Evolution of Virtual Plants Interacting with their Environment

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Abstract: In current virtual worlds, plants are most often represented as static objects or, at best, morphological structures endowed with a simple set of growth rules. This paper presents an enhanced plant model for virtual worlds based on Artificial Life concepts. The virtual plants capture light and assimilate minerals from the environment, and their development is ruled by a set of genetic information which describes parameters concerning morphological as well as physiological processes. Two series of experiments are conducted. The first series discusses evolutionary adaptations of the virtual plants to specific fitness functions. The results reveal developmental constraints which can be related to the life of real-world plants. The second series investigates growth in environments with different lighting and soil configurations. Like natural plants, the virtual plants evolve morphologies in response to the encountered resource disposition. All simulations illustrate how evolving virtual plants can contribute to the study of natural plants, and suggest that virtual worlds allowing plants to interact with their environment may lead to a range of coevolutionary dynamics close to those observed in natural systems.

Keywords: virtual plant, plant modeling, artificial life, evolutionary design

1 Introduction

As users explore virtual worlds, they should be able to interact not only with artifacts and other avatars, but also with native life-like entities such as artificial animals or plants. However, in current virtual worlds, plants are most often represented as either static objects or, at best, structures based on a set of morphological growth rules without physiology and important interactions with their environment [8,20,31].

Since the development of natural plants significantly depends on the environment they are exposed to, it stands to reason to consider models which incorporate more aspects affecting plant growth in nature. Biologists conceive elaborate plant models, so called "functional-structural models" for accurate studies on natural plants, but they are most often designed for individual or population level scenarios of specific species without genetic change [1,2,26,34]. Moreover, their complexity leads to computational problems which increase with the number of simulated entities [30]. Progress has recently been made by gaining a factor 5000 in computing speed for a whole tree architecture compared to previous L-system based methods [33].

To bridge the gap between these two approaches, a plant model of intermediate complexity has been developed. The model is intended to represent plant life in virtual worlds, but also to study scenarios of natural plants and plant communities. Such experiments may allow to gain insight into natural interaction processes and to understand how environmental factors affect them. Simulations at individual, population and evolutionary levels can be performed. In this paper, attention is mainly turned to evolutionary dynamics. The conducted experiments address the question if the virtual plants adapt to evolutionary constraints, and to what extent these adaptations can be related to straightforward observations on natural plants.

The next section gives an overview of the state of the art in the modeling of plants. In section three the used virtual plant model and its simulation platform are briefly presented. Several evolutionary experiments are described and discussed in section four. Section five concludes the paper with perspectives on the approach.

2 State of the art

Within the research fields of Artificial Life and evolutionary computation, only a small amount of works on plants have been carried out. They typically use the L-system formalism [28] as the representation of plant morphology. L-systems are formal grammars with the possibility of recursive applications in a parallel rewriting process. Starting from an initial axiom w, a set of production rules P is iteratively applied in order to form a string of characters from an alphabet A. The string represents the plant, and each character represents an elementary module. Positional information of the modules can be integrated by using a bracketed notation. The translation of the string into a geometric structure is

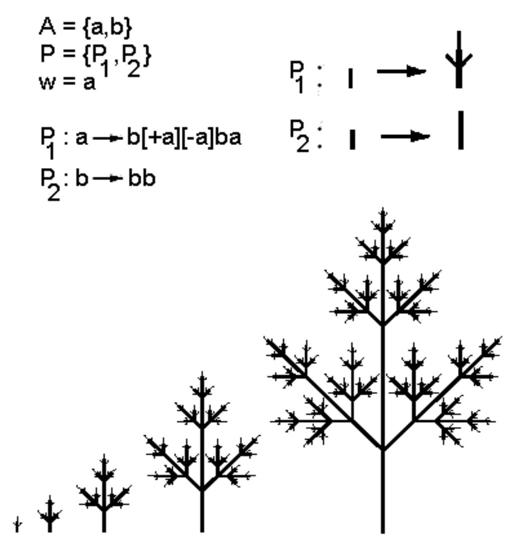

Fig. 1. Iterations of the L-system (A, P, w)

achieved by graphical interpretation using turtle geometry [28]. Figure 1 illustrates a basic L-system and the resulting plant after several iterations.

