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Sketch-Based Interfaces and Modeling (SBIM)

Sketch-based parameterization of L-systems using illustration-inspired construction lines and depth modulation

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A B S T R A C T

We present a sketch-based interface for parameter control of rule-based models. It allows intuitive specification and creation of plant structures with L-systems. Construction lines inspired by concept sketches are employed as a way to define and manipulate global-to-local characteristics of L-system models. The overall structure, posture and proportions of the plant are initially sketched by the user as 2D construction line arrangements. They are automatically encoded as a set of positional functions controlling internode lengths, branching angles, organ sizes, and stem shape. The depth in the stem is specified while sketching its construction line, by modulating input pen pressure as depth values. This is also inspired by line depth modulation techniques used in traditional illustration. The resulting positional functions are then used to parameterize pre-defined L-system templates representing phyllotactic patterns guiding the positioning of lateral organ surfaces such as leaves and petals. Results are presented for single monopodial plant structures, all generated from simple input construction line sketches.

1. Introduction

Global features, such as posture and silhouette, are essential characteristics in the depiction of a plant. They convey realism and distinctiveness to a model and can reflect the outcome of morphological development. Therefore, these features are important in a simulation-oriented context for plant modeling. However, in rule-based methods, such as L-systems [14], the global structure is given by the outcome of the interaction of local rules. This emergent aspect of the global properties makes them difficult to manipulate and control, since localized modifications cannot be specified easily, and changes in a single rule can affect the whole model.

Global-to-local specification was introduced into L-system-style models (actually, Chomsky grammars) in the form of user-controlled B-spline functions associated with parametric production rules [15]. These functions can be used to represent *positional information* and *morphogenetic gradients* in the plant model. In this manner, they allow regulating global features such as posture, insertion angles, and dimensions of the components of the model. Although they provide a powerful tool, manipulation of these functions introduces a degree of abstraction when creating shapes such as the curving stem or the silhouette of a plant. It would be more convenient to describe such features directly, without an intermediate construct. This convenience can be provided if construction lines from concept sketches (Fig. 1) are used as an interface for the definition of these functions.

In this work, we propose the use of botanical illustration-inspired construction lines to parameterize global features of L-system models. Illustrators use construction lines to determine the global features of the plant being depicted (Fig. 1). These lines are sketched in the very beginning of the illustration process to quickly indicate posture, contours, proportions, topology, and constraints [5,19]. They work as guidelines for the artist when the drawing is further developed and details are progressively added.

Additionally, one of the most challenging problems in sketch-based interfaces is the issue of inferring 3D information from 2D strokes. In the case of concept sketches, the 2D strokes provide indications and constraints of how this inference should occur in terms of global features. For concept sketches of plants, silhouette boundaries and inclination lines can be naturally expressed in 2D since they already correspond to 3D information projected into the plane facing the viewer. However, the stem (or main axis) shape is intrinsically 3D. Therefore, it should be represented as a 3D curve and not by its projection into a plane.

Unambiguously mapping a 2D curve into 3D is a very hard problem, especially if no depth information is provided. In order to define a 3D stem in the concept sketch of a plant arrangement, we propose using the pressure data obtained from the pen of a tablet. The idea is that the user would apply more pressure when drawing the parts of the stem that are closer and less pressure for parts that are farther. This is inspired by traditional ink line-based techniques aiming at providing depth perception to an illustration (Fig. 2). The rule is as follows: thick and hard lines

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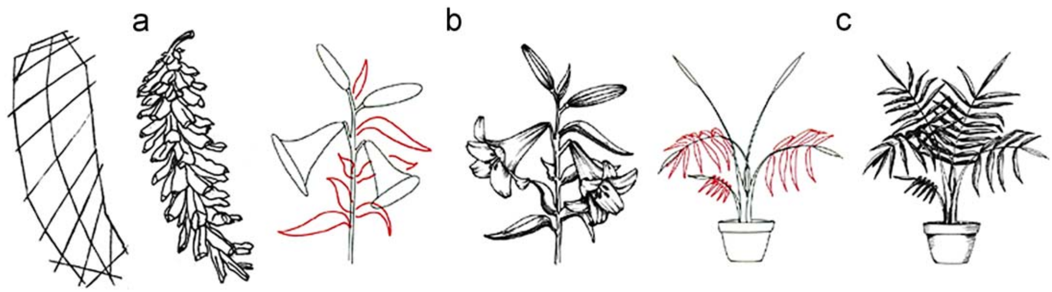

Fig. 1. Botanical illustrations at two drawing steps: concept sketches using construction lines and finished rendering. (a) Pine cone [19] © 1991 Eleanor B. Wunderlich. Used by permission; (b, c) lily, palm [4] © 2008, Publications International, Ltd. All rights reserved.

Fig. 2. Ink line-based depth modulation and perception. (top) Traditional science illustration and (bottom) circles: thick and hard lines advance in relation to thin and soft. Used with permission, copyright 1998 Bill Andrews.

advance (i.e., more pen-pressure, more ink) in relation to thin and soft lines which recede (i.e., less pen-pressure, less ink) [5,16].

Our technique is based on a specific example of construction lines for botanical illustration shown in Fig. 1(a) [19]. This illustration example was used by Prusinkiewicz et al. [15] to exemplify what was intended with the introduction of positional functions into L-systems, and by Anastacio et al. [1] as the main reference for the definition of concept sketches. Similar construction line arrangements are also used in this paper. Our approach is illustrated in Fig. 3. The process starts (a) with sketching the construction lines that define the overall structure of the plant (Section 3). An interpretation of the construction lines (b) is then used to automatically derive a set of positional B-spline functions (Section 4). These functions are used as parameters for productions in a predefined L-system template (Section 5). Finally, sketched organ surfaces (c) are incorporated in the model (Section 6), leading to its final 3D presentation (d, e).

Our approach thus incorporates sketch-based interfaces into the modeling process based on L-systems. Although productions are not specified via sketching, the global attributes of a monopodial model and its organ surfaces are obtained directly from what the user draws. This contributes towards a more intuitive way to create L-system models.

2. Previous work

The first sketch-based interfaces for plant modeling focused on directly drawing branching structures [11,12]. Okabe and Igarashi [11] present a system that creates 3D trees from freehand sketched lines using models based on the work of Weber and Penn [18]. Later on, they improved their approach by assuming that trees spread each branch in a way that maximizes the distance to the other branches [12]. The key contribution of their method is the inference of a 3D geometry from the 2D sketches of the branching structure.

Ijiri et al. [8] introduced *floral* and *inflorescences diagrams* to organize sketched flower organs into flowers, and entire flowers into inflorescences, in a botanically correct way. By adding domain knowledge to the sketch composition, they were able to provide a more efficient method for sketching a plant model. Although restricted to the arrangements given by floral and inflorescence diagrams, their work represents a clear advance in sketching complex structures and positioning individually sketched elements.

In order to make the composition of a 3D plant model more general, while providing a seamless transition from the initial sketch to the detailed 3D model, Ijiri et al. [6] proposed to use a hierarchy of billboards. The billboards work as drawing planes for sketching individual organs. The organs can be saved into a library and reused later on. This work extends their previous technique and allows for a wider variety of plant models. However, in this case, the way the arrangement is composed is left to the user, without relying on botanical guidelines.

Anastacio et al. [1] considered botanical illustration techniques to determine how the initial sketch should be defined and interpreted. The structured initial drawing is referred to as a *concept sketch*. The concept sketches are interpreted in the context of biologically motivated rules for phyllotactic patterns, and combined with sketched organ surfaces to yield realistically looking monopodial plants. This technique provides a way of defining both the structure and the individual elements using SBIM.

