3D and 4D forest models
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Change of (information) paradigm in forestry

- New demands for modern ecosystem services: biomass quantity and distribution, carbon cycle and footprint, timber quality and market, cultivation options, ecological and recreational functions, urban areas, ...
- Full forest information: “Google Nature” in your mobile phone
- 3D models, 4D time development
- Complete virtual environment: view from any location
- Quantitative: obtain any volumetric or geometric numerical results from any region
- Predictive: how will trees grow in different scenarios?
Smart forest and infosphere

- See it, scan it, handle it with quantitative structure models (QSMs)
- Can do, will do: crowdsourcing – mobile lidar for everyone
- Upscaling: from terrestrial laser scanning (TLS) to satellite data – large comprehensively analyzed test plots for large-scale calibration
- Hyperspectral lidar information
- Represent leaves as “gas” or stochastic primitives around branches with matching leaf area density etc.
QSM - Quantitative Structure Model

* Compact tree model containing essential topological and geometrical tree properties
  - Branching structure, branching order
  - Volumes, lengths, angles, taper, etc.
  - Rapid advances in laser scanning technology: lighter, cheaper, faster
  - => Ubiquitous laser scanning (cf. radars in cars)
Compact usable information

3 scan positions, high resolution (1,6M points)

Model (14 000 cylinders)
Forest plot QSMs

- Fast modelling, tens of big trees in an hour
- Parallel computing allows hundreds of big trees in an hour
- Use the smallest required surface patch size instead of all points
- Robust cylinders as geometric primitives
- Surface continuity not required
Cover sets and segments

Figure 5. A cover which is a partition. Different colors denote different cover sets.

Figure 6. Comparison of the covers of a branch. The minimum diameters (d) of the cover sets are 2 cm (left) and 10 cm (right). The smaller cover sets can capture much more detail.

We generate two mutually related covers which are used for different purposes. First, we generate a cover \( C_B = \{ B_i \} \) of \( r \)-balls, which will then induce the other cover, a partition \( C_P = \{ b_i \} \). The cover \( C_B \) is used to approximate the structures of \( M \) and to define the neighbor-relation for the partition \( C_P \), which is used to define the components and segments of the tree. The cover \( C_B \) of \( r \)-balls is random, but to distribute the balls evenly along the surface, there are two restrictions: (1) the minimum distance between the centers of two balls is \( d \); and (2) the maximum distance from any point to the nearest center is also \( d \). The parameter \( d \) is a little smaller than, or equal to, the radius \( r \), and it controls the size of the cover sets in the partition \( C_P \). The partition \( C_P = \{ b_i \} \) is induced by the \( r \)-balls: for each ball \( B_i \) there is a corresponding set \( b_i \) that consists of those points of \( B_i \) that are closer to the center of \( B_i \) than any other point.

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2.8. Segmentation

When the tree components and their bases are determined, the next step is to segment these components into branches. Each component is partitioned into segments that correspond to the whole or part of a real branch or trunk. In particular, segments should not have any bifurcations. This kind of segmenting also defines the tree structure, i.e., the branching-relations of the child and parent branches for each branch. It is also straightforward to fit cylinders to these segments. Examples of segmented tree parts are shown in Figure 7 and Figure 1 shows a segmented tree.

2.8.1. Overview of the Algorithm

The segmentation process takes place at the level of the cover sets, and the basic tool is their neighbor-relation. The procedure starts from the base of a tree component and, step by step, a cut region and its extension, a study region, move along the component (see Figure 8). The cover sets are the building bricks of the tree surface and the cut region is a layer of these bricks that separates the component into two parts. At each step the cut region moves to the neighboring layer of cover sets. Every cut region is expanded or “grown” along the tree component into the study region that consists of multiple layers of cover sets. Each study region is checked for connectivity to find out possible
Other geometric forms

Figure 1. Geometric primitives. From left to right: circular cylinder (circyl), elliptic cylinder (ellcyl), polygon cylinder (polcyl), truncated circular cone (cone), and polyhedron (trian). Top: perspective side view. Bottom: orthographic top view.

