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STEM MODELING FROM TERRESTRIAL LASER SCANNING USING THE BLOCK MINIMUM APPROACH

*Modelagem de Tronco de Árvore a partir de Dados de Laser Scanner Terrestre
usando a Abordagem do Block Minimum*

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ABSTRACT

Terrestrial laser scanner is widely used in forestry surveys to map and estimate tree dimensions. The main problem is still how to reconstruct the tree geometry from the laser scanner point cloud. This study introduces an approach to model individual stems in automatic manner from terrestrial laser scanning data. Unlike the traditional approaches, the proposed algorithm does not assume that the stem is circular and therefore adapts better to the point cloud, leading a more flexible estimate of the geometry along the stem. The idea is to transform the point cloud to a linear problem and to apply filtering algorithms, similar to those used for DTM extraction in airborne laser scanning. The minimum-block algorithm was tested on laser scanning data collected in a pine forest in South Brazil.

Keywords: Tree Volume Estimation, 3D-modelling, Terrestrial Laser Scanner.

RESUMO

Laser Scanner terrestre é amplamente utilizado em pesquisas florestais para mapear e estimar as dimensões da árvore. O principal problema ainda é como reconstruir a geometria da árvore da nuvem de pontos do laser scanner. Neste artigo é descrita uma abordagem para modelar troncos individuais de forma automática a partir de dados da varredura do laser terrestre. Ao contrário das abordagens tradicionais, o algoritmo proposto não assume que o tronco é circular e, portanto, adapta-se melhor à nuvem de pontos, levando a uma estimativa mais flexível da geometria ao longo do tronco. A ideia é transformar a nuvem de pontos para um problema linear e aplicar algoritmos de filtragem, semelhantes aos usados para extração de DTM em digitalização laser aerotransportado. O algoritmo de bloco mínimo foi testado com dados de laser scanner terrestre coletados em uma floresta de pinheiros no sul do Brasil.

Palavras-chave: Estimativa de Volume de Tronco, Modelagem 3D de Árvore, Laser Scanner Terrestre.

1. INTRODUCTION

Forestry industrial and preservation activities are especially interested in assessing tree parameters to describe biomass and wood production. These parameters lead to relevant information for ecological and economic studies, such as preservation of some species or estimation of wood production. When dealing with preservation, forestry engineers rely on few measurements to estimate the total volume of a tree. The traditional assessing methods are field surveys, like measuring the perimeter and diameter of a stem with a metric band or calliper. A more accurate estimate can be obtained cutting the tree and using a xylometer to measure the volume, but this cannot be done if the intention is to preserve the tree. An option is to use terrestrial photogrammetric methods to estimate the diameter of a stem by measuring pixel distances in the image, as described in Dean (2003), Larsen (2006) or Silva et al (2013). A more recent technique relies on the use of terrestrial laser scanners. The literature describes a wide series of attempts to compute stem volume and shape from a laser scanner point cloud. For a better overview on the methods see Bienert et al. (2007), Pfeifer and Winterhalder (2004) or Seidel et al. (2011).

The main idea behind available stem section modeling algorithms is to assume the cross section of the stem to be regular, like in Bienert et al. (2007) or Király and Brolly (2008). So, the problem is solved adjusting the best circle for each case. This analysis can be performed at different heights, leading to a cylindrical representation of the stem, like in Thies et al. (2004).

In this paper we introduce a method to model the cross section of stems, which is not based on the circular cross section assumption. To model a complete stem, the method also divides a stem in smaller units, according to the height. The main difference, compared to the parametric methods is that a free curve, built up by discrete points, is used to model the perimeter from a sub-set of the point cloud. The paper is organized as follows. In Section 2 a brief review of the previous work on this issue is presented. In the third section we present the model and methodology. A series of experiments are presented in Section 4 and the results are

presented and discussed in section 5.

2. RELATED WORK

Terrestrial laser scanner as a tool to automate forest inventory has been topic of research in the last three decades. Some research concentrates on automatic detection of individual trees, like the work of Simonsen et al. (2003), Brolly and Kiraly (2009) or Liang et al. (2011). After solving the problem of detection, the research concentrates on the estimation of tree geometrical parameters such as its diameters and height, as shown in Aschoff and Spiecker, (2004) or Raunonen et al. (2013). The comparative study on the use of different terrestrial scanners, presented in Ducey et al. (2013), shows that terrestrial scanners are capable of providing detailed digital tree and forest models but also that scanner attributes can influence the estimate of exact tree metrics.