An alternative way to derive the branching structure from sketched global elements is suggested by Zakaria and Shukri [20]. Their technique, named *sketch-and-spray*, consists of directly sketching an initial structure for a tree (allowing copy-and-paste and individual deformation of branches), followed by "spraying" leaf surfaces (sketched in a separate environment) around a

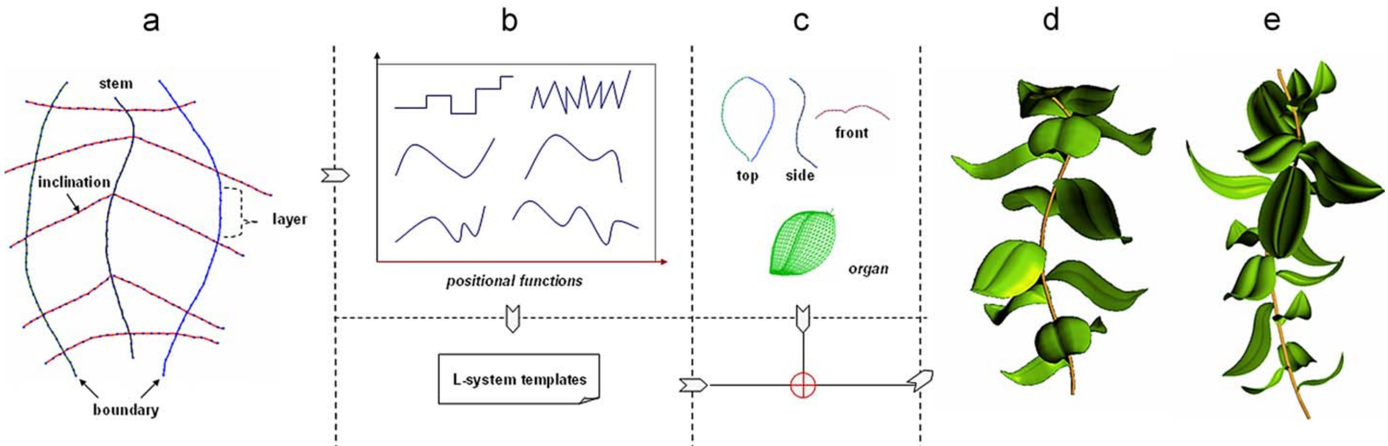

Fig. 3. The pipeline for our approach. (a) The user creates a construction-line-based sketch (with or without stem depth modulation) which is interpreted to (b) automatically derive a set of positional functions, which parameterizes a predefined L-system template. (c) Plant organ surfaces are constructed from sketches and referred to by the L-system productions, resulting in the final models, without (d) or with stem depth modulation (e). Labels in (a) and (c) indicate the role of the construction lines.

region of the crown. The branches in the initial structure then "grow" towards the sprayed leaves in order to complete the tree model.

Specifying a 3D curve from a given 2D sketch is an important problem in sketch-based interface and modeling. The fundamental issue lies on how to add depth information for different parts along the curve out of 2D sketches from a single viewpoint. Cohen et al. [3] present a system where the user first sketches the curve from the current viewpoint and then draws its shadow on the floor plane. The sketched curve and its shadow are then correlated by the system to compute the 3D shape of the intended curve. Ijiri et al. [8] use a method which automatically computes depth (z values) to a sketched 2D curve, resulting in a curve with constant curvature in 3D space. In their system, the 3D curve has a similar appearance to the input 2D sketch (e.g., a sketched 2D sine curve generates a 3D spiral curve).

The first attempt to use SBIM with L-systems was proposed by Ijiri et al. [7]. Their method allows the user to control the shape of the main axis of a recursively defined structure, and its depth of recursion, with gestural sketching. The stroke affects the module representing the main apex, changing its direction. It also controls the depth of recursion by prompting a new derivation step every time the sketched stroke reaches a length that is a multiple of the predefined apex size.

The work being presented proposes going further in the use of SBIM with L-systems. Instead of only controlling the recursion depth and the main axis shape, we propose using concept sketches [1] as a way to control the appearance of an L-system model. The interpretation of the sketched construction lines provides a parameterization for a set of predefined L-system templates that implement different phyllotactic patterns. The parameterization makes use of the mechanism of positional functions introduced by Prusinkiewicz et al. [15]. This technique differs from Anastacio et al.'s [1] by the use of the interpreted information and the construction of the plant model. It also provides a potentially easier way to create L-system models for plant structures. Furthermore, depth values are added to the 2D stem construction line by modulating pen-pressure values, providing a more realistic depiction of the overall plant posture.

3. Plant sketch processing

This section briefly revisits the aspects of the process of interpreting concept sketches that are utilized in this work, which are based on the work by Anastacio et al. [1]. Refer to the mentioned paper for more details. The inference of 3D depth information from the pressure applied to the pen of a tablet device is also described here.

3.1. Stroke capturing

The stroke capturing mechanism used for the construction lines consists of four steps: resampling, reverse subdivision, conversion to a B-spline curve, and anchor point calculation. In the first step, the sparse input points received from the pointing device (mouse or tablet) are resampled to a density of one point per pixel. Then, in order to reduce the number of points and to smooth the stroke, three steps of Chaikin reverse subdivision [17] are iteratively applied, resulting in a stroke very close to the original sketched one. The points resulting from the reverse subdivisions are used as the control points of a quadratic B-spline.

3.2. Structural components

The overall structure of the plant is defined by three groups of construction lines: stem, boundaries, and inclination lines (Fig. 3(a)). The stem line defines the main axis of the plant. The boundary lines are drawn on the left and right sides of the stem and determine the silhouette of the plant by establishing a bounding volume that contains the lateral organs. The inclination lines intersect both boundary lines and the stem and define the inclination (branching angle) of plant organs along the stem. The region between consecutive inclination lines is called a *layer*. Any number of plant organs can be placed within a layer.

3.3. Node position

A *node* is the point in the stem, or main axis, where an organ originates. The chord length distance between two consecutive nodes (and, therefore, two consecutive organs) along the stem is called *internode length*. When defining a concept sketch, the user is able to specify the number of nodes/organs that should be placed per layer. These nodes are evenly distributed inside a layer, which implies that the internode length is the same for all nodes in the same layer.

3.4. Branching intersections

The branching intersections define how big the organs should be so that they fit inside the bounding volume specified by the boundary lines. This information is obtained on a per-layer basis. For each layer, the angles between the inclination lines on the left and right sides of the stem and a reference vector defined with respect to the internode up directions are calculated. These two pairs of angles (one pair for the upper inclination lines and another for the bottom inclination lines) are linearly interpolated between the nodes inside the layer. Then, from each node, a ray is cast to each side of the stem with inclination given by its corresponding interpolated angle. The intersection of this ray with the respective boundary line determines how big the organ placed at this node should be, so that it fits inside the plant bounding volume. Therefore, the distance from the node position to this intersection point provides the organ size.

3.5. 3D stem

Among the strokes drawn to define the structural components of the concept sketch, only the stem stroke directly corresponds to an actual element of the final arrangement (the other two groups of strokes—boundaries and inclination lines—provide indirect indications about the arrangement's structure). Consequently, this is the only stroke that has a 3D nature. In order to capture this characteristic of the stem shape, we use the pressure information obtained from the tablet's pen to represent depth for the stroke. Higher pen pressure means bolder strokes that appear closer to the viewer and lower pen pressure indicates lighter strokes that are further from the viewer. The middle point of the device's range of pen-pressure values is considered the "normal pressure" and is mapped to the drawing plane depth value. Pressure values above the middle point are mapped to closer values in relation to the drawing plane depth. Similarly, pen pressure values below the middle point are mapped to deeper values in relation to the drawing plane depth. The maximum and minimum pressure values are mapped onto pre-defined depth values.

4. Function definition

The information extracted from the construction lines sketch needs now to be passed to an L-system. We define this kind of positional information by using B-spline functions [15]. These functions are referenced from inside L-system productions, returning a value that may be used as a parameter or applied in the calculation of a parameter for a rule. They are employed to represent *positional information* and *morphogenetic gradients*, such as relative branching points, organ distribution, element dimensions, deformations, etc. A function is given by a uniform cubic B-spline calculated from a set of control points. The control points for each function are obtained by re-sampling information obtained from the concept sketches (internode lengths, inclination angles, organ sizes, and stem shape) for each structural component.

