

Modeling the tree branch structure at very high resolution

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1. Introduction

Knowledge on the structure of vegetation is required in a number of applications. Depending on the scale at which the modeled processes occur or at which the parameters of interest are required, this can either be dominated by larger structures, e.g. a stand or plot, by single tree positions, or at finer details like the individual branching structure. At even finer spatial resolution individual leaves or needles can be described. Modeling as such can occur spatially explicit or as a distribution. In the first case of 3D modeling the available modeling methods use polygons or polyhedral surfaces, freeform curves and surfaces (Farin, 2002), or parametric primitives (Mäntylä, 1998) like, e.g., cylinders or, in the case of planar shapes, ellipses. These geometric elements are assembled in order to represent the geometric structure. Additional information, e.g. optical properties, can be attached to the individual elements. In the case of modeling by distributions, parameters of interest, e.g., the orientation of leaves, are modeled by describing their distribution, e.g. percentiles or average value and variance. Both types of models can – in principle – either be derived from measurements or constructed by assumptions on the structure of the modeled elements.

Radiative transfer modeling using ray tracing allows generating (simulating) synthetic images from a modeled 3D scene by forward modeling (Morsdorf et al, 2012). The scattering behavior within the canopy requires a model of the individual needles or leaves for producing faithful simulation results (e.g. Disney et al., 2010, Disney et al., 2006. Models for extracting the branch structure only from measurements were described, e.g., by Thies et al. (2004) and Bucksch and Lindenbergh (2008). Using only the available measurements of a terrestrial laser scanner (TLS) placed inside the forest and an orchard, respectively, these approaches are not able to model individual needles or leaves. One way to describe for example a forest stand including individual needles or leaves is to use software packages of computer graphics to generate artificially the foliage orientation and variability within the individual tree crowns. For this generation of virtual forest stands several assumptions and generalizations are required. Rutzinger et al. (2010), e.g., extract tree location, height, stem diameter and crown diameter from mobile laser scanning data and “grow” tree models (Weber and Penn, 1995) reaching the measured parameters. Côté et al. (2009) used for the reconstruction of 3D tree architecture from terrestrial LiDAR scans a generic conifer shoot model based on the model description of Smolander and Stenberg (2003). However, there is still a lack of detailed information concerning actual shoot structure as stated in Côté et al. (2009).

To overcome the limitation of actual shoot structure information, we present an approach for reconstructing exact geometric information on individual twigs, needles, and leaves from measurements. This reconstruction can be performed with sub-millimeter accuracy using a measuring arm in an indoor setting. At the current stage, the approach requires, next to the measurement itself, manual interaction. Individual needles and leaves as well as twig fragments are modeled in terms of their position, length and direction. Basics of the applied 3D modeling approaches were developed within the NEWFOR (Hollaus, 2012) project for a coarser scale (i.e. tree structure) and are adapted and improved for branch modeling within the 3D-VegetationLab project.

In Sec. 2 the measurement device and the sample branches, one coniferous and one deciduous,

are described. In Sec. 3 the methods are explained and the results are discussed in Sec. 4.

2. Study objects and data

2.1 Study objects

One coniferous and one deciduous branch are selected as objects for the modeling. Both branches belong to the end part of the corresponding tree limbs, and carry a typical structure of their species, which makes them – in principle – also suitable for cloning all over the tree. The objects also have similar structures in the sense that both branches are composed of one “primary” and several “secondary” branches.

The coniferous branch (Fig. 1) is taken from a fir tree (*Abies alba*) and is approximately 80 cm long and completely covered with needles. The “secondary” branches spread about 40 cm sideways from the “primary” one, mainly in one plane. They contain many shoots that are attached to them. While not of importance for the reconstruction method, the oldest part of the branch was estimated to an age of 5 years. The shoot location within a secondary branch was used to determine the age of the shoot, with the end shoots considered as first year shoots, whereas others decrease in the age while moving from the branch end towards the branch joint.

The deciduous branch (Fig. 2) comes from a European beech tree (*Fagus sylvatica*). Comparing to the coniferous branch, it is slightly bigger in size (c.a. 1 m in length), but has a similar planar spreading of the secondary branches. Twigs with attached leaves are sparsely distributed over the secondary branches making the object structure more “open” and less complex. Scanning of the branch indoors required a fast transportation of the cut branch to the measurement device because of the fast drying out process.

