An Interactive Plant Pruning System Based on GreenLab Model: Implementation and Case Study

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***Abstract*—Functional-structural plant models (FSPMs) attract much attention from researchers in the area of both plant science and computer science. Such models make it possible to have interaction between human being and virtual plants. However, attempts of simulating pruning are still few, and obtaining self-organized reaction as in real plants remains a challenge. In this paper, we present an interactive system of plant pruning based on GreenLab model, where bud dormancy can burst into branches by modified source-sink balance after pruning. With the mechanism feedback in the model, users can change the form and growth of plant via different pruning policies. Virtual experiments show that our system gives realistic result, and can potentially serve for applications in agronomy, education and virtual reality.**

I. INTRODUCTION

Functional-structural plant models (FSPMs) [1] describe in quantitative way the development of three-dimensional structure of plants as governed by physiological processes and affected by environmental factors. It is desired to simulate two basic processes of plant as well as their interaction in a FSPM: organ production (development) and organ expansion (growth). On this basis, virtual experiments can be made to have an instant and cheap way of obtaining response of plant to human management.

Pruning is a common activity in horticulture and silvaculture. FSPM basically make it possible to operate on plant 3D structure, but such work remains few, and to obtain realist plant reaction remain scientifically challenging. L-peach presented an example of virtual pruning experiment [2], where the number and type of buds that break after pruning follows certain statical distribution. Yet the question is whether we can simulate the response of pruned plant in a self-organized way without forcing the distribution. This will depends on the mathematical model supporting the behavior of virtual plant.

In this paper, we present a plant pruning system based on GreenLab, a generic functional-structural plant model simulating trees [3] and crops [4]. The reaction of plant is simulated based on a simple hypothesis that bud activation and organ growth are all controlled plant source-sink ratio. The paper is organized as follows: firstly a brief introduction to GreenLab model is given, secondly the implementation of pruning system is described, followed by the examples of pruning experiment as case study. Conclusion and discussions are given in the end of paper.

II. GREENLAB MODEL

GreenLab model was designed to provide dynamic representations of morphogenesis and architecture of a plant on the basis of a minimal number of mathematical equations and biological rules. Its detailed description can be found in several publications [5] [6]. Here we give a brief introduction to this model to recall essential concepts linked to current system.

A. Time step

In GreenLab model, the plant growth process is discretized into discrete time steps according to organogenesis. At each growth cycle, the model computes the production of new organs, the allocation of biomass among all growing organs, biomass and size of each individual organ, and then new biomass production will be computed as a function of leaf area.

B. Botanical concepts and their equivalence in GreenLab

In trees there are different levels of organization. The smallest botanical unit is a metamer, which consists of one internode, one apical bud, axillary bud(s) and leave(s), and occasionally flowers. Successive metamers created in the same growth period gives a growth unit, and an annual shoot is made by one or more successive growth units. Simultaneous development of buds gives branching structure. Different type of buds give shoots of different vigor, called physiological age (PA) [7].

GreenLab uses dual-scale automaton to simulate dynamics of tree architecture [8], where user can define the potential components of each kind of metamer, growth unit, and axis, according to PA. An axillary bud in a metamer can develop in to a branch containing new metamers, as shown in Fig.1. In current pruning system, the behavior of a bud, being dormant or active, will depends on plant source-sink ratio, as defined below.

C. Computing source-sink ratio

In GreenLab, a simple empirical formula is used to compute the biomass production at cycle n as a function of plant leaf area, see Eqn. 1.

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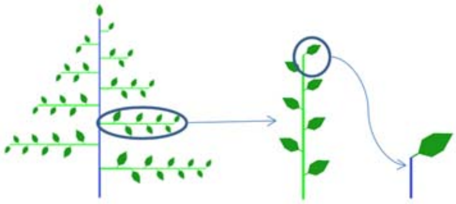

Fig. 1. Illustration of tree structure organization, from left to right: plant, branch and metamer

$$Q_n = E \cdot S_P \cdot \frac{1}{r} \cdot \left(1 - \exp\left(-k \cdot \frac{S_n}{S_P}\right)\right), \qquad (1)$$

where E is environmental factor, k and r are constant model parameters, S_P is the maximum projection area this plant can occupy, state variable S_n is a total leaf area at cycle n, computed as result of biomass allocation.