4.1. Internode length

All the values for internode length are given relative to the whole stem's arc length. The initial function (x, y) point, which has independent or x-coordinate value equal to 0.0, has a dependent or y-coordinate value equal to the relative distance d_1 from the base a of the stem to the first node P_1 (Fig. 4(a)). From then on, the function (x, y) points have values of the independent coordinate equal to the relative node position on the stem and, for the dependent coordinate, equal to the internode length (Fig. 4(b)). This value depends on the layer i that contains the node, and is equal to the arc length L_i divided by the user-defined number of nodes in layer i. The exception is the point P_n at the topmost inclination line. This point has the dependent value equal to the remaining distance to the end of the stem, given by d_2 (Fig. 4(a)). In this manner, exceeding nodes are pushed outside the stem length. This leads to a constant internode value for each layer, resulting in a piece-wise constant function (Fig. 4(b)). This uniform distribution inside a layer supports the representation of masses of organs from the illustration point of view. Note the number of nodes per layer is a global constant (the same value for all layers). The user can change its value, but it is not necessary. The idea of having this as a constant is to have the drawing defining the density of organs in each layer.

4.2. Stem shape

In our approach, the stem shape can be specified by ignoring or considering pen-pressure depth modulation; we call it 2D or 3D stem shape, respectively.

4.2.1. 2D stem shape

The stem shape is given by a function determining how much the L-system turtle should turn considering its current heading.

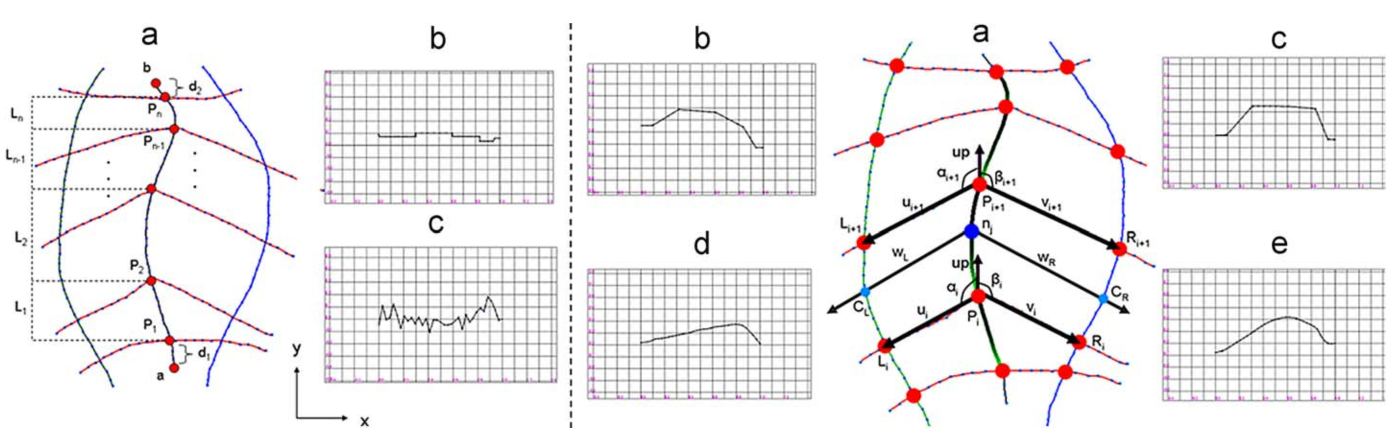

Fig. 4. *Left block*: (a) Scheme of construction lines for the internode length function (b) and the stem shape function without pen-pressure depth modulation (c). The stem shape function is defined by the turtle turning angle (degrees) between consecutive tangent vectors along the stem construction line. In both functions, the x-axis corresponds to the relative position (arc-length parameterization) along the main stem construction line from points a to b. *Right block*: (a) Scheme of construction lines defining inclination angles (α, β) and organ sizes (u, v); (b, c) functions defining left and right inclination angles; (d, e) functions defining left and right organ sizes.

As in the previous functions, the independent coordinate value is given by the relative position along the stem. The dependent value corresponds to the angle in degrees (as usually given in L-systems), by which the turtle turns between consecutive tangent vectors along the stem construction line. Fig. 4(c) shows one example of this function.

4.2.2. 3D stem shape

In order to represent the stem in 3D, two positional functions are defined. These functions provide the angles that the L-system turtle should turn to the left and down ("yaw" and "pitch", respectively) at a given position along the stem in order to follow the 3D curve given by the user via the tablet. These angles correspond to the Euler angles that should be applied to the turtle's orientation frame. It should be observed that they are given in relation to the global coordinate system and not the moving turtle's frame. Therefore, at every production step, the turtle's orientation must be aligned with the global coordinate system before applying the corresponding rotations.

The values for the yaw and pitch angles are obtained from the vector $\vec{s}$ formed by the initial and end points of each segment of the 3D stem stroke (Fig. 5). The angles are obtained as follows:

$$yaw = \arctan\left(\frac{s_x}{s_y}\right)$$

$$pitch = \arctan\left(\frac{s_z}{\sqrt{s_x^2 + s_y^2}}\right)$$

where (s_x, s_y, s_z) are the components of the vector $\vec{s}$ given in the global coordinate frame.

In the yaw function (Fig. 5(b)), the independent axis represents the relative position of the turtle in relation to the stem arc-length (as in all the other positional functions) and the dependent axis represents the yaw angle in degrees (the angle of rotation to the left or about the turtle's up vector, $\vec{U}$). In the pitch function (Fig. 5(e)), the independent axis equally represents the relative position of the turtle in relation to the stem arc-length and the dependent axis represents the pitch angle in degrees (the angle of rotation downwards or about the turtle's left vector, $\vec{L}$).

4.3. Inclination angles

For the inclination angles, we have two functions: one for the left side of the sketch and another for the right side. We need a linear interpolation between two consecutive inclination vectors $\vec{u}_i$, $\vec{u}_{i+1}$ (left side) and $\vec{v}_i$, $\vec{v}_{i+1}$ (right side). The resulting intermediate vectors are given by $\vec{W}_L$, $\vec{W}_R$ for the left and right sides, respectively (Fig. 4 (*right block*) (a)). The angle values, given in degrees, are set as the dependent value of the function. The independent value is again the relative position of a node along the main axis. For the points in the extremes of the function (independent values equal to 0.0 and 1.0), the dependent value of the respective closest point is assigned (α_1 or β_1 and α_n or β_n, correspondingly). This assures that the angle values in the bottom and upper parts of the stem, which do not have nodes, are constant and equal to the value for the closest node. This results in piece-wise linear functions, since we have linear interpolation between consecutive pairs of angle values. A sample of a pair of such functions can be seen in Fig. 4 (*right block*) (b, c).

4.4. Lateral organ sizes

There are also two functions for the organ sizes: one for the left side of the structure and another for the right side. Both are given by the size values calculated for every node. These values are given in relation to the whole stem arc-length. Similarly as it is done for the inclination angles, the points in the extremes of the function have dependent value equal to the value of the respective closest node. Examples of organ size functions for both sides can be seen in Fig. 4 (*right block*) (d, e).

5. Phyllotactical settings

Pyllotaxis is the arrangement of plant organs around the stem. Common types of phyllotaxis include *distichous*, *decussate*, and *Fibonacci* patterns (Fig. 6), which we incorporated into our models. These patterns were selected because they are found in a large number of plants and yield significantly different plant structures.

