Evolutionary Design of Virtual Plants

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Abstract - This paper presents a technique of evolutionary design for plants in virtual worlds, inspired from Richard Dawkins' adaptive walks within the space of biomorph structures. The design is carried out by interactive sessions with a multi-agent platform of generic virtual plants. The plants, growing in a three-dimensional environment, are based upon the fusion between a two-substrate transport-resistance model and an L-system formalism. Two simulations highlight the interest of modeling interactions with the environment and a framework of physiological processes for resource management. Resource assimilation allows obtaining growth differences between the individuals depending on their access to light and soil minerals. Resource flow and allocation inside the virtual plants induce phenotypic plasticity. These dynamics contribute to a range of adaptive growth patterns.

Keywords: biomorphs, evolutionary design, plant modeling, virtual worlds

1.0 Introduction

Virtual worlds are fascinating from both the science and entertainment point of view. Aside from immersed users, they may be populated with inanimate objects, but also with life-like elements such as animals and plants. However in current virtual worlds, plants are most often represented as either static items or, at best, structures based on a set of morphological growth rules without physiology and important interactions with their environment [1,2,3]. Yet the development of a natural plant depends on the environment it is exposed to. A deficiency in important resources may lead to reduced growth or even death. Moreover, the morphology of many natural plant species significantly adapts to local environmental conditions, a phenomenon called phenotypic plasticity [4]. In order to embrace these aspects for virtual plants, it stands to reason to consider virtual worlds which incorporate the fundamental mechanisms that control plant growth in nature.

As the creation of three-dimensional models of complex objects such as plants is a difficult task, conventional modeling tools like manual CSG based systems often turn out to be inappropriate, and alternative design methods must be considered. In his book "The Blind Watchmaker" [5], Dawkins describes adaptive walks within the genetic search space of simple two-dimensional structures called biomorphs (figure 1). For each generation, the user selects a biomorph to survive and reproduce, so that the structures gradually adapt to a given design purpose. This process is a form of evolutionary algorithm [6], inspired from the concept of natural and artificial evolution as originally proclaimed by Darwin [7].

Interactive design of plants has been performed using models based on both procedurally generated [8] and L-system generated [9,10] structures, but these approaches only considered morphological development, whereas physiology was not taken into account. This paper presents the evolutionary designs of plants and highlights the interest of modeling interactions with the environment, combined with a conceptual framework of physiological processes for resource assimilation, flow and allocation. Both aspects contribute to a range of adaptive growth patterns.

The next section gives an introduction to the modeling of plants. After the presentation of the virtual plant model in section three, some design sessions and relevant simulations are described in section four. Section five concludes the paper with reflections on the approach.

2.0 Background

The origins of computer modeling and visualization of plants can be traced back to the 1960s, when Ulam simulated the development of branching patterns using cellular automata [11]. About ten years later, Honda was probably the first to introduce a computer model of tree structures [12]. Since then a huge amount of work has been devoted to this research field. As the aims of study can differ from one plant model to another, there exists a variety of approaches. According to the traditional classification suggested by Kurth [13], physiological and morphological models can be distinguished.

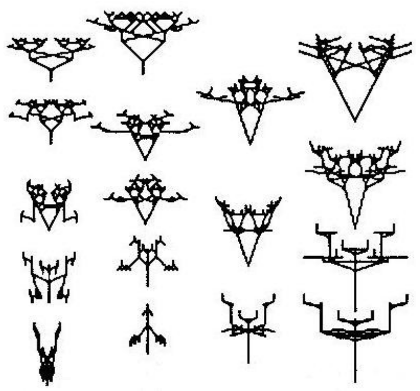

Figure 1: Biomorphs

Figure 2: Iterations of the L-system $\{A, P, \omega\}$

2.1 Physiological models

Physiological models, also called process-based models, reflect metabolic processes inside a plant. Their architectural structure remains low detailed, as the individual plant is merely decomposed into a fixed number of compartments such as root, stem and crown, exchanging substances in terms of mass variables. The attention is primarily turned to carbon balance, due to its importance for plant growth, by modeling photosynthesis, carbon allocation and respiration. However other influential substances such as soil nutrients can equally be taken into account. Because of their manageable architecture and their small number of parameters, physiological models are convenient for plant representations at a rather coarse scale [14].