Biomass generated in this growth cycle will be allocated to growing organs according to their relative sink strength. The sum of organ sink strength gives total plant demand, see Eqn2.

$$D(n) = \sum_{O} \sum_{i=1}^{n} \sum_{p} f_O(i) \cdot N_O(p, n-i+1) \qquad (2)$$

where p is PA of organs, O refers to type of organs, $f_O(i)$ is sink strength of i-aged organ of type O, defined usually with a Beta law in GreenLab applications [4]; $N_O(p, n-i+1)$ is number of i-aged organs O of PA p, given by the automaton simulating plant organogenesis. For trees, there is another component of demand for ring growth [3].

The ratio of plant production to demand is defined as source-sink ratio, noted as Q/D, which will be the determinant of bud fate in this pruning system.

D. *Self-organized mechanism*

A key assumption of GreenLab model is that the fate of a bud (active, dormant or dead) is determined by source-sink ratio Q/D. Very interesting pattern has been created under this mechanism [6]. In current version, reactivation of the dormant buds is introduced to simulate burst of buds caused by updated source-sink ratio by pruning. As only active buds are taken into in computing D, removal of terminal active buds in pruning will augment Q/D and drive the activation of dormant axillary buds. The amount of re-activated buds, from top to bottom, is positively related to the updated source-sink ratio after pruning. For each CA, there is a parameter controlling the dependency of bud activation on source-sink ratio.

III. IMPLEMENTATION OF PLANT PRUNING SYSTEM

Our system is implemented in object-oriented style and using C++ programming language. The key points of the system is presented below.

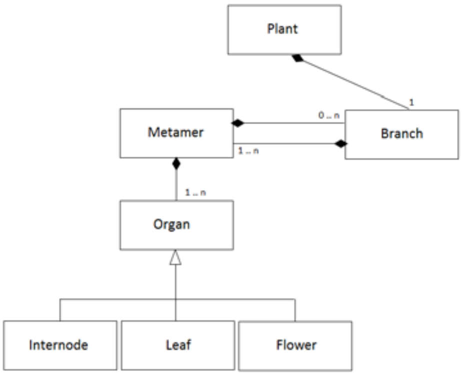

Fig. 2. Classes diagrams

A. *Basic Classes*

As GreenLab model simulate plant growth at organ-level, we defined a class *Organ*, each object has properties like *Age*, *CA*, *Demand*, etc. From class *Organ* derived several child classes including *Internode*, *Blade* and *Flower*. A class *Bud* is used to define apical or axillay buds. A class *Metamer*, containing a list of organs, one apical bud, several axillary buds, is used to define metamer, the basic botanical unit of plant as described in section II-B. A class *Branch*, consists of a list of successive metamers, is used to define the bearing axis of various branches in plant structure. Finally, a class *Plant* define the whole plant. The class diagrams of these classes are presented in Fig.2.

B. *Metamer-Branch Recursion*

Almost all operations on a plant (such as calculating total leaf area, plant demand, total plant weight) involve traversal of the whole tree structure, which is implemented in our system using *Metamer-Branch* recursion. For an example, to get the total demand of plant, we will sum up the demand of metamers in the trunk; while the demand of a metamer is sum of organ demand in this metamer plus sum of metamer demand from sub-branches. Thus, starting from the trunk (a *Branch* object), two classes, *Branch* and *Metamer*, will invoke each other's method to get demand until all of the plant structure is visited. Most operations are implemented in the similar approach.

C. *GUI Interaction*

In each growth cycle, all organs, whose space position and orientation are calculated after the allocation of biomass, will be showed three dimensionally. The rendering and interactive part of our system is implemented using OpenGL, part of which is illustrated in Fig.3.

