Kasetsart J. (Nat. Sci.) 48 : 105 - 110 (2014)

Virtual Simulation of Plant Growth Towards Light

Cherdsak Kunsombat

ABSTRACT

A plant growth simulation model was developed based on a diffusion-limited aggregation (DLA) model, which was modified by taking into account the influence of a light stimulus. The plant structure and the direction of growth were determined by adjusting the two parameters, α and θ, which control the strength and the direction of light, respectively. The simulation results showed that virtual plant growth can respond to the light source. The plant growth tended toward the light source in a designed direction between 60 and 120°.

Keywords: Plant growth simulation, virtual plant growth, DLA, diffusion-limited aggregation, plant growth toward light

INTRODUCTION

The problem of plant growth simulation is a current research topic, since it plays an important role in agriculture and industry and involves multidisciplinary aspects in the fields of biology, physics, mathematics and computer science having attracted the attention of researchers in many fields such as the plant sciences (Cieslak *et al*., 2008; Boudon *et al*., 2012), agriculture (Room *et al*., 1996), botany (Cieslak *et al*., 2011), landscape design (Kiniry *et al*., 2008), environmental science (Hanan, 1997; Foxa *et al*., 2001), entertainment (Hart *et al*., 2003) and education (Sen and Day, 2005; Faruk Senan *et al*., 2008).

Despite the volumes of work on this problem, no complete solution has been presented. In general, the interaction of a plant with light is still an interesting problem. Nowadays, there are many approaches to solve the problem. However, one of the famous approaches is based on L-systems (Sen and Day, 2005). Although, L-systems have been accepted as a practical approach, this does not mean that they produce the best model as currently, there is no definition to show which approach is good or not, because of the lack of a quantitative comparison method. In this paper, a new and different approach has been proposed based on the diffusion-limited aggregation model (DLA) of Witten and Sander (1981). This is a simple model that can mimic plant growth toward light. By modifying the DLA model, the plant structure and the direction of growth can be determined in any direction. Moreover, the bending angle of the plant can be measured in a quantitative result.

MATERIALS AND METHODS

In the standard DLA model, initially, a nucleation seed is placed on the bottom. Then, a particle is released from the upper line in a random position and moves in random walks until it contacts the seed, then it sticks to it and becomes the cluster. Then, the next particle is released. This process continues until a large number of particles have been formed. To modify the standard

Department of Physics, Faculty of Science, Kasetsart University, Bangkok 10900, Thailand.
E-mail: fscicsk@ku.ac.th

Received date : 05/08/13 Accepted date : 21/11/13

DLA model so that it can mimic the plant growth toward light, biased random walks are used. Biased random walks are defined by the probability that the particle will move up, right, left or down at the next step, depending on α and θ, according to Equations 1a–1d:

$$Pu = 0.25 - 0.25\,\alpha \sin\theta \quad (1a)$$

$$Pr = 0.25 - 0.25\,\alpha \cos\theta \quad (1b)$$

$$Pl = 0.25 + 0.25\,\alpha \cos\theta \quad (1c)$$

$$Pd = 0.25 + 0.25\,\alpha \sin\theta \quad (1d)$$

where Pu, Pr, Pl and Pd indicate movement up right, left and down, respectively, α is a parameter ($0 \leq \alpha \leq 1$) which controls the strength of the light source and the angle, θ, is a parameter ($0 \leq \theta \leq 180$) which controls the direction of growth as shown in Figure 1.

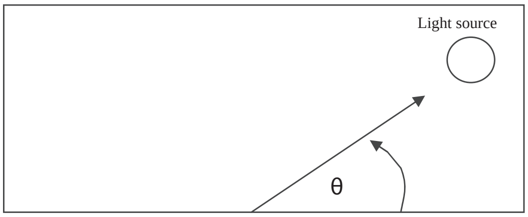

Figure 1 Simulation model for 600 × 300 lattice ($0 \leq x \leq 600$ and $0 \leq y \leq 300$), where the angle, θ, is measured from the x axis.

Simulation was carried out using an algorithm with a 600 × 300 lattice. Initially, a nucleation seed was placed at the bottom (x, 0). Then, a single particle at a time was released from the upper line in a random position and was allowed to diffuse in biased random walks according to the probability defined by Equation 1, until it hit the seed or the growing cluster. At this stage, the next particle was released. This process was continued until as large a number of particles had formed as desired.