2.2 Morphological models

Morphological models primarily describe plant architecture by making use of its modular structure [15]. They consider the plant as a composition of repeated modules like leaf, fruit or fine root which dynamically appear and disappear during the plant development according to a number of morphological growth rules. The probably most widely used representations of plant morphology are based on L-systems [16]. L-systems are formal grammars with the possibility of recursive applications in a parallel rewriting process. Starting from an initial axiom ω , a set of rules P is iteratively applied in order to form a string of characters from an alphabet A . The string represents the plant, whereas each character represents an elementary unit. Positional information of the units can be integrated by using a bracketed notation. The translation of the string into a geometric structure is achieved by graphical interpretation using turtle geometry [16]. As an example, figure 2 illustrates a simple L-system and the resulting plant after several iterations.

2.3 Virtual plants

Morphological and physiological processes of plant development are profoundly interwoven [17], and in the last decade many models emerged as the coupling of both aspects. They typically hold characteristics of process-based models and depict a 3D representation of the plant structure. Because of their complete picture of plant development, these models are also termed "virtual plants" [18].

3.0 The plant model

There exists a large number of virtual plant models, but they are most often specifically designed for or adapted to representing given plant species [19,20,21] and not intended for performing evolutionary dynamics. A new model has been conceived which closes this gap.

3.1 Environment

The physical environment is a continuous 3D space composed of the soil and the sky, homogeneously divided into a number of voxels each of which holds local environmental information. Light and minerals are resources of prime importance for the growth of natural plants [22]. The sky voxels provide light which

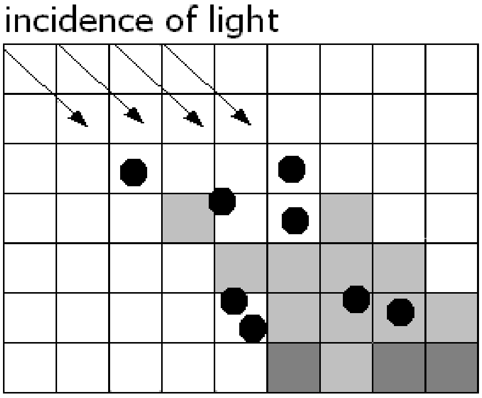

Figure 3: Shadow casting in sky voxels

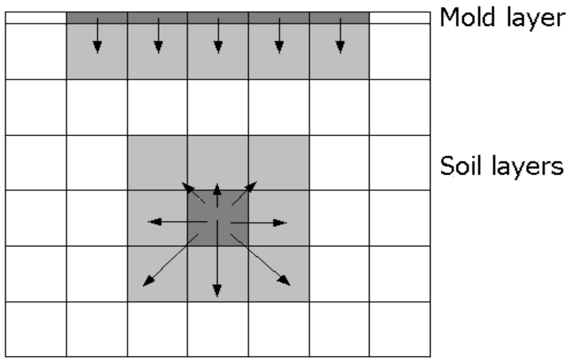

Figure 4: Diffusion among mold and soil voxels

is captured by the leaves in order to produce carbon via photosynthesis. If an object is situated aboveground, it casts shadows. In such case, the light intensity of all sky voxels following the angle of incidence is decreased (figure 3). Soil voxels contain minerals which are assimilated by the fine roots. Diffusion, a passive movement from regions of high concentration to regions of low concentration, leads to mineral balance between neighboring voxels (figure 4).

3.2 Virtual plant

A virtual plant is divided into an aboveground and belowground component called shoot and root respectively. Their morphologies are expressed by an L-system whose alphabet is detailed in table 1. The geometric shape of the plant modules is based on sphyls (cylinders with spherical ends). The shoot and root morphologies of virtual plant seedlings both start with the single non-terminal character A which is subsequently modified by the respective L-system production rules. A small amount of initially available biomass allows the young plant to develop its first modules, but subsequently it has to rely on the acquisition of resources. In the scope of this paper, only deterministic context free L-systems, also called D0L-systems [16], are applied. The predecessor character of the first rule is A , that of the second rule is B and so on. As an example, figure 5 shows the sample L-system of a simple bush.

The physiological processes of a plant are based on a two-substrate version of the transport-resistance model [23]. Shoot and root hold separate substrate pools for carbon and minerals. Photosynthesis charges the shoot carbon pool, and root assimilation supplies the root mineral pool. Growth occurs through the conversion of carbon and minerals into biomass, deducting a certain loss to litter. The exchange between the carbon and mineral pools is represented as a function of substrate concentration difference divided by a resistance. Thornley [24] suggested that all physiological models of plant development should start with this irreducible framework. When shoot and root produce new biomass, it is redistributed to the apex modules according to the quality of locally available resources. Advantageously situated apexes receive proportionately more biomass than apexes with low access to resources. Once the biomass of an apex reaches the required cost, its corresponding production rule is applied. After a limited span of life the plant dies and its resources are restituted to the environment.