3D plant structure can be viewed by skeleton, frame or mesh mode. Users can rotate, move, zoom or select the plant interactively at any plant age. To continue plant growth, user can click the button *Next Cycle*. Once an object is selected, for example, a leaf as in Fig. 3, a rectangle will appear to indicate the selection. Then user can click button *Delete* to remove this object. Notice that if an internode is deleted, all

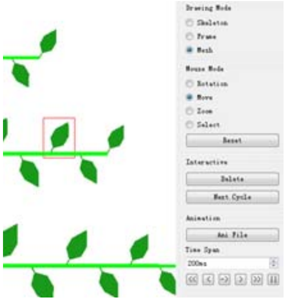

Fig. 3. Interactive Interface. Left: zoomed view of plant in Fig. 1. Right: control panel for pruning.

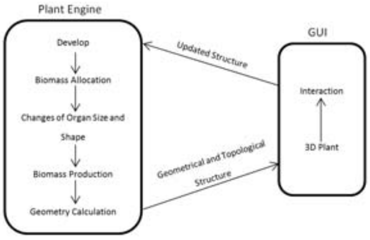

Fig. 4. Process of Interaction

of its upper part, including apical bud, stem and sub-branches, will be removed from plant structure.

After user interaction, the plant topological structure will be sent back to the growth engine with updated information (if any) for computing plant growth and development. Firstly bud activity (dormant or giving birth to organs of active and dormant buds) will be decided according to the source-sink ratio (Q/D) in the updated structure. The available biomass will be allocated among organs in the new structure. Organ biomass and size, biomass production will computed afterwards, and send the new geometrical and topological information of next cycle to GUI interface. The whole process of interaction is showed in Fig.4

IV. CASE STUDY

We will see in this section an application of the system to get different pruning strategy of a sample tree. The tree used in this virtual experiment is set to 16 years old. This tree is pruned once at cycle 5. Instant change of tree structure at cycle 7 is shown for comparison. Four pruning strategies were tested:

- Without pruning (Fig. 5);
- Tip removal of the trunk (Fig. 6);
- Tip removal of the trunk and all primary branches (Fig. 7);
- Pruning of all branches and trunk tip (Fig. 8);

To see clearly the change in plant structures, only stems of trees are showed in Figs. 5-8. As we have set different dependency of branches to the source-sink ratio, given different pruning strategies, the plant gives different types and amount of branches from dormant buds. More branches appear from re-activated buds at lower position under strong pruning.

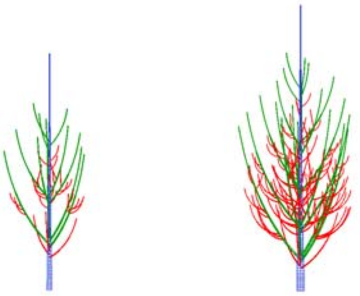

Fig. 5. Without pruning: cycle 5 (left) and cycle 7 (right)

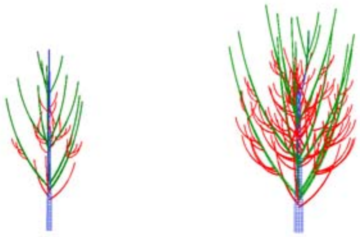

Fig. 6. Tip removal of the trunk: cycle 5 (left) and cycle 7 (right)

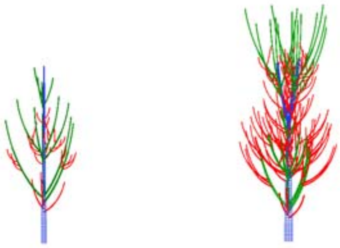

Fig. 7. Tip removal of the trunk and all primary branches: cycle 5 (left) and cycle 7 (right)

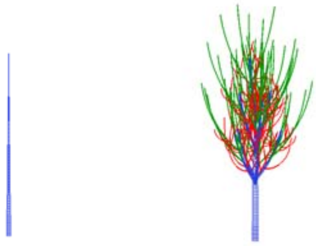

Fig. 8. Pruning of all branches and trunk tip: cycle 5 (left) and cycle 7 (right)

The final tree structures at cycle 16 for all pruning cases are illustrated in Fig.9. The corresponding rendered 3D plants are showed in Fig.10. The result of our virtual experiment looks very realistic: more strongly pruned plant gives more branches and wider crown.