RESULTS AND DISCUSSION

Figure 2 shows the morphologies for plant growth, where $\alpha = 0.05$, $\theta = 60.0°$ and the nucleation seed is placed at position (150, 0), while the number of particles was increased from 1,000 to 7,000. The angles of the center of mass of plants in Figure 2 were calculated for different numbers of particles of 1,000, 3,000, 5,000 and 7,000 and produced results of 64.7, 62.8, 61.2 and 60.3°, respectively. These results show that the angles tend to approach 60.0° which indicates that the plant is responding to light by growing toward the light source in the designed direction.

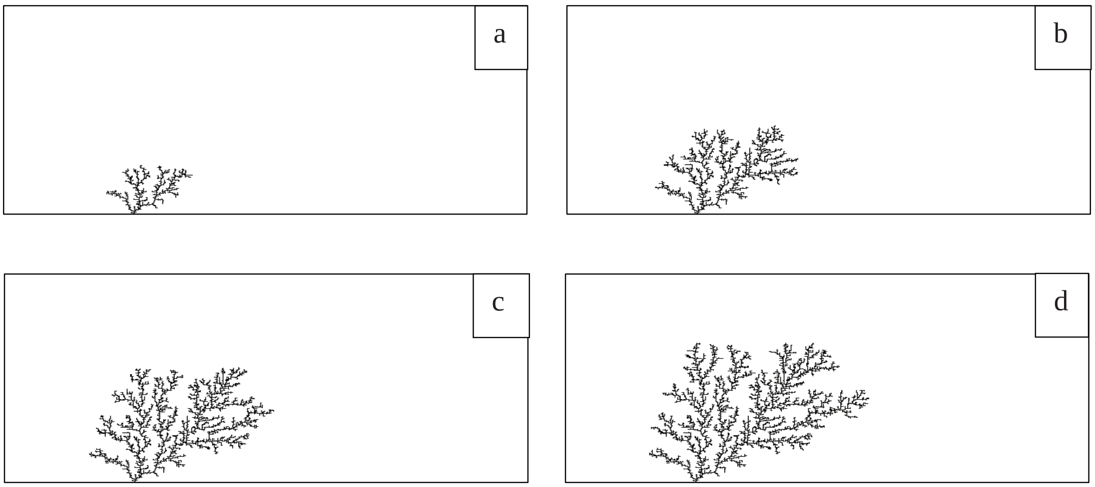

Figure 2 Morphologies for plant growth, where $\alpha = 0.05$, $\theta = 60.0°$ and the nucleation seed is placed at position (150, 0) with an increasing number of particles of: (a) 1,000, (b) 3,000, (c) 5,000 and (d) 7,000.

Figure 3 shows the morphologies for plant growth, where α = 0.05 and θ = 90.0°. In this case, the nucleation seed was placed at position (300, 0), while the number of particles was increased as in Figure 2. The angles of the plant center of mass were evaluated using different numbers of particles of 1,000, 3,000, 5,000 and 7,000 and produced results of 90.0, 90.0, 90.6 and 90.0°, respectively. These experiments showed that the angle approximated 90.0°. It can be seen that when the light source is moved to 90.0°, the plant responds to light by growing in a bottom-up direction.

Figure 4 gives the morphologies for plant growth, where α = 0.05 and θ = 120.0°. Now, in this case, the nucleation seed was placed at

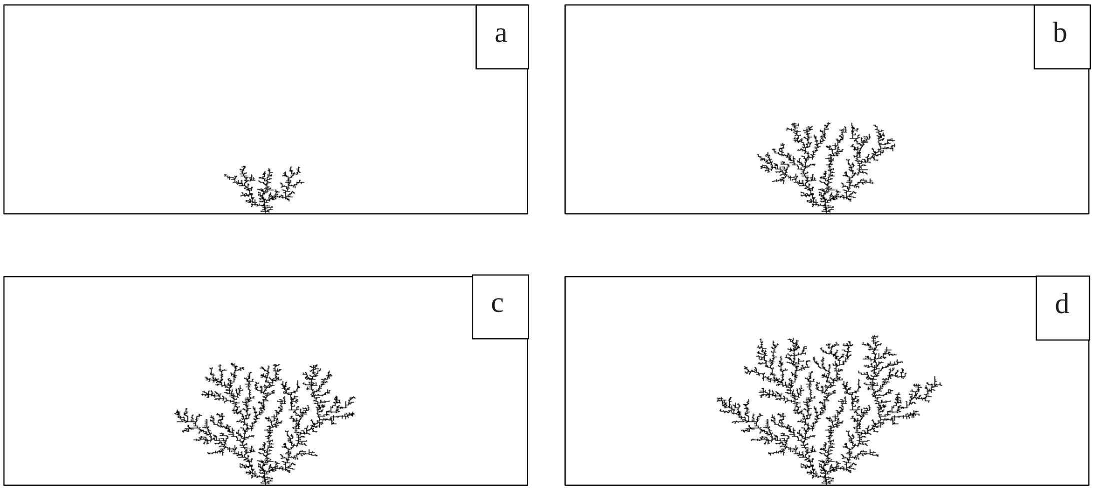

Figure 3 Morphologies for plant growth, where α = 0.05, θ = 90.0° and the nucleation seed is placed at position (300, 0), with an increasing number of particles of: (a) 1,000, (b) 3,000, (c) 5,000 and (d) 7,000.

