VISUALIZATION OF TIME-VARYING NATURAL TREE DATA

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ABSTRACT Given a set of global (natural) tree parameters measured for many specimens of different ages for a range of species, we have developed a tool that visualizes these parameters over time. The parameters include measures of tree dimensions like heights, diameters, and crown shape, and measures of costs and benefits for growing the tree. We visualize the tree dimensions by animating tree growth over time, while the accumulated costs and benefits are visualized using animated bar charts.

Since our visualization system is targeted towards application for city planning purposes, the tree growth animation should produce trees of an appearance close to nature while being conform with the measured parameters. We have developed a system for single-stemmed trees. In addition to the measured data, we use biological knowledge to model general tree growth and to adjust to specific species. We have implemented several computationally fast methods to improve the natural growth and appearance of the trees, where the main task was to keep the tree growth modeling and the tree rendering interactive. Thus, the user can interact with the 3D visualization system during the tree growth modeling and rendering process. We have applied our visualization techniques to the growth and the temporal costs/benefits changes of nine single-stemmed tree species.

KEY WORDS Tree Growth Visualization, Growth Data, Biological Data

1 Introduction

Trees are considered an important feature of a pleasant and beautiful cityscape. In urban environments, a large number and a large variety of trees can be found. The decision of what trees to plant is not done arbitrarily or just on economic reasons by choosing any tree from a set of trees that grow under the given climate. An important factor is that the planted trees fit into their environment in terms of size, shape, and appearance. Such considerations cannot be made from a static point of view. Instead, one needs to consider that trees may change their size, shape, and appearance significantly over time.

Data for the growth of trees are available but mainly consist of simple diagrams or tables expressing tree features at a certain age. This does not help the city planners to find the appropriate tree they are looking for, as one cannot deduce the tree would fit a specific environment. Our goal was to visualize tree growth data in a way that helps city planners to find the appropriate tree for each site. Development of such a computerized visualization program for tree growth data was suggested by Peper et al. [1] already.

For this purpose a dynamic system is required that can display trees at any point of their lifetime and can model the growth of trees over a given time period. Preferably, the dynamic visualization system is coupled with the displaying of benefits and costs at any phase of the growth procedure. The tree growth system has to provide the presentation of a whole range of urban trees that grow under the given conditions. Moreover, it should support including new species at any time.

We present a framework of such a tree growth visualization system. The system is based on species-dependent growing parameters that are to be fed to the system for each species that is entered into the system. The growing parameters are mainly based on measurements of real tree dimensions varying over time and estimated global characteristics. In addition, some biological knowledge about how trees build up their branching structure over time is used. The species-dependent data serves as input to the time-varying visualization of a prototypical tree of that species.

The data we are using throughout the paper has been collected by scientists with the USDA Forest Service, Center for Urban Forest Research, at the University of California, Davis. The scientists measured a large number of street trees of different species and different ages in the San Joaquin Valley City of Modesto, California. The data includes easy to measure quantities like the dimensions of a tree, e. g. tree height, crown height, or crown width, and also more qualitative estimates like annual benefits, e. g. pollutant uptake, energy savings, etc., and annual costs, e. g. planting, pruning, or watering costs. The study included eight single-stemmed tree species, to which we apply our visualization methods. In addition, we use another single-stemmed species measured by the same group. More details on the data including a list of measured values and a list of the examined species are given in Section 2.

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The modeling and simulation of plants, in general, is a well-studied topic in computer graphic, though it is typically not based on real, i.e. measured data. The most common approach for a formal description of plants are Lindenmayer-Systems [2]. For L-Systems many extension are known today [3, 4, 5, 6]. We also use these ideas for our tree model, therefore the growth is controlled by local production rules. Our model and therefore our local parameters have to be based on global parameters, we are provided with. For this reason we use inverse modeling [7, 8], especially the model by Rudnick et al. [9]. We describe how the choice of global parameters and a change of their values impact the local growing rules. Such global parameters include simple aspects such as the tree's height but also more complex aspects such as the crown shape, and the leaf and branch distribution (influenced by the distribution of available light). The growth model and its manipulation by global parameters is described in Section 4, and some biological background on tree growth used for the model is described in Section 3.

Finally, we have to estimate the parameters that influence our tree growth model from the set of measured quantities. This mapping of species-dependent properties to size, shape, and appearance parameters used in the growth model allows for a realistic modeling of a whole range of different species by using a single tree growth model. How we derive the desired parameters is described in Section 5.

