Methods and Tools for Modeling 3D Plants with Detailed Features

Shenglian Lu[1] ⓘ, Guo Li[2] ⓘ and Ming Chen[3] ⓘ

School of Computer Science and Information Technology, Guangxi

Normal University, China

Guangxi Key Lab of Multi-source Information Mining & Security, China

[1] lsl@gxnu.edu.cn,[2] liguo@gxnu.edu.cn, [3] mingchen@gxnu.edu.cn

Corresponding author: Ming Chen, mingchen@gxnu.edu.cn

Abstract. Modeling plants with detailed features is an interesting but challenging topic. A graphical toolkit for modeling 3D plants is presented in this paper. The proposed toolkit consists of a series of key modeling algorithms and a pipeline to create 3D plants with detailed features. In this toolkit, detailed features such as flower buds, leaf buds and internodes can be fully modeled and displayed instantly. These detailed features can reflect the richness of plants and the varied plant appearances in different seasons, which is necessary for applications such as the botany education, scientific research and high-end video products. The toolkit has been applied in plants modeling and the designed 3D models have been used in studying botany knowledge and training agricultural planting technology.

1 INTRODUCTION

Plants are vital to nature and human life, which play an important role in computer-aided design technology and its applications such as architectural design, urban planning, computer game, and video products. Establishing a 3D model with detailed features is a critical step in the above applications and is challenging. The main reason is that plants not only have unusually complex shapes and structures, but they also should meet their unique internal physiological mechanisms. In this field, various methods have been proposed, which include the famous L-systems initiated by Lindenmayer and Prusinkiewicz [11], reference axis technique [3] and GreenLab model [6]. The above methods can capture a variety of plant shapes. However, they are computing-intensive and a

large number of input parameters are required such that skilled users are expected. With the widespread applications of various measuring devices in industry, more and more people begin to use these devices to reconstruct 3D plant models [1, 13]. These data-based reconstruction methods focus on the overall structure of plants and need time-consuming data acquisition and post-processing. More intuitive and easy-to-use modeling packages are still required such that plants with detailed features can be modeled quickly and naturally.

Lintermann first proposed an intuitive interactive design pipeline for designing 3D plant models [4]. In their approach, space multiplies as high-level multiplier components to represent plant organs such as leaves, ridges, leaflets or branches. Parameter-based modeling methods and interactive design methods are combined with the L-system to model more complex plants, known as *L-Studio/VLab* [11] first and upgraded to be *L+C* later [12]. GroIMP is an open-source software that extends the chain rewriting principle of L-Systems to the graph rewriting one with relation graph growth [2]. Another modeling platform [5], i.e., AMAP, generates plants by adjusting the parameters of predefined hard-coded models and supports script languages to create, explore and analyze plant structures. SpeedTree [7] is another popular plant modeling system. In recent years, with the rapid development of advanced interactive technologies such as touch screens and digital brushes, sketch-based plant modeling interactive design has become more and more popular [8,15], which provides a more intuitive modeling way. Some researchers have also combined sketch-based design with physical simulation technology to generate morphological structures of plants [10,14]. The generated virtual plant models should be closer to their physiological characteristics and natural conditions.

Although many above tools for modeling plants are available, all are dedicated to plant species instead of plant varieties. Thus, the resulted models are still too rough and lack detailed features reflecting the diversity and seasonal variations in plant species. Seasonal variation is a very important feature of plants. For example, in spring, the branches of deciduous trees grow leaf buds and flower buds instead of leaves and most tree branches often have irregular bulges or depressions. The purpose of this paper is to propose a sketch-based design pipeline and to provide a modeling toolkit for generating 3D plant models with detailed features. Such detailed features including flower buds, leaf buds and internodes, etc. on the branches should be fully modeled and displayed. These detailed features could reflect the morphological differences among plants and the varied plant appearances in different seasons. This is useful and necessary for applications such as botany education, scientific research and high-end video products.

2   OVERVIEW OF THE DESIGN PIPELINE

Modeling 3D plant shapes in the proposed graphical toolkit include four steps (see Figure 1): 1) first design the two-dimensional (2D) plant skeleton via sketch strokes; 2) generate and design the 3D plant skeleton; 3) create the branch mesh model automatically; 4) place organs on the branches to produce the complete plant.

3   DESIGN OF PLANT SKELETON

The skeleton of a plant refers to the spatial topological structure of its main branches and defines its overall shape. So, the simple skeleton is first designed before starting to model the other complex features. The design of plant skeleton consists of two steps, i.e., 2D skeleton modeling and 3D skeleton modeling.

<center>(a)   (b)   (c)   (d)</center>
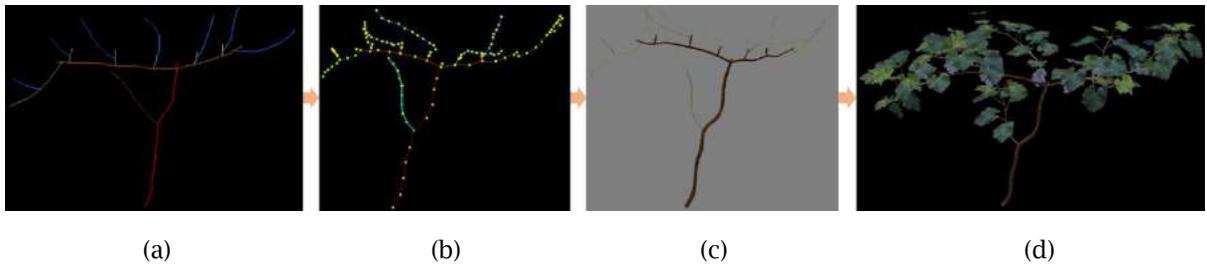
Figure 1: Four intermediate models in the proposed toolkit: (a) the 2D plant skeleton designed via sketch strokes, (b) the 3D skeleton automatically or interactively obtained, (c) the corresponding branch mesh model automatically generated from the 3D skeleton, (d) organs such as leaves and fruits properly placed on the branches.

