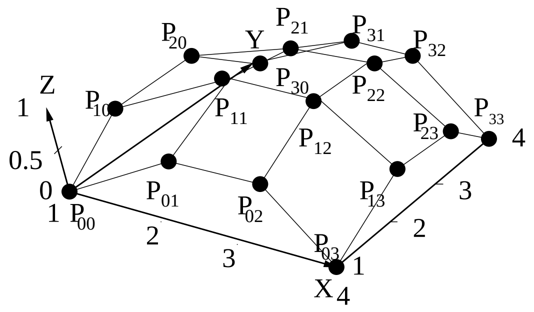

Figure 1: Control points for bicubic Bézier patch

2.1.2 Bézier Patch

Just as with two dimensional curves, three dimensions patches may use a variety of control strategies, including Bézier, Hermite, and B-Spline bases. A Bézier patch requires sixteen control points. The four corner points control the position of the patch and lie on its surface. The intermediate twelve points control the tangents to the patch along the edges and at each corner and may be used by the designer to "pull" the surface of the patch into the shape desired (Figure 1) [Farin88a, Barte87a].

The Bézier form of the bicubic parametric patch has a very concise matrix formulation specifying a vector point, $P(s,t)$, on the surface in terms of the sixteen control points. This relationship [Fireb93a], is expressed as:

$$P(s,t) = SBPB^TT^T \tag{1}$$

where: $S = \begin{bmatrix} s^3 & s^2 & s & 1 \end{bmatrix}$ (s parameter row vector)

$B = \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$ (Bézier coefficient matrix)

$P = \begin{bmatrix} P_{00} & P_{01} & P_{02} & P_{03} \\ P_{10} & P_{11} & P_{12} & P_{13} \\ P_{20} & P_{21} & P_{22} & P_{23} \\ P_{30} & P_{31} & P_{32} & P_{33} \end{bmatrix}$ (Control point matrix)

B^T = Transposed B matrix (switch rows and columns)

$T^T = \begin{bmatrix} t^3 \\ t^2 \\ t \\ 1 \end{bmatrix}$ (Transposed t parameter vector)

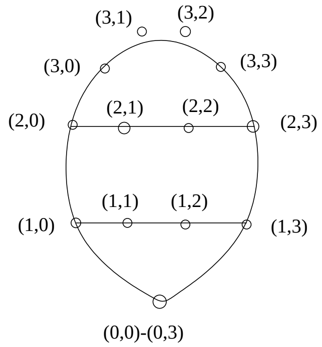

Figure 2: Petal structure with sixteen control points

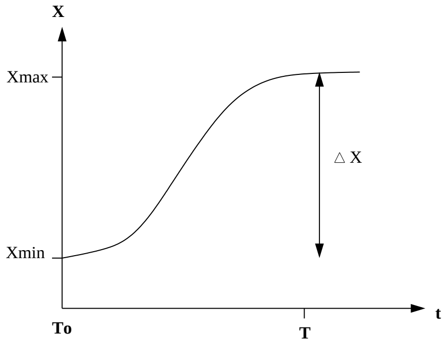

Figure 3: General growth function

For the regular and symmetrical petal, we can keep $P_{00}, P_{01}, P_{02}, P_{03}$ as one control point, thus making the control easier. To make it simpler, $P_{30}, P_{31}, P_{32}, P_{33}$ could be put together as one point if the top of the petal is a discontinuity point. As shown in figure 2, four control points are located at the bottom of the petal while the base portion of the petal is simple. The other two groups of four control points usually control the middle part of the petal. The last four control points play an important role in shaping the petal, providing that they are located at the top of the petal. When we consider the structure for the petal surface, we need to pay attention to where the discontinuity points are, in which the two groups of the four control points can be joined, forming a corner control point. The part of the surface formed by the same group of four control points will generate a smooth and continuous curve. So the surface structure will be changed if the discontinuity points are different.

Bicubic Bézier patches have become a popular tool for surface modelling. The obvious advantages include: Ease of interactivity–the control point effects are readily observed and understood, and the control points themselves are easily modified, either numerically or interactively; Representational efficiency–complex surfaces are represented by a very small set of numbers. So this approach is applied here as the surface representation for our flower petal modelling.