Character	Compartment	Geometry	Function
l	shoot	sphyl	captures virtual light
b	shoot	sphyl	creates a branching structure
r	root	sphyl	assimilates minerals in the soil
c	root	sphyl	creates a branching structure
A... Z	shoot / root	none	predecessors of the production rules
[ ]	shoot / root	none	indicate a ramification
+ - < > $ &	shoot / root	none	represent 3D rotations by fixed angles

Table 1: The L-system alphabet

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Shoot:

Axiom: [A]
Production rules:
A →[>b[B]A]$$$$$[>b[B]A]$$$$$$[>b[B]A]
B → >>l

Root:

Axiom: [A]
Production rules:
A →[<c[B]$$A][[B]$$A]
B → >r
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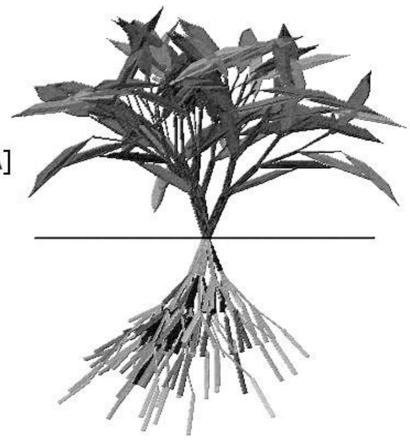

Figure 5: Sample L-system of a bush

3.3 Genotype

The development of the virtual plants is ruled by a set of "genetic information" recorded in a genotype. It contains the parameters and production rules of the L-systems as well as the variables regarding the transport-resistance model. In order to restrict the genetic search space, the evolving elements within the genotype are limited to those which have the greatest impact on the resulting plant morphology. Evolution only affects the L-system production rules, the geometric shapes of the plant modules and the rotation angles. All other parameters described in the genotype are fixed. In particular, the physiological processes of the transport-resistance model are predefined and not subjected to evolution. Mutations are introduced by several genetic operators each of which is associated with a probability. Some act on the entire production rules and some on the characters of the successor strings. The operators acting on the characters are applied to each production rule. The used operators are

- Delete character: A random character in a rule is deleted
- Insert character: A random character in a rule is inserted
- Permute character: Two adjacent characters are switched
- Duplicate character: A random character is duplicated
- Mutate character: A random character is replaced by a new character
- Delete rule : A randomly selected rule of the L-system is deleted
- Insert rule: An empty rule is appended
- Duplicate rule: A randomly selected rule is duplicated
- Mutate parameter: Shapes and rotation angles are slightly modified

4.0 Results

The following section presents the procedure of evolutionary design and some of its results. Two simulations regarding resource deficiency and phenotypic plasticity are conducted in order to point out the potential impact of modeling plant physiology in virtual worlds.

4.1 Evolutionary design

The design is performed by interactive sessions conducted with a simulation platform. The plants are growing in a "virtual garden" which typically holds not more than nine specimens per generation. Just as for Dawkins' biomorphs, a small population is displayed on the screen, and the user chooses one shape for reproduction, according to his/her fancy. Each plant constitutes the phenotype which results from developmental processes, based on the information in the genotype, and interactions with the environment. A seed of the mother plant is situated in one corner, and a number of mutated children are seeded at even distances. Figure 7 presents the virtual garden from a bird's eye view. It can be observed that, due to disadvantageous mutations, not every plant develops complex structures. Among the sample population, one plant grows poorly and another plant does not germinate at all. Plant growth is simulated during a fixed period of time. The user can manually move the camera angle of the 3D visualization and assess each plant from arbitrary points of view.

