Visual Model of Plant Development with Respect to Influence of Light

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Abstract. This paper deals with simulation of plant development and focuses on influence of light. Most of the previously published methods dealing with light in these simulations use sky discretization, source of aliasing error which was never mentioned in literature. This paper investigates the problem and proposes a solution to it. The second influence which strongly affects the shape of a plant is the relationship between the amount of light and the activity of buds. We offer here a simplified model to demonstrate this dependency.

1   Introduction

As the technology and methods involved in computer graphics grows more advanced, the provided methods and algorithms become correspondingly more precise and accurate. This tendency can be observed in the area of visual plants simulation, where it presents itself somewhat specifically. Although *ad hoc* methods [14, 16, 19, 27, 28, 29] are still popular and frequently used, biology has begun to exert a beneficial pressure on this area of computer graphics *e.g.,* [9, 15, 18, 20, 21, 23, 25, 26], an impact equally useful in both fields.

As mentioned in [18], the interaction between the plant and the environment is often times neglected. The bulk of previous work mostly considered the plant as a closed system. The former works approximate the fact that the shapes of the plants differ due to their interactions with a surrounding environment by injecting randomness into the model generation phase. Plant–environment interactions has not been entirely excluded from scholarship, and with the tremendously useful aid of computer graphics [1, 2, 12, 13] and this area has found its way into scholarship more and more frequently [3, 4, 6, 7, 18, 24].

This paper is structured as follows. Section 2 reviews previously published methods and findings. The growth model is dependent on the calculation of the light, so the algorithm for the skylight approximation is briefly discussed in Section 3. Section 4 deals with the growth model with modules description and their typical actions. Section 5 focuses on the influence of light and the resulting error caused by a fixed number of lights in scene. Finally, the results of our simulations are presented in concluding Section 6.

2   Previous work

Begin with year in 1984, Aono and Kunii [1] used light, wind, and gravity for bending the branches of trees in certain directions. The phenomenon of self-shadowing of branches however did not fall within the scope of their study.

In 1988, Arvo and Kirk [2] introduced *environment sensitive automata*–ESA in order to investigate the simulation of the climbing plants as well as the spreading grass. This method is based on ray-tracing algorithm. The ESA detect their surrounding environment by casting rays. The information obtained is then used to measure the distance to the obstacle and determine whether or not the ESA will fall into shadow. The second function of this information is also used for varying the size of the blade of grass.

Greene [12, 13] used voxel space automata to simulate roots searching for viable paths on stony ground and to simulate growth of climbing plants. He uses stochastic growth (the random walk). In order to decide a new position of the growing element, multiple random trials are made, position and orientation of a growing element are randomly perturbed, the fitness function is evaluated, and the element is moved to the best place. 3DDA sampling of the trajectory of the sun calculates locally the amount of light. Several rays are cast for every growth element and the coefficient of the sky exposure is evaluated as a relative number of occluded and free rays.

An alternative method of the light direction and the light amount estimation is found in the work of Chiba *et al.* [7]. They introduce a leaf-ball, an approximation of a cluster of leaves with the growing element in the center. The amount of light is estimated by the projection of these balls on the celestial sphere in the center of which the leaf-ball concerned is located. A hidden surface algorithm or 3DDA in voxel space estimates the amount of skylight. If the amount of light remains under a certain threshold, then the branch is treated as withered and is removed. The direction towards the brightest spot is defined by summing the participating vectors associated with each ray reaching the celestial sphere. In 1996, Chiba *et al.* used the same algorithm to calculate both the amount of the light and the direction to the brightest point for leaves [6]. The maximum is used for bending leaves to the direction of the light, while the amount of the light is used for coloring leaves.

