A simulation model for interactive tree growth in a complex environment

KDS Jinasena[1*] and DUJ Sonnadara[1]

[1]*Department of Physics, University of Colombo, Sri Lanka*

*damithsj@gmail.com

Abstract

This paper presents a dynamic modelling framework for simulating the growth of a tree with environment interactions which allows a tree to adapt to the distribution of light and proximity to solid obstacles. In our method, growth space of a tree was implemented as a grid of voxels and light was approximated as a Laplacian distribution where each voxel has a discrete intensity value. Sensitivity to the environment was simulated based on the hypothesis that a branch has a higher tendency to grow towards availability of light. Generation of a branch was determined by probabilistic evaluation of the growth candidates (buds) based on the resource availability in the environment. Geometric properties of the branches were continuously evaluated with addition of branches in order to represent the growth of the tree. Our model generates dynamic output which shows response to the light and the presence of obstacles in the growth space.

Keywords: **Plant models, Stochastic models, Botanical tree models, Self-organizing tree models, Monte Carlo**

I. INTRODUCTION

Visual simulations of natural phenomena have become a very important area of research in computer graphics. Simulation of trees in particular, is a widely popular area of research and there are many works carried out in order to produce natural-like trees. Tree growth is a complex process in nature which associates with many internal and external factors and therefore simulating visually realistic tree growth is a quite difficult task. Various techniques have been proposed in the context of modelling trees but there are very few models available for simulating the tree growth. In addition, most of the available models are not capable of generating dynamic outputs and representing interactions with the environment.

In this paper, we present a method which simulates the dynamic tree growth starting from a seedling until it becomes a mature tree. This method allows stochastic development of branches where probability of generating a branch is based on the availability of sunlight and the space for growth in the surrounding. Usage of stochastic methods has reduced the user involvement during tree generation and generates unique results each time even-though the environmental conditions are unchanged.

II. RELATED WORK

Simulation of plants has a long history and the first deterministic model was proposed by Honda [3] which considered a tree as a recursive structure characterized by parameters such as branching angles and the ratio of module sizes at consecutive recursion levels. Tree development characterized by the botanical knowledge was introduced by de Reffye *et al.* [1]. Their model for generating tree is based on the activity of buds where at a given clock signal, bud can possess one of the activities according to specific stochastic laws characteristic for each variety and each species. A model which enables interactions with the environment was proposed by Greene [2] where he has used voxel space data to represent the relationships with environment like intersection, proximity, and occlusion. Method introduced by Palubicki *et al.* [9] has considered a tree as a hierarchically organized modular structure where growth of the tree takes place by addition of new shoots. More recently, tree models have been created based on competition for resources [5] and dynamic reactions to their environment by computing the temporal light conditions and the inverse tropism of a tree model [10].

III. METHOD DESCRIPTION

Our model is based on the procedural bifurcation modelling [3] and the probabilistic occurrences of branches [7] was used where the stochastic growth with the environmental sensitivity was simulated based on Dielectric Break-down model (DBM) [8]. DBM is Laplacian growth algorithm where it tries to grow the branching patterns that occur in electric discharge towards the maximum resource availability. DBM was applied to the formation of trees also [6] where, the generation algorithm is based on the hypothesis that the growth probability of branches depends on the resource availability of surrounding environment. This research is also based on the same hypothesis but here we are focusing on real-life tree growth where addition of new shoots affects the properties of inner branches and the maturity of a tree. A tree was defined using topological and geometrical structures where, binary-tree data structures were used to store the data. Topological data for branching structure was calculated using Strahler analysis [4, 11] and properties of inner branches were calculated continuously with the addition of new shoots.

For botanical trees, as for many other natural branching patterns, the width of the branches decreases when moving from the root to the terminal nodes. In general, it is the same for the length of the branches but less significant thus, in this research we have assumed the branch length to be fixed for modelling convenience. For a branch having Strahler order k, decreasing function for width $W(k)$ can be given as follows [12].

$$W(k) = \begin{cases} c \times k^{\alpha}, for\ polynomial\ growth \\ c \times \beta^{k}, for\ exponential\ growth \end{cases} \quad (1)$$

where c, α and β are numerical constants

TABLE I
NUMERICAL CONSTANTS AND THEIR DEFAULT VALUES IN EQUATION 1

Constant	Value
c	0.67
α	1.15
β	1.50

Once the topological data were calculated for the tree, geometrical structure was obtained by converting each edge in the mathematical tree into a botanical branch in terms of predefined fixed length and width calculated using the decreasing function *W(k)*. Each node was converted in terms of branching angle and the inclined angle uses fixed values with random perturbations in order to simulate the realistic appearance of trees.