Although terrestrial laser scanning produces a large number of point coordinates, its main disadvantage is that the survey is not controlled as to meet the borders of the objects or points of interest. Therefore, a high point density is preferred to model a three-dimensional object. The amount of data demands a higher degree of automation in the modeling step, which, as Brolly and Király (2009) state, may introduce reduction and generalization of the dataset.

Traditional modeling approaches rely on the assumption that the stem cross section is circular and that the radius varies along the height. Therefore, the basic task is to fit the best circle or cylinder to a sub-set of the point cloud, reducing the problem to two dimensions. This model can be found in the work of Pfeifer et al (2001), Brolly and Király (2009), Bucksch, and Fleck (2011) or Schilling et al. (2011). For example, Liang et al. (2011) propose a method to model the trunk dividing it in 20 cm slices. Each part is modelled projecting the points on the horizontal plane and circles are fitted to the points. Kelbe et al. (2013) also use the circular model and a least square fitting. At the end, the model consists of a collection of circles at different heights along the trunk. Trunk parameters can then be computed assuming that the trunk section is circular. Another example is described in Henning (2006) who use a series of overlapping cylinders to describe the trunk.

According to Brolly (2013), stem cross-sections can be modeled more accurately by more complex functions than a circle when the tree is scanned from multiple positions. For example, Aschoff and Spiecker (2004) used ellipses to model the stem. A non-parametric model can be found in Pfeifer et al. (2004), where the use of B-splines is proposed to estimate the stem cross section without the assumption of circularity. Our approach follows the same principle but it is based on the well-known filtering approaches used in aerial laser scanner DTM production. The advantage is its simplicity and the capability to use known point filtering methods by transforming data into an appropriate system and without the use of splines.

3. METHODOLOGY

The proposed approach consists of different steps. First, a coarse edition of the point cloud around the stem is performed. Then, the stem is divided in slices to perform the analysis. For each slice, the points are projected on a bi-dimensional space and represented in polar coordinates. This representation allows performing pruning and estimating the contour of the cross section. The steps are described in the following paragraphs.

After collecting a 3D point cloud, the first step is point cloud editing, in order to isolate the tree of interest in the large data set. This task can be performed manually or using automatic or semi-automatic methods; see for instance Schilling et al. (2011). The aim is also to discard noisy points and other unwanted objects. It must be pointed out that the editor can also eliminate branches and leaves that belong to the tree, which can simplify the analysis but, on the other hand, may also introduce errors. A coarse edition, for example using a bounding box around the trunk, allows reducing the branches, but a fine edition is necessary to isolate the stem. The method introduced below aims at reducing the fine edition by automated methods.

Our approach follows the common practice of dividing the stem in small parts because the stem is not regular and its cross section varies along the height. The choice of the thickness of the slice has to consider the point cloud density, because enough points need to be available to model the cross section, and the leaning of the tree. Leaning of the stem would shift the points

of the upper part of the section in relation to the bottom, introducing a stronger variation of the coordinates in leaning direction. This shift can be expressed by eq.1:

$$k = ht * \tan(s) \tag{1}$$

where k stands for the shift in the leaning direction, ht is the slice height and s is the leaning angle, considering $s=0$ when the tree is vertical. For example, if we consider an angle of 20 degrees and accept a maximal shift of 10mm, then maximal slice height would be 27mm.

After separating the stem into slices, the analysis is reduced to a bi-dimensional problem projecting the points on the horizontal plane. At this point, common parametric approaches adjust a circle to the bi-dimensional point set and therefore the center of the circle and its radius need to be estimated. In our approach this computation is not necessary. Although the center of the circle is expected to lie in the centroid of the point cloud, this normally does not happen because of the irregular spatial distribution of the points along the surface and the presence of other parts of the tree, like branches. Nevertheless, if the centroid lies within the cross section of the stem, the perimeter can be described in polar coordinates in terms of radius R and angle Θ :

$$R = (x^2 + y^2)^{1/2} \tag{2}$$

$$\tan(\Theta) = y/x \tag{3}$$

where:

x and y - coordinates of the points projected on the horizontal plane (Cartesian system),

R, Θ - radius and angle (polar system with origin in the centroid).