3.1 Sketch-based Design of 2D Plant Skeleton

The 2D plant skeletal design is carried out by sketch, which determines the overall spatial shape of the plant. To facilitate users to design the 2D skeleton structure, one interface (Figure 2) is developed to provide a set of brush sketch tools. Herein, one can easily draw and edit trunks, main branches, lateral branches, leaf-cluster branches and shoots. After alternatively and repeatedly performing these tools, the outline of a plant, i.e., the 2D skeleton, can be drawn with several strokes. Different colors and stroke sizes are used to define different branch types (strokes).
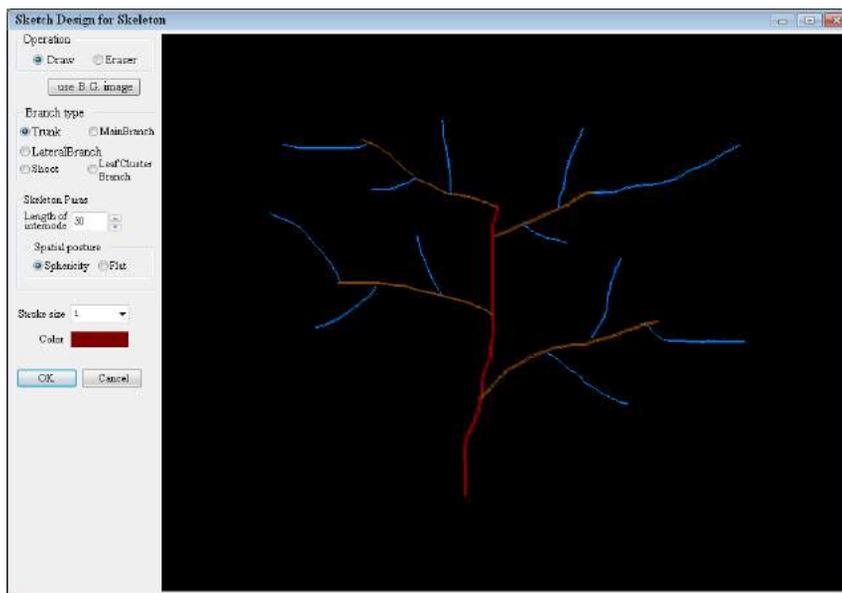
Figure 2: The interface for sketching the 2D skeleton of a plant.

3.2 3D Design on the Plant Skeleton

After obtaining the 2D skeleton, an algorithm is devised to generate a flat 3D skeleton. Firstly, the 2D plant skeleton is converted to a flat 3D one (Figure 3a). The flat 3D skeleton will be further

processed to be more natural (Figure 3b and Figure 3c), in which each skeleton line has a more natural spatial orientation.

3.2.1   Transformation of 2D skeleton to 3D skeleton

The skeleton obtained from the sketch design could be easily transformed into a 3D one. The 3D skeleton is first flat (see Figure 3a) due to the lack of depth information. More explicitly, the modeled branches are initially flattened on the two sides of the trunk and their distributions are very different from these of the natural plants, so one more step is needed to make the branch distribution more faithful to the reality.

As plant branches often tend to extend around their trunks to obtain the maximum sunlight, that is, the plant branches have the largest occupancy rate in space. Based on this knowledge, the branch skeleton line of Figure 3a is automatically adjusted to generate a spherical shape as shown in Figure 3b and Figure 3c, which is much more natural than the flat model in Figure 3a.

One plant has three types of branches, i.e., main branches, lateral branches and new shoots. The main branches are directly connected to the trunk, the side branches are grown on one main branch and there are multiple levels of side branches; the outermost ones are shoots (only shoots have leaves, flowers and fruits). When dealing with one flat model, main branches are first processed, wherein the angle between each main branch and the trunk is kept unchanged; secondly, set the axis of the trunk as the rotation axis and rotate these main branches one by one. The rotation angle for each main branch can be optimally evaluated via one complex math model such that the total sunlight can be maximally obtained. Actually, in the real world, main branches growth follows not only the maximum-sunlight-exposure rule but also the random rule. So, it is not necessary to obtain the exact optimal rotation angles with one complex math model. In this paper, the proposed system will traverse all main branches and force them evenly distributed in 360 degrees and meanwhile the random rule is also applied. In other words, randomly select some percent of main branches (10% in the paper) and randomly plus or minus one random degree (the degree is bounded within 5 degree in the paper). After processing all main branches, the side branches on each main branch will be dealt in the similar way: each main branch will be regarded as the rotation axis and its side branches are rotated one by one. Figure 3c shows the final result in the side view. The above rotating strategy simply imitates the plant growth rule of the maximum sunlight-exposure.

(a)   (b)   (c)
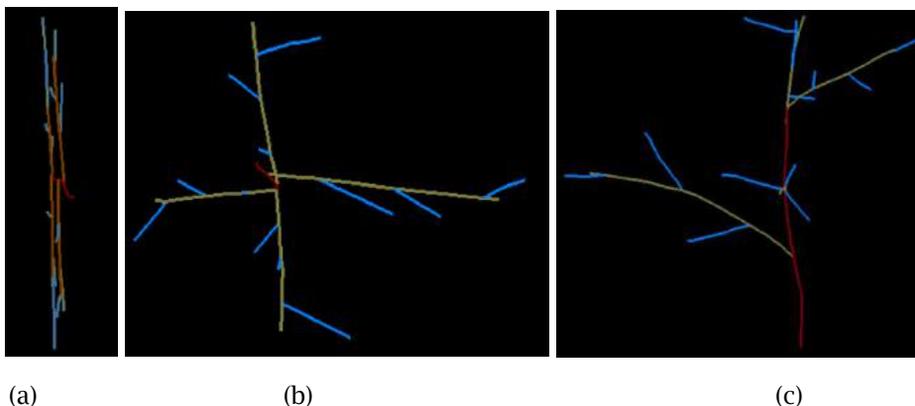
Figure 3: The generation of 3D skeleton: (a) a flat skeleton (top view), (b)the 3D skeleton after rotating main branches (top view), (c) the 3D skeleton after rotating the side branches (side view).

3.2.2 Internode segmentation

In the plant physiological structure, most organs including leaves, buds, fruits and so on grow at nodes and the skeleton line need to be segmented with nodes for the final canopy reconstruction. In other words, the segmentation is to tell the software where to locate the organs on the plants. In biology, the part between two nodes on a branch is called internode.

One intuitive method is to divide all skeleton lines into multiple segments with a preset equal length and all internodes have the same length (see Figure 4a). However, in nature, the length of internodes are usually not equal. Especially for the newly grown shoots, the internodes on the top are often shorter than these on the bottom. Thus, it is unreasonable to segment shoots evenly. Out of this knowledge, we use a cubic polynomial interpolation shown as Eq. (1) to divide the skeleton lines:

$$y = p_1 x^2 + p_2 x + p_3 \tag{1}$$

where y is the length or width of an organ, x equals to the internode order number of the leaf counted from its owner branch top end to the bottom end, which is positive integer. For some particular plant type, after acquiring the width or length of sampling leaves with scanner devices, p_1, p_2 and p_3 are optimally fitted using least square method. Once p_1, p_2 and p_3 are obtained, the length and width of one designed leaf can be determined by inputting its corresponding internode order number and all leaves on each branch will be modeled in the canopy reconstruction.