In Sect. 3 several possibilities for finding good initial values and parameters from the data are presented, and the sensitivity of the fitting problems on the initial values is studied. In Sect. 4 we use generated stem models and simulated laser-scanning to study the error related to the shapes as well as the effects of data quality. The simulated shapes are not meant to represent any particular trees; rather, they were chosen to portray various geometric characteristics in a somewhat exaggerated manner to analyze the performance and inherent properties of each geometric primitive. In Sect. 5, real field data are used in further tests. As no volume estimates are available for the field data, we use reconstructed models as references in Sect. 5.1. Simulated laser scanning is carried out for the reference models and the resulting point clouds are reconstructed for the second time, in order to show how the approaches work with more realistic stem models.

2. Shapes

Here we consider various geometric shapes suitable as geometric primitives. The shapes are shown in Fig. 1, and they are described in Sects. 2.1 to 2.5. Cylinders and cones have a few common parameters: the starting point \( p \) in three dimensions, the axis direction \( a \) (unit vector), and the length \( h \) in the axis direction. The shapes are rectangular, so the top and bottom planes are perpendicular to the axis \( a \).

2.1. Circular cylinder

The simplest reconstruction shape is the circular cylinder (circyl). In addition to the common parameters it requires only one parameter: the radius \( r \). When using a circyl, the cross-section of a fraction of a branch is approximated as a disk with the radius \( r \). For the circyl, the envelope area...
The intact portions of the root systems were completely suspended indoors and individually scanned with a Leica ScanStation terrestrial laser scanner (Leica Geosystems AG, St. Gallen, Switzerland) from three lateral locations located at approximately 120° from each other and within 6 m of the center of each stump (Figure 2a). Any broken root pieces associated with a root system were placed on the floor and included in each scan. Three targets (Leica Geosystems HDS 3" × 3" square Planar Targets, Leica Geosystems AG, St. Gallen, Switzerland) were visible in each scan and used to co-register the scans into a single 3D point cloud of each root system. All scans encompassed the whole root system with a resolution of 2.5 × 2.5 cm at 50 m and a laser beam width of 4 mm (Figure 2b). The co-registered point cloud comprised of all three scans was used to fit the 3D QSM models.

Figure 2. Root system images: (a) Root system 3 suspended at scanning; (b) A 2D reprojection of the TLS point cloud data of root system 3, showing the effects of sensor obscuration (black shadow); (c) Top view of the QSM of root system 3; (d) Oblique bottom view of the QSM of root system 2.
A day’s work (scan from 10 spots, QSM on laptop)
QSM vs. allometry: Australian Eucalypt plot (109 trees)

Fig. 7. Comparison of destructively measured reference tree AGB with AGB derived from allometric equations. (Left) AGB from species-specific allometric equations. (Right) AGB from allometric equation of Eucalyptus tree. 

Fig. 8. Sensitivity analysis, TLS point cloud. (a) Sensitivity analysis of \( n_{\text{min}} \), the minimum number of points per patch, which define the patch size, with the \( \text{e.r.m.s} \) of \( d \) for each \( n_{\text{min}} \). (b) Sensitivity analysis of \( n_{\text{min}} \) for each species. (c) Sensitivity analysis of TLS point cloud. (d) Final QSM model.

Fig. 9. Error bars indicate the 95% confidence interval around the mean of 10 reconstructions.
The FGI hyperspectral lidar

- New concept & technology in laser scanning
- Active hyperspectral imaging simultaneously with topographic information
- Spectrum directly available for each point
- Based on supercontinuum laser technology
Hyperspectral lidar (HSL)

Applications

Backscattered Reflectance
R=740nm, G=672nm, B=606nm

Water Index
Blue = Moisture, Red = Dry

Normalized Difference Vegetation Index
Black = 0.1, Green = 0.9

Modified Chlorophyll Absorption Ratio Index
Black = -0.07, Yellow = 0.3
HSL: target recognition

Target classification example

- Rotten apples
- Red apples
- Green apples
- Light gravel brick
The growth of a tree (forest, organism, branching system) is a stochastic process -- not random, but unpredictable to some degree: genotype + environment.

A structure snapshot of the tree/forest (at any time) is the result of this process that contains deterministic, self-organizing and constraining elements (e.g., two branches cannot occupy the same volume; the competition for light and resources).

The structure data are distribution functions \( p(u) \) in some measurement space spanned by \( u \).

