APPLICATIONS FOR POINT CLOUD SKELETONIZATIONS IN FORESTRY AND AGRICULTURE

A. Bucksch, R.C. Lindenbergh, M. Menenti

Delft Institute of Earth Observation and Space Systems (DEOS), Delft University of Technology, The Netherlands

ABSTRACT

In recent years, both airborne and terrestrial laser scanning developed to a standard technique for acquiring information on terrestrial landscapes. Here forest inventory and orchard management is considered. Inventory and parameterization of individual trees in orchards and forests are of large interest in nowadays society because of the potential of economical maximization of orchard production and the sustainable management of forests.

Complex objects like trees require a detailed structural analysis before an analysis of single trees is possible. Skeletonization is such a structural description that enables the extraction of length, diameters, volumes and position of individual branches but also of trees as a whole. In this paper an overview of current possibilities for skeletonization algorithms on trees is given. A new method of skeletonization, especially designed for the analysis of tree data is described and its applicability demonstrated on airborne and terrestrial laser scanning scenarios.

The evidence reviewed in this paper leads to conclude that skeletonization is a valuable tool for forest inventory and orchard management. It will be shown that skeletonization offers the possibility of species independent measurement of trees, which make skeletonization a general tool for parameter extraction on trees that empowers also research fields different from orchard management and forest inventory.

Keywords: Laser scanning, skeleton, point cloud, tree parameters, forestry, hydrology, tree physiology, orchard management

1. INTRODUCTION

The goal of this paper is to give an overview of possible applications of skeletons on laser scanning point clouds. The paper focuses on application examples related to the automatic extraction of complex tree structures from scanning data and the consecutive parameter extraction using skeletons as an organizing principle. In this section first the overall motivation is outlined. After that the airborne and terrestrial laser scanning setup is explained. The section finalizes with an intuitive explanation of our definition of a skeleton.

1.1   Motivation

Laser scanning captures the real world in a 3D picture, like a photo camera. Basically a 3D picture, or laser scan, assigns a distance between the camera and a surface to every discrete location in the picture. Until now, analysis of such 3D pictures was mainly focused on the acquisition of surface information. For example fitting known geometries like planes, cylinders or spheres to the 3D picture [Lukacs et al. 1998] or finding these geometries in the data with calculation expensive methods like 3D Hough transform [Rabbani 2006]. Therefore data is often analyzed by the means of an existing model, which has to be verified, instead of analyzing the data to extract an abstract structural data description, which can be used later to perform measurements within the data. Less attention was drawn to the problem of extracting the underlying structure of the captured objects. This underlying structure is masked by irregularities such as noise and biases. When laser scanning is applied to capture complex real world objects, such as trees, the underlying structure can provide useful tools for navigating through the data to positions of interest. Using a tree as an example, positions of interest are the beginning and the end of a branch in order to extract its length. An obvious benefit of such a structure is that its extraction is data driven, and therefore adjusting to irregular shapes in nature, which are hard to be approximated by an a priori approach. For example the shape of a pipe in an industrial installation can be approximated by many connected cylinders, while the wall of a house can be approximated by a plane. But what is the shape of a tree suffering from deformed of broken branches? Or consider a tree in an industrial orchard, which is cut and deformed by humans to maximize the light falling into its crown: what is its shape?

1.2   Laser scanning

Laser scanning is capable to measure thousands of distances per second from the instrument to the targeted surface [Shan et al. 2008]. These scanners are used to obtain data of large objects like trees, houses, whole towns or forests. Typically these objects are represented in a point cloud. A point cloud is therefore a point wise sampling of a 3D surface.