The key point in the approach is to observe the variation of the radius (R) in relation to the angle (Θ). For a circular cross section the function $R = f(\Theta)$ is a horizontal line (constant radius) if the origin lies in the centre of the circle. If there is a shift in x and/or y the function is no more a straight line, as shown in figure 1. Equation 4 displays the Cartesian representation of the function after shifting the origin by (a, b) .

$$R^2 = (x-a)^2 + (y-b)^2 \tag{4}$$

where R stands for the radius, and x and y are the coordinates of the points projected on the horizontal plane, similar to eq. 2, and a and b represent the shift in x and y .

Expanding equation 4 and substituting x and y by the polar representation (Equations 5 and 6), the model can be described by equation 7, a model of the contour using a sine-like function.

$$x = R \cdot \cos(\theta) \quad (5)$$

$$y = R \cdot \sin(\theta) \quad (6)$$

$$a^2 + b^2 = 2 \cdot R \cdot (a \cdot \cos(\theta) + b \cdot \sin(\theta)) \quad (7)$$

Because the stem cross section is not always circular, it is not possible to apply equation 7 without introducing strong generalization. Nevertheless, a natural characteristic of the borders of the cross section is its smooth variation. Therefore, the variation of the radius as function of the angle is expected to be smooth, following the sine-like pattern of equation 7 with a superposed unknown function $W(\theta)$ that would represent other details like depressions and tree knots.

$$a^2 + b^2 = 2 \cdot R \cdot (a \cdot \cos(\theta) + b \cdot \sin(\theta)) + W(\theta) \quad (8)$$

After the transform, the problem is simplified to a function of one variable. The basic hypothesis is that the contour is smooth and therefore the radius does not present hard variations in relation to the angle. Branches would appear as points with very long radius compared to the neighboring region, as displayed in figure 1.

In order to obtain an initial guess of the contour, the angles are sampled into a finite discrete set, between 0 and $2 \cdot \pi$. The number of discrete steps to represent the section depends on the scan density and the size of the stem section. A fine angular discretization would produce more blanks (absence of points). On the other hand, too few angular values would produce a rough representation of the perimeter. We could use 360 values, with steps of one degree, but we adopted 300 values in order to have a round number.

The next step is to identify and eliminate the branches from the contour. This can be

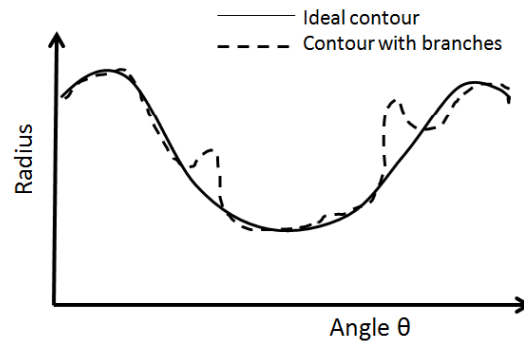


Fig. 1 – Ideal contour in polar coordinates and an example of a contour with branches.

performed by applying the same principles that guide DTM extraction when dealing with airborne laser scanner. The case is simpler, because it is one-dimensional and the radius can be treated as the height in DTM extraction. The aim is to reduce hard variations in the contour. There are various approaches in the literature to process a point cloud of aerial laser scanning such as analyzing the slope, adopting the block minimum filter or applying mathematical morphology. A survey can be found in Sithole and Vosselman (2004) or Shao and Chen (2008). A comparison of different approaches to derive a DTM filtering an Airborne Lidar point cloud is also presented in Zhang and Whitman (2005) or Seo and O'Hara (2008). In our experiments we use the block minimum approach, described in Sithole and Vosselman (2004).

The block minimum approach assumes that, considering a region along the surface of the tree, at least one point belongs to the stem. Points on the surface within this region will have values close to the minimum and branches larger values. The discriminant function is a buffer zone limited by a surface of equal radius close to the minimum. The buffer zone defines a region in 3D space where points of the stem are expected. The user has to define the size of the buffer. Normally, the value can be chosen considering laser scanner range accuracy and bark roughness. In our examples, we used a Leica HDS-3000 laser scanner, with a range accuracy of ± 4 mm at 50m. That means that the points are expected to be within a range of 8mm. Therefore, we chose the buffer 3 times this value (24mm).