In Section 6, we show the results we obtain with our visualization system when feeding it with the data of nine street trees. We visualize the growth of a prototypical tree, whose changing dimensions over a period of 50 years are given by the measured data. Within the visualization we also display the changing costs and benefits. Using our tool, city planners are in the position to compare the advantages and disadvantages of individual tree species for their desires in terms of tree growth, costs, and benefits. Their analyses allow for choosing the species most suitable for the city planners' purposes. Our results show that we are able to deal with species of rather diverse appearance. Moreover, the system is scalable in the sense that any new species could be dealt with by just feeding new measured data to the system.

2 Data

The measured street tree data we are visualizing is taken from study the above-mentioned study by Peper et al. [1]. In this study, trees of different species were measured. We visualize the data for Silver Maple (*Acer saccharinum*), European Ash (*Fraxinus excelsior*), London Plane (*Platanus x acerifolia*), Bradford Pear (*Pyrus calleryana*), Goldenrain tree (*Koelreutaria paniculata*), Sweetgum (*Liquidambar styraciflua*), Southern Magnolia (*Magnolia grandiflora*), and Chinese Pistache (*Pistacia chinensis*). For one additional species namely Hackberry (*Celtis occidentalis*), we got additional data also measured by the Center for Urban Forest Research. These species represent a high percentage of the street trees in Modesto, California, and thus represent the common street trees planted. The trees used for the measurements were randomly chosen among trees in an urban environment.

The data collected for each tree includes age, diameter at breast height (DBH), tree height, crown diameter, height to the base of the crown, a visual estimation of the crown shape, and two digital photographs. With the help of a logarithmic model functions of time for predicting the several dimensions are computed. Thus we have functions $f_{DBH}(t)$ describing the DBH, $f_H(t)$ describing the tree height, $f_{CD}(t)$ describing the crown diameter, and $f_{CH}(t)$ describing the crown height as the difference between tree height and height to the base of the crown, where t is the age of the tree in years. This data is given for all species. As these modeled functions do not extrapolate well, we only rely on data for trees of age higher than four years. The digital photographs and the visual estimation of the crown shape together with the ratio of crown height and crown diameter give the shape of the crown for the trees at any age.

In addition to these measurements of global dimensions we also use important data of some local but general properties for each tree species. The first property we have been provided with is an estimate of the average area of one leaf. The second property is an estimate of the angles between the branches, which is an important feature for creating a realistic branching structure. The estimated data includes the inner angle between the trunk and a branch and also the angle between two branches. The angles are always given in form of intervals due to inter-subject variation in nature.

In addition to these data describing the actual growth of the tree, other data describing the annual costs and benefits of the street trees are provided [10]. All the costs a tree produces each year like costs for planting, watering, removal, infrastructure repairs etc. are given as functions of time. Additionally, all properties of the trees we benefit from like energy savings, air quality improvement, CO_2 sequestration, rainwater runoff, and esthetics are also given as functions of time. Both costs and benefits are given in terms of U.S. Dollar to be comparable.

3 Biological Background

In this section we give a brief overview on the biological background of tree growth. We refer the interested reader for more detailed information on this topic to botanical books [11] or for information on several tree species used in urban environments to the manual by Dirr [12].

Trees are plants growing over a long period of time and building up a large and complex branching structure. We only present the visualization of the growth of broad-leaved trees in this paper, as we do not have any data for conifers. Nevertheless, we believe that our methods can easily be applied to conifers as well. Within broad-leaved trees there is a main distinction between single-stemmed and multi-stemmed trees showing different growth characteristics. Our model is targeted towards single-stemmed trees which represent the larger group from the study. Single-stemmed trees are characterized by a single trunk not only below the crown but also within, i. e. the trunk is clearly noticeable from the bottom to the top.

The result of the annual growth of one branch we refer to as branch segment. So one branch consists of many segments each representing its growth in one growing season. The growth of one branch segment is divided into two phases, the primary growth phase and the secondary growth phase. The primary growth phase includes the elongation from a bud to a branch segment combined with a thickening of the branch. During this elongation phase the branch produces leaves and lateral buds. Elongation is terminated by producing an apical bud. The primary growth phase lasts one growing season. From then on, the branch segment is in its secondary growth phase. In the secondary growth phase the branch segment only grows in diameter and not in length anymore. The buds produced in one growing season can produce new branch segments in the next growing season, whereas the branch segment growing out of the apical bud elongates the branch. The probability to produce new branch segments decreases for the lateral buds with increasing distance to the apex. The annual growth of a branch is schematically shown in Figure 1.

There exist two types of leaf and bud arrangement along the branches, namely opposite and alternate. Trees with opposite leaf and bud arrangement always produce a pair of lateral buds on opposite sides of the branch segment, trees with an alternate arrangement only produce one lateral bud at one position of the branch segment.