IV. SUMMARY OF THE ALGORITHM

In this research, we have used the voxel space as the method of representing the growth space of the tree. In general terms, voxel space means a region of three-dimensional space, partitioned into identical cubes (volume elements or *voxels*). There are many possible ways of representing the tree geometry and the environment with grid of voxels. Greene [2] has used a voxel occupation method to represent the tree geometry where the trees were simulated from predefined geometric elements according to rules based on simple relationships like interactions, proximity, and occlusion which were evaluated with voxel space. It also occupied probabilistic growth mechanism where multiple trials are attempted in which an element's position and orientation are randomly perturbed, and trials which best fit a set of rules is selected.

Voxel representation of environment has been used in the self-organizing tree models [9]. In that model, shadow propagation method based on voxels was used to compute the exposure of each bud to light where they were able to represent the competition of buds and the branches for space or light successfully.

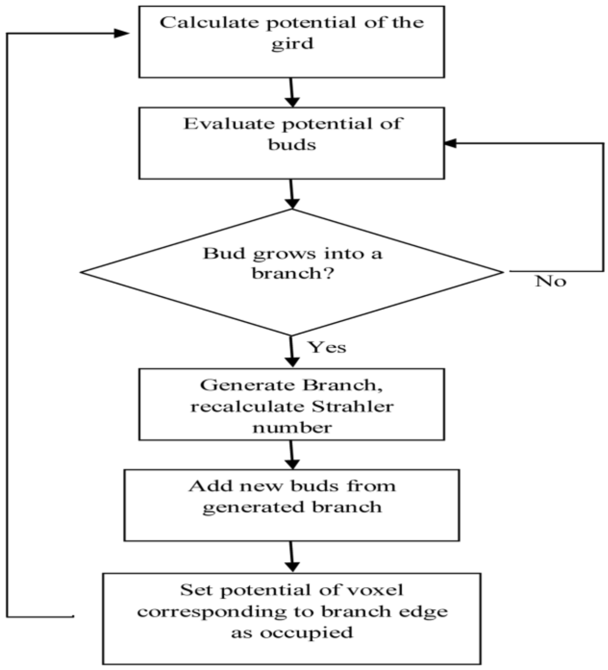

FIG. 1 Overview flowchart of the algorithm

Our model is based on the assumption that light distribution in the space is similar to a discrete charge distribution where, light source is represented by positive charge (ϕ = *1*) and boundaries of the grid has assigned negative potential (ϕ = *0*). Each other voxels has assigned a potential value in between by evaluating the potential distribution. Growth of the tree is taking place by locating the potential corresponding to a bud and the decision of growing a bud into a branch was taken based on its potential value. FIG. 1 shows an overview flowchart illustration of our algorithm. We have used stochastic development of branches where the growth of branches is occurring from buds. A bud has two options to choose from in one growth cycle. That is to remain dormant (retaining the possibility of growing in the future) or grow in to a branch. Decision of generating a branch from a bud is determined by probabilistic evaluation of resource availability in the environment. This process continues to add branches until maximum level of binary branching has reached which we used as the height of the tree.

Our model uses a root-to-leaf reconstruction method to simulate the growth of the tree. As described above, we assume that the development of the tree is taking place by addition of new branches to the structure where, the decision of extending a bud into a branch is based on DBM. When a new branch was added, it assigned the Strahler order one ($k = 1$). If the newly added branch has a sibling branch with $k = 1$, then the Strahler order for the parent node was set as 2 according to the definition of Horton-Strahler analysis. Recalculation of Strahler order continues until the root node is reached to update modified Strahler order of inner branches due to the addition of new branch.

After the recalculation of Strahler order for branching nodes, geometrical information were regenerated using decreasing function $W(k)$ for the nodes which have changed the Strahler order. This was done by starting the re-growth from root or from the top most node which has changed the Strahler order and traverse till the leaf nodes are reached. Regeneration of geometrical data has given the possibility to implement dynamic interactions with environment and to simulate the real-time growth of the tree.

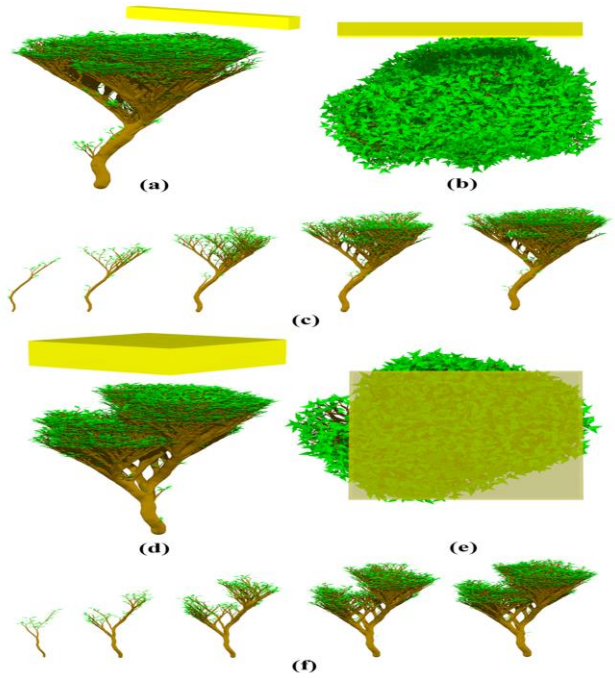

FIG. 2 Tree growth with different positioning of the light source where the light source is indicated in yellow cube/cuboid (a),(b),(d),(e). All the results are 'grown' from seedling until it becomes a mature tree. (c),(f) shows different stages of tree growth corresponding to the positioning of light source