The properties of a point cloud are distinguished dependent on the scanning platform. In this paper we distinguish between a terrestrial laser scanning platform (TLS) and an airborne laser scanning platform, (ALS). The ALS platform [Figure 1] uses the Time-of-Flight principle for distance determination from a airborne vehicle like an airplane or a helicopter. The Time-of-Flight

principle is measuring the time between a sent pulse and its returning reflection from the object surface. Airborne systems capture only 2,5D data with low local resolution. [Table 1] lists typical values for the Actual Height Model (AHN) of the Netherlands [AHN 2009], which collected ALS measurements covering the whole Netherlands. Furthermore the two helicopter based systems FLI-MAP and FLI-MAP 400 are listed, which fulfill the specifications of the upcoming AHN2. When considering the sampling of trees we may characterize ALS as collecting sparse data, suffering mainly from undersampling.
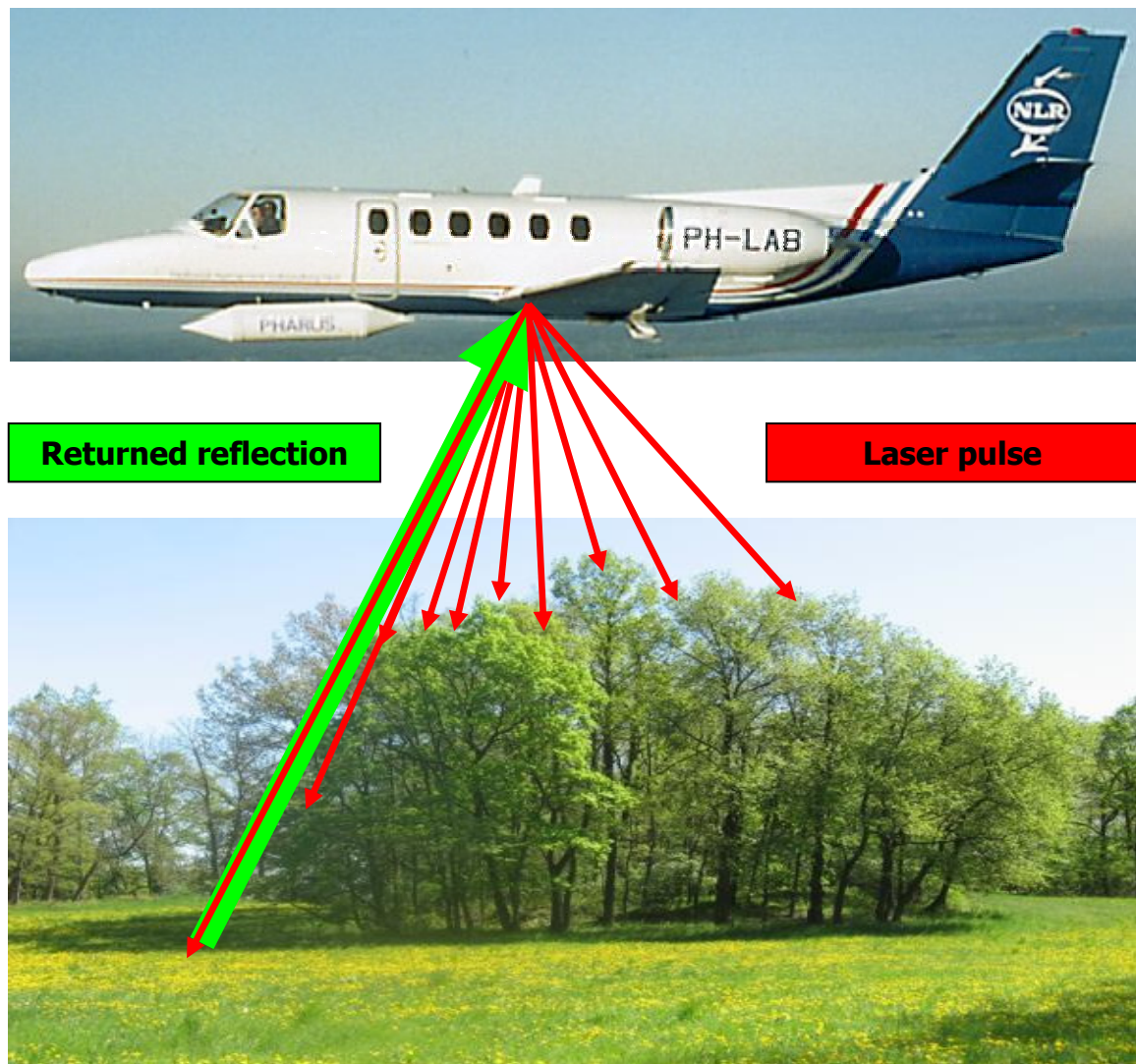

Figure 1: Simplified principle of airborne laser scanning.