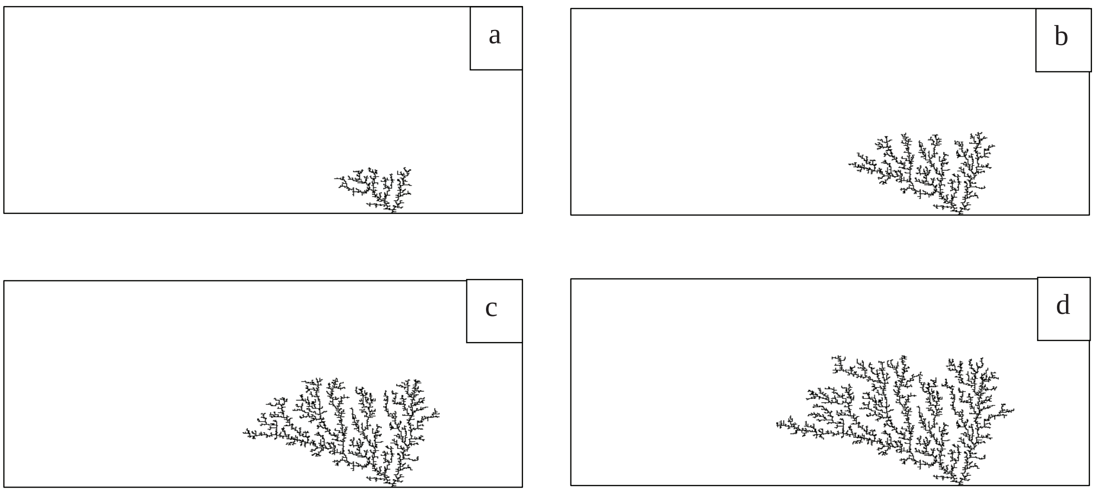

Figure 4 Morphologies for plant growth, where α = 0.05, θ = 120.0° and the nucleation seed is placed at position (450, 0), with an increasing number of particles of: (a) 1,000, (b) 3,000, (c) 5,000 and (d) 7,000.

position (450, 0), while the number of particles was increased as in Figure 2 and Figure 3. The angles of the center of mass were calculated using different numbers of particles of 1,000, 3,000, 5,000 and 7,000 and produced results of 112.0, 117.0, 118.0 and 119.0°, respectively. These experimental results showed that the angles tended to 120.0° indicating that when the light source was moved to 120.0°, the plant was still able to respond to the light source by growing toward the light source in the left top in the designed direction.

The above simulation results showed that the plant center of mass tends to aim towards the light source in the designed direction. However, when the angle, θ, is different from the above simulations, the angle of the center of mass is not in accordance with the designed direction. Table 1 shows the angle of the center of mass with the angle, θ, between 10 and 170°. It was found that when the angle, θ, was less than 60° or more than 120°, the angle of the center of mass deviated from the designed direction indicating that this simulation model was suitable for values of θ in the range between 60 and 120°.

The present model does not include object interaction and illumination. However, the simulation results shown above are similar to the results of Haevre and Bekaert (2003) whose model used L-systems and included the illumination and the object interaction. Nonetheless, the present model can determine the direction of light source in any direction and the bending angles of the plant can be measured in two dimensions.

Next the case was considered of a leaning plant growing for a few days near a light source such as a window. Figure 5 shows the simulation of plant growth near a window, where $\alpha = 0.05$, $\theta = 60.0°$ and the nucleation seed was placed at position (150, 0), while the number of particles was increased from 500 to 5,000. The results show that the plant grows toward the window and then moves out of the window toward the light. These results can be compared to the results of Soler *et al*. (2001), where their results were based

Table 1 Simulation results repeated 10 times for the angle, *θ*, between 10 and 170°.