V. IMPLEMENTATION AND RESULTS

Algorithm for the simulation of tree growth with environmental sensitivity was implemented in C++ and the output was rendered with POV-Ray (ray tracer). Topological and geometrical structures were stored in binary tree data structures where each node was defined as a struct and for the implementation of grid which represents the environment, vector arrays based data structures were used. C++ program was designed to generate a separate POV-Ray file for generation of each branch and named that file sequentially. By rendering each of the resultant POV-Files and combining each rendered output as a movie, it is capable of simulating the real-time growth of the tree.

Growth of the Tree with a Light Source

Generating the tree starts by placing the seedling as the first branch of the tree structure and adding sub branches recursively to the structure. At each step, it will add a new branch to the structure and according to the rules defined with Strahler order; branch width for all branches in the tree were recalculated. Output from each iteration was interpreted as a POV-ray file which was then rendered as a snapshot of the tree development. Typically, plants show positive sensitivity to the direction of the light. We have generated results with different positioning of the light source and observed that the tree growth always follows the tendency to grow towards the light source.

FIG. 2(a, d) illustrates results obtained for different environment configurations where, the position of the light source is shown as a yellow cube/cuboid. From these results it can be seen that the addition of branches taking place biased to the direction of the light source. As a result, branches facing the light source are growing faster than the branches opposing the light source. Our model generates the output at each addition of a branch which, represents the growth of the tree. FIG. 2 (c, f) represents different stages of the tree growth for corresponding light configurations for the final outputs of (a) and (d).

Interaction with Obstacles

Usage of voxel based development and the DBM driven growth mechanism made it possible to simulate the growth of the tree when there are obstacles present in the environment. Obstacles were represented as zero potential voxels (blue colour objects in FIG. 3) and the growth algorithm avoid growing the tree inside an obstacle since the probability of growth inside obstacle is zero according to DBM.

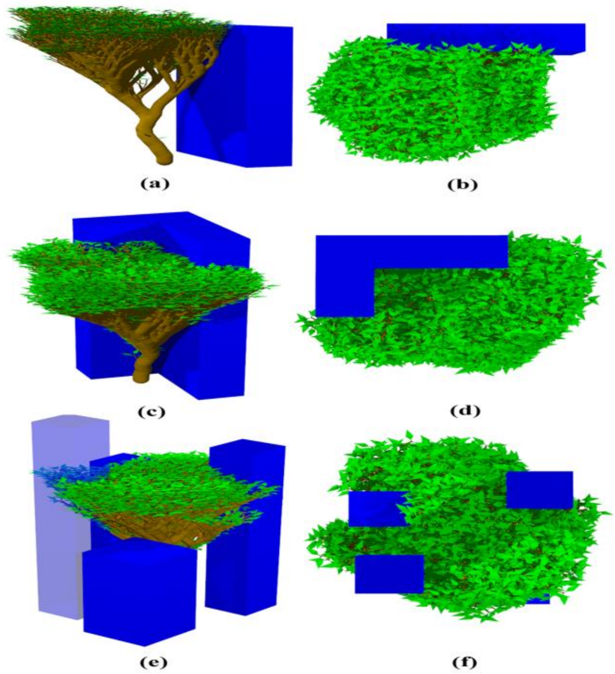

FIG. 3 Generated outputs with interactions with obstacles.

FIG. 3 shows results obtained for different configurations of obstacles and it can be concluded that the tree is trying to avoiding the obstacles and optimize into the free space similar to the natural trees.

VI. CONCLUSION

In this paper, we presented a new modelling framework for simulating tree growth which enables interactions with environment in different ways. To our knowledge, it is the first attempt to simulate the stochastic tree growth using a procedural model based on environment data accompanied by DBM. With the combination of DBM model and Dynamic topological data, we were able to represent complex interactions with the environment with a simpler algorithm.

Our method, so far developed as a framework for modelling the stochastic tree growth with environment interactions thus the results obtained do not based on any real tree specific parameters. Furthermore, we have only used primitive graphic details in the final results. In order to get more realistic trees, basic growth parameters and the visual appearance of branches need to defined using such tree specific data.

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