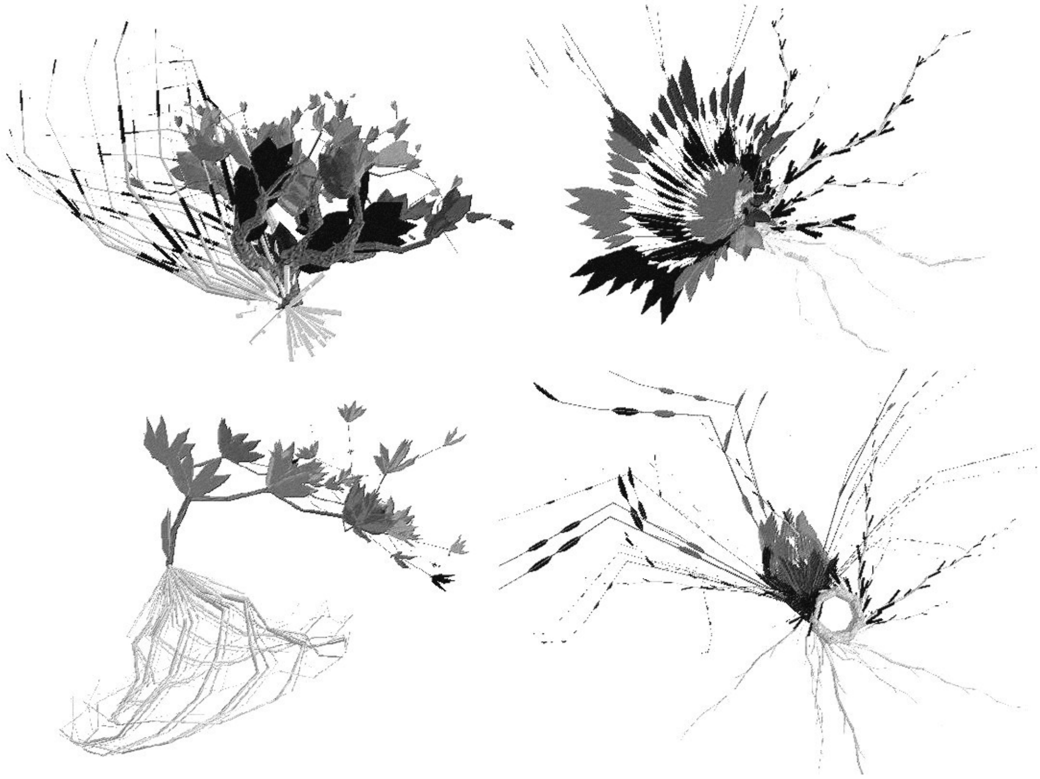

Figure 6: Evolved virtual plants

To grant evolution as much freedom as possible, the genotype of the initial mother plant only contains empty L-system production rules. Since there are no rules to apply, this plant does not germinate. However, mutations may lead to the appearance of non-trivial rules. After a few generations, the first individuals which develop root and leaf modules allowing to obtain the resources necessary for growth emerge, and evolution takes off. Figure 6 shows some of the achieved results. The individuals have especially been designed for appealing screenshots, by selecting crooked shapes and non-functional aerial roots.

4.2 Plant physiology and interactions with the environment

The integration of resource assimilation into the model allows to obtain developmental differences between individuals depending on their local environmental conditions. Insufficient light or soil minerals result in reduced growth. In order to highlight this phenomenon, two simple familiar looking virtual plants have been evolved. The first plant grows high and adopts a tree-like shape. The second plant grows close to the ground and represents a herbaceous species.