(a)   (b)
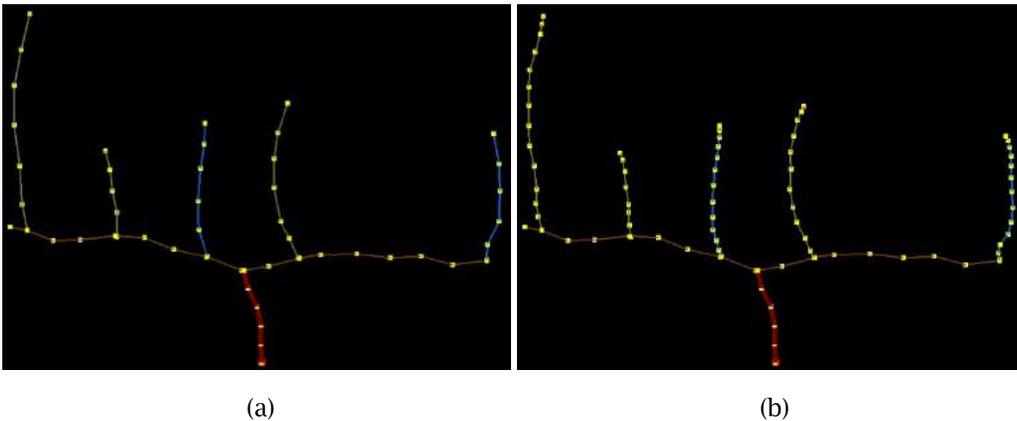
Figure 4: Comparison of two segmentation methods on shoots: (a) the result of the average segmentation method, (b) the result of the allometry segmentation method.

3.2.3 Interactive design of the 3D skeleton

The 3D skeleton could be designed interactively in the provided interface (Figure 5a). Three optional modes are provided: node mode, line mode and group mode. In the node mode, one can pick an anchor point (node) at each branch skeleton and drag it to any position by mouse. The line mode allows to choose a skeleton line on the skeleton model to perform three operations including "copy", "move" or "delete". The group mode is provided to easy and speed up the design of branches, in which all sub-branches can be chosen synchronously when their parent branch skeleton is selected and all operations such as "copy", "move", "rotate", "scale" and "delete" can be carried out on sub-branches in a batch mode (see Figure 5b).

(a)   (b)
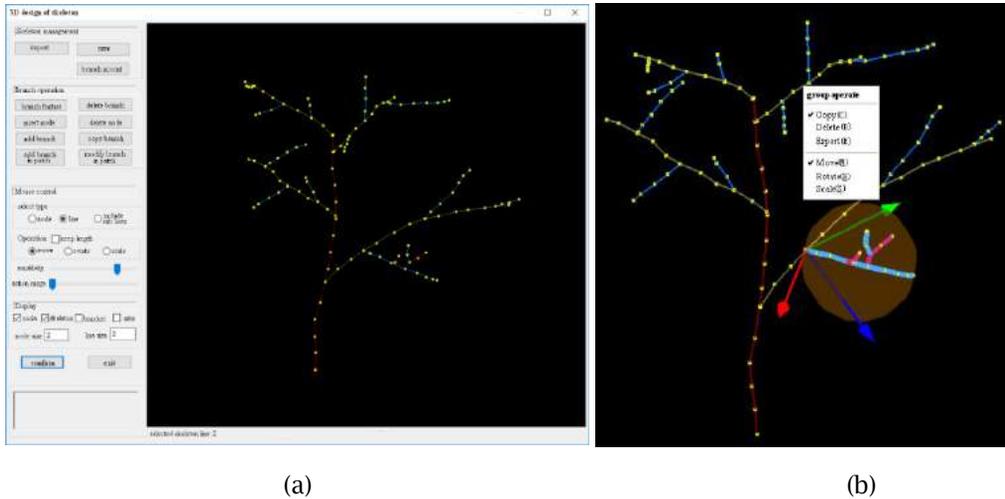
Figure 5: Interactive design on branches: (a) edit operations for designing branches, (b) designing sub-branches in a batch mode.

Some batch operations are provided to easy the design of plant skeletons. For example, one can modify the properties (color, radius, etc.) of branches which have the same branch type; or add branches to the skeleton in a batch mode (see Figure 6c).

3.3   Individual Definition of Branch Type

In the designed plant skeleton, each skeleton represents a branch, and each skeleton has a branch type. The initial branch type of a skeleton line is user-defined when it is first generated in the 2D sketch design step. The properties of each skeleton can be modified through the interface (see Figure 6a). For example, one can define which type of branches can grow leaves, buds or other organs. As branch type information will significantly influence the texture map and the location of organs on the branch, defining the proper type for each branch will be important.

(a)   (b)   (c)
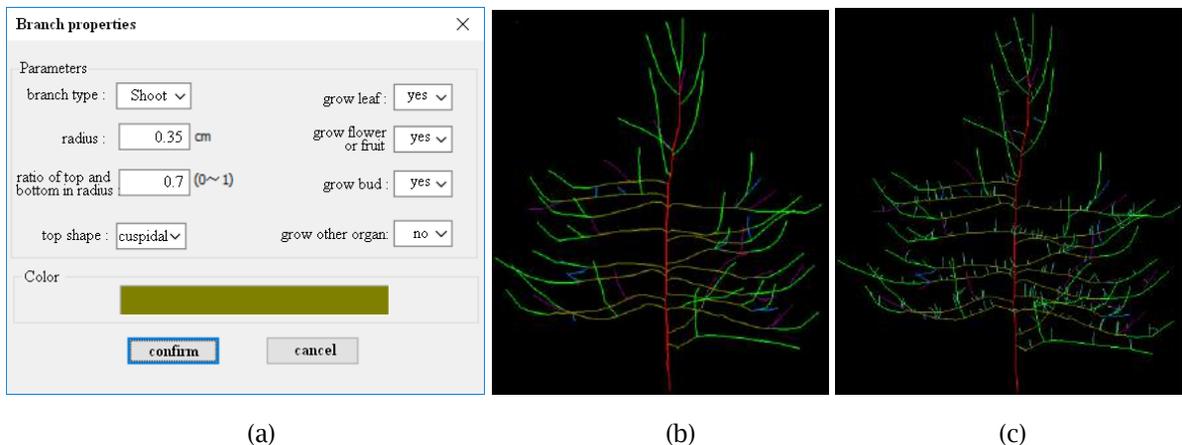
Figure 6: The edition of branch properties: (a) the interface for modifying branch properties, (b) the skeleton of an apple tree, (c) adding cluster branches to the apple skeleton in a batch mode.