In 1986, Niklas [22] pioneered the evolution of virtual plants by performing an adaptive walk through a space of branching L-system patterns, based on simple hypotheses concerning the factors that have the greatest effect on plant evolution. Jacob [15,16,17] published a series of papers concerning the evolution of context-free and context-sensitive L-systems representing simple artificial plants. Both approaches were considered and extended by Ochoa [23] who evolved 2D plant structures and showed that L-systems are an adequate genetic representation for studies which simulate natural morphological evolution.

In the spirit of interactive evolution, Mock [20] modeled artificial plants for a virtual world where the human observer chooses the most interesting-looking individuals for further reproduction. Likewise, some applications such as the Second Garden [31] or the Nerve Garden [8] appeared in the past years on the Internet, allowing users to evolve and interact with L-system based artificial plants and plant communities in virtual online worlds.

Referring to natural evolution which emphasizes efficiency rather than aesthetics, Ebner [10] evaluated virtual plants for their amount of captured sunlight and showed that plants under competition grow high compared to small bushy plants which develop when evolved independently. Other recent research applies evolutionary algorithms to the so-called “inverse problem”, i.e. the construction of a model which best describes a given target plant structure [3, 7].

Functional-structural models are mainly designed to understand the impact of morphology on plant growth compared to environmental factors, and to study the architectural strategies of plants with respect to developmental constraints such as the capture of resources or competition. A plant community is represented as a number of virtual plants which grow concurrently in a multi-agent approach [12]. The pioneering work of the AMAP team [2,9] were followed by many others, progressively improving algorithms and including more and more physiology in originally purely structural models. Important examples are

– LIGNUM [26], especially conceived for trees and combining a physiological model with a morphological description of the tree crown,
– L-PEACH [1] using L-systems both to simulate the development of tree structures and to solve differential equations for resource allocation,
– ECOPHYS [29] and SIMWAL [18] which incorporate a physiological into a 3D description of the plant structure and additionally feature submodels for the flow of assimilated substances,
– GREENLAB [33,34] which uses a mathematical simplification to speed up 3D architecture computations their coupling to physiology.

Due to their detailed morphological and physiological description of a plant, functional-structural models open up new possibilities to simulate and investigate natural phenomena that could not be studied with previous generations of plant models [30], for example to infer unknown physiological parameters from the simple observation and simulation of plant architecture [35].

3 The plant model

In the attempt to strike a balance between the evolutionary ALife approach and the complex functional structural models, an intermediate plant model has been developed. Based on a simple concept of generic virtual plants, it is able to carry out simulations of evolving plant communities while emphasizing the most important morphological and physiological aspects of a single plant. In some previous papers, the model was introduced and analyzed for its potentials regarding applications in virtual worlds [5] as well as the study of life history traits observed on natural plants [4]. Therefore, it is only briefly presented in this paper.

The physical environment is a continuous 3D space composed of a soil and a sky, divided into a number of discrete voxels. The sky voxels provide light which is captured by the leaves in order to produce carbon via photosynthesis. Soil voxels contain minerals which are assimilated by the fine roots. Resource dynamics are shading in the sky and mineral diffusion in the soil. Other significant resources such as water and CO2 are currently not modeled, assuming that their supply is constant and sufficient.

A virtual plant is divided into an aboveground and belowground component, called shoot and root respectively. Both morphologies are expressed by an L-system producing terminal modules, such as flowers, leaves or fine roots, and non-terminals called apexes. The model allows for stochastic L-systems [27], but here only deterministic context free L-systems, also called D0L-systems [28], are applied. This choice was made to disengage the evolutionary dynamics from contingencies at individual level.

The physiological processes of a plant are based on a two-substrate version of the transport-resistance model [32]. Growth occurs through the conversion of carbon and minerals into biomass. New biomass is distributed to the apex modules. Advantageously located apexes receive proportionately more biomass than apexes with poor access to resources. Once the biomass of an apex reaches the required cost, its corresponding production rule is applied.

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. However, in view of investigating morphological design which is the main issue of this paper, the genetic search space has been restricted. The evolving elements within the genotype are limited to those which have the greatest impact on the resulting plant morphology, i.e. the L-system production rules. All other parameters described in the genotype are fixed.