2.2 General Growth Function

In previous work [Prusi93b] the growth of biological organism has been determined by equation, which a-priori fix the final form of the organism even before the growth starts. Here, we reject this approach and instead seek methodologies that can enable the growth function to take account of natural perturbation, such as climate effects, organic effects, and artificial perturbation caused by human intervention.

Continuous processes such as the elongation of skeleton segments, growth of cell clusters, and gradual increase in branching angles over time can easily be described by growth functions. A popular example of the growth function is an S-shaped function, monotonically increasing from minimum to maximum with growth rates of zero at both ends of time interval (To, T), as shown in Figure 3. This function is often applied in higher plants. The growth is slow initially, accelerating near the maximum value stage, slowing again and eventually ceasing.

2.3 Growth Function for Petal Area

However, different growth functions are presented here for the flower petal surface when we use the bicubic patch to generate the petal. Usually, bicubic parametric patch modelling suffers from lack of a high-level modelling abstraction for shape control. So the growth function is applied in the x, y, z directions for each control point.

We can focus the area growth in petal development. From the concept of leaf area growth for one duration [Hunt78a], which takes account both of the magnitude of leaf area and its persistence in time, the new growth function is developed which relates growth rates and time. From the relationship between growth and the time, we can obtain the equation for growth rate. It is presented in equation (2) for the z axis direction growth. When we have a function to represent the growth rate, as in equation (3), we can have the integral equation to calculate the growth during that duration, as shown in equation (4).

$$l = \dot{Z} = \frac{dz}{dt} \tag{2}$$

$$l = f(t) = a * t^2 + b * t + c \tag{3}$$

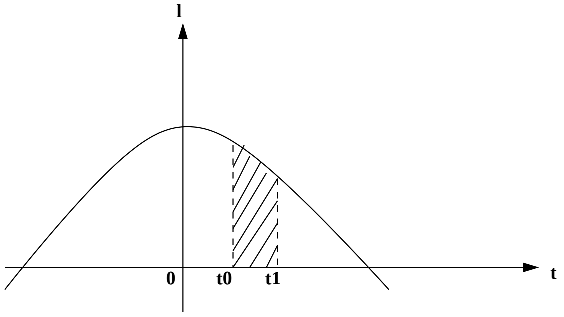

Figure 4: Growth function for petal area

$$Z = \int_{t_0}^{t_1} f(t)dt \qquad (4)$$

(t: time; l: length growth rate; Z: the growth in z axis direction; a, b, c: constants)

In Figure 4, the shaded area represents the total growth during a specific time interval (t_0,t_1). It is obvious that this growth could be negative, which means the coordinate position decreases for that time interval, compared with the previous position.

The advantages of this new growth function are:

The $f(t)$ function could be changed at any moment of the development animation, that is, we can change equation (3) at any time. It means that the growth rate changing tendency and growth acceleration for the flower petal can be different for the same petal in one growth procedure. It provides the possibility to have unusual petals by breaking the growth tendency.

The growth rate is under control with the appropriate $f(t)$ curve. It means that the shapes for the flower petal surface are fully controlled by this function. We can generate different petal shapes by setting appropriate growth rates with this function.

Although the time interval is fixed for its recursive process, the specific time interval could be set with different $f(t)$ equations. It means that we can do the adjustments for growth rate by controlling the time interval. The specific growth procedure can be recalled by retrieving the time interval when the desired shape is not achieved.

The flexible growth rate curve allows variation for individual control points. It means that we can apply a different growth function for one control point or some of the control points. A unique irregular petal will be generated when only one or some control points have different growth tendencies.

The essential differences between our growth function and the general growth function are as follows: firstly, the general growth function has a fixed growth tendency while that one presented here can have various growth tendencies by using different growth equations. This means that our growth function is changeable. Secondly, the general growth function has no control of the growth rates during a time interval while ours can show and change the values of all the growth rates.