2.2 Measuring device

A measuring arm (METRIS MCA, 3600 M7) is used to acquire exact geometric information. The instrument used has a triangulation laser scanner mounted on its head, and therefore allows contactless object scanning. A laser stripe is constantly emitted and intersects with an object’s surface if pointed at it. This illuminated cross section is mapped by a camera and furthermore 3D coordinates of the illuminated area are derived. If the laser stripe is moved over the object, a so called “scanning strip” is recorded. Larger areas are covered by scanning several strips. The METRIS measuring arm provides automatically oriented scans of the object. The mounted scanner provides a point cloud that has different along- and across-strip resolution. The across-strip resolution depends upon both the laser strip width and the resolution of the camera, and goes up to 0.05 mm. The along-strip resolution, on the other hand, is usually about 0.5 mm, which is mainly driven by the moving speed of the arm’s scanning head. A slow movement of the head can significantly increase this value and provide a large number of acquired points. Due to its construction, the instrument has a limited operational range that allows scanning of objects up to 1.5 m in size. Besides, there is an operational limit which dictates the size of the acquired scan, i.e. the number of points that can be processed by the system.

2.3 Acquisition method

The arm’s resolution and operational range, on the one hand, and the objects’ structure and size, on the other hand, appear as the most prominent factors during the scanning. Those specific characteristics of the instrument and objects are the reason for introducing separate acquisition strategies for coniferous and deciduous branches.

2.3.1 Coniferous branch

The complex structure of the conifer branch and its large extend (comparing to the operational range) affect both object stability and accessibility during the scanning procedure. Therefore, a two-stepped strategy is introduced to acquire a representative point cloud of the model. First, the overall structure is in the focus, then, each “secondary” branch is measured. In the first step, the main branch and large secondary branches are scanned using a number of scan strips and

ensuring overlaps between the scans. Then, the secondary branches are separated physically (i.e. cut) from the object and measured separately. Therefore, co-registration of all the scanned parts is required in the second step (Fig. 1).

The co-registration is done for each secondary branch independently, transforming its coordinate systems to the main branch's coordinate system. This procedure is done using the spherical heads of pins as targets that are present in both scans. Tree pins per each secondary branch are introduced in zones close to branch joints i.e. in the overlapping scan areas (Fig. 1). Based on the points that represent those targets, different spheres are fitted and then their centers are used for the co-registration. This acquisition approach also allows to model each secondary branch independently and latter to build the final model by merging all the models into one structure.

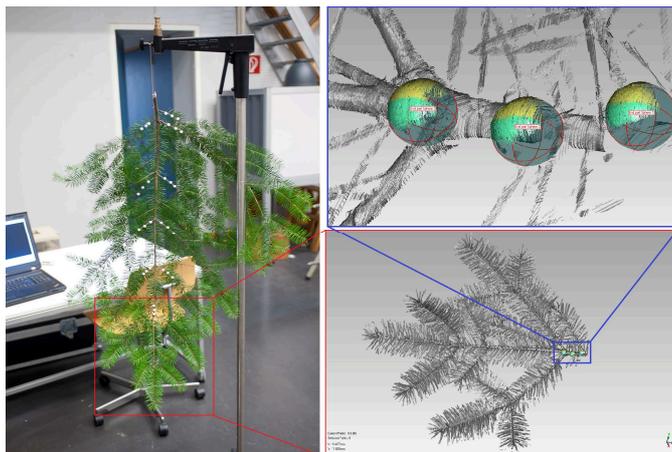


Figure 1: Left: conifer branch prepared for the measurement; Bottom right: detail showing the point cloud of a scanned (“secondary”) part; Top right: detail showing the spheres for co-registration.

The point cloud of the coniferous branch (Fig. 2, right) has over 40 million points. The branches are covered from both sides. As visible in Fig. 1 (bottom right), the first and second year shoot at the end of the tree are not perfectly symmetrical. This holds for the directions and lengths as well as for the branching structure.