The model has been implemented as a simulation platform. It is developed in C++ and uses the Open Dynamics Engine [24] for collision detection and the OGRE library [25] for graphical representations. As described in [5], small amounts of plants are readily rendered in real time, allowing users to manually move the camera angle of the 3D visualization and to assess each individual from arbitrary points of view. Plants can be interactively added, relocated and deleted, and all genetic parameters may be instantly modified during their lifetime. However, a limiting factor for interactive rendering of large scenes is the huge amount of geometry that has to be processed for each frame. With view to applications in virtual worlds, this issue can be overcome by converting the plant morphologies into computationally less expensive data structures like simplified static meshes or even billboards which are regularly updated while the underlying growth processes are constantly ongoing.

4 Experiments

In the scope of this paper, virtual plants are bred by a typical evolutionary algorithm [14]. The seeds of a plant population are placed in a sufficiently large environment and grown for a fixed amount of time. Subsequently, the developed structures are evaluated according to a given

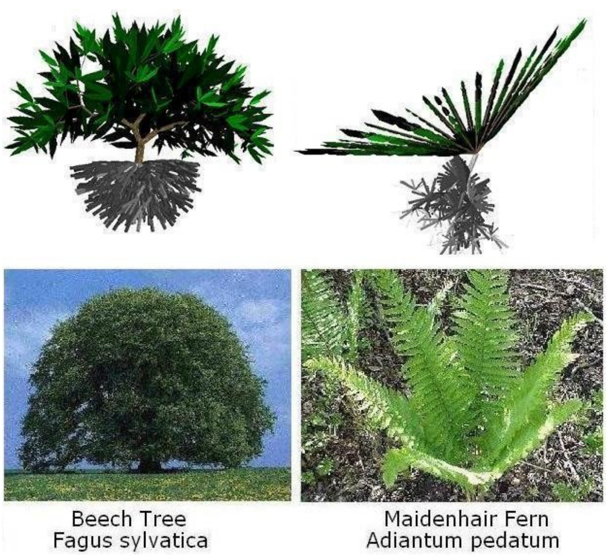

Fig. 2: Typical shoot morphologies

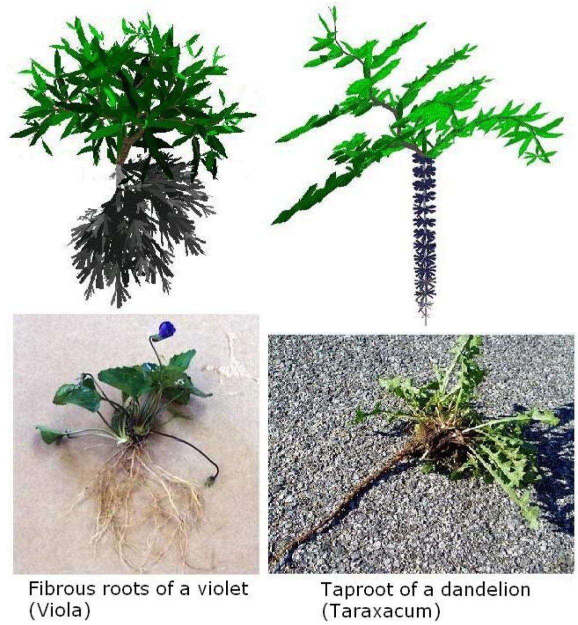

Fig. 3: Typical root morphologies

fitness function. The best individuals survive and give birth, via crossover and mutation operations, to the next generation of seeds. The experiments are terminated after one thousand generations, which represents a trade-off between maximizing the number of generations and keeping the simulation time reasonable. One evolutionary run would take about two hours on a 2 GHz PC.

Two series of evolutionary simulations are performed. The first part discusses evolutionary adaptations of the virtual plants to specific fitness criteria in a constant environment. Conversely, the second part applies only one fitness function and investigates evolutionary adaptations to different environments.