The choice of phyllotactic pattern determines productions in the L-systems template. The functions discussed in Section 4, provide the information on the stem shape, the placement of organs, and their inclination angle (Fig. 3(b)). These functions are general for any kind of plant that fits in the used sketch guidelines. However, information is still missing on how much the L-system turtle should rotate about the stem between consecutive nodes, and how many organs should be placed at

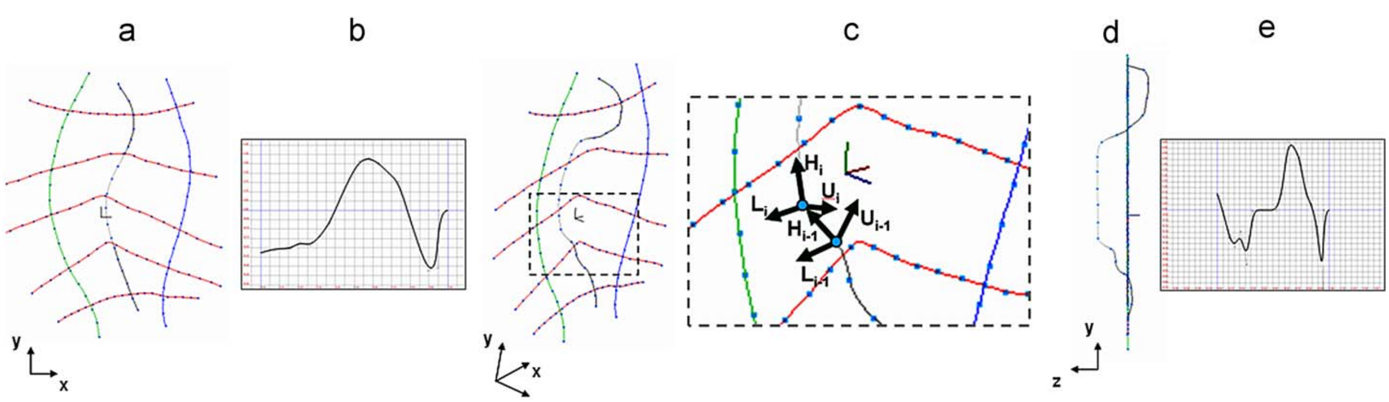

Fig. 5. 3D stem shape defined by pen-pressure depth modulation. Construction lines in three different views: front (original sketching view point) (a), diagonal (c) and (d) side views. Notice the depth of the stem construction line in (c, d). The higher the pen pressure, the more the turtle is oriented in the direction of the negative *z*-axis (c, d). This orientation is represented by the pitch angle (e). The yaw angle (b) is conceptually equivalent to the 2D turning angle (cf. Fig. 4). This is the "sideways" orientation of the turtle.

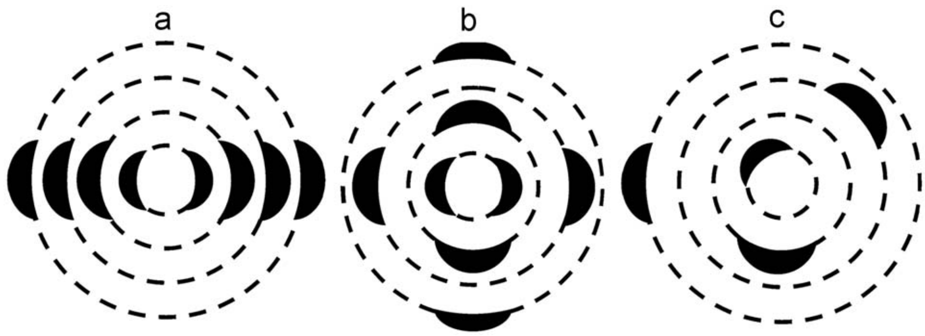

Fig. 6. Patterns of phyllotaxis available in the system. (a) Distichous; (b) decussate; (c) Fibonacci spiral.

each node. This information is given by the user-chosen phyllotactic pattern.

5.1. Distichous phyllotaxis

Distichous phyllotaxis is especially common in different kinds of fern leaves [15]. It is characterized by a pair of organs at each node growing in opposite directions (i.e., 180° apart). There is no relative rotation between consecutive nodes. A diagram illustrating this pattern is given in Fig. 6(a). An L-system specification of a monopodial plant with distichous phyllotaxis is given below:

Axiom : $A(0)$
Productions:
1: $A(x) \to S(x)B(x)A(x+\Delta x)$
2: $S(x) \to @R(0,1,0,0,0,1)+(Y(x))\&(P(x))F(\delta(x))$
3: $B(x) \to L(x)R(x)$
4: $L(x) \to [+(\varphi_L(x))Organ(h_L(x))]$
5: $R(x) \to [/(180)+(\varphi_R(x))Organ(h_R(x))]$

In this L-system, x is the relative position along the stem arc-length; Δx is the resolution with which the stem is drawn; $\delta(x)$ is the internode length; $Y(x)$ and $P(x)$ are the values of the yaw and pitch angles at x, respectively; $\varphi_L(x)$ and $\varphi_R(x)$ are the values of the branching angles calculated from the inclination angle function for the left and right sides at x, respectively (Fig. 4 (right block) (b,c)); $h_L(x)$ and $h_R(x)$ are the values of the organ size function for the left and right sides at x, respectively (Fig. 4 (right block) (d, e)); @R(hx, hy, hz, ux, uy, uz) is the symbol that transforms the L-system turtle to the specified heading (hx, hy, hz) and up (ux, uy, uz) orientations; + is the symbol that rotates the L-system turtle to the left; & is the symbol that rotates the L-system turtle down; /(180) is the symbol that rotates the turtle by 180° around the stem; and *Organ*(y) represents the drawing of an organ of size y.

5.2. Decussate phyllotaxis

Decussate phyllotaxis is similar to distichous phyllotaxis in that a pair of opposite organs is placed at each node. However, in the decussate case, each pair is rotated by 90° with respect to the previous pair. Fig. 6(b) illustrates this pattern. In terms of production rules, it requires keeping track of how the previous node is positioned. In the actual implementation, a node counter was added as a parameter in the sequence of productions and, whenever this counter indicates that the current node has an odd numbering, a rotation of 90° about the stem is applied before the organs are placed. Branching angle and organ size values are applied as in the distichous pattern for the non-rotated nodes. For the ones that are rotated, the arithmetic average between the left and right values is taken for both the branching angle and the organ size parameters. A corresponding L-system is given below:

Axiom : $A(0,0)$
Productions:
1: $A(x,i) \to S(x)B(x,i)A(x+\Delta x, i+1)$
2: $S(x) \to @R(0,1,0,0,0,1)+(Y(x))\&(P(x))F(\delta(x))$
3: $B(x,i)$: {
  if $(i\%2 == 0)\theta = 0;$
  else $\theta = 90;$
  } $\to [/(\theta)L(x,i)R(x,i)]$
4: $L(x,i)$: {
  if $(i\%2 == 0)\{$
    $angle\ = \varphi_L(x);\ length\ = h_L(x);$
  } *else* {
    $angle\ = (\varphi_L(x)+\varphi_R(x)) * 0.5;$
    $length\ = (h_L(x)+h_R(x)) * 0.5;$
  }
  } $\to [+(angle)\ Organ\ (length)]$
5: $R(x,i)$: {
  if $(i\%2 == 0)\{$
    $angle = \varphi_R(x);\ length = h_R(x);$
  } *else* {
    $angle = (\varphi_L(x)+\varphi_R(x)) * 0.5;$
    $length = (h_L(x)+h_R(x)) * 0.5;$
  }
  } $\to [/(180)+(angle)Organ(length)]$

In this L-system, i is a counter of nodes, and thus of organ pairs attached to the stem. The remaining symbols have the same meaning as in the distichous case.

5.3. Fibonacci spiral phyllotaxis

Fibonacci spiral pattern is characterized by one organ supported at each node, and a rotation around the stem given by a divergence angle of 137.5° between consecutive nodes. A scheme for this pattern is shown in Fig, 6(c). As in the decussate case (Section 5.2), a counter keeps track of the number of the current node. This number is multiplied by the divergence angle and reduced to the [0, 360) interval. The resulting angle value is used as the parameter of a linear interpolation to calculate its branching angle and organ length from the function values for the left and right side. The equations are defined as follows:

$$\varphi(x,\theta) = (a)\varphi_L(x) + (b)\varphi_R(x)$$
$$h(x,\theta) = (a)h_L(x) + (b)h_R(x)$$

$$(a,b) = \begin{cases} \left(1-\dfrac{\theta}{180}, \dfrac{\theta}{180}\right), & 0^\circ \leqslant \theta \leqslant 180^\circ \\ \left(\dfrac{\theta}{180}-1, 2-\dfrac{\theta}{180}\right), & 180^\circ < \theta \leqslant 360^\circ \end{cases}$$

where x is the position of the current node relative to the stem chord length, θ is the calculated phyllotactical angle for the current node, $\varphi(x,\theta)$ is the branching angle at the current node, and $h(x,\theta)$ is the organ size. The resulting L-system generating monopodial structures with the spiral phyllotaxis is given below:

Axiom : $A(0,0)$
Productions :
1: $A(x,i) \rightarrow S(x)B(x,i)A(x+\Delta x, i+1)$
2: $S(x) \rightarrow @R(0,1,0,0,0,1) + (Y(x))\&(P(x))F(\delta(x))$
3: $B(x,i)$: {
$\theta = (i * 137.5)\%360;$
$angle = \varphi(x,\theta); length = h(x,\theta);$
} $\rightarrow [+(angle)Organ(length)]$

Note that the method used here to calculate organ size is simpler than the method proposed by Anastacio et al. [1]. That method calculates a smooth shape compound of two half-ellipses around the position of the organ in the stem. Theirs is a more precise approach than the linear interpolation used in this section which, in some cases, may generate cardioid curves. However, their calculations take into account several different variables that cannot be straightforwardly represented in a single-variable function. Furthermore, the simpler solution proposed here works well enough for cases that do not require higher levels of precision.