4   MESH GENERATION OF BRANCHES

Based the 3D skeleton, its 3D mesh model of a plant can be generated easily after simply inputting some feature parameters such as internode length, internode protrusion height and curvature, etc. as shown in Figure 7a. Since the skeleton of a branch is the central line of this branch, the mesh of the branch can be generated with a simple construction algorithm [16]. The parameter "posture" used to control the bending degree or straightness value of the generated branch mesh model. When "bend" is selected, a cubic B-splines curve is used to mathematically represent the skeleton with a bent shape (see Figure 7b). If "straight" is selected, each two adjacent points on the skeleton line in a branch are connected as a line segment with a straight shape (see Figure 7c). While Figure 8 demonstrate how to generate the mesh model from a B-plines curve. In this scenario, one B-spline curve will be evaluated to interpolate given points, which are drawn interactively or obtained by 3D scanner. Later, three parameters denoted as "vertical division", "horizon division" and "radius" are used to define the mesh model. The parameter "vertical division" is to define the split number of the B-spline curve (set as 8 in Figure 8b and 12 in Figure 8d). At each split point P_i, one circle C_i with P_i as its center and "radius" as its radius value will be defined on the normal plane at P_i. Circle C_i will be divided by the preset parameter, i.e., "vertical division" (set as 6 in Figure 8b and 20 in Figure 8d). Finally, simply connect all divided points on C_i to obtain the mesh models of branches. Each top skeleton line will be assigned to one predefined "radius" value, and Eq.(2) will be applied to calculate the radius of their parent branches' "radius" value:

$$r^2 = \sum_i r_i^2 \tag{2}$$

where the square of one parent branch's "radius" is equal to the sum of the square of its subbranches' "radius". The proposed toolkit also provides parameters to control the resultant surface details of the branches. For example, one can generate a bulge effect on the node of a branch mesh by simply setting the parameter "convex ratio". This modeled bulges will bring a more naturally visual effect than a flat surface without bulges on the node (compare Figure 7d and Figure 7b). Figure 7f demonstrates an example of branch mesh model with different top postures (oblique v.s cuspidal). All these feature modeling tools support one to quickly and easily control the detail level of the mesh model of the designed skeleton.

(a)   (b)   (c)

| (d) | (e) | (f) | (g) |
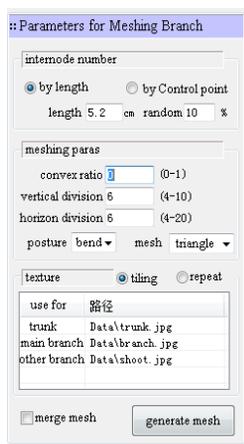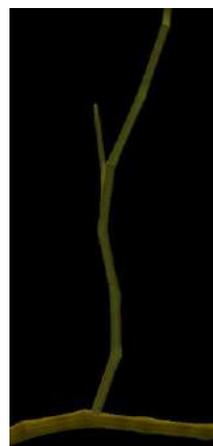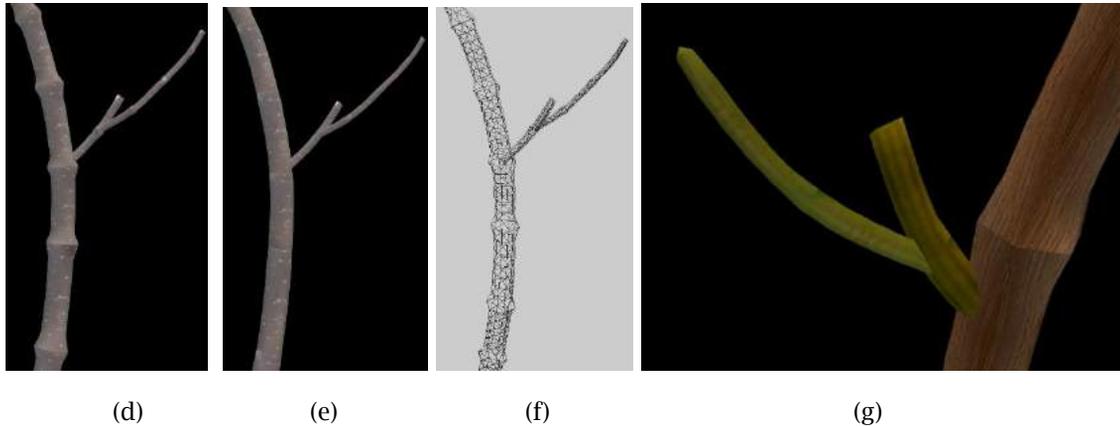
Figure 7: The Mesh generation interface and results: (a) the parameter-input interface for mesh generation, (b) the bent shape example, (c) the straight example, (d) the branch with bulges on the node, (e) the branch without bulges on the node, (f) the mesh model of (d), (g) different top postures on one branch.

5   CANOPY RECONSTRUCTION

The final step is to place the organs such as leaves, flowers, and fruits on the branch mesh model to create the complete 3D plant model. Since all the skeletons have been segmented into internodes, this step is to place the varied organs on the node of the proper branches based on the branch type information.

The placement process is done in an interactive and superposing manner. More explicitly, four types of organs ,i.e., leaves, flowers, fruits and buds are selected and defined mathematically. (see Figure 9a): each organ is provided in the form of a template file (3D mesh model), which could be modeled by using 3D design software such as 3ds MAX and Maya, or generated from 3D scanned data measured by using scanner devices. Users can control the precision and resolution of the template of a organ. On the other hand, the precision and resolution of organ's template could also affects the precision and resolution of the final generated plant canopy model. We can provide a series of varied template files for the same type of organs such that the modeled organs can be varied on the generated plant canopy model (see Figure 9b).

Figure 9a shows all input parameters needed after specifying the one-to-one ownership of the organ types and the branch types. Through those parameters, one can specify whether the objective organs should be placed to all nodes of a branch or only to the top node or user-set nodes. The number on each node is also a required parameter. In addition, some simple parameters allow to easily control the size and orientation of these organs. For example, one can set different sizes of the leaves along a shoot through the interface shown in Figure 10a. In this way, a more natural plant organ size can be obtained.