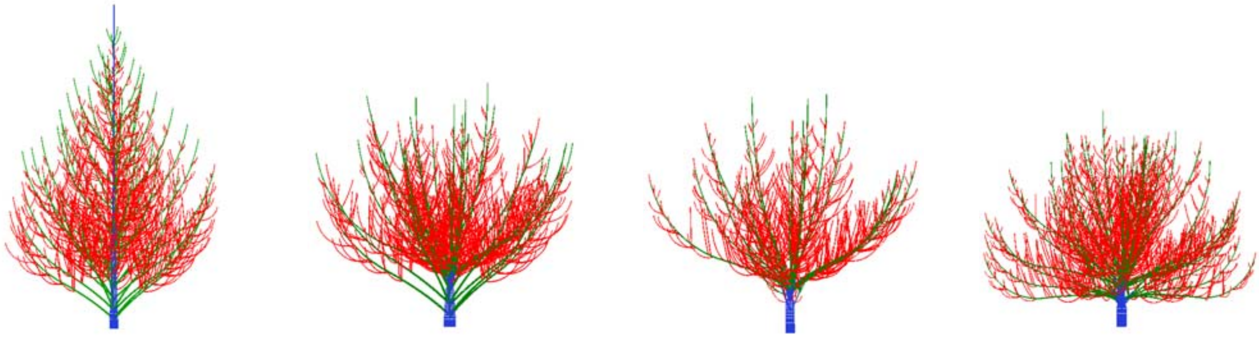

Fig. 9. Tree skeleton at cycle 16 from different pruning strategies in Figs. 5-8

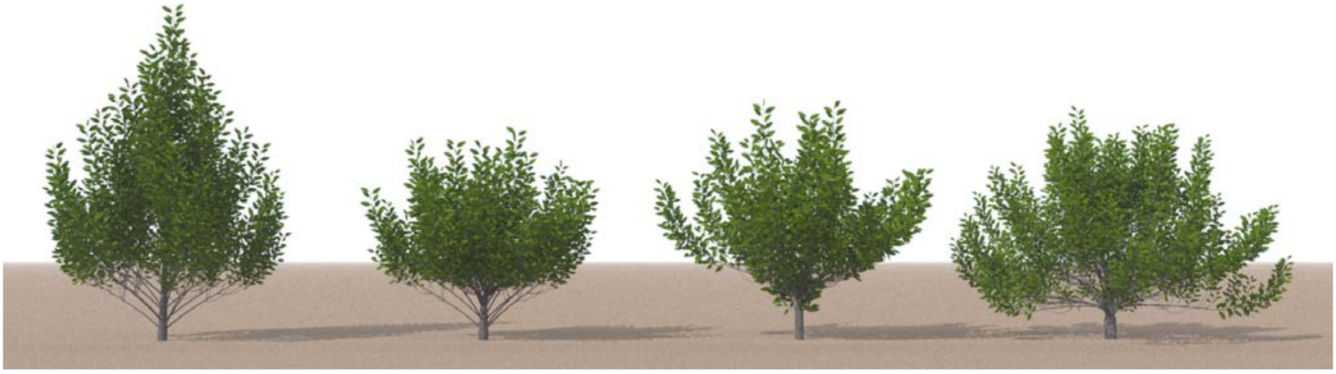

Fig. 10. Tree 3D shape at cycle 16 from different pruning strategies in Figs. 5-8

V. CONCLUSION AND DISCUSSION

We established an interactive system for plant pruning based on GreenLab model. Resulting from the feedback mechanism of the model, the structure and growth of plant can be affected by users through pruning. As illustrated in the section IV, the resulting structures of a tree are both botanically and visually realistic under different pruning strategies. The new feature introduced into the model, re-activation of buds from dormant state, is proved to be a key component to achieve our goal. This system may serve for education, entertainment and research in plant science.

Nevertheless, the current work raises several scientific questions if the goal is to simulate faithfully the behavior of a real tree. For example, to which degree the bud break out is dependent on its source-sink ratio, and how to quantify this relationship of real trees. Currently, pruning changes the plant demand but not the source. In further work, source of plant need to be also updated after pruning, instead, a biomass reserve should be introduced explicitly into the model.

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