TLS is operating from the ground and collects scan points at a very high point density in its spherical surrounding [Figure 2]. Mainly two principles are used for capturing large objects, as shown in [Table 1]. The already introduced Time-of-Flight principle and the phase-based principle, in which a continuous beam is emitted and received and the phase shift back at the receiver is used to determine the distance between the object and the scanner. Also TLS data contains varying point density and local under sampling because of its spherical scan geometry, but suffers more from the noise and biases within the data.
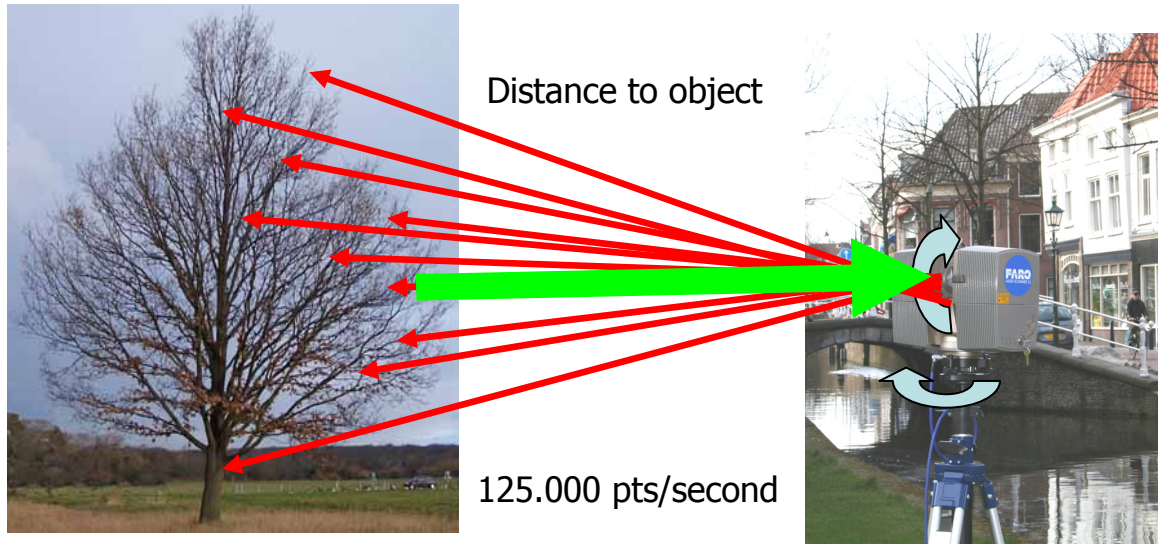
Figure 2: Simplified principle of terrestrial laser scanning.

Both scanning platforms share the problem of occlusion effects. This effect occurs in areas where the laser beam is not able to measure the distance, because the actual surface is behind another surface. For example if a branch is measured, then the branch crossing behind will be partly not measured from that same scan position. Data facing the problems named above is called imperfect throughout the paper.

Table 1: Typical values for laser scanning setups: The ALS values correspond to a flight height of 100m and the TLS values to a full 360 degree scan.

ALS			TLS	
AHN	**FLI-MAP**	**FLI-MAP 400**	**Phase based (Z+F Imager 5006)**	**Time-of-fligh (Leica Scan Station)t**
$1\,pt\!\!\big/\!m^2$	$10\,pt\!\!\big/\!m^2$	$50\,pt\!\!\big/\!m^2$	$100 Mio.\,pt\!\!\big/\!360^o$	$100 Mio.\,pt\!\!\big/\!360^o$

1.3   Skeletonization

As already discussed, laser scanning captures real world objects and represents them as a point cloud. The obtained point clouds for skeletonization are derived from the real world as we recognize it, namely from 3 dimensional Euclidian space. The study of point clouds as an 3D object representation and the possible information extraction from them is still under active research. Meanwhile the majority of research is focusing on the extraction of surface information; this paper is dedicated to a structural approach.