After identifying the points close to the local minimum, the mean radius within the neighborhood is computed. The adoption of the

mean value minimizes the effect of random noise and the reduction stated by Brolly and Király (2009) and is a reasonable solution if the stem is not vertical.

Finally, the profile is transformed to Cartesian coordinates, leading to a closed polygon. The center of the cross section can then be computed from the modeled cross section, obtaining a better estimate than the initial one. This process is repeated for different heights, dividing the stem in small sections. Combining the results, a model of the tree is available.

It is also necessary to fill blanks in the contour because a laser scanning survey may result in shadowed regions. This can be performed assuming that the stem is circular and computing the area of the missed circular section, as described by Wezyk et al. (2007). In our approach we use a linear interpolation in the polar system. The use of a straight line to interpolate values and fill blanks in the polar system produces part of a spiral in the Cartesian system, filling the blank with varying radius within the two available borders. The spiral provides a better adjustment between the curves before and after the blank region.

4. EXPERIMENTS

In order to illustrate the method described in the previous section we use real data that was captured in South Brazil using a Leica HDS-3000 terrestrial laser scanner. The object of interest is an *Araucaria angustifolia* (Bertol.) tree, a conifer also known as Brazilian pine, which has a peculiar shape, with a long and straight stem and is native of the southern region of South America. *Araucaria* forests, in the past, comprised about 35% of the vegetation cover of southern Brazil (Coutinho and Dillenburg, 2010), but because of intensive logging were extremely reduced and this specie is now endangered and therefore under federal protection.

For the tests *Araucaria* trees were scanned from different positions in order to get a three-dimensional view. Artificial targets were set around the test trees, which were visible from different scans, in order to grant the availability of enough control points. The registration step has to be performed carefully, because it may introduce severe geometric errors that cannot be removed in the later steps. When scanning

trees with terrestrial laser scanner shadows are expected, causing the tree to be incomplete. Shadows can be reduced changing the position of the scanner and taking many scans, but they cannot be completely eliminated, especially at the upper part of the tree.

As a first example, we use a 14 m high tree that was scanned from the ground at two different stations. Figure 2 displays a photograph of the tree. The trunk is relative straight and vertical and branches appear only at the top of the tree. Nevertheless, knots are visible at points where former branches were present.

As displayed on figure 3, the surface of the tree is very rough and also not regular, because knots are visible at different heights and directions. Some parts of the surface are also covered by the bark, others are clean and at some locations the bark is falling apart from the trunk, which makes it difficult to establish the real perimeter of the trunk. As Brolly and Király (2009) state, the laser measurement is affected by the presence of all this details on the surface, while traditional measurement methods, such as the calliper and the tape, measure the outer surface of the bark. The key in figure 3 marks the height of 1.3m above the terrain. The mean point density is about 1 point/cm² at the height of 1m and decreases as the height grows. The point cloud was later registered. A pre-processing step was performed in order to isolate the trunk and reduce the presence of branches. This was



Fig. 2 – Example of *Araucaria angustifolia* (Bertol.) tree.

done using a rectangular bounding box around the trunk. The aim was to reduce the presence of long branches, but small parts of them, close to the trunk still remain. In order to reduce such branches, a fine edition would be necessary, but was not performed, because our aim is to filter them in the next step, which reduces the manual work and time needed to edit the point cloud. Classical stem modelling methods, like Simonse et al. (2003), Broly and Kiraly (2009) or Wezyk et al. (2007) assume that the stem was previously cleaned and use only points on the trunk's surface, which demands a fine filtering step.

The first data set comprises a 50 mm thin slice at 4.1 m above the terrain. The point density is not irregular because the region lies high from the ground. Some parts of the tree may be occluded by branches or the scanner may not be in the best position for its measurements. The points were projected on the horizontal plane, obtaining the bi-dimensional set displayed on figure 4a as grey dots. The centroid of the point set was computed and lies close to the right side of the tree, because of the different point density of the multiple scans and the presence of branches. This centroid is not a good estimate of the center of the cross section if we consider that the point density may vary along the surface, but can be used as origin for the next steps.