(a) (b) (c) (d) (e)
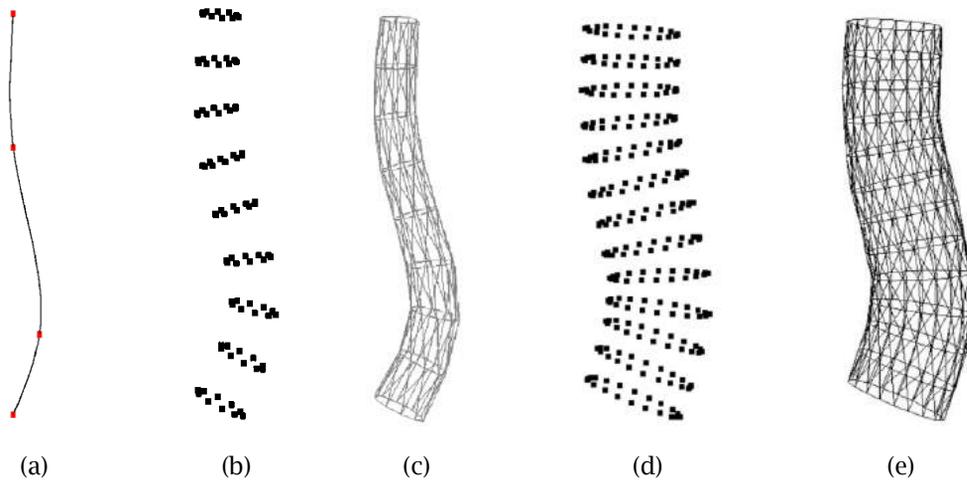
Figure 8: Generate the mesh of a branch using a B-spline curve: (a) the B-spline curve is evaluated to interpolate four given points, (b) use nine split points to divide the B-spline curves into eight portions and obtain division vertices by sampling eight circles with 0.1 radius, which are on the normal plane at each split points of the B-spline curve.("vertical division" is 8 and "horizon division" is 6 and "radius" is 0.1), (c) the generated mesh model from (b), (d) the generated vertices with "vertical division" parameter being 12, "horizon division" parameter being 20 and radius being 0.2, (e) the generated mesh model from (d).

(a) (b)
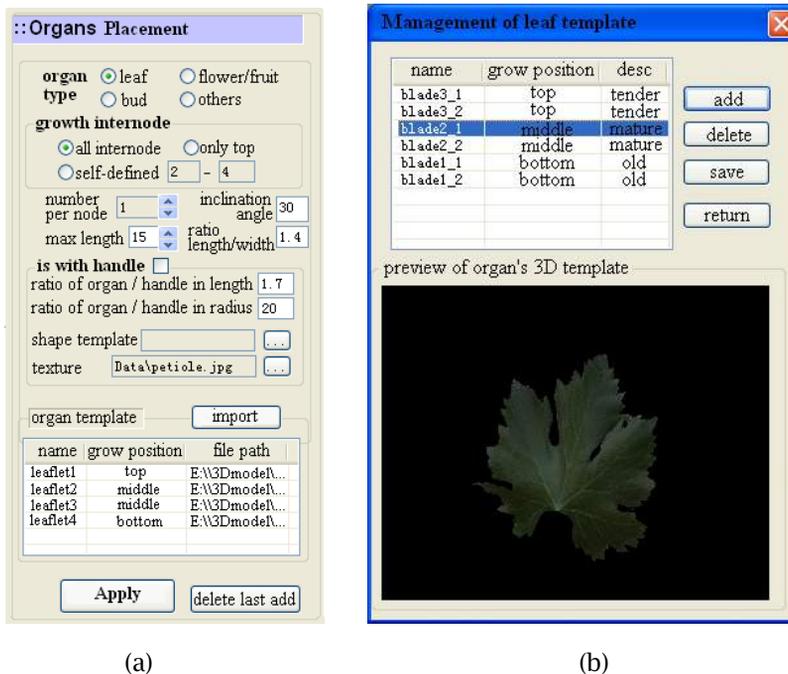
Figure 9: Organs placement: (a) the interactive interface, (b) the interface for managing 3D template of a leaf.

(a)   (b)   (c)
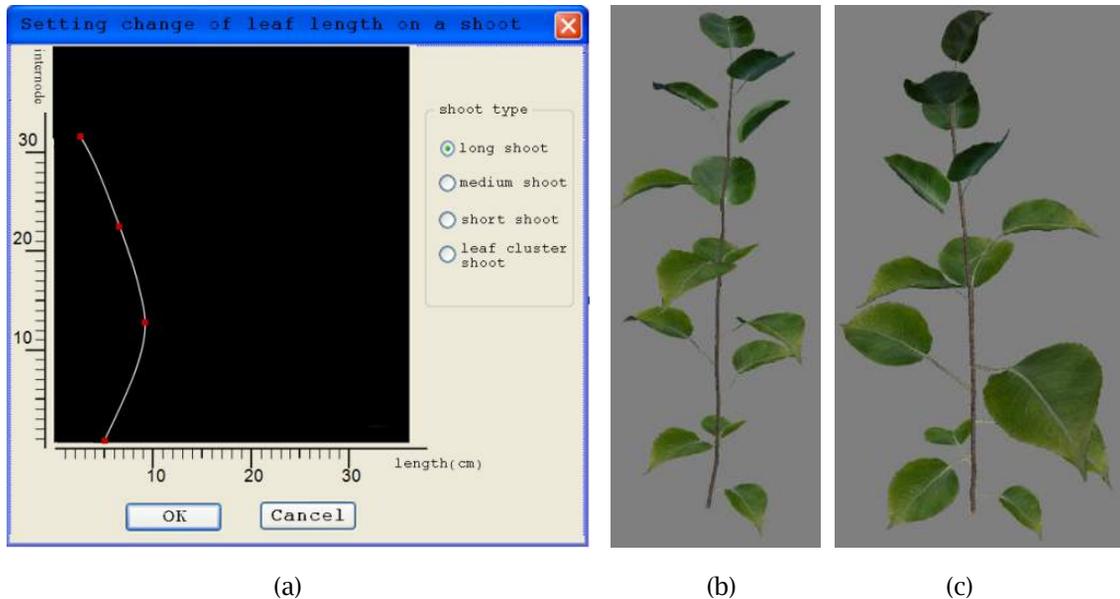
Figure 10: Design the size of leaves on a shoot: (a) the design interface, (b) the sizes of leaves on a shoot vary in a small range, (c) the sizes of leaves on a shoot vary in a larger range.

