1 Computer-Generated Plants

Introduction

For over thirty years, botanists and computer scientists have made considerable efforts to develop effective methods to synthetically generate natural objects. As early as in 1966 the first method for the simulation of a branching structure via a computer was introduced. This method used the so-called cellular automatons, an arrangement of square cells on a grid that could adapt to different conditions directed by a computer program. Based on a simple rule mechanism, and provided the appropriate rules were applied, the model then grew from an initial cell into the adjoining cells and developed a branching structure. Contrary to these discrete models, later models worked continuously. Since then, multiple different methods have been developed. Moreover, in parallel to the rapid development of computers, the complexity of digital design and the visual quality of synthetically produced images has reached a point at which it is rather difficult to differentiate between computer simulations and actual photographs.

Today, synthetically produced natural objects are frequently used in computer graphics and in related fields. Plants, for example, are the components of many computer images since it is almost impossible to create outdoor scenes without incorporating such natural objects. Thus, the corresponding synthetic plant models have become more and more integral parts of many modeling systems. At the same time, expectations for the quick and perfect rendering of virtual images have grown among a wide range of commercial users.

Outside of computer science, many other areas benefit from these models: landscape designers are now able to visualize and predict the results of their planning, architects enhance their simulations with computer-generated plants, and in botany models are used to determine physiological parameters. In modeling and simulation as well as in the game industry more and more realistic plant and landscape models have become essential tools in designing realistic-looking environments.

In this book, we mainly focus on the modeling of plant vegetation and the production of images associated therewith. Natural landscapes consist of a multiplicity of elements. Although these elements for the most part contain similar mathematical characteristics, they can differ in their methods of production and in their representation. For example, in computer graphics objects such as rocks, clouds or trees are known as fractals. However, this is only a basic description of a fundamental geometrical characteristic, which for each class of objects has to be converted separately into different production procedures.

Although the methods for the simulation of clouds or mountains are related directly to the underlying mathematical principles of fractals, vegetation is rendered completely differently. Here, various geometrical aspects of modelling play significant roles, and the fractal characteristics of the plants are, at best, to be found in the recursive structures of the models. What differentiates one plant from another is not so much the general mathematical parameters but rather the concrete detailed structure. Thus, the question of efficient modelling, including especially interactive systems and their evaluation, is the decisive factor.

The aspects treated in the following chapters are grouped into three major areas: methods for the modeling of single plants, methods for the modeling of plant communities and landscapes, and rendering methods for such synthetic landscapes, whereby the first two areas are looked at from the botanical point of view as well as from the point of view of computer graphics.

Here, however, conflicts become apparent about what is regarded as important in each respective discipline. For example, for a botanist a geometrical plant model is interesting in two ways: it permits the visual validation of the underlying production process, and it is used to calculate mathematical characteristics, such as the interaction of light with the plant and the environment. The visual model as such is not of much concern here.

This is completely different in computer graphics: here the geometrical model is used because of its visual effect. The underlying processes are only important in as much as they must permit us to efficiently produce a complex geometry. The exclusive visual evaluation often leads to the production of botanically incorrect models so that in a certain situation a desired result can be achieved.

This divergence between the disciplines surfaces throughout the book. But since this book is primarily directed at readers in computer science, and particularly in computer graphics, botanical aspects are often kept in the background. Hence, the botanical introduction in Chap. 2 is not meant to serve as a knowledge base for biologists, but rather to enable a general understanding of botany by the nonbiologist.

For the same reason, the technical descriptions of algorithms and geometry-producing methods are more detailed. Chapter 4 takes into account all essential stages for the modeling of plants using computers and introduces the models in the order in which they were developed. Aside from the purely bibliographic aspect, the variety of possible solutions becomes evident with the abundance of details provided. Later chapters describe rendering issues and demonstrate the results of various researchers and artists in the form of many synthetic images.

Before getting into details, a short overview should outline some relevant questions. In each of the following sections, specific problems involving the translation of the general steps into practical applicable procedures are demonstrated.

This should help the reader to easier identify and coordinate the problems treated later on in the book.

1.1 Modeling of Virtual Landscapes

In botany, vegetation is viewed on different levels of abstraction. Based on the already existing data of individual plants, emphases are put on plant populations, concentrations of similar plants, which combine into plant communities of various kinds and in this way populate typical forms of landscapes that are called aerials.

This type of classification is also logical for the computer graphics community, since the modeling methods for the different stages clearly vary. Geometrical details play a large role with individual plants. Plant populations, however, are viewed more or less statistically, which makes geometrical characteristics, such as shading conditions, less significant. With plant communities and aerials, this effect is strengthened: here only statistical aspects, in combination with biotic and abiotic environmental factors, are considered.

When a virtual landscape is created, starting with the overall description of the aerial, a number of spatial refinements have to be created, finally ending in the geometric design of each individual plant. Already at this point, the abundance of geometrical and formative complexity of this global task becomes apparent.