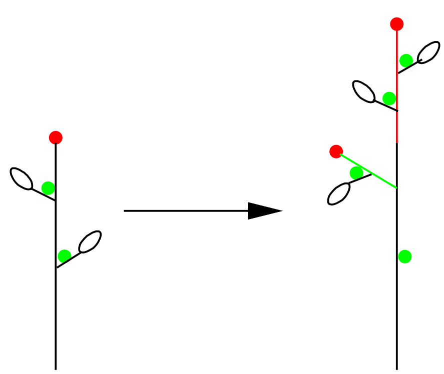

Figure 1. Annual growth of a branch for a tree with an alternate leaf arrangement. The apical bud (red) on the left-hand side produces an apical branch segment (red) on the right-hand side with a new apical bud (red) and new lateral buds (green). One of the lateral buds on the left-hand side produces a lateral shoot (green).

Another important topic in tree growth are the leaves because they produce the energy allowing the tree to grow. The energy is produced by the process of photosynthesis and thus trees tend to grow leaves where good lighting conditions exist. Branches exhibited to more light grow longer and faster and produce more leaves than branches exhibited to fewer light. Branches not retrieving any light at all may stop growing and eventually may die.

Trees are trying to maximize their total leaf area exhibited to light. Thus trees with smaller leaves produce more leaves to reach the same total leaf area that trees with larger but fewer leaves have. That is the reason why trees with smaller leaves bifurcate more often and produce much more branches than trees with larger leaves do.

4 Growth Model

For modeling the tree growth we are using our previously developed model [9] and refer the reader to this more detailed explanation.

Within our growth model we want to generate a complex branching structure being similar to that of a real grown tree. To generate complex branching structures, computer models typically use iteratively and simultaneously applied local production rules. In order to generate branching structures that consider global properties like the global functions described in Section 2 or the available light distribution, we have to extend these local production rules to rules that couple local reproducibility with global growth properties.

In our model a branch consists of branch segments representing the annual growth. A branch segment is defined by its length l, diameter d, starting point s, and direction o. A bifurcation is characterized by the bifurcation angle, the divergence angle, and the ratios in length and diameter between the parent branch and the child branches. The bifurcation angle denotes the angle between the new and the old branch and the divergence or twisting angle describes the rotation of the child branches around the parent branch because not all branches lie in one plane.

The tree growth is modeled in equidistant discrete time steps. We chose to use 20 time steps per year. In each step the production rules for the branches are applied to all branch segments.

Every branch has an order representing its depth in the branching structure. The trunk has order 0, the branches coming out of to the trunk have order 1 and so on.

4.1 Branch length

For calculating the length of each branch, its order, its relative position $p_r \in [0, 1]$ along the parent branch, the length of the parent branch l_p, and a scaling factor s_l are used. The scaling factor $s_l \in [0, 2]$ is a factor every branch gets randomly assigned during its initialization. It depends on the scaling factor $s_{l,p}$ of the parent branch and a uniformly distributed random factor in $[0.6, 1]$. The length calculation of the branches is done with the help of a crown shape function $c : [0, 1] \to R$, which is represented by a geometric function that returns the relative length of a branch

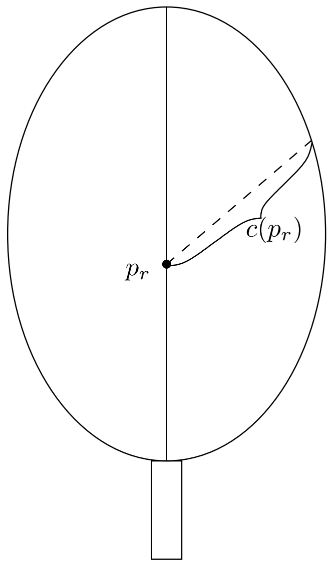

Figure 2. Example for elliptical crown shape function: p_r is the relative position and $c(p_r)$ the computed relative branch length.

at a relative position p_r along the trunk to fit the crown shape, see Figure 2. If the crown shape is given as a texture, computing $c(p_r)$ is just finding the last black pixel starting from p_r and going into a species-dependent direction. The crown shape function is applied recursively for the entire branching structure, i.e. the length of each branch is determined with respect to the crown shape function applied to its parent branch. For tree species changing their crown shape significantly over time we are using two crown shape functions c_1 and c_2, for a young tree, or an old tree respectively and interpolate linearly between them, depending on the age. Multiplying the relative length of a branch $c(p_r)$ with the length of the parent branch $l_p(t)$, with an order-depending factor, and with the length scaling factor s_l yields the new length

$$l(t) \quad = \quad s_l \cdot \frac{c(p_r) \cdot l_p(t)}{v + (1 - v) \cdot order} \ .$$

The factor $v \in [0, 1]$ is a species-dependent factor defining how much shorter the branches of higher order are. Again the growth is only added to the length of the last branch segment, i. e. the only segment of the branch in primary growth phase.