2.3.2 Deciduous branch

The deciduous branch is scanned in one step because its sparse structure allows an easy access to the entire object. However, the area of the leaves and the high resolution of the scanner produce a large amount of data that exceeds the operational limit of the arm. Therefore, several smaller scans (i.e. files) are collected to cover the whole object. Since the object and scanner coordinate system were fixed during the scanning, there was no need for the final co-registration of these scans. The final point cloud of the deciduous branch is shown in Fig. 2 (left). It contains almost 50 Million points. The scans were only acquired from the leaf top and bottom side.

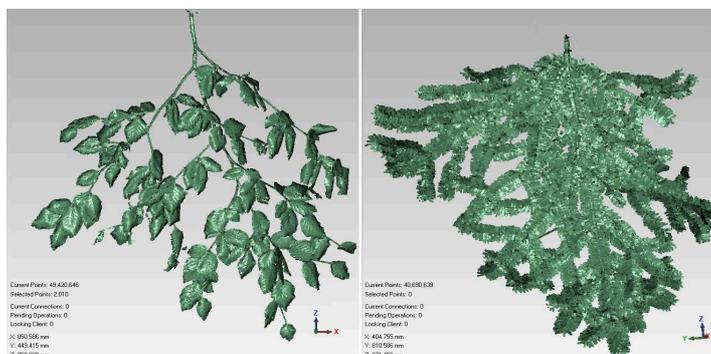


Figure 2: Left: Point cloud of the deciduous branch; Right: Point cloud of the coniferous branch

3. Methods

Needles and leaves are the elementary unit in modeling the coniferous and deciduous branch, respectively. Since it is not possible to represent them in a geometrically similar way, two separate methods are proposed to model those objects. Both methods start with a common task where the corresponding branch structures are modeled, and then, during the modeling of their elementary unit, they split into two independent procedures. Following this logic, the Sec. 3.1 will first discuss the extraction of the branch skeleton, and in Sec. 3.2 and Sec. 3.3 the proposed modeling methods are described.

3.1 Modeling branch structure

The branch structures of the two objects are very similar, i.e. both have branch joints and cylindrical wooden parts that connect them. Thus, topologically correct 3D polylines are used as a model for both the coniferous and deciduous branch structure. Those polylines are digitized (manually) from the corresponding point clouds.

The open structure of the deciduous branch allows a fast digitization without interruptions of the entire object structure in one coordinate system, i.e. the object coordinate system (OCS). This included digitization of the leaf stalks.

The digitization of the coniferous branch structure is not so straightforward. The presence of needles disturbs the digitization process making the selection of stem points much more time consuming comparing to the deciduous branch. Therefore, an automatic procedure for point reduction is implemented before the digitization. The point cloud reduction is based on the voxel model derived from the scanned part and an estimation of a local voxel density. A property of the original point density is, that it is strongly influenced by the instrument's scanning pattern.

Voxelizing the data with an appropriate voxel size, the native structure of the object is emphasized rather than the scanning properties of the instrument. A voxel is considered as foreground (i.e. filled), if it contains at least one point from the original point cloud. The voxel density is the percentage of filled voxels in the 33-neighborhood of the center voxel (sphere of radius 2 in voxel space). An empirically driven thresholding on the local voxel density is done to reduce the starting point cloud. The used voxel size is 1 mm, which is close to the width of an average needle of the conifer branch. After the reduction procedure most of the needle points are removed from the starting data set, and the remaining points (mainly points from the stem) are used for digitizing the skeleton of the scanned part (Fig. 3). Since the co-registration of all the scanned parts is already done, the resulting 3D polyline structure is in a coordinate system of the conifer branch, i.e. in the OCS.

