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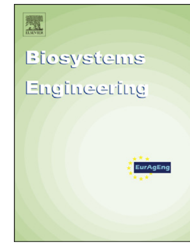


Research Paper

# Deciduous tree reconstruction algorithm based on cylinder fitting from mobile terrestrial laser scanned point clouds

*Valeriano Méndez* [a,*], *Joan Ramon Rosell-Polo* [b], *Ricardo Sanz* [b], *Alexandre Escolà* [b], *Heliodoro Catalán* [a]

[a] *Department of Applied Mathematics, Polytechnic University of Madrid, Ciudad Universitaria, s/n, 28040 Madrid, Spain*

[b] *Department of Agricultural and Forest Engineering, Research Group on AgroICT & Precision Agriculture, University of Lleida, Av. Rovira Roure, 191, 25198 Lleida, Spain*

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Vector reconstruction of objects from an unstructured point cloud obtained with a LiDAR-based system (light detection and ranging) is one of the most promising methods to build three dimensional models of orchards. The cylinder fitting method for woody structure reconstruction of leafless trees from point clouds obtained with a mobile terrestrial laser scanner (MTLS) has been analysed. The advantage of this method is that it performs reconstruction in a single step. The most time consuming part of the algorithm is generation of the cylinder direction, which must be recalculated at the inclusion of each point in the cylinder. The tree skeleton is obtained at the same time as the cluster of cylinders is formed. The method does not guarantee a unique convergence and the reconstruction parameter values must be carefully chosen. A balanced processing of clusters has also been defined which has proven to be very efficient in terms of processing time by following the hierarchy of branches, predecessors and successors. The algorithm was applied to simulated MTLS of virtual orchard models and to MTLS data of real orchards. The constraints applied in the method have been reviewed to ensure better convergence and simpler use of parameters. The results obtained show a correct reconstruction of the woody structure of the trees and the algorithm runs in linear logarithmic time.



## 1. Introduction

Geometric reconstruction can be used to obtain a detailed structural analysis of trees. The aim is to derive vegetative parameters such as leaf area, canopy volume or woody volume from massive data point clouds. Direct use of raster information, e.g. a photograph, can be used to obtain any of these parameters (Phattaralerphong & Sinoquet, 2007). Reconstruction of tree geometry supports the implementation

* *Corresponding author*. Department of Applied Mathematics, E.T.S. Ingenieros Agrónomos, Polytechnic University of Madrid, Ciudad Universitaria, s/n, 28040 Madrid, Spain. Tel.: +34 917 308 355.

E-mail addresses: valeriano.mendez@upm.es, v.mendez@bbva.com (V. Méndez).