After transforming the Cartesian coordinates into polar coordinates and resampling the angles to 300 values between $-\pi$ and π , an initial representation of the perimeter as a profile



Fig. 3 – Detail of the surface of an *Araucaria angustifolia* (Bertol.) tree. The key marks the height of 1.30 m.

is obtained. These points are displayed in figure 4b as grey dots. The variation of the stem contour is perturbed by the branches that are visible at angles between 1.0 and 2.5 rad which represent the branches of the right side of figure 4a. In order to apply the block minimum method, a 24mm buffer was used. The black line displayed in figure 4b is the mean radius associated with each discrete angle. Because the point cloud is dense enough, there are no blanks that need to be filled, so the inverse transform can be applied and the cross section obtained, as displayed on figure 4a as a dark line.

As a second example we use a data obtained a second tree (30m height). A set of trees was scanned from different stations in a forest. It was expected that all trees were covered from different angles to grant complete coverage. Nevertheless, this tree was visible from just two stations, in a not suitable geometry, and therefore a complete view is not available. Figure 5 displays a 10 cm sub-set at 4.3 m height. In this detailed representation it is possible to notice that the stem was not completely covered and two branches are visible rising up from the stem. A part of another branch also appears in the dataset as an isolated cluster. This is a complicated example that will be used to illustrate the advantages of the method. The centroid of the point set was computed and lies close to the right side of the tree, because of the blank at the left side and the high concentration of points on the right side, as displayed on figure 5a. Again, data was analyzed and the stem modeled, leading to the results shown in Figure 5a and 5b as dark lines. In this case, the blank was filled with a linear function in the polar coordinates system. Note that a line in the polar system is a curve with varying radius in the Cartesian system. Three facts are visible in the example. Note that the blank was filled following a smooth curve and the estimated contour lies between the point set, which is reasonable considering the possible random errors. Branches were also removed from the stem. The right branch is represented by a larger number of points and therefore caused a stronger perturbation of the curve. The result is a small convexity at the point where the branch grows.

Figure 5 can also be used to discuss weak points of the algorithm. If the first estimate of

the centroid lies outside the tree, the approach doesn't work properly, because it overestimates the cross section. Nevertheless, this problem can be reduced if the procedure is repeated from the bottom to the top of the tree. After processing one cross section at the bottom, without branches, its center can be used as a better estimate of the center for the next section, which grants that the point lies within the tree. Problems are to be expected at the top of the tree, where there may be more points on the branches than in the stem. The algorithm also underestimates the cross section when the visible area of the trunk is below 50%. In such cases, the visible part is correctly modeled, but the hidden side is interpolated applying a curve. Because the centroid of the points is not the center of the trunk when half the tree is scanned, then the interpolation produces a curve inside the trunk, smaller than the circle, as displayed on figure 6. But, if the center of the tree is available, then the method would enable a better estimate.

The results displayed on figure 6 were obtained simulating a single scan by cutting off

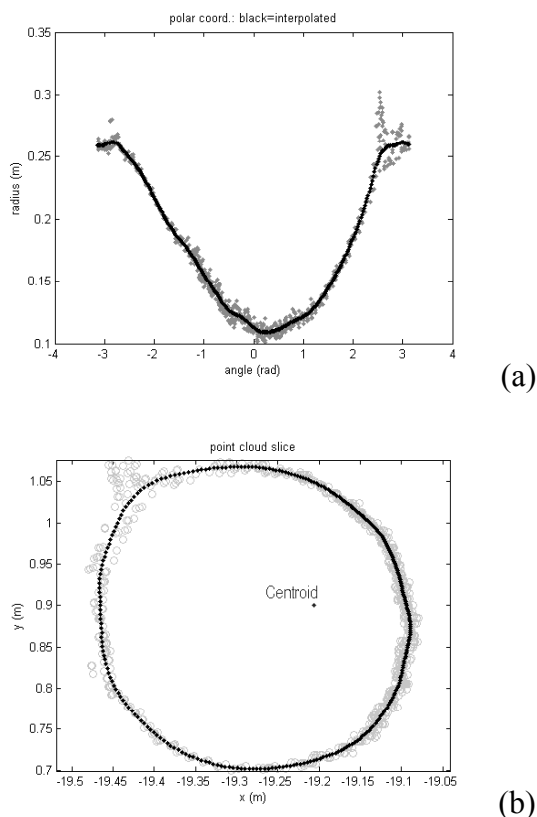


Fig. 4 – Cross section of a 5cm section, at 2,1m. (a) Point cloud in polar coordinates (grey) and estimated mean value (black) and (b) final cross section (black) overlaid to the original points (grey).