Obtaining object structure can help in various point cloud applications. Such applications aim at object identification or analyzing the shape parts of a tree in terms of size. A skeleton is a one-dimensional, "line-like", description of the object structure. Skeletons are represented as curves, collections of ordered points or graphs. Their extraction from a point cloud faces several algorithmic challenges, such as centeredness, topological correctness and robustness.

At this stage we can summarize that tree skeletonization extracts a skeleton, from a point cloud including the branching points of the tree like shown in [Figure 6b]. Such a skeleton gets useful if it has the following characteristics:

The skeleton represents correctly the topology of the object as sampled by the point cloud; it is geometrically centered within the point cloud and it is connected.

Note here that a structure description, like a skeleton, contains both, topological and geometric aspects. As a skeleton is "line-like" and centered within the object, it is used to recognize positions of interest within the object. Therefore, the surrounding data of a point of interest is analyzable. An intuitive example is the diameter at a certain stem height, where the skeleton can be followed from the bottom to the desired height.

Skeletonization of trees as a special case and its application to orchard management and forest inventory on selected examples is the application focus of the paper. In addition we will show the connection to existing research, like flood plane modeling and tree physiology that can be empowered by the use of skeletonization.

2. RELATED WORK

In this section an overview of approaches to derive a skeleton from terrestrial laser scan data is given. To our best knowledge skeletonization was not done before on individual objects in airborne laser data, therefore the related work is limited to terrestrial laser scan data.

A first successful way of tree skeletonization is explained in [Gorte et al. 2004]. In this approach the sequential data thinning method of [Palágyi et al. 2001] is used to skeletonize terrestrial laser scanner point clouds. Applying this method requires rasterizing of the point cloud. On this raster the morphological operations opening and erosion are used to produce a skeleton [Serra 1982]. Drawback of this algorithm is the large number of parameters that need to be controlled, like resolution of the raster, and type and size of the structuring element. Furthermore, centering is hard and connectivity can not be guaranteed. This approach was later extended to so-called Dijkstra Skeletonization [Gorte 2006]. The connectivity of the skeleton was improved by considering several raster resolutions. Both [Gorte 2006] and [Gorte et al. 2004], have one important drawback. To extract a centerline from an object, the hull of the object should be completely sampled. Due to occlusion effects this is in practice only achieved in rare cases when working with high point densities.

A graph-reduction approach is proposed in [Bucksch et al. 2008]. An adaptive octree is used to subdivide the point cloud into octree cells. Instead of looking at the number of points within the cells this octree subdivision relies on the directions by which the point cloud is passing through the octree cell sides, which is the key to operate on only a few data points if necessary. Only two parameters are needed as input for this algorithm, a threshold to determine when a cell side is considered to be crossed and a minimum allowed cell size to terminate the subdivision process. From this octree an initial graph, the so-called octree graph, is extracted. This octree graph is reduced to a skeleton. The reduction follows a set of rules, which are applied to systematically remove redundant structures in the graph. As a

direct result segmentation in topological different segments is achieved, where every vertex in the resulting skeleton graph is corresponding to a certain segment in the point cloud. The algorithm shows good stability to gaps and robustness to noise in the point cloud.

Recently [Hui et al. 2007] introduced a semi-automatic approach using tree allometries to produce a model of a tree only for visualization purposes. Their aim is simply to create a plausible model, and not to quantify any tree parameters. The described procedure computes a rough skeleton of the main branches, until approximately two third of the tree height. The remaining tree is generated based on species dependent allometries of known branching behavior. The calculation of a surface mesh is based on an estimated diameter at certain positions. Species depended allometries are used to estimate the diameters and to produce a polygonal mesh of the tree surface.

For more general information the reader is referred to [Biasotti et al. 2008] as general overview of skeletal structures and to [Cornea et al. 2007] for detailed background on the extraction of skeletons from point clouds.