The direction or the organ is also another important parameter to be decided. For all organs including leaves, the inclination angle between the placed organ and the ground will be defined. For the leaf organ, the inclination angle is evaluated as below:

If the inclination angle between a branch and the ground is larger than 45°, use Eq.(3) to obtain the inclination angles of the leaves on it:

$$LI = a_0 \times exp\left(-\frac{LP}{a_1}\right) + a_2 \tag{3}$$

where LI is leaf inclination angle, LP represents the leaf order number, while a_0, a_1 and a_2 are the coefficients which will be fitted in least square manner after acquiring leaf inclination angles using measured devices for particular plant. After that, all inclination angles of the leaves on each branch can be determined.

When the inclination angle of a branch is less than or equal to 45°, the direction of the leaves are automatically calculated by a maximum space visibility algorithm of the leaves. In this case, the branch grows horizontally. A sub-division hemisphere (Figure 11a) is used to calculate the maximum space visibility of a leaf. The sub-division hemisphere is generated with a radius which is 10 times to the radius of the minimum surrounding circle of the plant skeleton. If the line connecting the center point of a leaf and the center point of a triangle in the sub-division hemisphere does not intersect with any other leaf, it means the leaf is visible. One can calculate the visibility of a leaf by counting its visibility with every triangle in the sub-division hemisphere. Each leaf's optimal ration angle along XYZ axis, i.e., inclination angle, can be evaluated by a greedy algorithm.

<div align="center">(a)   (b)</div>
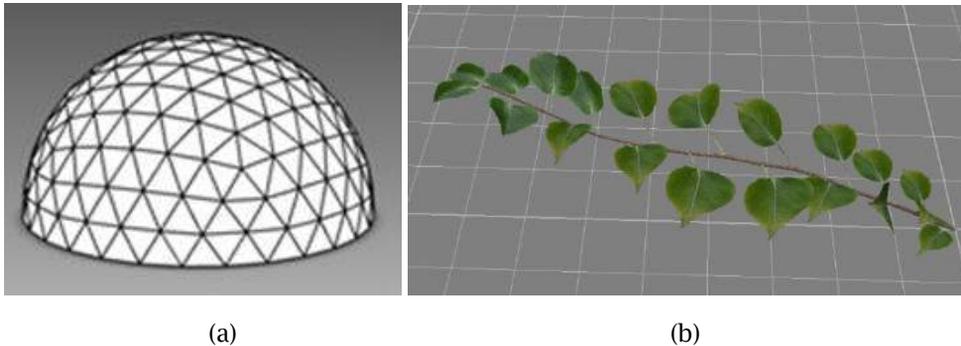
Figure 11: Evaluate the rotation angle of the leaves when its owner branch grows horizontally: (a) the hemisphere for calculating the visibility of a leaf, (b) the final result, in which the leaves on one branch are of maximum space visibility.

6 RESULTS AND DISCUSSIONS

The above proposed toolkit is coded in C++ and compiled with VS 2017 and win7 64bit. The testing PC is with a CPU 3.4GHz i7, NVIDIA GeFore 9500 GT and 8GB DDR4. Examples include 3D models of various plants ranging from little crops to big trees in different seasons.

6.1 Modeling Apple Trees

In this example, apple trees with detailed features in varied seasons are modeled. Firstly, fit the parameters in the quadratic equation (1) to calculate the internode length of the shoot. This can be done by choosing several shoots from a true apple tree and measuring each internode length, then fit the parameters by using least square method. The internode length of shoot in apple tree could be simulated with very low errors (see Figure 12), including Bias, MSD (Mean Squared Deviation), RMSD (Root Mean Squared Deviation) and SPE (Squared Prediction Error). In this case the parameters p_1, p_2, p_3 are -0.06, 0.821, 3.707, respectively.

Similarly, the parameters in equation (3) could be also fitted once measured data are sampled from real apple trees. As such, we can get a_0=116.7, a_1=1.525, a_2=-29.11. Here a_2 is regarded as the asymptote of a curve, that means (to apple canopy) below the seventh youngest internode, leaf inclination fluctuated around -29.11º.

Figure 13 shows the results of designing the 3D model of an apple tree in the early spring germination stage. During this period, flower buds, leaf buds and axillary buds sprouts on the apple branches. The continuous growth characteristics (red circled portions), i.e, short internodes, on a branch can be modeled and shown by the proposed method, which is important for botany education and training. Figure 14 is a 3D model of a flowering apple tree.

6.2 3D Reconstruction from Digitized Data

This experiment shows the plant structure reconstruction from real digitized data. Firstly, the nodes on each branch on a plant are digitized by a 3D digitizer (PATRIOT, Polhemus Inc., USA; https://polhemus.com/motion-tracking/all-trackers/patriot/) with a pre-established data measurement regulation. The regulation is necessary for distinguishing different branches in later process. For example, we collect one point at each node on a branch and digitize the branches. Two

points at the top of a branch are represented the end of this branch. All the measured points are exported into a .txt file, which can be imported into our toolkit to form a 3D skeleton directly according to the measurement regulation. One can quickly complete the canopy reconstruction by the proposed modeling pipeline. Figure 15-17 give the reconstruction results of a grape tree, gardenia tree and watermelon stand, respectively. Each example took two persons around one and half hour after an hour training: one used 3D scanner to acquire point cloud data of the objective plant and the other used the proposed toolkit to design the 3D model with the acquired point cloud.
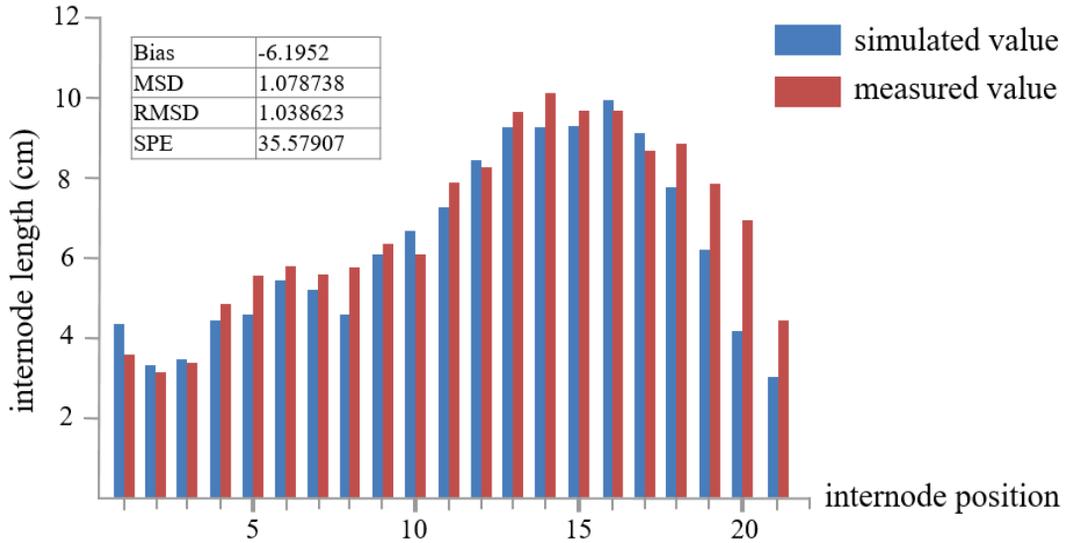
Figure 12. The error analysis of for an apple tree model.