6. Modeling organs

In the final step, surfaces representing desired organs (leaves, petals, entire flowers, etc.) are incorporated into the model. Any organ surface specification method can be used. In our system, the organs surface geometry is defined by the sketch-based 3-view stroke input method [1] shown in Fig. 3(c). This method provides a simple and quick way to create a varied range of plant organ surfaces to be used in the L-system models, employing a minimal number of strokes.

Four strokes are used embedded into three different viewpoints. The left and right boundaries are provided in a top view; the midrib or spine is given in a side view, and the cross-section is drawn in the front view (Fig. 3(c)). These strokes are combined in a composition of the *cross-sectional blending* surface with the

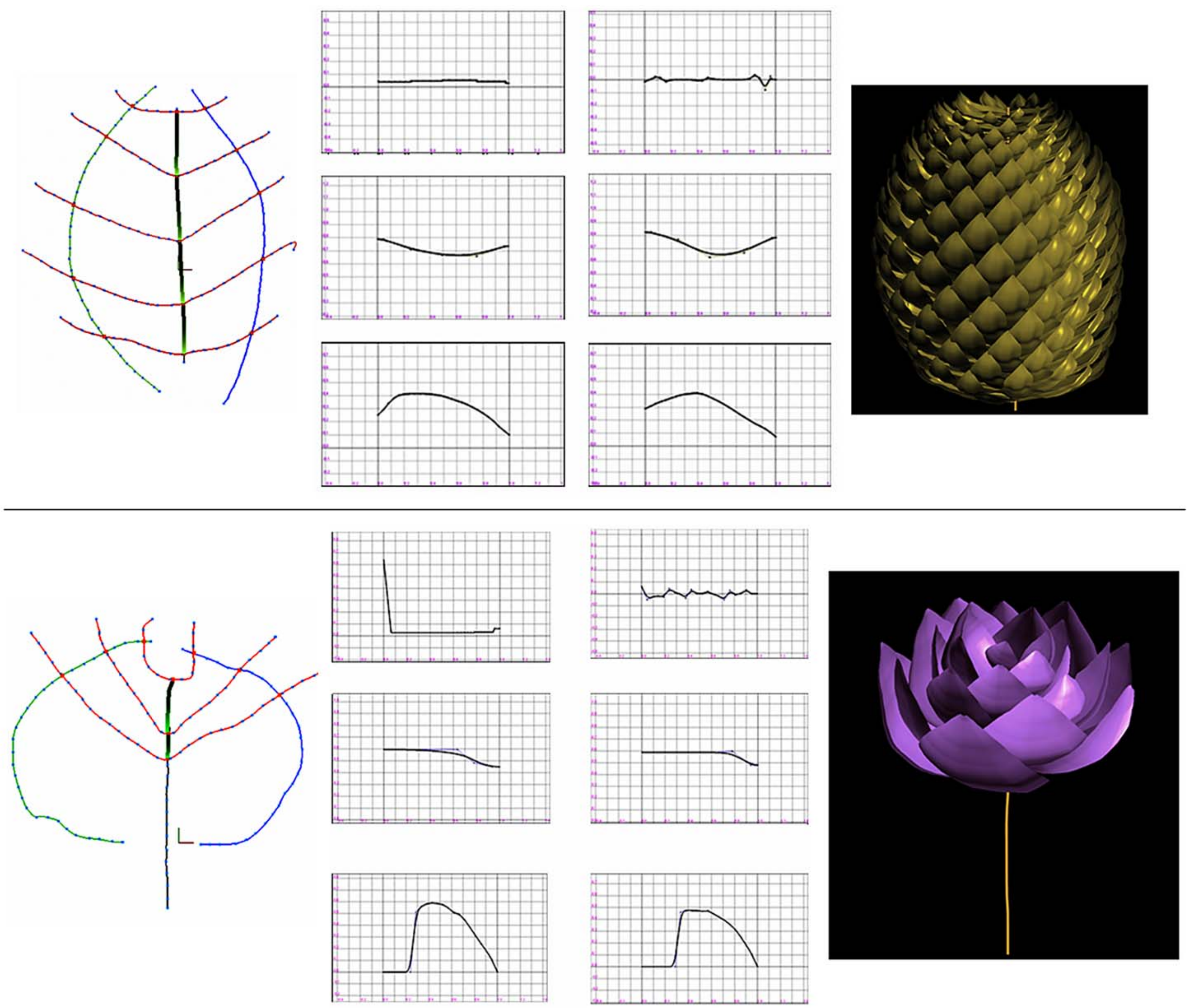

Fig. 7. Models of a pine cone and flower with 55 and 13 nodes per layer, respectively.

orthogonal deformation operation [2] to provide the final organ surface. For more details, refer to Anastacio et al. [1]. To have this surface displayed in an L-system model, the triangles that compose its mesh structure are written to a text file. The file is parsed by the L-system modeling program [10], which recreates the mesh and incorporates its instances as defined by the organ placement algorithm.

7. Results

Application examples were generated on a 2.8 GHz Pentium 4 with 1 GB of RAM and a GeForce FX 5200 128 MB video card. The results show that our approach produces plant models matching the construction lines arrangements of the input concept sketch. Based on our experiments and observations, most of the time spent creating a model is due to user edits of the sketched construction lines and L-system fine-tuning. The system instantaneously generates an L-system from the input sketch. A user can create simple models in just a couple of minutes.

In our system implementation, the sketch strokes are drawn in a dedicated program, which launches a *cpfg* [10] visualization window displaying the resulting L-system model with the chosen phyllotactic pattern. If further editing of the L-system is desired, the resulting model can be exported to L-studio [13]. We observed that this complementary organization, while missing immediate feedback, provides a good workflow and is adequate enough for the production of appropriate results.

Figs. 7–9 show results with the stem shape defined without depth modulation. In each figure, the derived positional functions are displayed as follows (from left-right and top-bottom): internode length, stem shape, left inclination angle, right inclination angle, left organ size, and right organ size.

7.1. Models with different patterns

Fig. 7 shows a simple sketch can be used to model a pine cone with 55 organs (scales) per layer and the Fibonacci spiral phyllotaxis and a flower with 13 nodes per layer. Fig. 8 illustrates