Since branches grow towards light, we adjust our model such that light influences the scaling factor s_l. When there is sufficient light at the apex the scaling factor increases, and decreases in case of missing light. We only apply the light-dependent change of the scaling factor s_l to branches of order 2, which turns out to work well. To assure that branches do not grow too long the scaling factor only changes in a certain range.

4.2 Bifurcation

In our model, the apical bud always produces a new branch segment, which elongates the branch. The lateral bud (or the pair of lateral buds) can produce a new branch segment which starts a new branch of one order higher than the order of the branch it emerged from. The probability whether a new branch is started is determined by the local tree density, the available light at this position, and a random factor which depends on the tree species and its bifurcation probability.

For these new branch segments the scaling factors s_l and s_r are generated and also the angles characterizing the bifurcation are determined. The angles used are inspired by the ones that can be seen in nature at the tree species. In particular, branches tend to spiral around its parent branch.

4.3 Light

As explained above light is one of the main factors affecting the growth of a branch. Therefore the available light at every position inside the crown has to be computed in each step. In our model this is done by dividing the crown space into equal sized cuboids. For each of these cuboids its density is computed, which measures the volume inside the cuboid that is covered by leaves and branches. The density is inversely proportional to the light passing this cuboid. From outside the crown, light rays simulating daylight are cast through the crown volume of the tree. At each cuboid that is traversed by a ray, the ray's intensity decreases according to the density within that cuboid. For each ray that traverses a cuboid, the amount of light intensity that arrives at this cuboid is accumulated. After having accumulated the intensity over all light rays, the amount of available light at each position inside the crown is known and influences the growth in the subsequent time step.

5 Visualization Parameters

The given data for each tree species includes

- time-varying functions for the global tree dimensions,
- time-varying functions of costs and benefits,
- estimates of the angles between the branches,
- the size of an average leaf,
- information on the branch arrangement (opposite or alternate),
- some digital pictures of some specimens, and
- scans or photographs of a leaf and the bark structures (textures).

This data is used to derive the parameters of the growth model.

The information on the branch (and leaf) arrangement, whether they are opposite or alternating yields the decision which precise model to use: the one with only one lateral branch or the one with two opposite lateral branches. In addition the bifurcation probability is lower in the latter model, as one bifurcation produces twice as much branches.

The height function $f_H(t)$ enters the model directly as the height of the trunk at time t. The precise lengths of all branches of higher order is computed by using the trunk length as explained above. Similar the diameter at breast height function $f_{DBH}(t)$ enters the model by defining the radius of the bottom trunk segment at time t.

The two functions $f_{CH}(t)$ and $f_{CD}(t)$ are roughly defining the crown shape of the tree. For simple automated construction of crown shape textures as needed for the branch length computation one can use an ellipse with the values of these two functions as major and minor diameters. If one is interested in a more precise crown shape or if the crown shape is more complex than just an ellipse, one can construct the crown shape texture manually. The digital photographs of the trees and also the ratio $f_{CD}(t)/f_{CH}(t)$ can be used to obtain the texture.

The average leaf size is used for computing the density in the cuboids, which has a large impact on the light computation and therefore on the growth of the tree. Furthermore small leaves are growing with a smaller distance to each other than large leaves do. Therefore also the distance between two neighboring leaves is determined by the size of an average leaf.

The estimated angles between trunk and branch or branch and branch are simply included into the bifurcation rules. Thus, the specific angles for one bifurcation are chosen randomly from the given intervals.

With the help of the time-varying costs and benefits functions animated bar charts with the accumulative costs and benefits in U.S. Dollar are computed and rendered as shown in Figure 3.

Scenario: In order to show the overall process of deriving the parameters for one common street tree species in Modesto, we use the example of the London Plane Tree, which is a species with alternate leaf arrangement. The functions for the global dimensions are directly included into the model. The ratio $f_{CD}(t)/f_{CH}(t)$ turns out to be nearly constant and equal to one. Thus there is no significant change over time and only one crown shape has to be constructed. The photographs show a more or less round crown without any specific criteria. Thus we chose to use a circle as crown shape texture. The leaves of the London Plane Tree are medium-sized to large and the area is included into the light computation. The angles between trunk and branch and also the ones between branch and branch are chosen from the interval $[50°, 70°]$. The example of the London Plane tree shows that any species can easily be visualized by our system if the required measured data and estimates are given.