The growth process rules \( q(s) \) of a tree model are also probability distributions (DFs): how likely is a tree to make a given choice (in some \( s \)-space) at a given time?
Sample distributions $p(u)$
4D tree growth

- **HYPOTHESIS**: the genotype of a tree and environmental constraints can be represented by low-dim. stochastic DFs $q(s)$
- This handles competition and other development effects in a consistent manner, and reduces the problem dimension
- 4D measurement data and fitting $q(s) \rightarrow p(u)$ to 3D-data $u$-point distributions: likelihood-free inference
- Applicable to other organisms, societies, cities: find the growth rules
FSPMs and synthetic trees

- We can use biology-based theoretical functional-structural plant models (FSPMs) such as Lignum, or
- More fully synthetic “4D-geometric” models that flexibly represent “typical” aspects of growth and structure without actual biological rules;
- Any practical model has elements of both; these are augmented with stochastic properties
- Deterministic parameters are turned into samples of DFs $q(s)$, and the parameters defining $q$ are now our new model parameters
- With such a tuned model, we can create statistically similar trees that are not clones
Structure distance measure

- Once we have a stochastic model with a parameter set, we create several sample trees from $q(s)$ out of which we create QSMs and thus $p(u)$ in selected spaces.
- We define the structure distance measure; i.e., the difference $D$ between two $p(u)$ -- in principle zero for statistically similar trees of the same $q(s)$.
- Then we minimize $D[p(u)_{data}, p(u)_{model}]$ iteratively (e.g., genetic algorithms) by tuning the parameters of $q(s)$.
- There is no unique choice for the model, $D$, $s$, or $u$, or the parametrization of $q$ and $p$ (e.g., Gaussian).
- The choices probably depend on the species; we just have to experiment a lot.
- Sometimes part of $q$ and $p$ may be essentially the same thing (e.g., distribution of branch tapering) so we get that part of $q$ directly.
Lignum simulation

Next, we examine the higher-dimensional optimization on the other data set. Namely, we use the DF that relates the total length of the offset branches to the length along their parent(s) from which they emanate. We use the first order offset branches and the only zero order parent branch, that is, the trunk. This DF characterizes the outward profile of a tree and, thus, determines the overall shape characteristics. Additionally, we include the inclination angles, at which the offsets emanate from the parent to account on the branching positions in space.

The DF's are shown in Fig. 5.

In this study, we estimated $L_R$, $Q$, $D_{\beta}$, $\zeta$, $\beta$, and $T$ (age in years) parameters of the tree. The data set was generated by a 15-year-old tree with $L_R$ and $Q$ following Gaussian distribution and others being static values, resulting in an 8-dimensional problem to optimize. The parameter values of the data tree along with the optimized values are shown in Table 3.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_R$ &amp; N(0.01, 0.003)</td>
<td>N(0.0084, 0.001)</td>
<td></td>
</tr>
<tr>
<td>$Q$ &amp; N(0.2, 0.05)</td>
<td>N(0.144, 0.054)</td>
<td></td>
</tr>
<tr>
<td>$D_{\beta}$ &amp; 15.0</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>$\zeta$ &amp; 2.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>$\beta$ &amp; 30.0</td>
<td>32.5</td>
<td></td>
</tr>
<tr>
<td>$T$ &amp; 15</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

$L_R$ and $Q$ affect the length of the branches and trunk, whereas $D_{\beta}$, $\zeta$, and $\beta$ affect the inclination angles and spatial organization of the branches. Additionally, we add the discrete parameter $T$ to estimated the age of the tree. We use the genetic algorithm for the optimization and different random generator seeds for the stochastic LIGNUM in order to exclude a possibility to find the exact solution to the problem. The data tree generated with the above parameter values is shown in the left panel of Fig. 6.

For the estimates we can see that $L_R$ and $Q$ were not accurately estimated, but the final tree form (Fig. 6) and the scatter comparison (Fig. 5) indicate that these parameters have compensated for each other. Similarly, the $T=16$ gave the close solution. However, the angle determining parameters were estimated quite accurately. We also can notice quite good convergence of the model to the data from the forms of the actual trees (Fig. 6).
Lignum simulation
Literature

- Raumonen & al. 2013, Rem. Sens. 5, 491
- Calders & al. 2015, Meth. Ecol. Evol. 6, 198
- Kaasalainen & al. 2014, Rem. Sens. 6, 3906
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