This complexity is also evidenced with the design of an individual plant. The existing approaches can be divided into procedural and rule-based methods. Procedural methods are parameterized algorithms for generating special models, while rule-based methods use a formal rule base, which produces a complex final state by application of rules starting with a simple initial state. The advantages and disadvantages of both approaches are analyzed. Then, we are describing a procedure that combines the benefit of both methods through merging rule-based and procedural elements.

Since the individual modeling methods use completely different parameters for the description of plants, it is an interesting question whether there is not a more fundamental universal parameter set and/or a general description that would approximate the many different procedures. Though such a description does not have to exist, not even in the mathematical or algorithmic sense, even a simple method for limiting the producible forms to what is meaningful in botany would make modeling a great deal easier.

Once the geometric data of a single plant model is generated, we are confronted with the difficulty of managing the massive amount of needed data for most models. To reduce the excess data, model representations must be created that depict a plant at different levels of detail. When displayed on the screen, depending on the projected size of the plant, the appropriate representation is used, which allows for a drastic reduction of the amount of data that has to be worked with.

First, however, efficient procedures must be found that can approximate what is actually visible for a potential viewer. If, for example, a virtual visitor strolls through a synthetically generated forest, it will not be necessary to show the trees in the hundredth row, since they most likely are covered up by those in front. Corresponding procedures for the deletion of such objects are used with success in other areas of computer graphics and must be adapted for synthetic landscapes.

Next we will deal with plant communities. In botany most often descriptive models are used instead of algorithmic ones to define plant populations and plant communities. Mathematicians, on the other hand, are more concerned with the description and simulation of interacting sets of discrete objects and the application of the results to plant populations.

By contrast, researchers in computer graphics are only interested in the descriptive models, and weather they can be converted into efficient algorithms. The same is true for the mathematical procedures, which often are found in ecology and that cannot be integrated easily. For example, the simulation processes used here are often too complex for application. Therefore, efficient procedures for the specification of plant populations must be found and, at the same time, the different conditions for the plant habitats, such as the availability of water and light, have to be taken into account.

An essential difference between the methods employed in computer graphics and those used by botanists is the complexity of the required systems. In botany, rather small areas are being examined and analyzed, and large amounts of data are simplified by means of abstraction. For image production, however, also large aerials of several square miles must be produced with visible details. Here, simply storing the locations of the corresponding plants can present a problem, since billions of positions have to be recorded. A challenge in computer graphics is to record the positions only if necessary and to disregard them as soon as a plant is no longer visible. This kind of "on-the-fly" computation raises a number of interesting questions.

Another challenge is to efficiently represent geometrical models of plant populations and plant communities. For example, it is necessary to find out what are visually essential elements in a plant community and how these essential elements can be depicted with the smallest possible geometric resolution. Although not all of these questions are addressed in this book, we will introduce approaches that at least let us insinuate the overall picture.

At this point it should be mentioned that the rapid development of computer graphics hardware most likely will not make procedures for the minimization of geometry obsolete, at least not during the next few years. The past decades have shown that the desired model complexities increased more rapidly than the corresponding developments in computer hardware. Of course, it is possible that at one point in the future, all essential requirements with respect to the graphical performance of computers will be satisfied, but for right now this is absolutely not the case.

1.2 Rendering Issues

Depending upon the area of application, different goals are pursued in landscape visualizations. In botany often only an approximate representation of the model is required. In architecture, and in some cases also in landscape planning, in computer games, and in simulation, images are required that, in addition to form, reflect light conditions as well as very detailed structures.

The film and advertisement industry demands photorealistic images for merging real-life characters with synthetic scenes, and for unique landscaping. Another abstract type of representation is required for cartoons, where images in comic style are needed.

Thus the question arises: what effects are necessary for generating synthetic landscapes? For example, is a complex simulation of the global illumination necessary for the computation of photorealistic images of plants? How do the different illumination factors affect the related "authenticity" or "reality" of the representation?

If approximate geometry representations are to be used for the reduction of the data, more questions emerge: What actually gives vegetation its characteristic appearance? In what places are we able to replace geometric detail with prefabricated pictures or textures? And how can the "area-fill-mass" in a large scene be represented? Furthermore, how do level-of-detail descriptions, meaning those that render a plant differently in detail depending on its projected size on the screen, integrate into the process, i.e., the rendering? What kinds of methods allow us to reduce the geometric quantity, meaning the quantity of the entire data that has to be produced and analyzed and processed? Moreover, how can the transition between different model representations be implemented without the viewer becoming aware of it?

Finally, it is useful to clarify what actually constitutes a "beautiful" landscape. This is an intensively researched area in the field of ecology as well as in the area of aesthetics. What can be derived from the expression "beautiful" in order to create a corresponding visually beautiful landscape and how can already created landscapes be improved? Are there any global limits for the number of different plant models needed in a scene?