6 Results

We have developed a growth model for single-stemmed trees that is controlled by some global and intuitive parameters for size, shape, and appearance. To use this model for visualizing real trees we have given an intuitive procedure for deriving the parameters from measured data of trees. The trees we modeled with our approach look quite realistic.

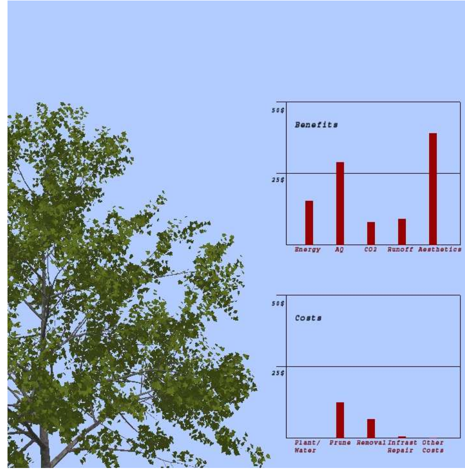

Figure 3. Visualization of London Plane tree with benefits and costs diagrams.

The pictures document the different appearance of the trees in shape and dimensions, which shows that our model works for the entire range of single-stemmed tree species no matter which crown shape or total dimensions the species has. In Figure 4 visualizations of other tree species from the study in Modesto can be seen, again documenting the variety. Comparing the two visualizations on the left-hand side, namely Hackberry and Souther Magnolia, one observes the significant difference between species with small and with large leaves. The leaves of the Southern Magnolia are much larger than those from the Hackberry. Thus, one observes more bifurcations for The Hackberry. The third image shows the Bradford Pear which is characterized by very small angles between the trunk and the branches. Its crown is very dense with many branches due to the small leaves. The right-most image shows a young Silver Maple, which is one of the two tree species of the study with opposite branch arrangement. Silver Maple is a large tree with relatively small leaves but nevertheless with an open crown. Obviously our tool does not only generate images but animations of growing tree species over time. Figure 5 shows a series of visualization of a growing Sweetgum in an urban environment. Special about Sweetgum is the changing crown shape over time, young trees are very narrow and the older trees are getting wider, but are still relatively narrow.

7 Conclusion

We have developed an interactive visualization system for tree growth data from single-stemmed trees. The underlying data is obtained from urban trees such that our tool

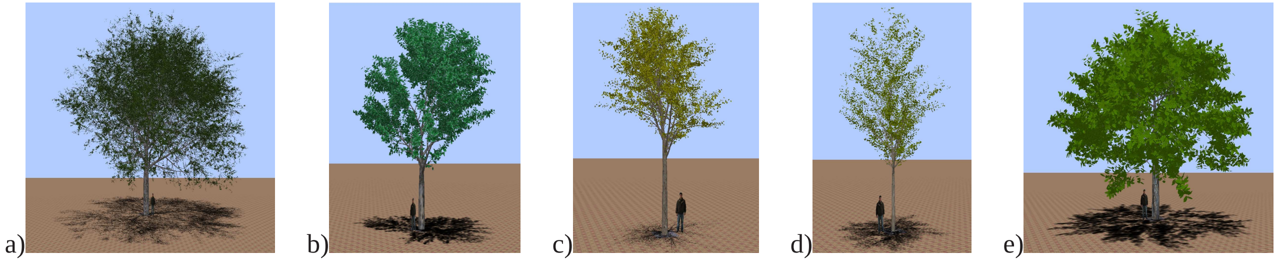

Figure 4. Modeled trees with the data from a study of street trees in Modesto, California: a) Hackberry, b) Southern Magnolia, c) Bradford Pear, d) Silver Maple, e) and Goldenrain tree.

Figure 5. Growing Sweetgum with a wider getting crown shape over time, at 10, 25, and 50 years.

can be applied to improve city planning concepts. Our tree growth visualization is based on certain species-dependent tree growth parameters, which determine the shape and the appearance of the respective tree and are derived from the measured data. The derivation can be done fully automated, while a manual adjustment of the crown shape texture based on the given photograph is recommended for some species. Our system is able to handle tree species with an alternate or an opposite branch arrangement.

The growth model we developed is based on parametric L-systems and includes the ideas of inverse modeling. We also included light computation because light affects the production of new branches and therefore the density of the crown and the tree's appearance.

We applied our system to nine single-stemmed street tree species commonly found in the San Joaquin Valley city of Modesto, California. From a study on these trees we got measured data representing their growth features. We derived the necessary parameters for the visualization system and thus visualized the growth of these trees showing quite realistic trees fitting the dimensions and also their natural appearance.

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