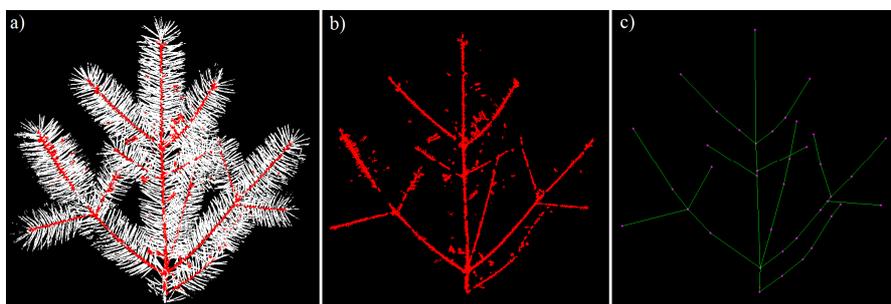


Figure 3: a) The classified original point cloud, based the thresholding the local voxel density; b) the reduced point cloud; c) the skeleton of the scanned part (right)

3.2 Modeling the deciduous branch

For modeling the deciduous branch it is assumed, that the wooden structure is available as 3D polyline. Thus, only the leaves need to be modeled. For each leaf, a local point cloud is extracted. This is based on a bounding box which is extracted per leaf. Based on those local

point clouds, for each leaf an ellipse is estimated and used as a model for that leaf. Before estimating the ellipse, the regression plane is fitted through the leaf point cloud (Fig. 4, left). This provides the orientation of the leaf plane.

Next, the leaf point cloud is orthogonally projected to the regression plane and boundary leaf points are extracted from this data set. The ellipse parameters (center point, major and minor radius, and axis orientation) are estimated by fitting the ellipse through the leaf boundary points (see Figure 4, right). These parameters are transformed into a description suitable for including it in the model coordinate system (MCS): the normal vector of the regression plane, the ellipse center point, the end point of the longer radius of the ellipse, and the minor radius.

To establish a correct topology in the final model, the estimated ellipse is translated to the closest end point of the branch skeleton. In this way the native orientation of the leaf (the regression plane) is preserved. The translation parameters are resolved from the equality condition of the end point of the longer radius of the ellipse (tip of the leaf) in MCS and the closest end point of the branch skeleton in OCS.

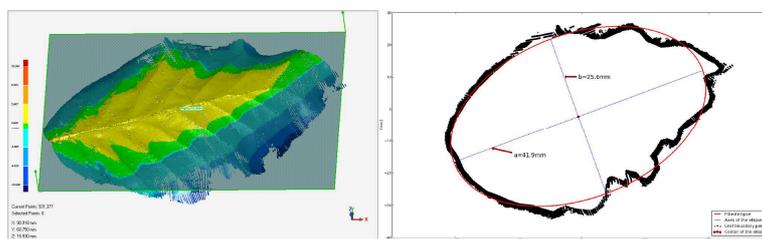


Figure 4: Left: The leaf point cloud with the regression plane; Right: the fitted ellipse displayed over the leaf boundary points

3.3 Modeling the coniferous branch

To handle the large data set, the modeling of all the scanned parts (the primary and the secondary branches) is performed independently and then, in the subsequent step, their models are combined into the final branch model. In the following a method for modeling of a shoot is presented. This method can either be applied to the entire branch, or the shoot can be cloned to populate the entire skeleton with the needles of the shoot model.

Using cloning is therefore a two step approach: (1) creating the shoot model, and (2) cloning the shoot model over the branch structure. A detailed workflow that includes also the skeleton modeling and all intermediate layers is illustrated in Figure 5. Since the proposed strategy allows an independent modeling of the scanned parts, only one is selected here to demonstrate the potential of the proposed method. The end part of the branch (see Figure 1) is taken because it has the most complex structure among other parts. Using a shoot model multiple times, enhances the efficiency of the modeling procedure. However, a typical data set needs to be selected when creating only one shoot model. This 3D model is assumed to be representative for all the shoots within the branch and used later, in the cloning step.