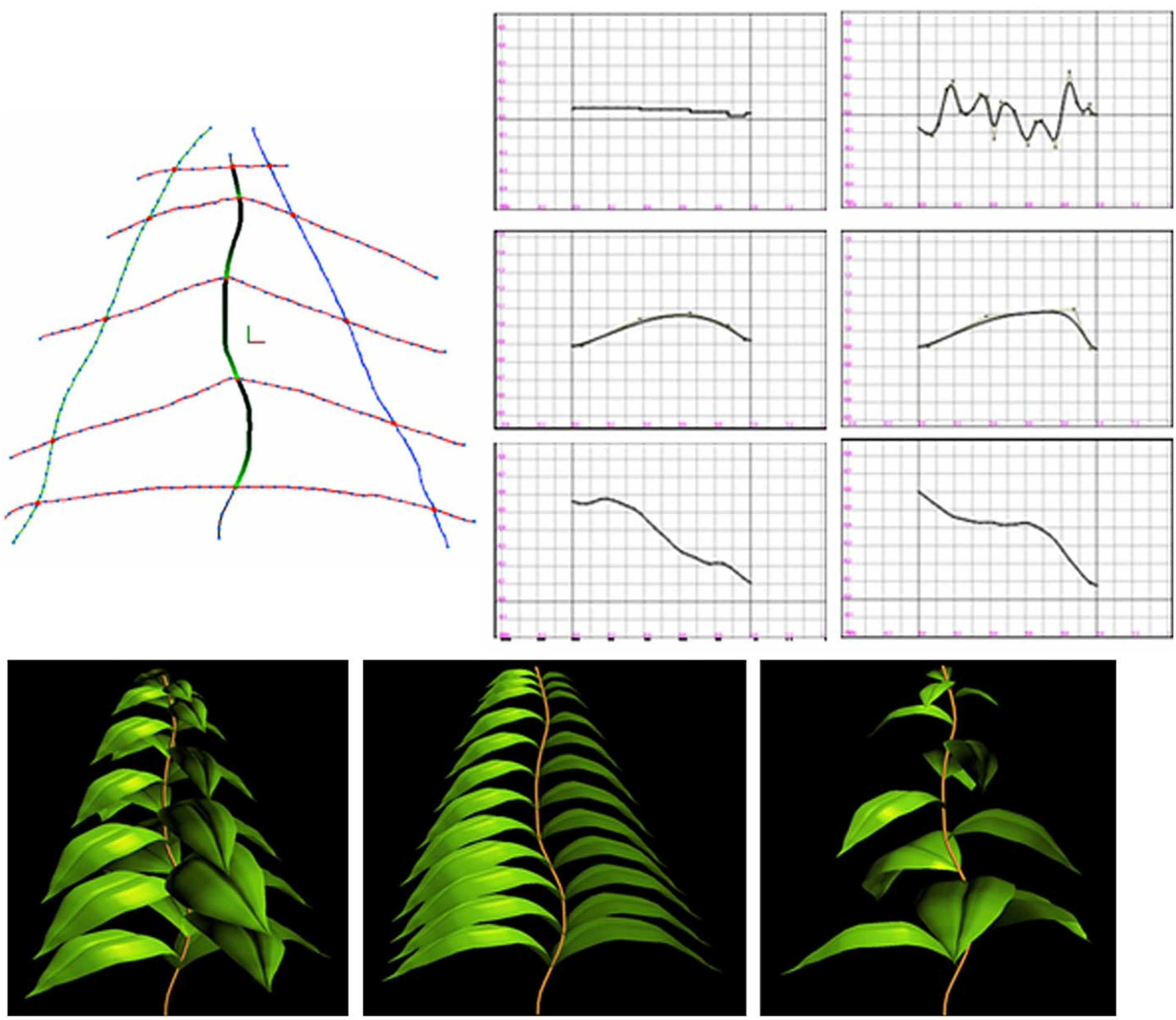

Fig. 8. Models with (left to right) decussate, distichous and Fibonacci spiral patterns.

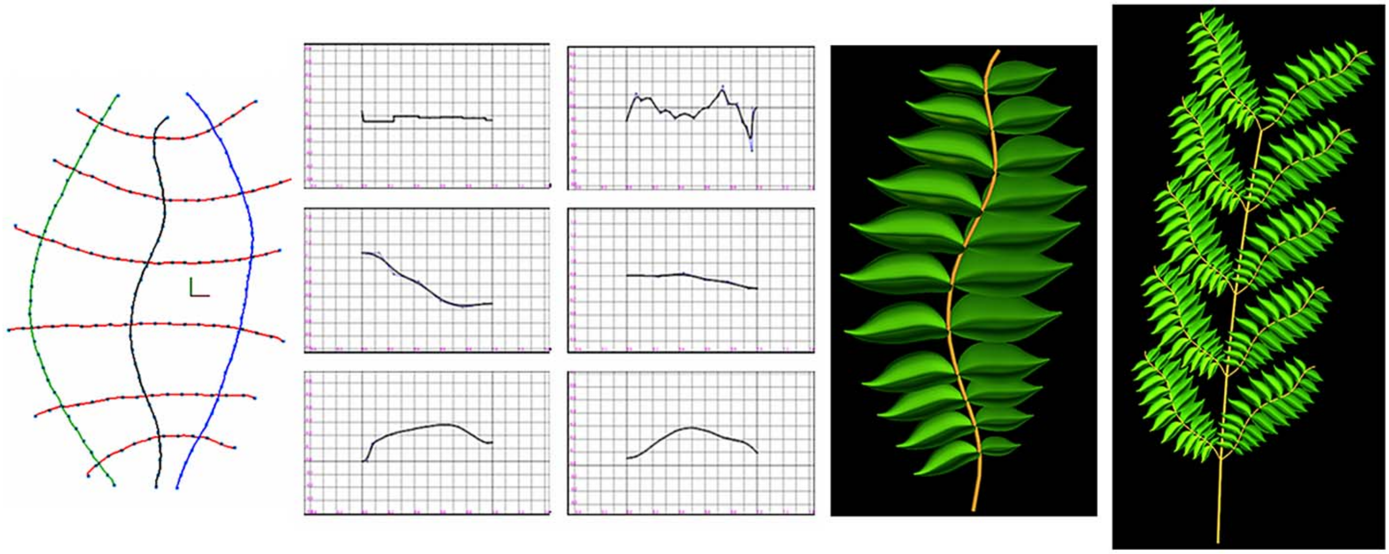

Fig. 9. Models of a single-compound leaf and a double-compound leaf. Stem shape defined without depth modulation.

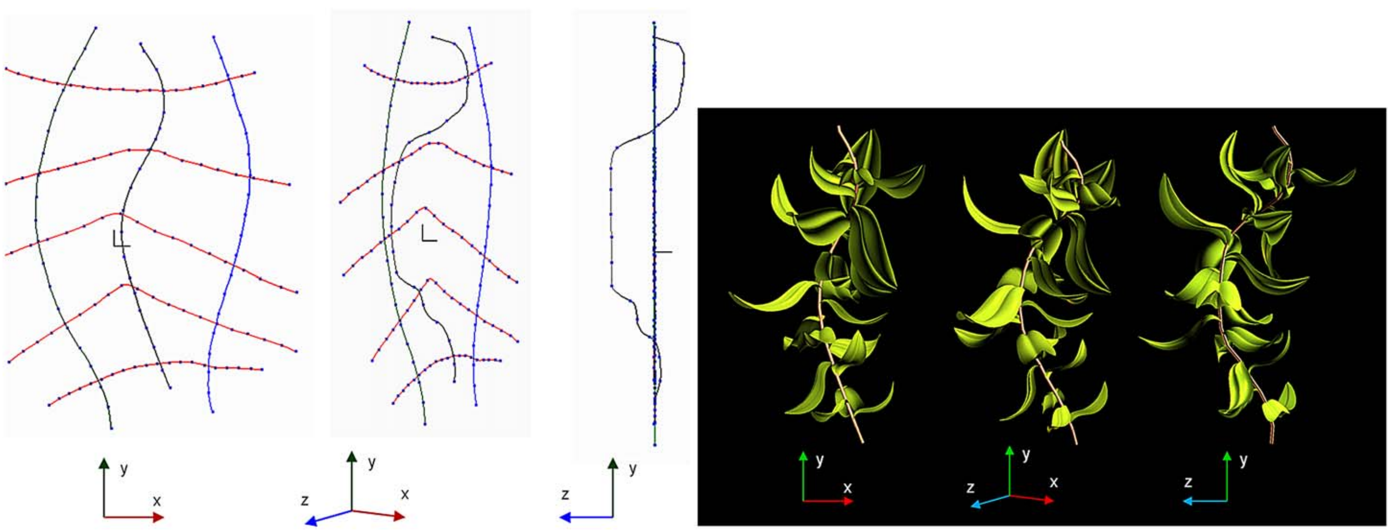

Fig. 10. Stem shape defined with depth modulation. Sequence of three views of the original construction lines and the corresponding final results.

the differences between the available phyllotactic patterns for a single concept sketch. All patterns have three nodes per layer. Even though the concept sketch is the same, the resulting plants look considerably different from each other.

7.2. Composing plant structures

Our system also allows the user to edit the generated model by changing its L-system rules. This allows fine-tuning of specific aspects of the model as well as its utilization as a module in the composition of another plant structure. An example of this is given in Fig. 9. It shows a model of a stem of a single-compound leaf along with the concept sketch and the derived functions used to model it. This model is then used as a module that is repeated along an axis following a distichous phyllotaxis pattern, resulting in a double-compound leaf (see Fig. 9).