The theory of L-systems is well-known in computer graphics. The survey of L-systems is presented in the book [22] while the latest results can be found in [18, 25]. Furthermore, there are two important environmentally sensitive extensions of L-systems published in [18, 24]. The context sensitive parametric L-systems were extended by query modules [24]. The query modules are parametrized components of the rewriting process and they can ask the surrounding environment for some values; *e.g.,* distance from the obstacle. Parameters of the module are set when the rewriting process asks the query module for them. Drawback of this conception is that the whole plant in the string rewriting phase must always be constructed. *Open L-systems* [18], however, do not suffer from this drawback. The rewriting step is preceded by a scanning phase, in which every so called communication module has set parameters without geometrical inter-

pretation of the string. The plant and the environment are treated as processes communicating via the exchange of messages. The communication modules can ask the environment for values (*e.g.,* location or presence of an obstacle, amount of the light, *etc.,*) and they can also inform the environment of certain values (*e.g.,* carbon dioxide).

The author of this paper published his findings of an efficient estimation of the light flux affecting every leaf [3, 4]. Here, the amount of light and the direction of the brightest point are simultaneously calculated for every leaf and bud in the scene by using a sampling of the scene from the light sources. The amount of light is used simply for changing the growth direction of branches and for a simulation of dying leaves owing to lack of light.

3   Approximation of the skylight

Most of the plants develop in outdoor conditions where both the skylight and sunlight play important roles. Although methods for the skylight approximation exist and are in fact applied *e.g.,* [8, 10], in the course of this particular study we will not directly address them. Instead, we suppose the sky to be approximated (discretized) by total number p light sources denoted by S_k, $k = 1, ..., p$. These lights are regularly spaced on a hemisphere with a very large radius (for example, using the algorithm of Max *et al.* [17]). The lights S_k have flux densities denoted by B_k, assigned according to the area of the sky which is approximated by S_k. We should note here that the assumption of the sky approximation fits in well with most of the algorithms for plant–light interaction published [3, 4, 5, 6, 18]. One problem however, relating to this approximation (aliasing caused by finite number of lights), will be discussed in Section 5.1.

4   The growth model

We use a biologically based stochastic model introduced by de Reffye *et al.* [9, 15] (see also [11, pp:1028-1030]).

The plant has a modular structure. The modules used in this paper are outlined in Figure 1. Although it was proven [22] that the class of plants describable in this model can be modeled by L-systems, this model has several advantages to L-systems. First, it is inherently parallel; in contradiction both to a sequential turtle graphics interpretation of the string of modules and to the sequential scanning phase of modules in Open L-systems [18]. Next, this model is intuitive; in contradiction to the textual form of L-system productions. Finally, this model is biologically based, it can be immediately and readily used by biologists; there is no need for an explanation of complex rules as is the case of L-systems. The principal intention of de Reffye's model is the simulation of plant development; on the other hand the simulation of plant development is only one of many possible applications of L-systems (but probably the most important one).

4.1 Modular structure

The model of a plant possesses a modular structure [25]. The plant is thought to consist of the modules as outlined in Figure 1. The goal of the simulation is to describe behavior of the modules so that a plant shape will emerge.

The most important module of the plant is a *bud*, which can assume one of two forms: an *apical bud* is always located at the extremity of the main trunk or lateral branch, whereas a *lateral bud* is situated at the leaf's axil (it is also called *axillar bud*). A *leaf* is always adjacent to a lateral bud. A *node* consists of one or more lateral buds and an identical number of leaves. An *internode* is a piece of stem located between two successive nodes. The node is either situated between two internodes, or at the tip of the branch. An *apex* is an apical segment with its apical bud.
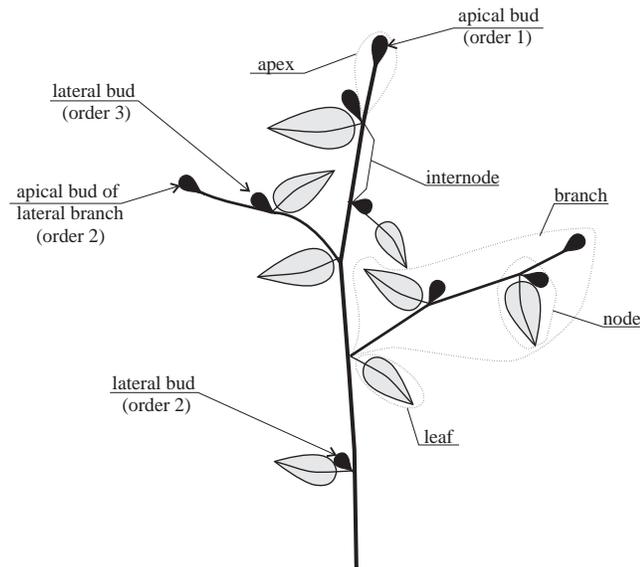
Fig. 1. Diagram identifies the ordering of plant modules. The modules are marked by arrows, whereas the group of modules are encircled in dashed lines.