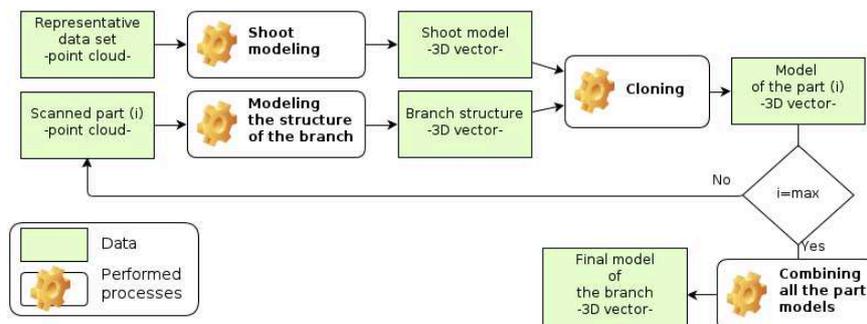


Figure 5: The workflow for modeling the branch

3.3.1 Modeling the shoot

A point cloud of a first year shoot (Fig. 6a) is selected as a representative data set for the shoot modeling by manually digitizing. Each needle is represented by a 3D line, with a starting and ending point, while the shoot's stem is represented by 3D polyline. Since the starting points of the needle lines are also the nodes of the stem poly line, the model is also topologically correct (Fig. 6b). The local coordinate system of the shoot model - the model coordinate system (MCS) - is defined with two reference points and one plane. The starting and ending point of the wooden part are selected as the reference points, whereas the regression plane fitted through the needle end points (Fig. 6c) is taken as the reference plane.

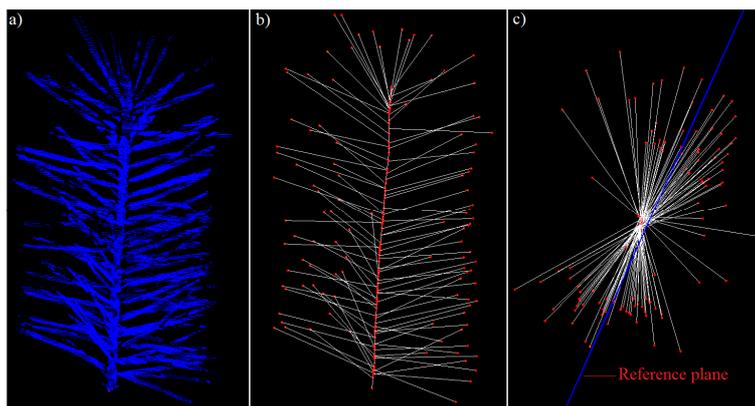


Figure 6: a) Point cloud of the representative shoot; b) the shoot model; c) the shoot model from the top view with the reference plane.

3.3.2 Cloning the shoot model

To build the conifer branch model by cloning, the shoot model is cloned over the branch skeleton. For each segment of the skeleton's polylines an appropriate part of the shoot model is firstly extracted and then cloned on this location. For example, segments that represent an end part of the skeleton are cloned with the whole shoot model, whereas middle segments are cloned only with a lower part of the shoot model. In case where the length of the skeleton segment exceeds the length of the shoot model, the lower part of the shoot model is used to bridge the remaining part of the segment.

The cloning procedure is performed by transforming the shoot model from MCS to OCS. Since the MCS is defined by the two points and one plane, the starting and ending point of the skeleton segment are used as the reference points, while a local plane is taken to resolve the orientation of the shoot model. The local plane is estimated for each skeleton segment independently, based on the local needle points filtered out during the point reduction procedure (see Sec. 3.1).

4. Results and discussion

In this Section the results of the cloning process are presented and discussed. The results are based on the shoot model shown in Fig. 6b, and the branch skeleton shown in Fig. 3c. The application of the above described modeling and cloning methods lead to the branch model shown in Fig. 7. The point cloud and the final branch model show a perfect correspondence for the location of the manually modeled shoot model (marked red in Fig. 7), exhibiting the same (ir)regularity of the needles especially at the end and with respect to their orientation out of the plane. The lower part of the shoot model shows a homogeneous density of needles. Therefore, this 1st year shoot could be cloned all over the manually extracted branch skeleton. At joints, where multiple sub branches connect, the 3D model, in some cases, exhibits more needles than the point cloud data suggests (Fig. 7).