(a)   (b)   (c)   (d)
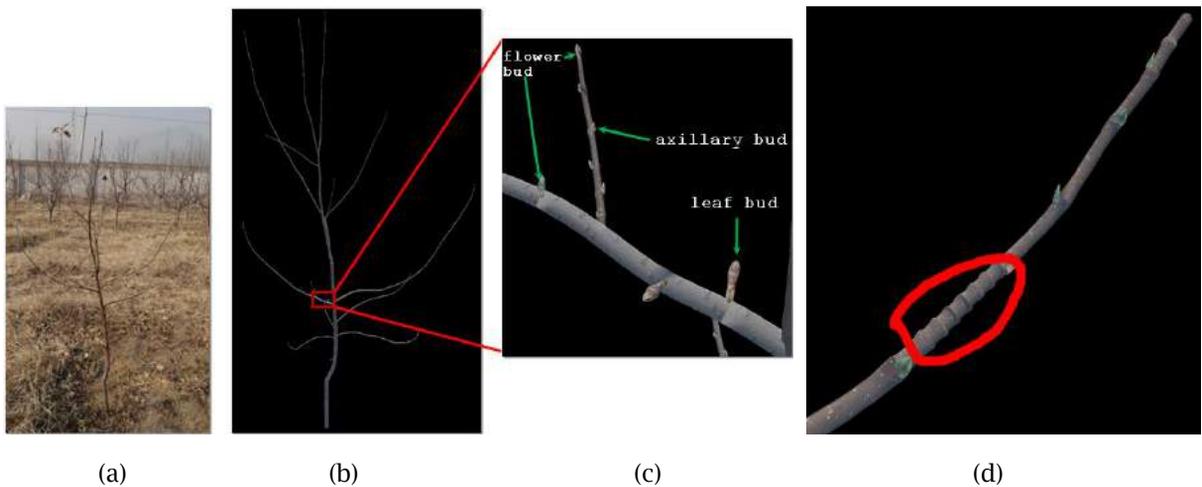
Figure 13: Designing an apple tree in early spring: (a) the photo of the real apple tree, (b) the final 3D model of the apple tree with 32k vertices and 60k triangles, (c) zoom in one branch, (d) the growth characteristics during the year on a branch, on which some short internodes can be obviously seen.
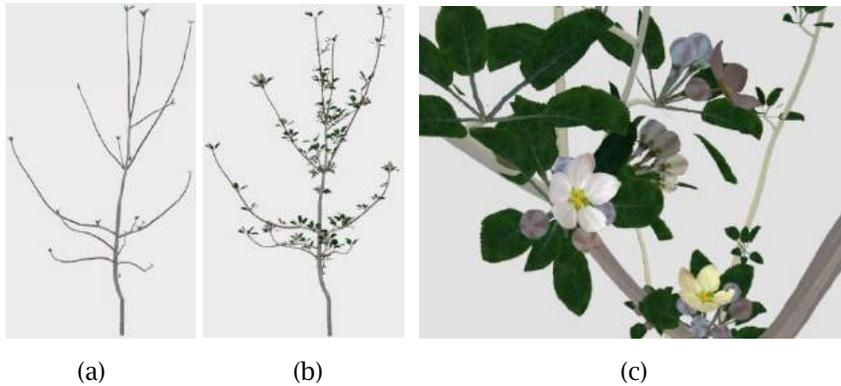
Figure 14: An apple tree model with tender leaves and flowers: (a) the model with tender leaves with 14k vertices and 19k triangles, (b) the model with leaves and flowers with 40k vertices and 60k triangles, (c) the local zoom view of the model shown in Figure 14b.
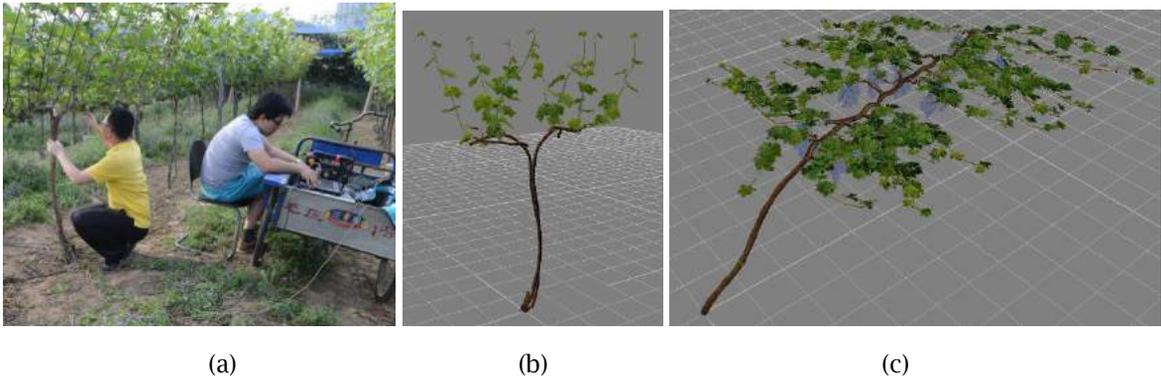
Figure 15: 3D models of a grape tree: (a) one got point cloud data with a 3D scanner and the other one used the proposed toolkit to design the plant with detailed features; (b) one designed grape tree model, (c)another designed grape tree model.