Our technique is based on a specific example of a construction lines arrangement (Fig. 1(a)). Therefore, it cannot produce a very wide range of plant architectures. However, one way to achieve more variety of plants is by composing L-systems of different models. The bromeliad created using image composition of concepts sketches shown by Anastacio et al. [1] was recreated by combining the grammars of two parameterized L-systems (Figs. 11 and 12). In Figs. 13 and 14, a model of a foxglove inflorescence (*Digitalis purpurea*) is composed from the construction line sketches for the flower and leaf arrangements. The distribution of the organs was edited in the L-system rules. Coloring and texturing were applied to the organ surfaces to improve the model appearance.

7.3. Stem shape with depth modulation

The user is able to vary pen-pressure values while sketching the construction line defining the stem. This provides a more realistic depiction of the plant posture. In our system, color is used to provide feedback about the depth of a section of the stroke, with further parts being lighter and closer ones being darker.

Fig. 10 displays three different views of the construction lines of a simple plant model with their corresponding results. The derived yaw and pitch functions are shown in Fig. 5.

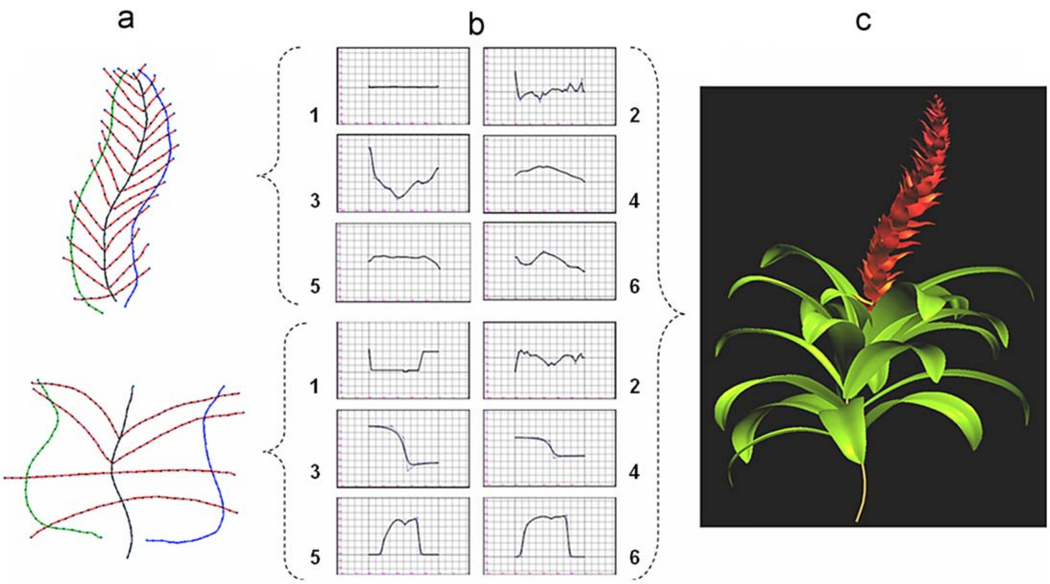

Fig. 11. Bromeliad model without pen pressure for the stem depth modulation. (a) Construction lines, (b) derived positional functions and (c) the final result. Functions are labeled as follows: (1) internode length, (2) stem shape, (3, 4) left, right inclination angles, and (5, 6) left, right organ lengths.

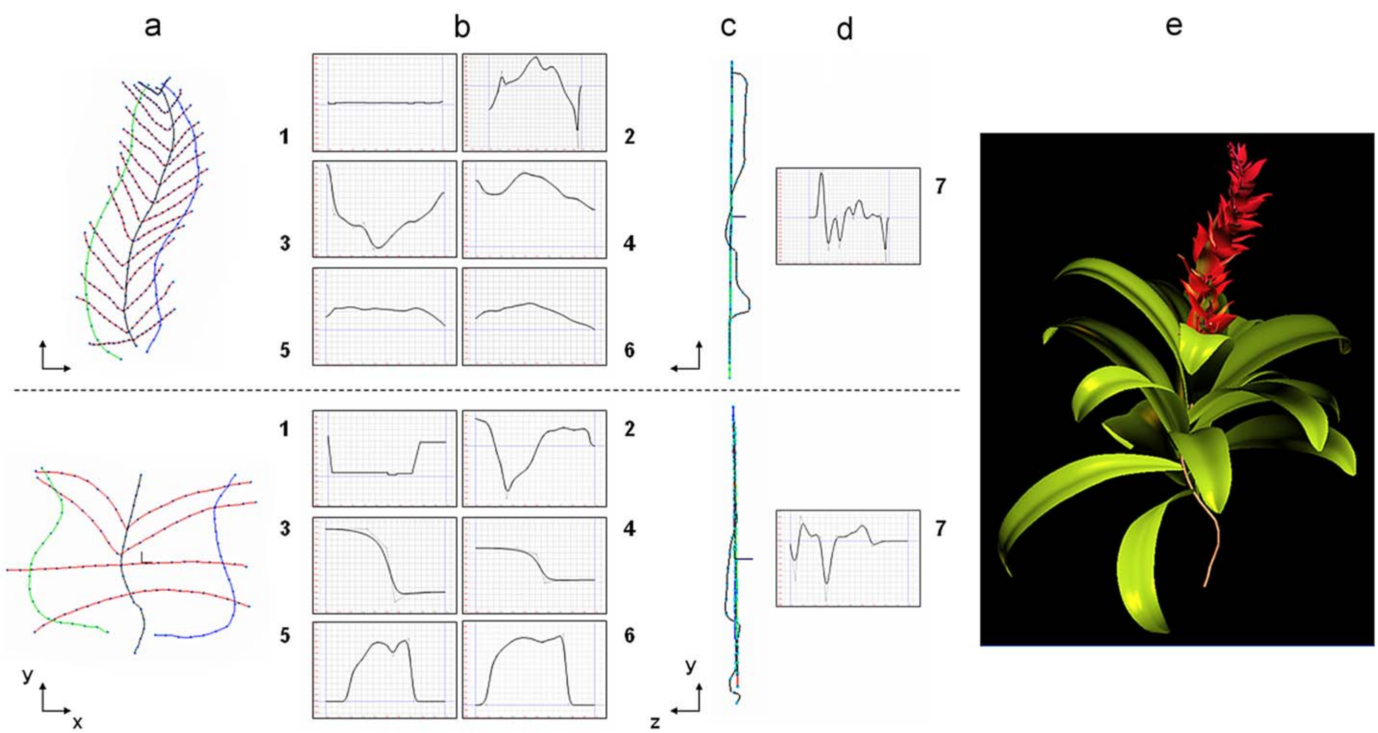

Fig. 12. Bromeliad model using pen pressure for the stem depth modulation. (a, c) Construction lines, (b, d) derived positional functions and (e) the final result. Functions are labeled as follows: (1) internode length, (2) yaw, (3, 4) left, right inclination angles, (5, 6) left, right organ lengths, and (7) pitch.

Figs. 12 and 14 show a composition for a bromeliad and foxglove models, respectively. The final results can be compared against the ones generated without stem depth modulation as shown in Figs. 11 and 13.

8. Conclusion

This paper presents a sequence of experiments aiming at creating a synergy between sketch-based and procedural plant modeling techniques. We use the construction lines from concept sketches [1] to define the overall plant structure based on traditional illustration techniques (Fig. 1). We propose translating these sketched construction lines into functions [15] that are used to parameterize L-system production rules. This establishes an interface between sketches and L-systems, making more intuitive the construction of models that fit in our selected collection of templates. More generally, other domains using procedural modeling techniques could benefit with the interface and approach proposed in this paper, by reducing the complexity of controlling the underlying parameters.