4.2 Action of modules

The bud is a basic growing element (plant engine [18]) which can perform several actions. Its actions depend on both environmental conditions of the plant (light, water, nutrients, *etc.,*) and internal ones (age, amount of meristem, *etc*). A bud can either *die*, or *bloom and die*, or *become dormant*, or *become an internode*. This final possibility, the process of becoming an internode, is the most important action because it causes growing and branching. This process consists of three

steps. At first, one or more lateral leaves appear beside the bud and the same number of new buds appear at their axils. Then the apical bud produces a piece of stem - the new internode. It is obvious, then, that every branch is a result of activity of its apical bud.

The branches as well as the buds are ordered in such a way (see in Figure 1) that the main trunk and its apical bud have ordering number one assigned. Every lateral bud as well as every lateral branch has its ordering number one higher than its bearing branch.

The bud's behavior depends on its ordering number in our simulation. The ordering number is used for indexing the table of attributes. This table is set either by the user or according to an applied architectural model used [9]. The table contains values which describe the lifetime of the bud, the geometry of the internode produced by the bud, the branching angle, *etc.*

The original model [9] is band on discrete time simulation, whereas our is band on continuous time simulation; [3] provides further details.

5   Influence of the light

In general, the plant development depends on many conditions. In order to understand what our model provides for simulating light influence, we will regard the other parameters of the model as fixed, supposing that they do not affect the plant at all. We will work only with light.

Assume, we have n buds denoted by D_i, $i = 1, ..., n$. These buds are represented by spheres of constant radius r - so they are of equal size, thereby easing the task of preparing the calculations. Let $A_D = \pi r^2$ denote the projected area of the bud. If the bud D is completely exposed to the light S_k (see in Section 3), the appropriate light flux contribution from this light to the bud is [8]

$$\Phi_{D,k} = B_k \ A_D.$$

The maximal light flux to the bud from all lights approximating the sky is

$$\Phi_D = \sum_{k=1}^{p} \Phi_{D,k} + \Phi_a, \tag{1}$$

where Φ_a denotes the flux of the ambient light in the crown of the plant. We use a constant amount of ambient light in the crown, in contrast to Reeves and Blau [27] who use exponential scaling of this coefficient. However, constant ambient light does not change the shape of the plant significantly if the directional lights are considered. The value of maximal possible light flux Φ_D is equal for all buds in scene.

Let $A_{D_i,k}^e$ denote the effective projected area of a bud D_i which is affected by light source S_k (we use the algorithm from [3, 4] for this calculation). Next we calculate the effective light flux denoted by $\Phi_{D_i,k}^e$, which takes into account the shadows cast by the other objects in scene from S_k to D_i. This value depends on shadowing the bud and it differs from bud to bud. It is equal to

$$\Phi_{D_i,k}^e = B_k \ A_{D_i,k}^e,$$

Analogous to (1) the total effective light flux from all light sources to the bud D_i is

$$\Phi_{D_i}^e = \sum_{k=1}^{p} \Phi_{D_i,k}^e + \Phi_a. \tag{2}$$

Next we denote by ϕ_{D_i} the relative light flux to $i-$th bud which is from (1) and (2) equal to

$$\phi_{D_i} = \frac{\Phi_{D_i}^e}{\Phi_D}; \quad 0 \leq \phi_{D_i} \leq 1. \tag{3}$$