We already mentioned that even the nonphotorealistic representation of a synthetic landscape has a distinct function. Accordingly, in landscaping and architecture, the results of planning are traditionally represented as sketches. Some of the reasons are that a sketch visualizes a model of an object, whereas a photorealistic representation renders a concrete instance. Additionally, it is easier to convince viewers to make changes in a sketch rather than in a realistic representation.

Also, the sketch does not confine the planner to a certain appearance, as would a realistic-appearing computer image. Yet, with the sketch, size and light conditions can be rendered more accurately. Furthermore, sketching makes it possible to emphasize important areas using contrasting methods, and thus to direct the focal point of the observer.

On the contrary, the abstract visualization of plants requires new methods for the production of images. Thus, one needs specially prepared models, in which the geometric data is reduced and changed with regard to the representation. There are a number of questions, some of which also have been of concern to the art community: how is form, and how are light and shadow represented? In Chap. 11 we show that there are numerous different rendering methods available for plants in traditional arts. While some of these techniques are applicable to synthetic rendering, for the most part completely new approaches are necessary, and structures of required geometrical models have to be changed accordingly.

Abstract representations increase the potential for visual expression and communication in computer graphics a great deal. In the future, the user will be able to choose the most appropriate rendering method from a wide variety of possible representations. The photorealistic representation is here only one of many options.

1.3 Applications

Some areas of applications for synthetic landscaping have already been mentioned. Particularly in ecology, plant models can also serve as a medium: they transport information about more deeper-lying processes, enabling the viewer to see even invisible things. This way, even the non-expert observer is able to easily gain insight into the underlying mechanisms of the systems. The effect is emphasized if the representation becomes conversant with the types of the argumentation and the environment of the presentation, which is especially possible through abstract renditions.

This transmission of underlying data plays a large role in visualization techniques. In biology and botany, visible and especially invisible parameters of ecological systems can be represented using synthetic landscapes. Soil structures, contamination, problem zones and habitats of species as well as sound problems are examples of such parameters, which can be added through special procedures into synthetic landscapes. Thus, landscape planners, designers and architects will benefit from synthetic plant images, since with a suitable visualization abstract planning results can visualize the desired results, which is especially useful within the framework of competition.

Furthermore, it is possible to represent non-existing plants, such as plants that have become extinct or plants that could still be developed in the future. This might be of great importance to scientists in botany, since genetic changes of economically valuable plants can be visualized before we actually obtain results. This way it could be possible to discuss botanic design parameters directly within the models themselves.

Besides displaying generated virtual landscapes or planning results, the models can be used for visualizing the development of ecosystems over time. So far, the only possibility to visually record such developments have been offered by interval photography. For long-term processes this is expensive and difficult to do, which is why simulation and visualization of the virtual counterparts can be a good alternative.

Another application area for synthetically generated plants is the regulation and measurement of models for the description of physiological procedures in plants, such as the determination of the light interaction and the energy exchange of the plant with its environment. Here specifically adapted models are imported into appropriate simulators, which compute from these models the values of the thermodynamic parameters.

In yet another application of simulation, realistic plant models are meaningful: driving and flight simulators need vegetation for the spatial orientation of the users. In particular, at ground level the realistic rendering of the vegetation is an essential component in conveying spatial reality.

Currently, the main area of application for synthetic plants is found in filmmaking. Virtual plants are used in specially designed external scenes or for special effects involving individual plants. Animation within geographical information systems, the visualization of whole landscapes and the production of interactively accessible landscapes for VR systems, and computer games conclude the list of possible application areas for synthetic plant geometry so far.

According to the aspects discussed above, this book consists of four parts. In the first part, which contains the Chaps. 2–6, we address the modeling of individual plants. Based on botanic and mathematical description procedures, Chap. 4 describes the so-called procedural methods for the production of plant geometries, in which the models are synthesized using special algorithms. This is supplemented in Chap. 5 by rule-based modelling. So-called Lindenmayer systems play an important role here.

In Chap. 6, we present rule-based object production, a method that combines rule-based and procedural modeling thereby eliminating a number of problems in the generation of plant geometries. This procedure is discussed with respect to already-existing methods.

The second part of the book is concerned with the modeling of terrain and its plant communities. It covers Chaps. 7–8. Here again, based on the work in botany and geology, a system description is attempted that makes it possible to furnish and handle the required complex data efficiently.

In the third part of the book that is found in Chaps. 9–11, we examine the rendering of synthetic landscapes. Starting with the fundamental algorithms of rendering, different approaches are described for the production of realistic looking landscapes. Here in particular the newest, most efficient methods are introduced. Level-of-detail representations play a significant role especially when quick rendering is given priority. Algorithms already make it possible to represent smaller landscapes interactively, and to virtually stroll around in them.

A chapter on nonphotorealistic rendering concludes the third part and briefly addresses the production of further images and their relationship to the arts. This is focussed upon in the last chapter. Here we present the work of several artists who motivated us to design interactive modeling programs for plants, organics, and whole ecosystems. Many of our ideas were developed before by artists such as William Latham, scientific artists such as Karl Sims or mathematicians such as Stephen Todd.

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