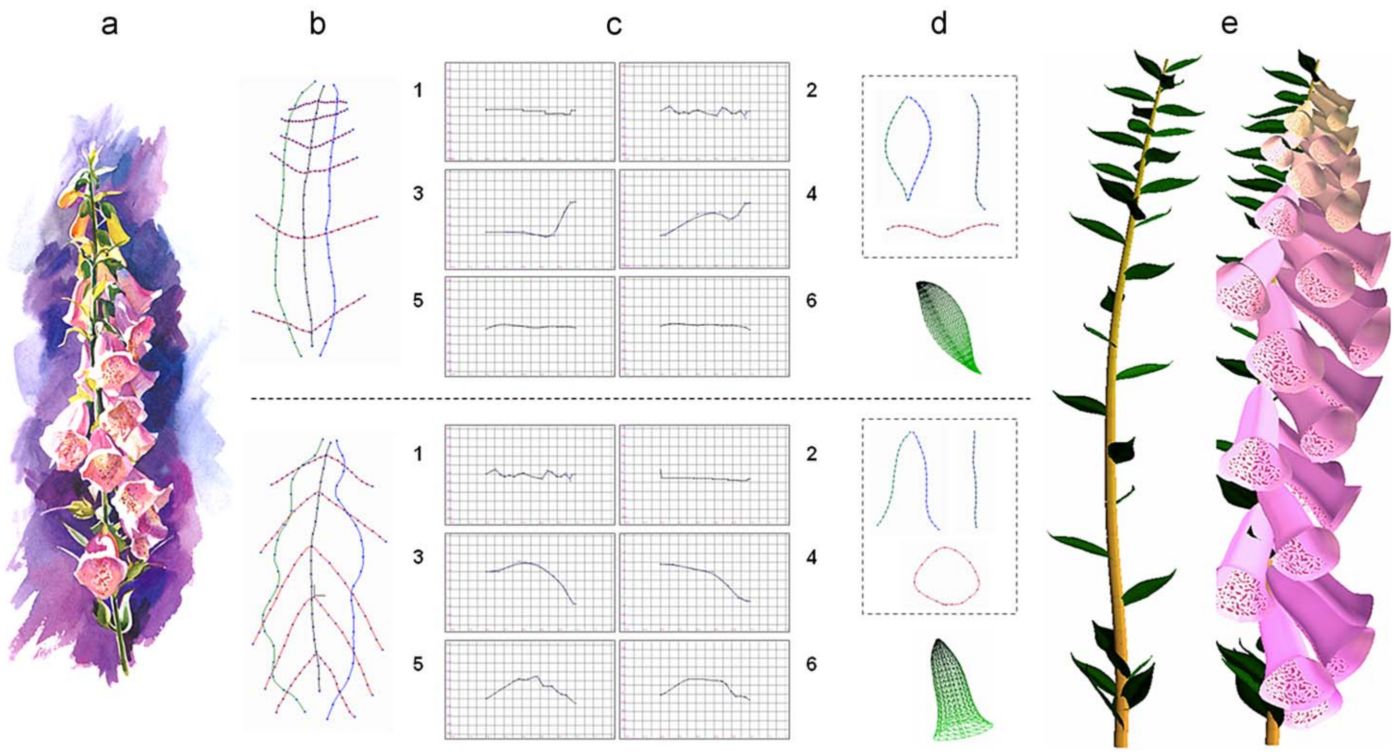

Fig. 13. Foxglove model without pen pressure for the stem depth modulation. (a) Botanical watercolor illustration used as inspiration [9], Used with permission, copyright 1993 Jan Kunz. (b) construction lines, (c) derived positional functions, (d) construction lines and resulting surfaces for the organs, and (e) the final results. Functions are labeled as follows: (1) internode length, (2) stem shape, (3, 4) left, right inclination angles, and (5, 6) left, right organ lengths.

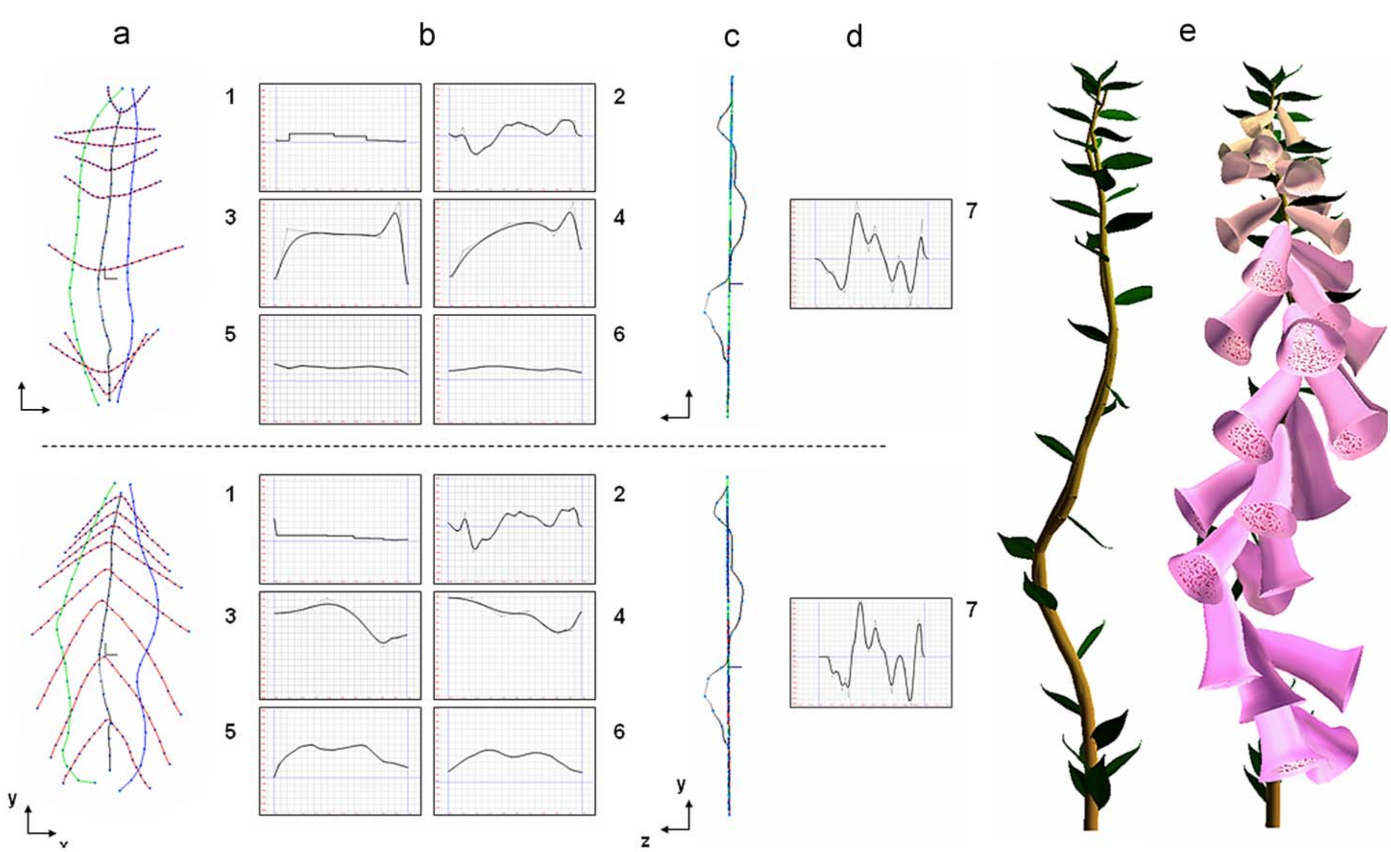

Fig. 14. Foxglove with pen pressure for the stem depth modulation. (a, c) Construction lines, (b, d) derived positional functions, and (e) the final results. Functions are labeled as follows: (1) internode length, (2) yaw, (3, 4) left, right inclination angles, (5, 6) left, right organ lengths, and (7) pitch.

Future improvements include investigating a more general definition of construction lines, covering the description of whole plants with different architectures. Concept sketches could be extended to describe sets of plants and ecosystems based on L-systems. We also plan to conduct formal evaluations and user studies to provide quality construction line-based sketching tools for botanical illustrators.

Using the pressure applied to the tablet's pen provides an effective way to input depth information. However, depending on the accuracy of the device, it can be quite hard to control how much pressure is being applied. Depending on the sensibility of the pen, abrupt variations of depth can occur and it takes some training for the user to feel comfortable about controlling it. A widget that would provide some visual help regarding the amount of pressure being applied and a way to edit the pressure at specific sections are being considered as future improvements.

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