Figure 16: The 3D models of gardenia trees: (a) one two-year gardenia tree with 17k vertices and 24k triangles, (b) one three-year gardenia tree with 27k vertices and 36875 triangles, (c) one adult gardenia tree with 19k vertices and 28k triangles.
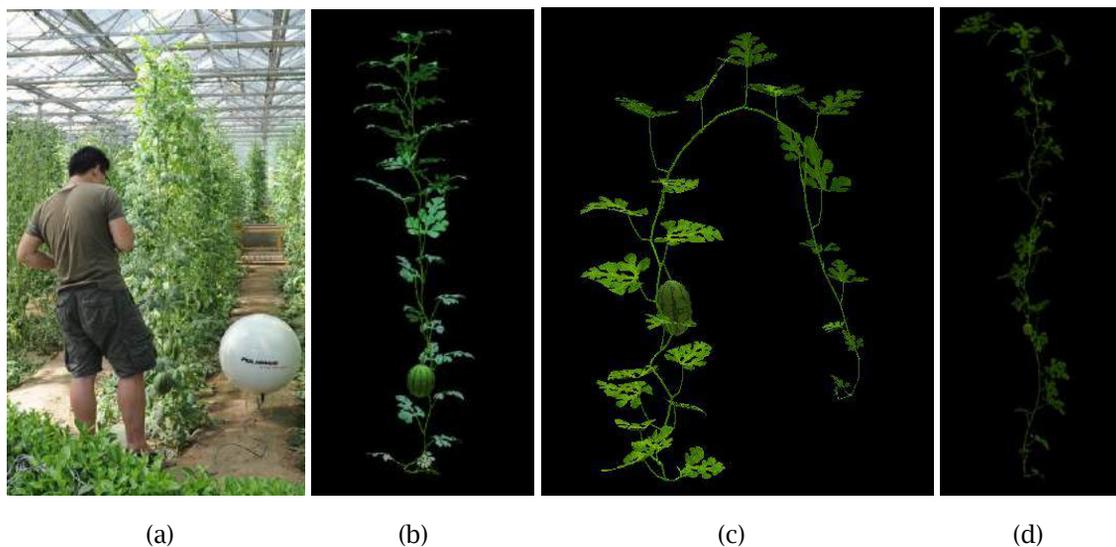
Figure 17: The 3D models of watermelon stands: (a) acquire point cloud of watermelon stands in the field, (b) to (d) three designed models under different cultivation patterns, the number of vertices and triangles of these models are from 9k to 22k and 12k to 31k, respectively.

7   CONCLUSIONS AND FUTURE WORK

This paper presents a graphical toolkit to interactively design 3D morphological structures of plants with detailed features. The developed toolkit allows users to design and generate 3D models of various plants at individual scales with detailed botanical features in an easy and intuitive manner, which is important for some particular applications including agronomy education, high-end video product, research and computer games.

Due to the morphological diversity and physiological complexity, the 3D modeling of plant shape and structure is still a challenging task. Many open problems are desired for further efforts, which include combining the design processes with more physiological parameters and functions for simulating the growth of plant under different environments, developing better interfaces with more intuitive parameters for new hands and providing organ templates for different plants. How to dynamically simulate the growth of plants under different environments and in different seasons are also listed in our future works.

Shenglian Lu, https://orcid.org/0000-0002-4957-9418

Guo Li, https://orcid.org/0000-0001-5539-7824
Ming Chen, https://orcid.org/0000-0003-0506-5308

REFERENCES

[1] Aijazi, A. K.; Checchin, P.; Malaterre, L.; Trassoudaine, L.: Automatic detection and parameter estimation of trees for forest inventory applications using 3D terrestrial LiDAR, Remote Sensing, 9(946), 2017, 1-24. https://doi.org/10.3390/rs9090946

[2] Buck-Sorlin, G. H.; Kniemeyer, O.; Kurth, W.: Barley morphology, genetics and hormonal regulation of internode elongation modelled by a relational growth grammar, New Physiologist, 10(4), 2005, 413-431. https://doi.org/10.1111/j.1469-8137.2005.01324.x

[3] De Reffye, P.; Edelin, C.; Francon, J.; Jaeger, M.; Puech, C.: Plant models faithful to botanical structure and development, Computer Graphics, 22(4), 1988, 151-158. https://doi.org/10.1145/378456.378505

[4] Deussen, O.; Lintermann, B.: Digital design of nature: computer generated plants and organics, Springer, 2005. https://doi.org/10.1007/b138606

[5] Godin, C.; Costes, E.; Caraglio, Y.: Exploring plant topology structure with the AMAPmod software: an outline, Silva Fennica, 31, 1997, 355-366.

[6] Hu, B. G.; de Reffye, P.; Zhao, X.; Yan, H. P.; Kang, M. Z.: GreenLab: A new methodology towards plant functional-structural model-structural aspect, In International Symposium on Plant Growth, Modeling, Simulation, Visualization and Their Applications (PMA), 2003, 21-35.

[7] IDV, http://www.speedtree.com, Speedtree.

[8] Ijiri, T.; Owada, S.; Igarashi, T.: Seamless integration of initial sketching and subsequent detail editing in flower modeling, Computer Graphics Forum, 25 (3), 2006, 617-624. http://dx.doi.org/10.1111/j.1467-8659.2006.00981.x

[9] Karwowski, R.; Prusinkiewicz, P.: The L-system-based plant-modeling environment L-studio 4.0, In Proceedings of the 4th International Workshop on Functional-Structural Plant Models, 2004, 403-405.

[10] Pirk, S.; Stava, O.; Kratt, J., Said, M. A. M.; Neubert, B.; Mech, R.; Benes, B.; Deussen, O.: Plastic trees: interactive self-adapting botanical tree models, ACM Transactions on Graphics, 31(4), 2012, 1-10. http://doi.acm.org/10.1145/2185520.2185546

[11] Prusinkiewicz, P: Modeling and visualization of biological structures, In Proceeding of Graphics Interface '93, 1993, 128-137.

[12] Prusinkiewicz, P.; Karwowski, R.; Lane, B.: The L+C plant modeling language, Functional-Structural Plant Modelling in Crop Production. Springer, 2007, 1-12.

[13] Sylvain, D.; Christian, J.; Pascal, R.: PypeTree: a tool for reconstructing tree perennial tissues from point clouds, Sensors, 14, 2014, 4271-4289. https://doi.org/10.3390/s140304271

[14] Wang, Y.T.; Wang, L.Y.; Deng, Z.G.; Jin, X.G.: Sketch-based shape‐preserving tree animations, Computer Animation and Virtual Worlds, 29(1), 2018, e1821. https://doi.org/10.1002/cav.1821

[15] Zhao, Y.; Barbič, J.: Interactive authoring of simulation-ready plants, ACM Transactions on Graphics, 32(4), 2013, Article No. 84. https://doi.acm.org/10.1145/2461912.2461961

[16] Lu, S.; Zhao, C.; Guo, X.; Wen, W.; Xiao, B.: A new paradigm for fast interactive design of crops, Intelligent Automation and Soft Computing, 16(6), 2010, 1147-1156.