3. APPLICATIONS

The section starts with a brief review of the skeletonization method used in the examples. After that extractable parameters from ALS data and their application in orchard management and forest inventory are discussed, followed by the evaluation of TLS data and their application to orchard management. The extracted parameters for forest inventory are connected to ongoing research in flood plain modeling, while the derivable parameters for orchard management are relatable to state of the art research in tree physiology.

3.1 Review of the SkelTre algorithm

The SkelTre method is an algorithm to extract a skeleton from imperfect data of trees. For this purpose the tree point cloud is subdivided by an octree into cubic cells. From these octree cells a graph is extracted. The graph extraction is based on an estimate how the actual surface, that is represented by the point cloud, is crossing the octree cell sides. A direction labeling is used to retract the extracted octree graph to a one-dimensional skeleton. The benefits of this skeleton are that the centeredness and topology, is provable good. Topology correctness is a prerequisite to enable proper navigation through the tree while centeredness enables us to measure e.g. diameters and lengths of tree parts. The principle is shown in Figure 3, for details on the skeletonization the reader is referred to [Bucksch et al. 2009a].
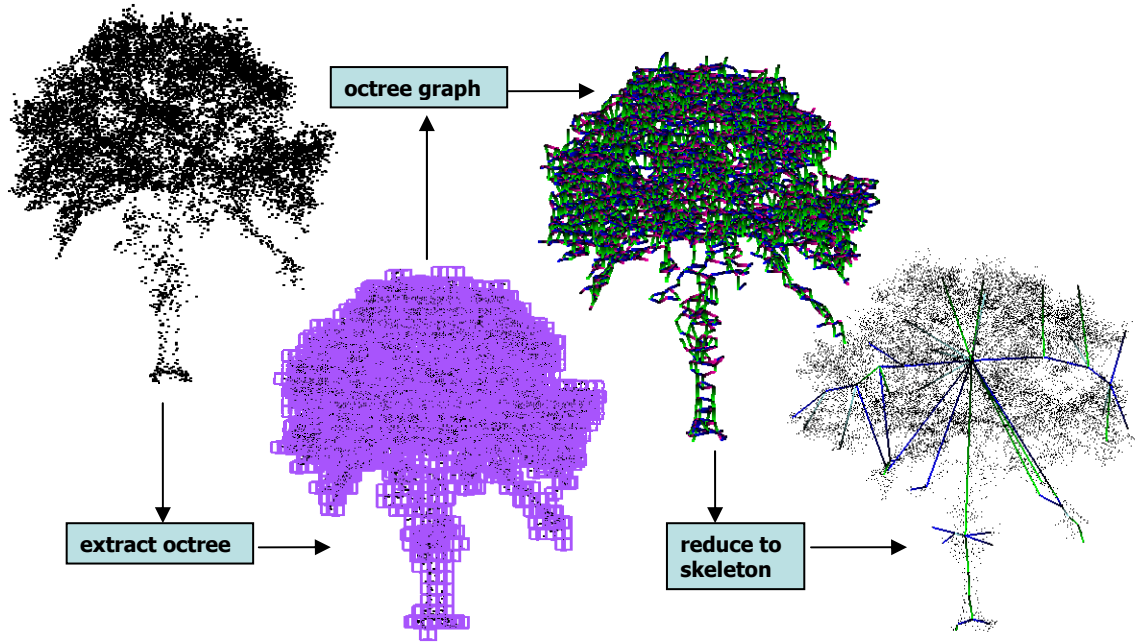
Figure 3: The principle of the SkelTre skeleton extraction.

3.2 ALS Applications

Forest inventory is aiming on collecting measures on trees within a forest to quantify changes and the amount of forest in certain regions. Useful parameters reflecting change and amount are the tree height, the breast height diameter (bhd), crown size and the tree to tree distance (tttd) [Woodall et al. 2006].