This value corresponds to the percentage of the amount of light obtained by the $i-$th bud from the sky. The relative light flux from the $k-$th light to the $i-$th bud is denoted by $\phi_{D_i,k}$ and it is equal to

$$\phi_{D_i,k} = \frac{\Phi_{D_i,k}^e}{\Phi_{D_i,k}}. \tag{4}$$

The relative light fluxes help us to more accurately determine the amount of light needed for the plant lifetime. It is also easier to manipulate with percentage values ϕ_{D_i} instead of the light fluxes $\Phi_{D_i}^e$.

5.1 Phototropism

There are several ways in which light affects the growth of the plant. The most commonly cited effect is *phototropism*. It has mostly the form of *heliotropism*, also called *sun seeking*. Phototropism [22, pp:58-61] is a change in the growth direction of a bud towards towards its light sources (*c.f.*, Figure 2). In order to simulate phototropism we calculate the new growth direction denoted by $\mathbf{d}_i'$ of i-th bud from its original growth direction $\mathbf{d}_i$, direction to the light $\mathbf{v}_k$, and the coefficient of phototropism $0 \leq H \leq 1$ as follows (see Figure 2)

$$\mathbf{d}_i' = (1 - H)\mathbf{d}_i + H\mathbf{v}_k. \tag{5}$$
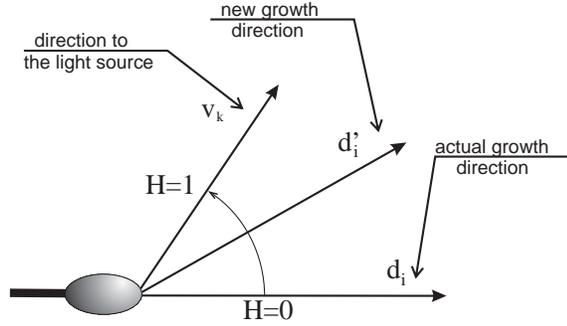
Fig. 2. Calculation of a new growth direction $\mathbf{d}_i'$ of a bud.

Let $\mathbf{v_k}$ denote the direction from which the light flux $\Phi_{D_i,k}$ comes to bud D_i. The direction to the brightest spot on the sky as seen by the bud D_i is *de facto* the direction to the light source contributing with $max\{\phi_{D_i,k}; k = 1,...,p\}$. However choosing the simple maximum gives rise to an error as shown on Figure 3. Here, the sources have almost the same contribution. The one light source differs by a very small value. Using the maximum value causes a strong and undesirable change in the growth direction as shown in Figure 3(b).
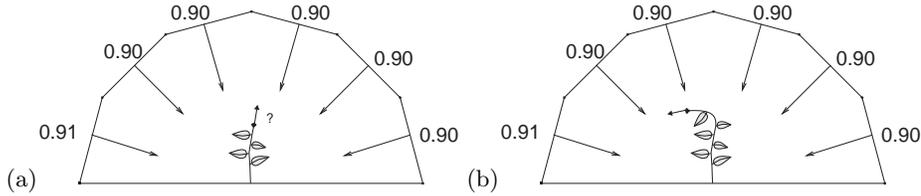
Fig. 3. A small difference in the amount of light causes a sudden change in the growth direction in which the plant is growing if the maximum of the light is simply chosen.