2.4 Factors Controlling Growth

With the theory for the growth rate, we need to consider what parameters are necessary for the petal shape control. However, in order to let a non-expert user with a general idea of the petal shape understand how to control the shape, only three factors are applied in our work. They will affect the petal surface obviously and effectively, that is the length, width and curvature growth factors. Increasing the parameter for the length factor will generate a longer petal for the same time interval.

For a regular and symmetrical petal, we can evenly locate the sixteen control points. The growth between two groups of four control points will be considered as having the same growth rate. For example, if the top four control points grow 1 unit value for the time interval, the next group of four control points grows $\frac{2}{3}$ unit value. The third group grows $\frac{1}{3}$ unit value if the bottom group control points remain on the petal base. Another factor is applied for this unit value control. Increasing the value means moving the control points upward to the top of the petal, which provide another approach to change the shape for the same petal family.

In summary, if a fixed petal structure is provided for the petal surface, the main three growth factors play an important role in surface change for the growth process. These three factors allow the user to control a bud growing into a flower with petals of different length, width and curvature after any time.

2.5 Implementation

We need to set up the growth equation by setting the values of the constants a, b, c. The growth rate value in length, width and depth and the growth factors for all the control points must be input to calculate the new positions after the specified time interval. The selections of all the values in

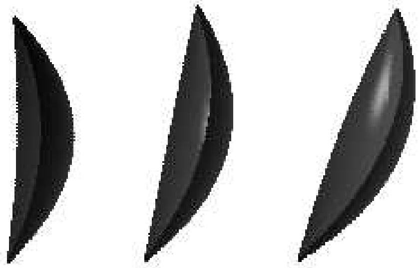

Figure 5: Petal growth (length rate:0.8; width rate:0.6; depth rate:0.2)

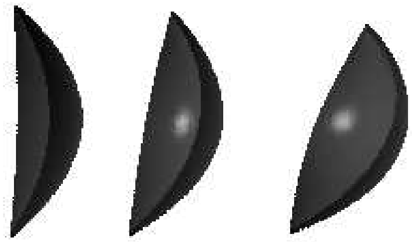

Figure 6: Petal growth (length rate:0.0; width rate:1.0; depth rate:0.1)

these two steps depend upon the desired petal shape. The growth factors for some control points should be reset if their desired surface growth tendency is changed. Then the new control points matrix will be generated , and the patch surface thus formed, will be rendered pixel by pixel with a forward differencing algorithm.

3 RESULTS AND GENERAL COMPARISONS

3.1 Comparison

All the petals in figure 5 and 6 represent the growth processes. Generally, the petal surfaces are getting longer, wider, more flat and opening wider with increasing time. With these figures, we can see there are three major advantages in our petal surface model. Firstly, varied surfaces can be obtained easily by changing the growth rate value in length, width and depth direction or changing the growth function. Comparing figure 5 and 6, the figure 6 has wider petals with a greater width growth rate. Secondly, the growth tendency can be broken by changing the growth rate for any factor at any time. Comparing figure 5 and 6, which both had the same growth rate at the beginning of their cycles, we see that figure 6 ends up with a different shape as a result of increasing the width growth rate. Thirdly, asymmetrical petals can be obtained by changing the factors for the control points, that is, moving the relative positions between all the control points. Comparing figure 9(a) and 9(b), they have different petal structures for different shapes though they share the same growth rate.

3.2 Results from the Control Points

In figure 7 and 8, small spheres represent the control points for the bicubic patch surface. From figure 7, we can see that three groups of four control points are located on the top and the main part of the petal to pull it into the desired shape. The remaining four control points are all in the bottom of the petal. Figure 8 is the same petal viewed from the opposite direction showing the control points lying behind the petal. From these two figures, it is obvious that the bicubic patch is effective in shape control for the petals.

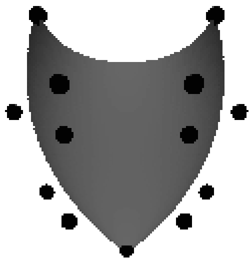

Figure 7: Petal with sixteen control points

Figure 9-12 show how the control points work to control the shape. From the same bicubic structure, the petal surfaces vary from the simplest shape in figure 9(a) to a more complex shape in figure 11(a). Naturally, a asymmetric shape will be obtained when the control points are not located symmetrically, as shown in figure 11(b).