As shown in [Bucksch et al. 2009b] the the breast height diameter (bhd) is robustly derived by analyzing the point distances from the skeleton. The bhd refers to the stem diameter at 1.30 meter height. While state-of-the-art research uses species dependent information to derive the diameter from an estimated crown size e.g. [Popescu et al. 2003] [Næsset et al. 2002], skeletonization allows a direct, data driven and species independent measurement of the bhd.
Another valuable parameter in this context is the tree-to-tree-distance (tttd). The tttd can be derived from a Delaunay triangulation, as shown in Figure 5, of the stem center location as given by the skeletonization. In this case the edges in the triangulation represent the distance between two trees.
While it is straight forward to recognize that the tree height is given by the skeleton as distance between the lowest and the highest end in the skeleton, it is also expected, that the crown size is derivable from the convex hull of the upper skeleton ends.
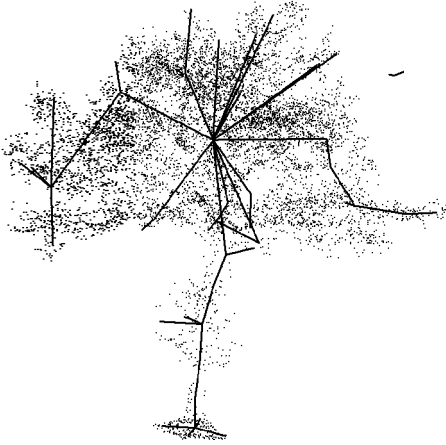
Figure 4: Example of a skeleton extracted from ALS data. The example cloud was scanned with a FLI-MAP 400 system and approximately 50 points per square meter.
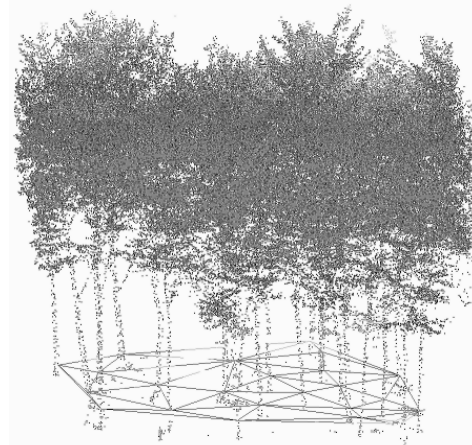
Figure 5: Delaunay triangulation of the stem centers enables the extraction of the tree-to-tree distance.

Modeling of flood plains is still under active research. The presence of trees in flood plains of lowland rivers causes friction for the runoff water in case of a flooding event. An important parameter to quantify this friction is the so-called hydrological roughness [Baptist 2005] [Asselman et al. 2002], which is derived from the breast height diameter (bhd) of the trees involved. From high density airborne laser altimetry data of the floodplains trees can be extracted that can be consecutively skeletonized using for example the SkelTre algorithm.

3.3 TLS Applications

Orchard management is the interpretation of tree parameters in order to monitor the vitality and performance of trees. From the tree parameters the actual needs per individual tree are derivable. A skeletonization of a honey crisp apple tree (*Malus x domestica* Borkh) from an orchard is shown in Figure 6. The similarity between the skeleton and the tree allows us extract the branch length as the length of the skeleton between a branch begin and a branch end. Again, by evaluating the distances of the local point cloud points to the skeleton, also the stem and branch diameters can be estimated. The relation between the 3D geometry of a tree and its physiological processes, especially for orchard trees, is an ongoing research topic [Fleck 2002] [Fleck et al. 2004] [Fleck et al. 2009]. Branch length and branch diameter are the main input parameters to such a geometry driven description of physiological processes, such as the photosynthesis. This may allow the prediction of the amount of fruit produced by an individual tree. Furthermore, length and diameter are useful for determining the solid volume of a tree, which is known as the biomass.