We would like to suggest a solution to this problem. The bud tends to grow in a certain direction, and it changes this direction only if it is really necessary. We denote by α_k the angle between actual growth direction $\mathbf{d}_i$ and direction to the light source S_k. We *scale down* the light flux $\Phi_{D_i,k}^e$, *i.e.*, we multiply it by $\cos(\alpha_k/2)$.
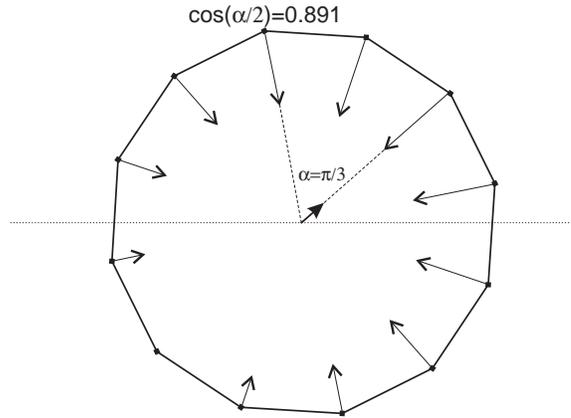
Fig. 4. Influence of the light depends on growth direction of the bud with $\cos(\alpha/2)$, where α denotes the angle between the actual growth direction of the bud and the direction of the light. Note, that the light shining from the back has no effect. For the sake of clarity, all of the directions are displayed; it is however only possible to describe and represent graphically the activity of the bud in upper half of the circle with a given growth direction and with an approximation of the skylight by hemisphere.

After this operation, the effective light flux is calculated for every bud according to (3) and (4). This solution is demonstrated in Figure 4. Meanwhile, we make the assumption that all light sources have equal contributions $\Phi^e_{D_i,k}$. We can then solve the dilemma of choosing specifically one light source by scaling down their contributions according to $\cos(\alpha_k/2)$ *i.e.*, the growth direction remains unchanged.

This author is aware, the number of lights approximating the sky is source of one subtle error. Figure 5 demonstrates behavior of the hyphotetical plant

| a) 4×2 | b) 5×2 | c) 6×2 | d) 100×2 |
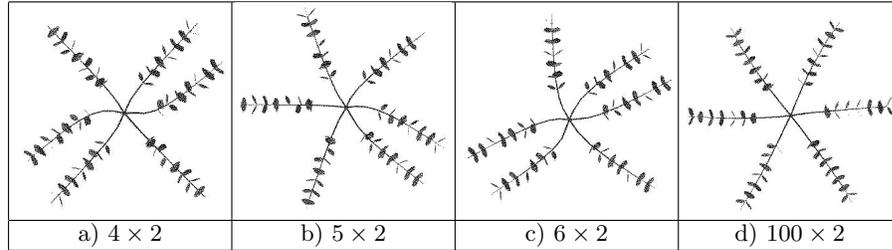
Fig. 5. Shape of a plant resulting from different number of lights approximating the skylight. The $a \times b$ means a subdivision in a horizontal and b subdivision in a vertical direction. A small number of the lights causes visual errors. Branches in (a)-(c) tend to grow in pairs towards certain light sources.

with only six branches strongly influenced with the light. The branches have coefficient of phototropism set to one and they therefore tend to grow towards the strongest light source. We can see that the growth direction *depends on the approximation of the sky*. If the number of lights is small, as in Figure 5 (a)-(c), several branches grow to the same light in certain distance. This distance depends on the size of the apical buds; they situate themselves at certain distances so as not to inhibit itself and therefore each other.
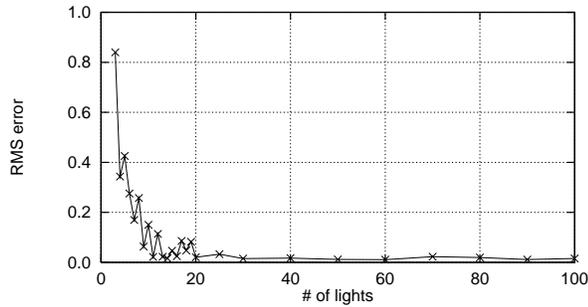
Fig. 6. Presents the error in the plant's shape due to approximation of the skylight.

