Proceedings of the 7th International Conference on Functional-Structural Plant Models, Saariselkä, Finland, 9 - 14 June 2013. Eds. Risto Sievänen, Eero Nikinmaa, Christophe Godin, Anna Lintunen & Pekka Nygren. http://www.metla.fi/fspm2013/proceedings. ISBN 978-951-651-408-9.

Optimize Tree Shape: Targeting for Best Light Interception

Jing Hua and **Mengzhen Kang**
State Key Laboratory of Management and Control for Complex Systems,
Institute of Automation, Chinese Academy of Sciences, China
**correspondence:* mengzhen.kang@ia.ac.cn

Highlights: It is assumed that plants have a certain kind of fitness so they can optimize their behaviors to maintain a specific target. Optimization algorithm is used to find tree shape that can maximize the light interception. The shape we got is reasonable and looks like a real tree, which proves partly the fitness of plants.

Keywords: Optimization, Tree Shape, GreenLab model, Fitness, Light interception

INTRODUCTION

It is observed that plants have some adaptively variable behaviors during their growth (Trewavas 2003), such as changing branch numbers and shape to intercept more light, transmitting biomass internally to guarantee growth of fruits, and reducing leaf area to preserve water in the arid environment, etc. From these phenomena, it is reasonable for us to assume that plants have a certain kind of fitness so they can change their behaviors in order to maintain a specific target. Trying to simulate and analyze this kind of fitness with virtual plants is an interesting and challenging work.

Functional-structural plant models (FSPMs), originated by combining Process-Based Models and plant structure, can be used to simulate plants fitness. In general, the simulation process in FSPM begins from a parametric setting, computes plant development (organ formation) and plant growth (biomass pruduction and partitioning) cycle by cycle, and finally gets some results such as organ biomass, organ number, 3D shape, etc. If this simulation process is regarded as a function whose inputs are model parameters and outputs are simulation results, it is possible for us to use some optimization algorithms to find parameters that can maximize or minimize some outputs. It is a feasible way to simulate the fitness of plants.

As light environment plays a key role for plant growth and development, light interception is a key topic in plant growth modeling. Tree shape, which is mainly decided by phyllotaxy, branching angle and bending, will greatly affect the light interception of a tree. Given the topological connections and organ sizes of a tree, there is an optimized tree shape that can maximize the light interception. In this work, we aimed to use some heuristic algorithms to find this optimized shape. Although it is just a simulation and needs further calibration, the result is interesting because the tree shape we got looks very similar to the real tree shape.

METHODS

We used GreenLab model to simulate growth of the tree. Detailed computation process can be referred to Yan HP et al. (2004) and Kang MZ et al. (2008). Once the simulation ended, we got topological connection of branches and size of all organs, based on which the 3D shape can be constructed. Our object is to find a tree shape that can maximize the light interception of this tree. Next we will describe briefly model parameters controlling tree shape, light distribution algorithm and optimization methods.

1. Parameters controlling tree shape

There are three important aspects that can affect tree shape: phyllotaxy, branching and bending. Firstly, phyllotaxy is the arrangement of leaves on a plant stem. As branches develop from axillary buds, phyllotaxy also decides the direction of branches. GreenLab model uses a parameter ϕ (ranging from 0 to 360 degree), which is defined as rotate angle between two adjacent internodes, to describe phyllotaxy, as shown in Fig.1. Secondly, branching angle is the angle between a branch and its mother stem. As it is assumed that branching angle increases along the main stem from top to bottom, GreenLab model uses a parameter θ (ranging from 0 to 180 degree) to describe the maximum branching angle, i.e., angle between the lowest branch and main stem, as shown in Fig.2. Other branching angles are calculated using linear interpolation. Finally, branches are seldom straight completely. They bend downward according to the gravity and upward according to the phototropism. As a result, branches are represented as many kinds of shapes. We use a method which originated from mechanical calculation to compute the branch bending. After simplification, there are two parameters K (larger than zero) and p (ranging from 0.0 to 1.0) that control respectively the degree of bending and the position where the branch begins to fold upward. The effect of these two parameters is illustrated in Fig.3.

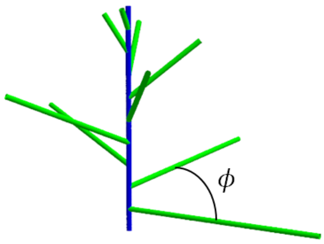

Fig. 1. Phyllotaxy angle ϕ, which is defined as rotate angle between two adjacent internodes