Automatic detection of branch length and diameter enables the development of orchard monitoring systems. Therefore the vitality and performance of an individual tree is related to its branch growth, one can think of a system that automatically determines the amount of water and fertilizer needed for an individual tree, or cuts certain branches to maximize the amount of light falling into the crown.
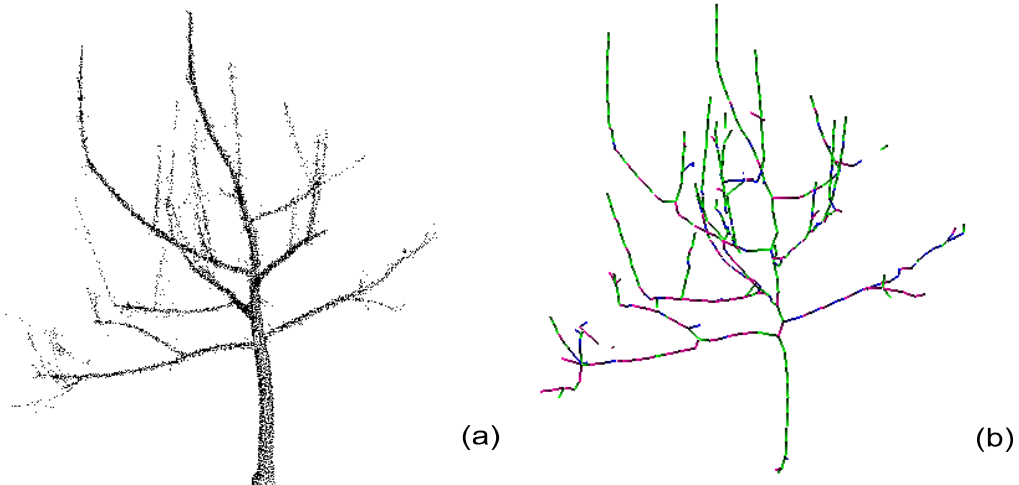
Figure 6: (a) the point cloud of an orchard tree and (b) the skeleton of the orchard tree.

4. CONCLUSION

Skeletonization is a new and highly valuable tool to acquire structural information from laser scanned trees. Skeletonization offers the possibility to extract parameters from sparse ALS data as well as from high density TLS data independent from the species.

The paper has shown that the extracted parameters are useful as input to existing applications in forest inventory and orchard management. Therefore the interpretation chain between obtained data and nature processes dependent on fixed objects like trees is expected to be connectable via a skeletal structure like the SkelTre Skeleton in many cases. The connection between the measured data itself and two processes was shown on two examples of ongoing research in flood plain modeling and tree physiology.

More generally, research on the relation between processes and the underlying structure will be done in future. Therefore, the extraction of a skeleton describing the underlying structure on imperfect data is important.

REFERENCES

[AHN 2009] *AHN:actual height model of the Netherlands.* http://www.ahn.nl/, last visited: 17. April 2009.

[Asselman et al., 2002] Asselman,N. Middelkoop, H Straatsma, M.R.M and Jesse, E.V.P. 2002: *Assessment of the hydraulic roughness of river flood plains using laser altimetry.* In: F. Dyer, M. Thoms and J. Olley, Editors, The Structure, Function and Management Implications of Fluvial Sedimentary Systems, IAHS Publication Vol. 276, International Commission On Continental Erosion and Unesco, Alice Springs,pp. 381–388.

[Baptist 2005] Baptist, M. *Modelling floodplain biogemorphology,* PhD Thesis at Delft University of Technology, Delft University Press, Vol. 5 Delft Hydraulic Series.

[Biasotti et al. 2008] Biasotti, Silvia Attali, Dominique Boissonnat, Jean-Daniel Edelsbrunner,Herbert Elber,Gershon Mortara, Michela Sanniti di Baja, Gabriella Spagnuolo, Michela Tanase, Mirela and Veltkamp, Remco 2008: *Skeletal Structures.* Chapter 6 in: Shape Analysis and Structuring, L. De Floriani, M. Spagnuolo (Eds.) Springer 2008.

[Bucksch et al. 2008] Bucksch, Alexander, Lindenbergh, Roderik 2008: *CAMPINO - A skeletonization method for point cloud processing.* ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 63, No. 1, pp. 115-127.

[Bucksch et al. 2009a] Bucksch, Alexander, Lindenbergh, Roderik and Menenti, Massimo 2009: *SkelTre - Fast skeletonization of imperfect point clouds of botanic trees.* Eurographics/ACM Siggraph Symposium on 3D Object Retrieval, München 28.March-3.April 2009.

[Bucksch et al. 2009b] Bucksch, Alexander, Lindenbergh, Roderik and Menenti, Massimo, Abd Rahman, Muhammad Zulkanain 2009: *Skeleton-based botanic tree diameter estimation from dense LiDAR data.* In proceedings: SPIE Optics and Photonics, San Diego 2-6 August 2009 (to appear).