Adaptations to fitness criteria

In these simulations, the environmental conditions are fixed to a "standard" configuration which is vertical light and an initial uniform mineral distribution in the soil. For the first batch of evolutionary runs, fitness is defined as the total biomass acquired during a given growth period. This function was chosen in order to study the emergence of plant structures with respect to the problem of efficient resource assimilation. The virtual plants evolve a number of different morphologies which, in view of the fitness function, can be interpreted as optimized resource gathering strategies. The aboveground part most often evolves into tree- or bush like structures. Another successful strategy, appearing less often but attaining the highest fitness values, is a star-shaped form spreading close to the ground (figure 2).

The prevailing morphology of the belowground compartment is a dense cluster of roots which rapidly

Fig.4: Flowers stored under the leaves

exploits the locally available minerals. In some runs, the plant develops a main coarse root reaching deep into the ground (figure 3). All evolved structures have also been adopted by natural plant species. However, the virtual plants do not develop any flowers. Flowers do not contribute to resource assimilation and are therefore discarded by evolution in favor of more leaves. The observed phenomenon alludes to an important trade-off in plant life : Reproductive allocation reduces growth rate and survival so that any plant needs to find a balance between these activities [11]. Deeper investigations on this topic can be found in [4].

The fitness of the second experiment multiplies the light available to the leaves, the minerals available to the roots and the number of grown flowers at the end of the simulation. As a result, all evolved plants store their flowers under the leaves. This phenomenon emerges because the amount of flowers is taken into account by the fitness function, and evolution favors morphologies where the flowers do not impair photosynthesis. Although the cause might not be light assimilation, some real plant species such as Zingiberaceae likewise develop flowers under the leaves at ground level (figure 4). Most ferns grow their reproductive structures on the lower surface of their leaves, and several tropical tree species such as the cocoa tree develop flowers on their main trunk and branches below the foliage [6]. The study suggests that, for natural flowering plants, light might be an evolutionary constraint to consider for the placement of their reproductive organs. Nevertheless, a vast majority of natural plants tend to develop flowers above the leaves. Other major constraints which are currently not represented in the plant model, such as an easy accessibility of pollinating insects, must prevail.

The third series of evolutionary runs in this subsection uses a fitness function multiplying the light available to the flowers, to the leaves, and the minerals available to the roots. In contrast to the previous experiment, the plants need to expose their flowers to the light in order to attain high fitness values. The simulations allow to produce a large variety of familiar looking flowering plants (figure 5). Movies of such evolved virtual plants can be downloaded at the LIAP5 website [19]. Due to the complexity of plant structures, designing 3D plant models is a difficult task when undertaken manually. The method of evolutionary design appears to constitute an efficient alternative. Additionally, the presented automated objective selection may be combined with a more subjective and interactive selection where a human observer chooses plants for reproduction according to aesthetic aspects [5]. The emergence of natural looking morphologies suggests that the applied fitness function comprises some of the most significant factors for the evolution of plants, and illustrates that the exposure of organs toward resources is of prime importance in the morphological design of natural plants.

Adaptations to environmental conditions

The second part of experiments investigates the potential of evolutionary adaptations to different environmental conditions. For all evolutionary runs, fitness is declared as the function used in the third experiment of the previous subsection. In each environment, holding a different lighting and soil configuration, thirty runs are performed. Experiment A evolves a comparison group of virtual plants which grow under the previously defined “standard” environmental conditions. In experiment B, the plants are seeded in a soil where minerals decrease with depth. Experiment C exposes the plants to lateral instead of vertical light. To compare and quantify the results of this subsection, figure 6 opposes the above- and belowground height and width of the individuals evolved in all three environments. The big circles signify the mean values for each experiment and indicate that the differences between the results are significant.

It can be observed that the virtual plants evolved in experiment B develop root morphologies which grow closer to the surface than in the experiments A and C. Due to the absence of resources in the soil, deep-rooting plants grow poorly because of less mineral assimilation and are systematically discarded by evolution. Like in nature, root morphology adapts to the encountered soil