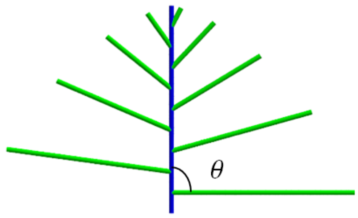

Fig. 2. Maximum branch angle θ

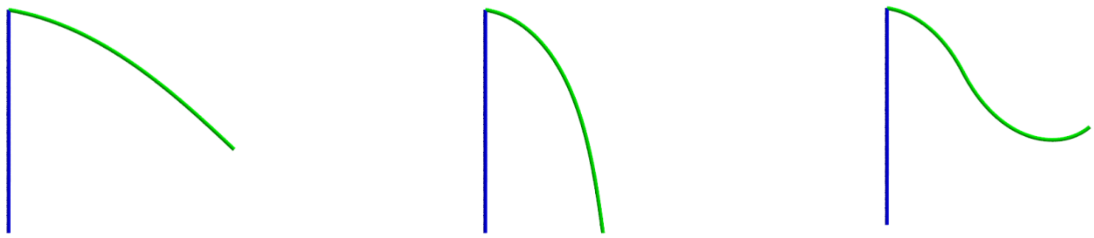

Fig.3. The effect of two parameters controlling the branch bending. Parameter values from left to right are: (1) $K = 0.02, p = 1.0$, (2) $K = 0.05, p = 1.0$ and (3) $K = 0.05, p = 0.4$

2. Light interception computation

In plant growth modeling, light interception is computed either by an empirical Beer-Law approach using leaf area index, or by summing up the light interception from individual organs. Since our object is to optimize the tree shape, we choose the latter method because it takes into account the detailed description of plant structure. There are several works concerning the light distribution in crop canopy (Wang XP et al. 2006, Zheng BY et al. 2011). Unfortunately, these methods can be hardly used in tree canopy because firstly there are more organs in trees than in a crop and secondly the ratio of single leaf size to the whole tree size is too small.

A simple light model is implemented in our system. Since leaf is represented as a mesh object in computer memory, several rays were emitted evenly into sky sphere from each point of the leaf mesh. For each ray, we counted leaves that this ray encounters (assuming n). The *visibility* of this ray is calculated as t^n, where t is the light transmittance of leaf. Finally, the *visibility* of a leaf is estimated using the mean value of *visibility* of all rays emitted from this leaf mesh. We use the sum of *visiblity* of all leaves (denoted by V) to measure the light interception of the tree.

3. Optimization algorithm

Given branch connections and sizes of all organs, the *visibility* V can be written as a function of four parameters described in part 1, $V = f(\phi, \theta, K, p)$. It is a typical optimization problem to find a set of parameters to maximize V. As the function is non-derivative or even discontinuous, heuristic algorithms are more suitable for this problem. We used PSO (Particle Swarm Optimization) algorithm (Shi et al. 1998).

As V has different sensitivities to different parameters, we used three steps to optimize. In each step, we fixed some parameters and optimize others. The order of optimized parameters is: firstly phyllotaxy, secondly branching angle and finally bending parameters.

RESULTS AND DISCUSSION

The simulation result is illustrated in Fig.4. All leaves are removed for showing more clearly the structure of the tree. We chose a relatively simple tree whose structure is shown in the left. The initial parameter values are: $\phi = 180, \theta = 25, K = 0.0, p = 1.0$, which means that all branches are straight and in a vertical plane, and all branching angle are the same. After optimization, we got the tree shape in the right, whose parameter values are $\phi = 48.52, \theta = 102, K = 0.0555, p = 0.21$. It is very intersting that the shape looks like a real tree. This result shows that it is possible to use optimization algorithm to get reasonable tree shape, and then proves partly the assumption that plants have a certain kind of fitness so they can optimize their behavior in a specific environment.

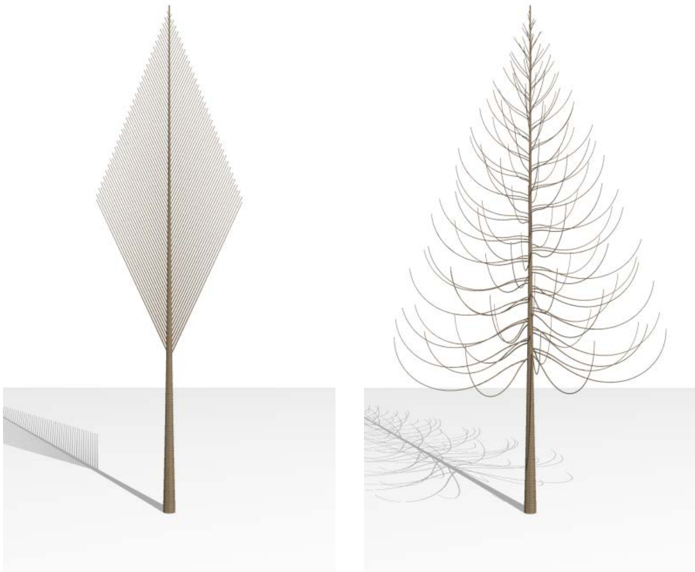

Fig. 4. Simulation result. Left is the topological structure of a tree and right is the optimized tree shape we got.

We choose a simple tree in this work just because of the computing efficiency, as both calculation of light distribution and the optimization algorithm are very time-consuming. There are no substantial difficulties to generalize this method to more complex trees because the computing time is proportional to the number of organs. What we need are just more powerful computers.

This method can also be used in crop fields to optimize phyllotaxy, leaf angle, and so on. It will be very useful if we could find the good crop shape in some conditions such as given planting density. It is challenging but deserves hard working.

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