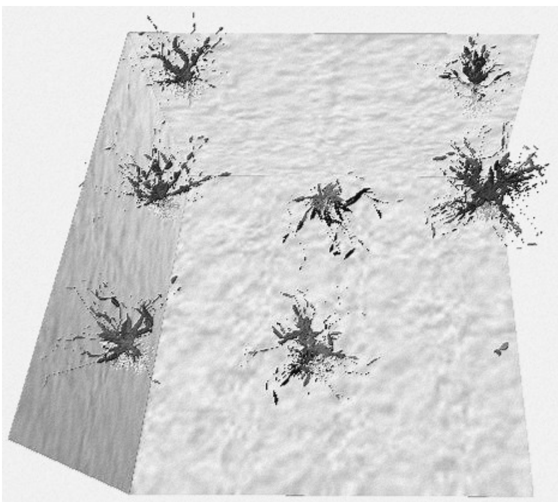

Figure 7: Virtual Garden

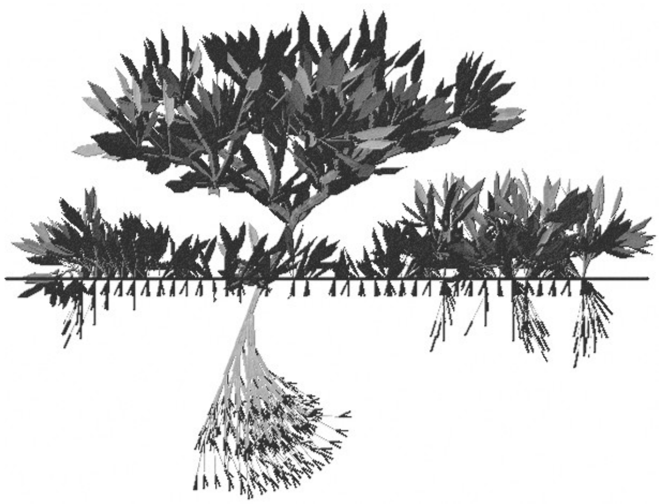

Figure 8: Growth depending on lighting conditions

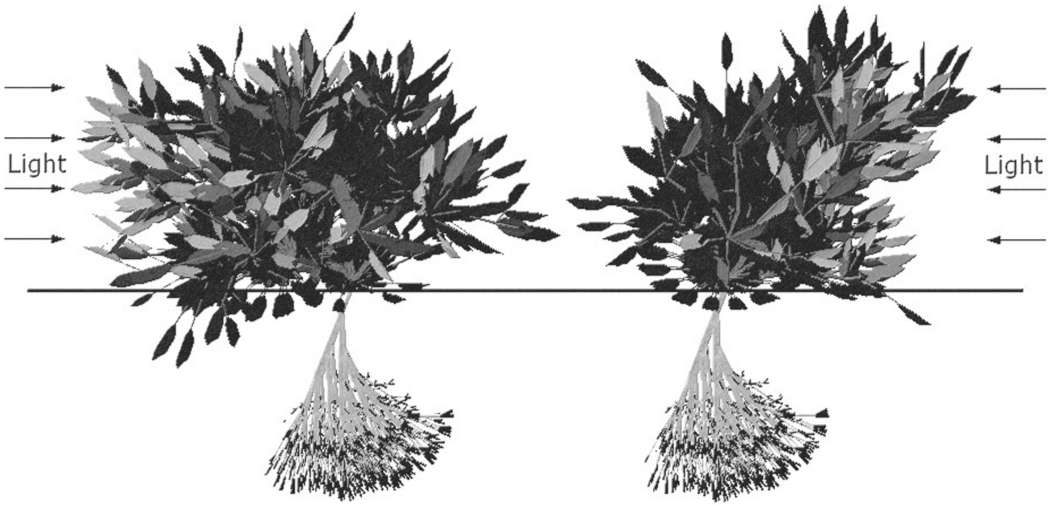

Figure 9: Phenotypic plasticity in response to lighting conditions

Figure 8 shows a number of herbaceous plants which have been seeded in the vicinity of a tree. The light is shining vertically, so that the area beneath its large crown is shaded. Due to low photosynthesis, the herbs located under the tree grow poorly compared to those without restricted lighting conditions.

A second motivation of modeling interactions between a plant and its environment is the phenomenon of phenotypic plasticity. Natural plants tend to grow towards major resources, in particular towards light [25]. Phenotypic adaptation to a given light source is illustrated in figure 9. Two individuals of the designed tree species are grown under light at different angles of incidence. Instead of vertical illumination, the plants are exposed to a lateral light source. It can be observed that the typical large crown of figure 8 is replaced by rather bushy forms. Due to the modified lighting conditions, different apexes are stimulated. Those situated on the opposite side of the tree gradually find themselves in the shadow and are penalized by less resource allocation.

5.0 Conclusion

Interactive evolution offers a convenient way to design complex three-dimensional objects for virtual worlds. In particular, this technique allows creating models without caring about or even knowing the underlying processes involved. The user simply inspects a population of individuals and selects an arbitrary shape, according to his/her design purpose, which is subsequently used for reproduction. Several genetic operators produce slightly mutated genotypes and allow to explore new phenotypic variations of the evolving object.

In this paper, a virtual plant model and its simulation platform have been presented and demonstrated to be an appropriate tool for the interactive evolutionary design of plants. The virtual plants are based on an L-system formalism and integrate resource management by a two-substrate version of the transport-resistance model. Two simulations highlighted the impact of physiological processes on plant growth. Due to interactions with the environment, a genotype produces different variants of the same originally selected phenotype. Resource assimilation allows obtaining growth differences between individuals depending on their access to light and soil minerals. Resource flow and allocation inside virtual plants induce phenotypic plasticity. Instead of designing a large number of predefined phenotypes, diversification can be achieved by one genotype which produces an unlimited number of distinguishable individuals. Apart from a gain in aesthetics and authenticity, this variety is an important step to the creation of biologically inspired virtual ecosystems.

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