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**Nomenclature**

| Variable | Description |
|---|---|
| A | Covariance matrix |
| $\alpha$ | Polar angle used in the iterative method to obtain $\vec{d}$ |
| B | A branch object |
| $B^*$ | Temporal branch built when a new point is included in the process |
| BN | A new branch built by the branching process |
| c | Centroid of a branch |
| $\vec{d}$ | Cylinder direction of a branch |
| $\vec{d^*}$ | Cylinder direction of a branch estimated by a numerical method |
| $\Delta\alpha$ | Polar angle resolution used in iterative method to obtain $\vec{d}$ |
| $\Delta\varphi$ | Azimuthal angle resolution used in iterative method to obtain $\vec{d}$ |
| $\Delta\theta$ | Angular resolution of laser |
| $\Delta y$ | MTLS longitudinal resolution (distance between vertical scans) |
| $\varphi$ | Azimuthal angle used in iterative method to obtain $\vec{d}$ |
| GNSS | Global navigation satellite system |
| HMT | Hidden Markov tree |
| $k_r$ | Factor of radius $r$ to determine whether P is aligned in current branch $B$ or allows a new branch $BN$ |
| $l$ | Distance from the laser sensor to a tree object |
| MTLS | Mobile terrestrial laser scanning |
| M | Directions to the centroid matrix |
| N | Number of points in the point cloud |
| $n$ | Number of points in a branch or cylinder |
| $n_b$ | Number of branches |
| $n_{min}$ | Minimum number of points used to determine the significant parent or predecessor branch |
| $n_p$ | Number of points of the considered parent or predecessor branch |
| $n_s$ | Number of points that freely seed a cylinder when the building of a new branch starts |
| O | An upper limit of growth of the algorithm response time |
| $ord$ | Branching order according to the terminology proposed by De Reffye, Edelin, Jaeger, and Puech (1988) |
| $ord_C$ | Order of the checked parent or predecessor branch used to determine the significant parent or predecessor branch |
| $ord_{min1}$, $ord_{min2}$ | Rank of order used to determine the significant parent or predecessor branch |
| P | An individual point of the point cloud |
| $P_1$ | Initial point of the cylinder axis that models a branch |
| $P_2$ | Final point of the cylinder axis that models a branch |
| $P_d$ | Projection of $P$ over the cylinder axis in a branch |
| $P_r$ | Initial point, placed at the base of the trunk, taken as origin of the tree model reconstruction. |
| $\theta$ | Angular position of laser beam |
| $r$ | Radius of the cylinder that models a branch |
| SCA | Space colonisation algorithm |
| TIN | Triangulated irregular network |
| $t_2$ | Value of parameter $t$ for $P_2$ in a vector straight equation defined by $P_1$ and $\vec{d}$ |
| $t_d$ | Value of parameter $t$ for $P_d$ in a vector equation of a line defined by $P_1$ and $\vec{d}$ |
| y | MTLS longitudinal position |
| $z_0$ | Height of the laser sensor |

of virtual tree models, such as use of the statistical framework of the hidden Markov tree (HMT) model introduced by Crouse, Nowak, and Baraniuk (1998) and used for constructing realistic apple trees by Durand, Guédon, Caraglio, and Costes (2005) and Costes et al. (2008).

In parallel with the use of massive data from photogrammetry or aerial scanning for the detection of trees and estimation of their general parameters, two main approaches are used to study their geometry at individual tree level. The first is based on digital photographs (Mizoue & Masutani, 2003; Phattaralerphong & Sinoquet, 2005, 2007; Shlyakhter, Rozenoer, Dorsey, & Teller, 2001; Tan, Fang, Xiao, Zhao, & Quan, 2008): graphic data are processed to determine the existence of vegetation and sensor parameters (camera height and its horizontal distance to the tree) allow a projection to be obtained on a voxel space, with which the tree-top and leaf area can be estimated (Phattaralerphong & Sinoquet, 2007). The use of a reduced voxel size to improve accuracy dramatically increases the processing time.

The second approach uses mobile terrestrial laser scanning (MTLS) to obtain a dense point cloud from which a detailed geometrical description can be extracted (Rosell et al. 2009; Sanz-Cortiella et al. 2011). Simonse, Aschoff, Spiecker, and Thies (2003) detected woody geometry from MTLS data using the Hough transform and Gorte and Winterhalder (2004) as well as Pfeifer, Gorte, and Winterhalder (2004) created a topology skeleton from a voxel space. The use of TIN (triangulated irregular network) to obtain geometric information about woody tree structure is limited by stem capillarity (Fig. 1) and usually supports extraction of neighbourhood graphs (adjacency relations between all the points). Pfeifer et al. (2004) obtained a model of major branches and stems with cylinder fitting. Other methods, which combine scanning data with texture information from high resolution photographs, have been proposed by Reulke and Haala (2005). Iterative closest point (ICP) algorithms have also been used to fit the guide lines obtained in different scans (Besl & McKay, 1992; Henning & Radtke, 2006). The algorithm iteratively revises the geometric transformation needed to minimise the distance between the points of the different raw scans.

It is easy to determine whether a point of the MTLS point cloud belongs to the trunk and main branches. However in the lowest branches, particularly the stems, it becomes more