[Cornea et al. 2007] Cornea,Nicu D., Min,Patrick, Silver,Deborah 2006: *Curve-Skeleton Properties, Applications, and Algorithms.* IEEE Transactions on Visualization and Computer Graphics Vol. 13, No. 3, pp.530—548.

[Fleck 2002] Fleck, Stefan 2002: Integrated analysis of relationships between 3D-structure, leaf photosynthesis, and branch transpiration of mature Fagus sylvatica and Quercus petraea trees in a mixed forest stand. PhD thesis at University of Bayreuth. Bayreuther Forum Ökologie, Vol. 97, 1-183.

[Fleck et al. 2004] Fleck, S., van der Zande,D., Schmidt, M. Coppin, P. 2004: Reconstructions of tree structure from laser-scans and their use to predict physiological properties and processes in canopies. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 36 (8/W2), 119-123.

[Fleck et al. 2009] Fleck,S., Embree,C.G., Nichols,D. 2009: *The systematic influence of Crop Load, Spur Type, 3D-Canopy Structure, and Leaf Zonal Chlorosis on Leaf Photosynthesis of 'Honeycrisp' Apple Trees.* Acta Horticulturae (submitted).

[Gorte et al. 2004] Gorte,Ben Pfeifer,Norbert. 2004: *Structuring laser-scanned trees using 3D mathematical morphology.* International Archives of Photogrammetry and Remote Sensing, Vol. XXXV, B5, pp. 929-933.

[Gorte 2006] Gorte,Ben. 2006: *Skeletonization of Laser-Scanned Trees in the 3D Raster Domain.* Lecture notes in geoinformation and cartography:

innovations in 3D Geo InformationSystems pp. 371-38. Berlin Heidelberg: Springer.

[Lukacs et al. 1998] Lukacs,Gabor Martin,Ralph Marshall,Dave 1998: *Faithful Least-squares Fitting of Spheres, Cylinders, Cones and Tori for Reliable Segmentation.* ECCV'98: Proceedings of the 5th European Conference on Computer Vision-Volume I, pp. 671—686.

[Palágyi et al. 2001] Palágyi,K. Sorantin,E. Balogh,E. Kuba,A. Halmai,C. Erdôhelyi,B. Hausegger, K. 2001: *A sequential 3D thinning algorithm and its medical applications.* In Proceedings: 17th Int. Conf. Information Processing in Medical Imaging, IPMI Davis, USA, Lecture Notes in Computer Science, Springer.

[Popescu et al. 2003] Popescu,S C Wynne,R H Nelson,R F 2003: *Measuring individual tree crown diameter with LiDAR and assessing its influence on estimating forest volume and biomass.* Canadian Journal of Remote Sensing Vol. 29, No. 5, pp. 564-577.

[Rabbani 2006] Rabbani,Tahir 2006: *Automatic reconstruction of industrial installations using point clouds and images.* P.h.D. thesis, Delft University of Technology, The Netherlands.

[Shan et al. 2008] Shan,J. and Toth,C. (Eds.) 2008: *Topographic Laser Ranging and Scanning.* CRC Press.

[Serra 1982] Serra,Jean 1982: *Image Analysis and Mathematical Morphology.* Academic Press, London.

[Xu et al. 2007] Xu,Hui, Gossett,Nathan, Chen,Baoquan 2007: *Knowledge and heuristic-based modeling of laser-scanned trees.* ACM Transactions on Graphics (TOG) Vol. 26, No. 4.

[Næsset et al. 2002], Næsset,E and Okland,T 2002: *Estimating tree height and tree crown properties using airborne scanning laser in a boreal nature reserve.* Remote Sensing of Environment, Vol.79, Nr. 1, pp.105-115.

[Woodall et al. 2006] Woodall, Christopher Hansen, Mark Brand, Gary McRoberts, Ronald Gallion, Joey; Jepsen.Ed 2006: *Idiana's forests 1999-2003* Resour. Bull. NC-253B. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.