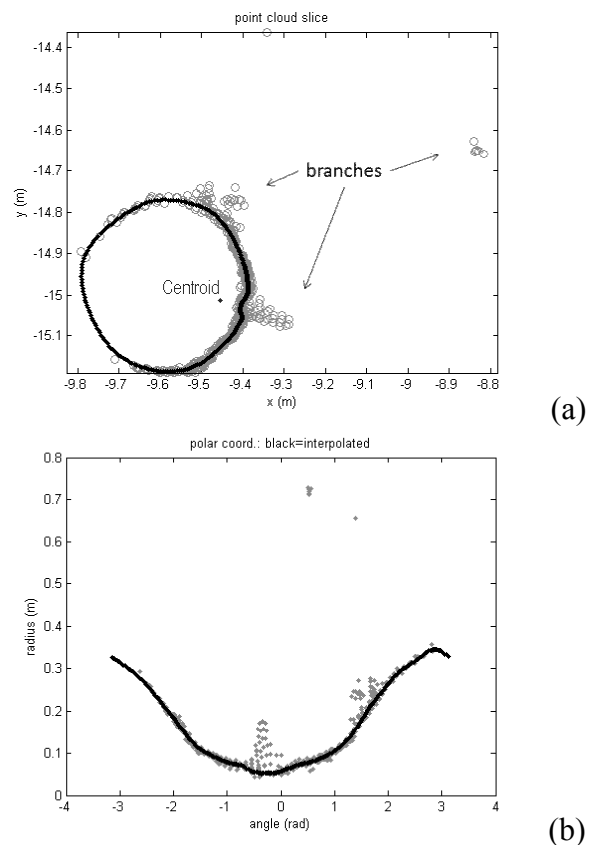


Fig. 5 – Cross section of a 10 cm section with occlusion and branches. (a) Point cloud in Euclidian coordinates (grey) and estimated cross section (black) and (b) Final cross section (black) overlaid to the original points (grey) in polar coordinates. Part of a second branch is also visible at the upper right corner of figure (a).

50% of the surface of the trunk. This is a coarse approach of a real situation, where the point density would vary stronger along the surface, but it is useful to illustrate the fact that the invisible side cannot be correctly simulated when the centroid is used as origin of the polar system.

The cross section estimation can be repeated for different heights. Once one section was modeled, a better estimate of the center is known. This estimate can be used to perform the analysis of the next section, because the tree is a continuous volume. This practice reduces errors because the choice of the origin of the polar system can be affected by branches or other unwanted data.

Finally, a comparative study was performed in order to evaluate the method. For this purpose the first data set (first tree) was used. Five slices (5 cm) were studied at heights of 2.1m, 2.6m, 3.1m, 3.6m and 4.1m. First, the bi-dimensional representation of the point cloud was used to

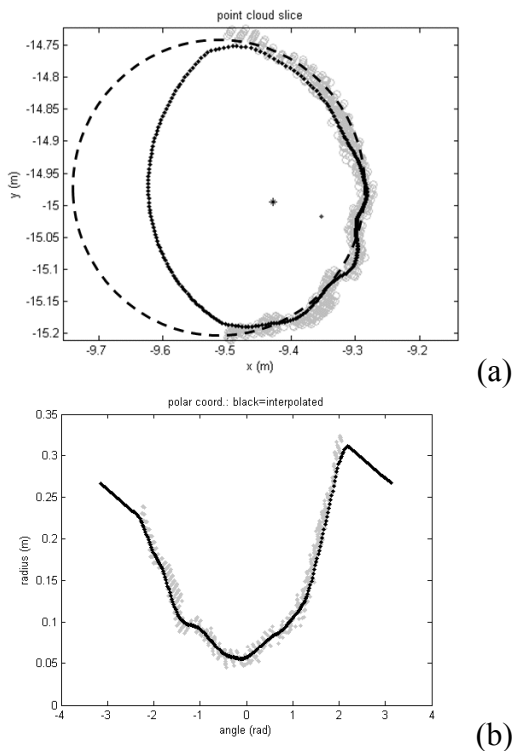


Fig. 6 – Simulation of a single scan covering 50% of the surface. (a) Point cloud in Euclidian coordinates (grey) and estimated cross section (solid black) and the solution using a circular cross section (optimal) drawn as a dotted line. (b) Final cross section (black) overlaid to the original points (grey) in polar coordinates.