	Angle of center of mass (°)										
θ	1	2	3	4	5	6	7	8	9	10	Mean
10	41.9	41.9	39.8	42.3	44.4	42.2	40.3	40.3	42.6	40.5	41.6
20	41.8	43.6	40.6	45.7	43.0	44.3	42.8	45.0	44.1	41.0	43.2
30	45.5	42.8	46.0	47.2	43.7	46.0	42.0	42.9	44.8	45.5	44.6
40	46.8	48.2	49.1	48.0	54.8	47.1	48.6	48.2	44.0	48.6	48.3
50	57.4	56.2	57.5	56.4	55.9	53.1	58.6	55.3	52.2	56.9	56.0
60	59.0	61.2	60.2	59.0	60.4	60.9	61.7	57.6	60.2	61.5	60.2
70	71.6	72.1	70.0	69.2	68.6	71.7	69.4	70.5	72.1	67.4	70.3
80	79.8	83.3	76.9	77.1	82.0	78.6	82.2	77.8	77.7	77.8	79.3
90	92.1	93.1	89.2	87.4	91.6	92.6	90.9	89.5	88.8	90.0	90.5
100	101.0	96.9	103.0	99.5	99.2	99.1	98.7	104.0	99.5	99.4	100.0
110	109.0	111.0	112.0	110.0	106.0	109.0	111.0	110.0	109.0	110.0	109.7
120	119.0	120.0	119.0	119.0	123.0	117.0	118.0	120.0	123.0	120.0	119.8
130	127.0	129.0	128.0	127.0	126.0	131.0	129.0	126.0	129.0	125.0	127.7
140	134.0	133.0	131.0	132.0	131.0	132.0	134.0	131.0	135.0	137.0	133.0
150	135.0	136.0	139.0	136.0	134.0	135.0	141.0	140.0	139.0	139.0	137.4
160	139.0	138.0	135.0	139.0	138.0	140.0	138.0	139.0	138.0	141.0	138.5
170	140.0	139.0	138.0	139.0	137.0	139.0	138.0	139.0	139.0	138.0	138.6

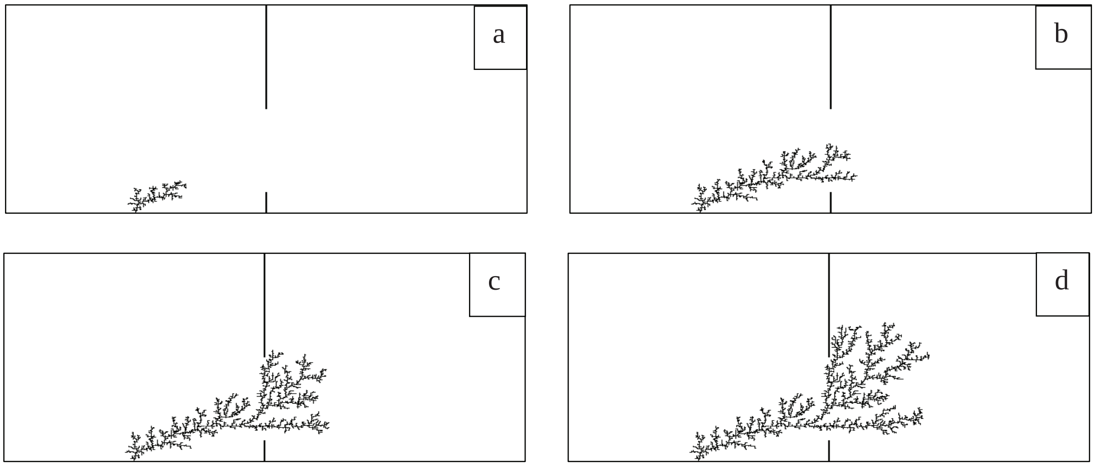

Figure 5 Morphologies for plant growth near a window (shown by the vertical line in the center of each figure), where α = 0.05, θ = 60.0° and the nucleation seed is placed at position (150, 0), with an increasing number of particles of: (a) 1,000, (b) 3,000, (c) 5,000 and (d) 7,000.

on accurate radiant energy transfer. Their model required accurate radiant energy exchange and as a consequence, it required more information from the environment and the plant characteristics, and thus was a complicated model.

Although the present model is in two dimensions, it is a simple model that can mimic plant growth toward light. The plant structure and the direction of growth can be determined in any direction. Moreover, the bending angle of the center of mass of the plant can be measured as a quantitative result. This model can be extended into three dimensions and can be modified by including environmental interactions, such as object interaction or interaction with other plants and illumination.

CONCLUSION

Plant growth simulation has been presented based on the DLA model. By incorporating the effects of the light stimulus, the plant structure and the direction of growth can be determined by adjusting the two parameters, *α* and θ, where α and θ control the strength and the direction of light, respectively. The model can be used to mimic plant growth toward light when the light source is located in a direction between 60 and 120° and the virtual plant growth responded well to the light source. However, when the angle, θ, was outside this range, the plant growth still responded to the light source but it deviated from the designed direction.

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