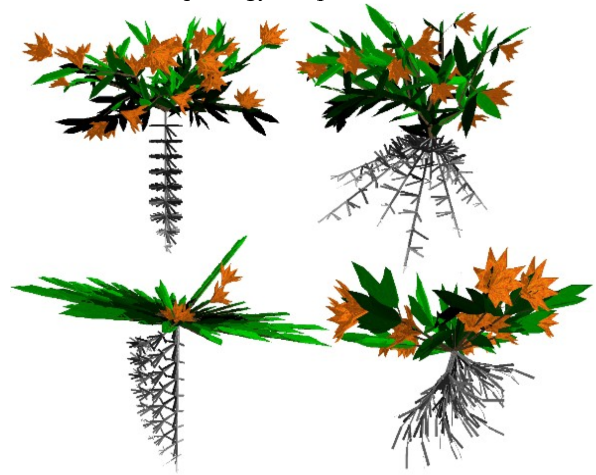
Fig.5: Familiar looking flowering plants

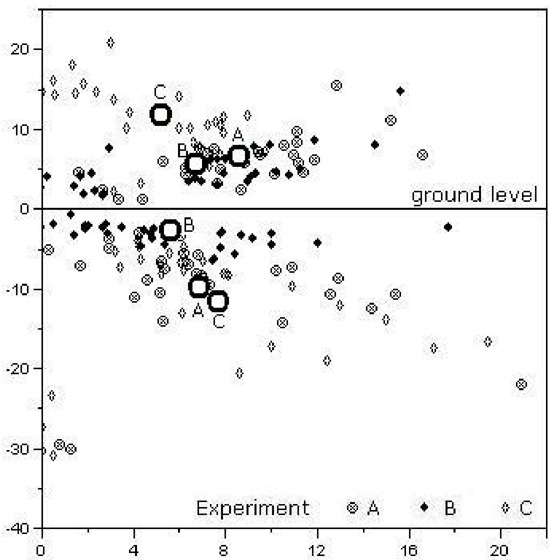

Fig. 6: Mean height and width of the evolved plants

conditions. In order to increase the chance of survival, real plants notably evolved adaptive capabilities that occur at individual level. As an example, it has been observed that palm trees are able to extend their root system towards nutrient-rich clumps and termite mounds, which points out a particular root foraging strategy [21].

In the experiments A and B, the plants exposed to vertical light tend to evolve flat and wide morphologies. Due to the absence of competition, they are not constraint to grow further in height. The lateral light of experiment C induces taller shapes. In the latter case, high growth allows to minimize self shading and to maximize the capture of light coming from the sides. Natural plants likewise need to adapt to the incidence of light of their environment since photosynthetic productivity depends on a close relationship between the geometry of the plant canopy and the position of the sun in the sky [13]. However, in contrast to the virtual plants, natural plants are capable of adjusting more morphological traits concerning photosynthesis, such as leaf angle, size or curvature.

5 Conclusion

The plant models of most virtual worlds incorporate only minimal physiology and interactions with their environment. On the other hand, functional-structural plant models conceived by biologists are not yet appropriate to large-scale scenarios of plant communities with genetic change. This paper presented a step towards the unification of both approaches and introduced an evolutionary model of generic virtual plants. Based on the multi-agent paradigm, it combines an L-system formalism with the transport-resistance approach for resource flow.

Two series of evolutionary experiments were presented. The first series, describing evolutionary adaptations to specific fitness functions, allowed to reveal constraints in the life of natural plants such as the trade-off in plant life between growth and reproduction, or the problem of self shading. The second series studied evolutionary adaptations to resource disposition. It was found that the above- and belowground compartments of the plants evolved morphologies in response to the encountered environmental constraints. Again, the observed pattern could be related to real-life plants. All experiments presented in this paper take advantage of a plant model interacting with the environment. The simulations illustrate how evolving virtual plants can contribute to the study of natural plants. They allow to single out specific aspects such as fitness criteria or environmental factors and to assess their impact on evolution.

These results suggest that the integration of such models into virtual worlds may not only enrich artificial environments from an entertainment point of view, but also produce a range of coevolutionary dynamics close to those observed in natural systems. Within one plant population, the impact of competitive pressure on some morphological and physiological traits was studied in [4]. Future research may aim at the evolutionary responses to competition between more than one species. Yet flora only constitutes a modest part of a complete ecosystem. Other agent types like fungi, parasites, herbivorous or pollenizing insects could be modeled and allow to produce cooperative and competitive dynamics in a system of different coevolving actors. In this respect, the current work marks the cornerstone for a biologically inspired virtual world.

6 References

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