Quantification of this effect is rather difficult. It cannot be quantified during the plant development, because next stage of the plant depends on the previous one, and therefore the error grows rapidly. We have tested virtual plant with about 200 buds and 3000 leaves. We run one simulation step, *i.e.,* we measured the amount of light, and we have saved the growth direction of the control plant. The control plant was measured with sky approximation by 10^4 light sources. Then the resolution was decreased, and the simulation was run again. The growth direction of the buds was measured once again, the data from which allowed us to generate the following normalized RMS error (see Figure 6).

We meet here a typical computer graphics problem - *aliasing*. Nonetheless, arriving at a solution is a straightforward task. We must increase the precision of the skylight approximation, *i.e.,* the number of lights. The approximation with 20 lights was visually sufficient in most of our simulations and below the level of recognition compared to the approximation with 10^4 lights. The branches are visually chaotical, so this error is registered only if the number of light is too small.

5.2 The others influence of light

The change in the growth direction of buds is one of several influences of light. As the light reaches leaves, they produce photosynthates [18] which are then transported to the adjacent buds. The amount transported has a great influence on the bud's activity. Their insufficiency causes buds to become dormant; on the other hand if there is a lot of photosynthates, the bud gives raise to a lateral bud. In [18], the influence of the light is simulated by two threshold values. If the amount of the photosynthates in the bud is above the first threshold, the bud produces lateral buds. If the amount is between these two thresholds, the bud grows. Insufficiency of the photosynthates, meanwhile, causes the bud to become dormant (inactive). These findings are in keeping with a well observed tendency of the plants for spreading more extensively if the light is enough.

However, this rather complex model can be simplified by remaping the influence of the light to the bud's growth rate. Let t_g and t_b denote time of birth of a bud and time of generation of the lateral bud respectively. The value t_b is set to a constant value T when the lateral bud is born. This constant is unique for the plant and typical for species. The bud D_i produces total length of internode denoted by l in the time $t_b - t_g$. Let t denote actual time and $t_g < t < t_b$. We denote by l_0 the length of an internode which was already produced by the bud in time $t - t_g$. The length denoted by

$$\Delta l = l - l_0$$

would be produced in time $t_b - t$ if the amount of light ϕ_{D_i} (*c.f.,* (3)) reaching the bud is equal to one. According to the relative light flux reaching the bud we *shift* the time of lateral bud production t_b to

$$t_b' = t + (t_b - t)\frac{1}{\phi_{D_i}}. \tag{6}$$

However, the remaining length of the internode Δl which will be produced does not change. So it will be produced in longer time *i.e.,* the bud is inhibited according to the incoming amount of light. According to [18], we should measure the amount of light coming to the adjacent leaf, but a direct measuring of the light reaching the bud enhances the calculation. The error caused by this simplification should be quantified.

We do not require any constant for a simulation of this influence of light. If the amount of light is low, the bud decelerates its growth by lengthening the time of next lateral bud generation.

6   Implementation and results

The program was implemented in *C*, uses *OpenGL* for the amount of light determination, and was run on *Silicon Graphics Indigo*^{2} workstation with Extreme graphics board and R4400 on 200MHz MIPS processor. We use previously published algorithm [3, 4] for the light calculation. The shaded pictures were ray-traced in `POVRay`.

Color plates demonstrates the plant growing near the obstacle and therefore spreading more extensively in the direction of incoming light. The branches are bend in the direction of the light as well. Another example shows the plant with branches strongly searching the light. We can see, that strong phototropism helps the branches to finding their way around the obstacles (no collision detection has been solved). Last two color plates show the same plant growing in different light conditions.

For more information visit `http://sgi.felk.cvut.cz/~benes/cas97.html`.

7   Conclusions

The purposes of this paper were to once again alert to the significance of the relationship between the plant and its environment and to study the light influence to visual plant development. We presented that the discretization of the skylight causes alias which presents itself somewhat specifically - with growing several branches parallel towards the light. Finally, we introduced the simplified model of bud growth with response to incoming light.

8   Acknowledgments

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