From the theory of bicubic patches, we know that a group of four control points will generate a continuous curve. That is, we need to put the corner control points at the discontinuity point. As shown in figure 12, there are two approaches when

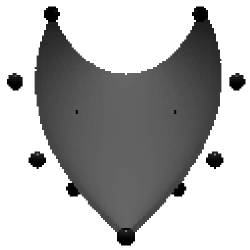

Figure 8: Petal with control points (view from the opposite direction)

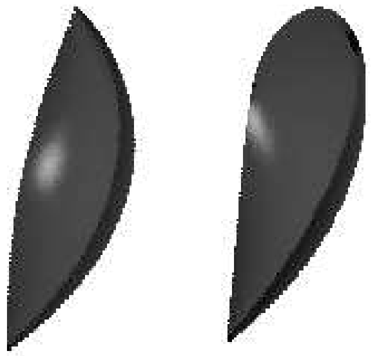

Figure 9: Symmetrical petal: (a)four control points are on the top together; (b)the top four control points generate the curve.

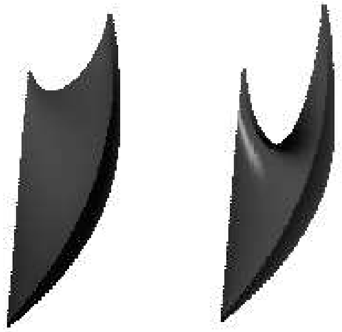

Figure 10: Symmetrical petal: (a)the top four control points pull down the curve; (b)the middle two control points on the top pull further down.

we use one bicubic patch to represent the shape. The first approach is to place a group of four control points together on the top as the discontinuity point. It is obvious that this will reduce the number of control points, which leads to less control for the other part of the surface. The second way is using two groups of four control points on the left and right site of the petal separately and they are joined on the middle top and bottom of the petal as corner control points. This has the advantage of retaining all the control points, although it requires a slightly different growth rule for the surface.

Furthermore, the easy access for control points and surface shapes provides the possibility of generate the petals at any stage, as shown in figure 13 and figure 14, with reflexed down and wrinkled petals. In summary, it provides a direct method of surface control. Compared to using predefined surfaces or generating surfaces from fixed original and final shapes, this method is more flexible and creative.

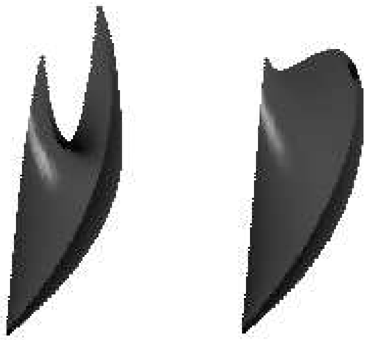

Figure 11: (a):Symmetrical petal (two control points on the top end pull inward); (b):asymmetric petal (two control points on the top exchange).

Figure 12: Symmetrical petal (discontinuity on the top)

4 CONCLUSION

This paper presents a description of various kinds of surface growth, and illustrates the use and results of some growth factors in some common cases. They may be assumed to be fixed relative to the growth surface or to the body being generated.

Most research in the field of plant development has focussed on the whole structure or geometry changes on the plant and ignored the surface changes on the plant organs. This means that the leaf or petal must be scanned or predefined

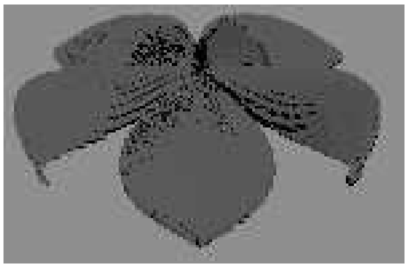

Figure 13: Flower petals at a mature stage

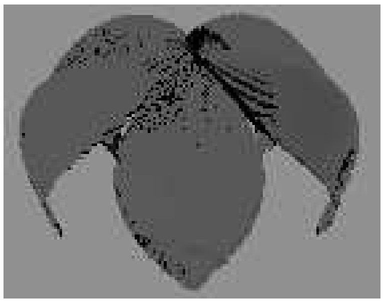

Figure 14: Flower petals development after the mature stage

before the development animation or a triangle is used to represent them which will obviously give unrealistic result.