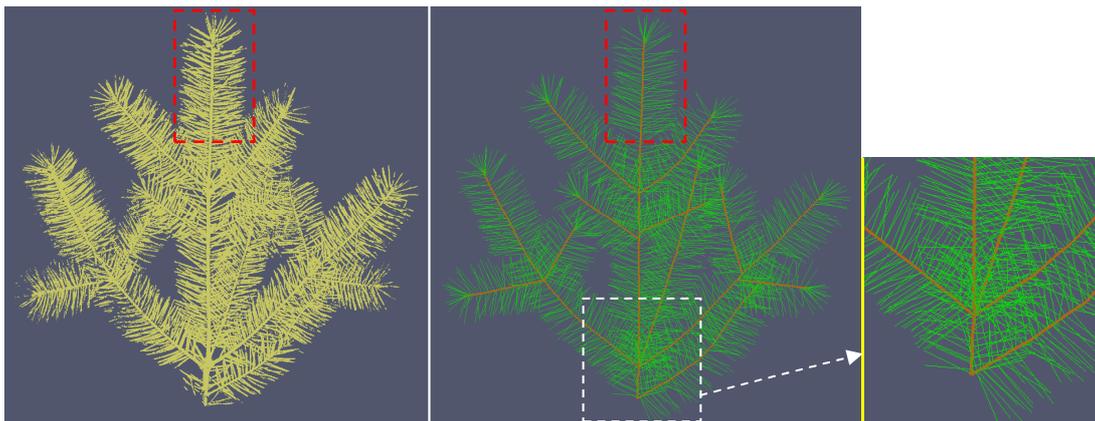


Figure 7: Point cloud of a coniferous twig versus its extracted 3D model. The red boxes show the shoot which was manually modeled and used for cloning; Left: Pointcloud; Middle: 3D model with classification into needles and branch structure; Right: Erroneous clumping of needles at joints

Considering the entire method of modeling, a number of steps include simplifications and cause differences between the geometric model and the acquired data. However, the entire method is data driven and allows modeling of the branch structure for each individual needle and leaf as well as the branches in between. A slight curvature of the needles was visually found in the data set but was neglected during modeling. The chosen model for a needle is the straight connection between the start and the end point of the needle. This rather simple model could be enhanced by using the average thickness of the needle for fitting an ellipsoid of revolution, which is favorable if the models are used i.e. for ray tracing analyzes where volumetric objects are preferred. However, also the orientation of the branch is available, which allows even more complex needle models to be applied, too.

Because the branch skeleton and the needle axis are digitized manually based on the point cloud, the location of the digitized elements is on the outer surface of the corresponding objects. If necessary, this error could be simply corrected by estimating or measuring the diameter of the corresponding object and translating the axis by half of the diameter. While a fitting approach would estimate the axis directly, the irregular point distribution, especially, in the case of a coniferous branch, poses an additional challenge to obtain a better geometric position in this way.

Concerning cloning, no 2nd year, 3rd year or even older shoots were used for this model. In general, the 1st year shoots have more needles than the older shoots and therefore an overestimation of the number of needles in the current cloned model is assumed. 2nd or 3rd year shoots could be simulated by reducing the number of needles before inserting the clone into the branch structure. Further investigations in this direction need to be performed.

Concerning the leaf model, the approximation of the leaf as an ellipse applies well to the beech leaves used in this study. However, the main consideration is a model with a small number of parameters, e.g. 5 in the case of an ellipse or 6 for a triangle. Fitting elements like an ellipse overcomes problems with gaps or inhomogeneous point densities in the acquired datasets. Alternative approaches include using the alpha-shape for the outline detection and the Douglas-Peucker algorithm for simplification in order to get a polygonal outline with a small number of points. Generally, the leaves are assumed to be flat which does not account for seasonality, although leaf curvature is visible in Fig. 4 (left). Again, ray tracing advocated for simple models.

5. Conclusion

Methods to model individual twigs, needles, and leaves, based on point clouds acquired with a measuring arm, at a high level of detail are presented. The model for coniferous branches

consists of 3D polylines with an additional classification, whether a line element represents a needle or belongs to the branch. Each line element can be transformed to a volumetric description by using their respective thickness value. The chosen model for representing a single leaf is an ellipse which acts as a good approximation for the complex leave structure. This study showed that the presented approach leads to promising results, which represent the real 3D branch structure based on measurements of the object. These detailed coniferous and deciduous 3D branch models can be used to build up larger twigs and branches by using cloning approaches. In this way virtual tree models can be enhanced or created that are used i.e. as input for radiative transfer and process modeling. While a faithful reconstruction is possible with the presented approach, measures of quality need to be derived before these results can be used in further applications. Likewise, for larger scenes to be modeled, the degree of automation needs to be increased.

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