digitize the contour following the center of the point cloud, when possible, and visually discarding the branches and noise. Then, this reference contour was used to evaluate the modeled cross sections. Assuming the digitized contour as reference and the center of the reference contour as origin, the radius difference between the modeled contour and the reference (Dr) was computed for each angular range, according to equation 8, to obtain the mean difference and the root mean square error (RMSE) of the difference, as displayed on Table 1. The mean difference lies below one centimeter. Considering that the radius is around 20cm, this difference is below 5% of the real value, which was considered satisfactory. The RMSE around 0.3 cm shows that the differences are small and that the modeled contour is close to the result a man would obtain digitizing the contour in the point cloud.

$$Dr = Rm - Rr \quad (9)$$

with:

Rm = modeled radius (using the Block Minimum - BM),

Rr = reference radius (digitized).

A second analysis was based on the comparison of the area of the digitized and the area of the modeled cross section. The results are displayed on table 2. The relative difference lies below three percent, which is a reasonable value. Figure 7 displays examples of two slices, at 2.1 m and 3.6 m. At 2.1 m, part of a branch can be seen at the left side of the graphic. The automated method was able to suppress such points in the computation of the contour. In the second example, at 3.6 m height, the point cloud is more irregular at the right side, turning it more difficult to estimate the right contour. Nevertheless, the automated method could avoid some of these perturbations.

A final test was performed comparing the computed diameter of the trunk to measurements made with a tape at heights of 0,8, 1,3 and 1,8 m, considering that 1,3 m is the breast height, as displayed on Table 3. The difference lies about 1 cm and the diameter measured with the tape is always larger. This can be attributed to the fact that the tape cannot follow the concavities on the surface. Nevertheless, the estimates are very close to the measured values.

5. CONCLUSIONS

A method was developed for modeling tree stems by converting the point cloud to polar coordinates and applying peak removal algorithms. The method has a high degree of automation, but still some parameters are needed. Some parameters depend mainly on the scanning density, which lies beyond the scope of this study. Although stem modeling from terrestrial laser scanning is not novel, this paper shows a solution based on well-known filtering algorithms that free the analysis of a priori geometrical hypothesis about the shape

Table 1: Mean and RMS of radius differences between non-parametric model and the digitized contour

Section(m)	Mean(cm)	RMS(cm)
2,10-2,15	0.680	0.377
2,60-2,65	0.802	0.436
3,10-3,15	0.829	0.465
3,60-3,65	0.851	0.455
4,10-4,15	1.049	0.532

Table 2: Comparison of the computed area and the digitized area of 5 different slices with 5cm thickness

slice height (m)	AREA Digit. (m ²)	AREA MNP (m ²)	Difference (m ²)	Difference (%)
2,10-2,15	0.109	0.111	-0.002	1.8
2,60-2,65	0.127	0.127	0.000	0.0
3,10-3,15	0.110	0.109	0.0001	-0.9
3,60-3,65	0.097	0.097	-0.000	0.0
4,10-4,15	0.091	0.093	-0.002	2.2
			mean=	0.88%

Table 3: Comparison of the computed and the measured diameter of the trunk

Slice height (m)	Computed diameter (cm)	Measured diameter Tape (cm)	Difference (cm)
1.75-1.85	42	43	-1
1.25-1.35	45	46	-1
0.75- 0.85	46	47	-1

of the cross section.

The method shows advantages because it does not demand the exact knowledge of geometric parameters like center of a circle or cylinder to model the cross section. The approach is therefore flexible and able to adapt to different stem geometry. It is also suitable to fill blanks when the point cloud does not cover the whole stem. The algorithm is a general solution for stem modeling in the sense that it is independent from geometrical assumptions and high point density.

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