We introduce a smooth surface model with a bicubic patch for the petal. It can simulate the surface development with easy access to individual control points. At the same time, the biological factors in length, width and depth represent the principle growth for the petal.

In addition, a new growth function is presented to enable the growth rate to change at any development stage. The flexible growth rate curve allows variation in the development tendency at a specific time interval. It therefore differs from other animations in which the plant grows according to a single growth function from the beginning to final stage.

In summary, we believe that the proposed modelling method and its extensions will prove useful in many applications of plant modelling, from research in plant development and ecology to the surface design of plant organs and in the production of animated plant models for use in virtual environments.

REFERENCES

[Aono84a] Aono,M, Kunii,T: Botanical Tree Image Generation, *IEEE Computer Graphics and Applications*, Vol. 4, No. 5, pp.10-34, 1984.

[Barte87a] Bartels,R, Beatty,J, Barsky,B: *An Introduction to Splines for use in Computer Graphics & Geometrics Modeling, Morgan Kaufmann Publishers*, 1987.

[Demko85a] Demko,S, Hodges,L, Naylor,B: Construction of Fractal Objects with Iterated Function Systems, *SIGGRAPH*, pp.271-278, 1985.

[Durik98a] Durikovic,R, Kaneda,K, Yamashita,H: Animation of Biological Organ Growth Based on L-systems, *Computer Graphics Forum*, Vol. 17, No. 3, 1998.

[Farin88a] Farin,G: *Curves and Surfaces for Computer Aided Geometric Design, Academic Press*, 1988.

[Fireb93a] Firebaugh,M: *Computer Graphics Tools for Visualization, Wm.C.Brown*, 1993.

[Fowle92a] Fowler,D, Prusinkiewicz,P, Battjes,J: A Collision-based Model of Spiral Phyllotaxis, *Computer Graphics,* Vol. 26, No. 2, pp.361-368, July 1992.

[Guo97a] Guo,B: Surface Reconstruction: from Points to Splines, *CAD*, pp.269, 1997.

[Hanan92a] Hanan,J: *Parametric L-systems and their application to the modelling and visualization of plants, PhD thesis, University of Regina*, June 1992.

[Holto94a] Holton,M: Strands, Gravity and Botanical Tree Imagery, *Computer Graphics forum,* Vol. 13, No. 1, pp.57-67, 1994.

[Hunt78a] Hunt,R: *Plant Growth Analysis, Arnold*, 1978.

[Jacob79a] Jacobs,W: *Plant Hornones and Plant Development, Cambridge Univ Press*, 1979.

[Linte99a] Lintermann,B, Deussen,O: Interactive Modeling of Plants, *IEEE Computer Graphics and Applications*, pp.56-65, Jan/Feb, 1999.

[Mech96a] Mech,R, Prusinkiewicz,P: Visual Models of Plants Interacting with Their Environment, *Proceedings of SIGGRAPH* , pp.397-410, 1996.

[Prusi90a] Prusinkiewicz,P, Lindenmayer,A, etc: *The Algorithmic Beauty of Plants, Springer-Verlag*, 1990.

[Prusi93b] Prusinkiewicz,P, Hammel,M, Mjolsness,E: Animation of plant development, *SIGGRAPH*, pp.351-360, 1993.

[Vienn89a] Viennot,X, Eyrolles,G, Janey,N, Arques,D: Combinatorial Analysis of Ramified Patterns and Computer Imagery of Trees, *SIGGRAPH*, pp.31-40, 1989.

[Weber95a] Weber,J, Penn,J: Creation and Rendering of Realistic Trees, *Proceedings of SIGGRAPH* , pp.119-128, 1995.

[Welch92a] Welch,W, Witkin,A: Variational Surface Modeling, *SIGGRAPH*, 1992.