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Fuzzy Hough transform-based methods for extraction and measurements of single trees in large-volume 3D terrestrial LIDAR data

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Abstract. This startup study suggests that more accurate and quicker methods of forestry terrestrial LIDAR data analysis can be developed, but new benchmark data sets with the ground truth data known are necessary for these methods to be validated. It follows from the literature review that the improvement in the methods can be attained by the use of newer Hough transform-based (HT) and other robust fuzzy methods for data segmentation and tree measurements. Segmentation of trees can be done by the limit fuzzification of the data around the breast height. Several HT variants having different properties can be applied to measure the diameter at breast height and the accuracies better than those offered by the commercial software seem to be attainable.

1 Introduction

Forest inventory methods require numerous and relatively accurate measurements made on trees. The parameters of the trees which are calculated from these data depend on the application. In the simplest case these are the tree height and the stem diameter at the height of human breast, that is, at 1.3 m – diameter at breast height (DBH), measured for each tree, and the number of the trees. Numerous other parameters can be of interest, for example, the height-diameter profiles, ovality of the stem, open stem height, shape and diameters of branches, diameter and other parameters of the crown, or the parameters related to the leafage. One of the measuring methods of choice is the terrestrial LIDAR (LIght Detection And Ranging) scanning [1,3,4,7,11,18,20,21,22]. Such scanning gives a 3D cloud of points indicating the surfaces of the tree stems, branches and leaves, and other objects of less or no interest possibly present in the measured area, like bushes or litter. A scan can contain millions of measured points forming a 3D image of a forest.

Probably the most frequently used technique in the analysis of the data cloud is the Hough transform (HT, the first version introduced in [8]). Its use is reported in nearly all the literature; however, it seems that even in some of the recent papers the scope of the versions of HT used is restricted, with the prevalence of the version for the detection of circles in its classical form, as introduced in 1975 [12]. Therefore, in the present paper we have tried to remind and partly check the possibilities of applying some of the more recent achievements in the domain of accumulation-based methods, for which the basic HT is a prototype (cf. [15], Chapt. 5.4). In particular, we use the fuzzy methods reported to be robust in the case of sparse measurements with a considerable content of erroneous data [6]. We present the methods operating basically around the breast height for segmenting the data into subsequent trees and measuring the DBH. The paper will be a starting point for a planned study on a larger set of measurement methods for trees, including their validation on large data sets.

2 State of the Art and new possibilities

In some of the papers on the analysis of terrestrial LIDAR data the explicit references to the literature on Hough transform are absent [3,5,18,20], although it is reported to be used in them. The paper by Aschoff, Spiecker et al. [1] (in [19]) directly cites the book [16] where the HT for circles introduced by Kimme in 1975 [12] is described. In the paper by Simonse, Aschoff et al. [18] this basic HT for circles is explicitly reported, but without any reference to the literature on HT. This paper is cited by Bienert, Maas et al. [3] (in [13]). In the paper by Vosselman et al. [21] (in [19]) the extension of the HT by using the lines normal to the surface of the object sought, first introduced by Illingworth and Kittler for circles in [9], is used to find cylindrical surfaces. Khoshelham [11] (in [17]) extends the Generalised HT to 3D data. One of the review papers on the HT [10] is cited in this paper. Khoshelham gives attention to the problem of efficiency, so the hierarchical and probabilistic HTs are considered. Therefore, the question of the scale at which the parameter space is divided is addressed in some way. This question has also been mentioned in [21], but no solution was proposed.

The Hough transform and the derived accumulation-based methods are indeed the right choice for the application considered. The main features of the LIDAR data which support such a choice are their sparsity and the presence of gaps and errors, or noise, in the data. As reported in [6], for some versions of the HT, the simplified measure of robustness which can be the share of outliers in the data that still does not prevent the HT from yielding a correct result, exceeds 50%, and when a properly fuzzified version of the method is used it can be as high as 70-80%. The tool which can make it possible to reach such a degree of robustness is the *weak fuzzification*. Furthermore, the *strong* or the *limit fuzzification* introduced in [6] can be used to stabilise the results of segmentation of the LIDAR forestry data into single trees.

In the present paper we shall extend on the good tradition of using the Hough transform for the segmentation and for selected measurements of large-volume terrestrial LIDAR data. Starting from some preliminary results we shall highlight the deficiencies of the methods applied until now and discuss the possibilities of

a **b**

Fig. 1. (**a**) A view of a fragment of the test stand. (**b**) Section through the LIDAR data of the stand around the breast height, contrast enhanced; fragments can be seen better in Fig. 3a08 and a37.

choosing the methods still rarely used or unused in the application considered. The concepts will be illustrated with results received for sample data described in the next Section.

3 Test data

The data were scanned at the Scots pine stand belonging to the Niedźwiady Forest District, Regional Directoriate in Szczecinek, West-Pomeranian Voivodship (North-Western Poland), with ground-based FARO LS HE880 LIDAR scanner. Nominal linear error was ±3 mm at 25 m. The data were overlaid from scans made from more than one position of the scanner. Average DBH of the trees in the stand was 26 cm and average height was 19 m. A fragment of the stand can be seen in Fig. 1a.

As a first data set, a layer of the data cloud around the breast height was cut from the whole available data. The thickness of the layer is 1 m and the breast height is 1.3 m, so the layer extends around $[0.8, 1.8]$ m above the ground level at the foot of a selected tree, further referred to as *tree37* (the ground was reasonably close to horizontal). The projection of these data onto a horizontal plane is shown in Fig. 1b. This was the *thick100* data set. Further, a 4 cm layer of the whole data around the breast height of the same tree was selected. This was the *thin004* data set.

The data on the trees in the centre are of better quality than those for the trees near the border of the region. Therefore, for further tests performed on the data on single trees, two example trees were selected (see Fig. 2c. The first tree, labelled *tree37*, chosen as an example of easy data, was near the central region and was scanned around from more than one scanner position (Fig. 3a37). The second tree, labelled *tree08*, an example of difficult data, was near the region

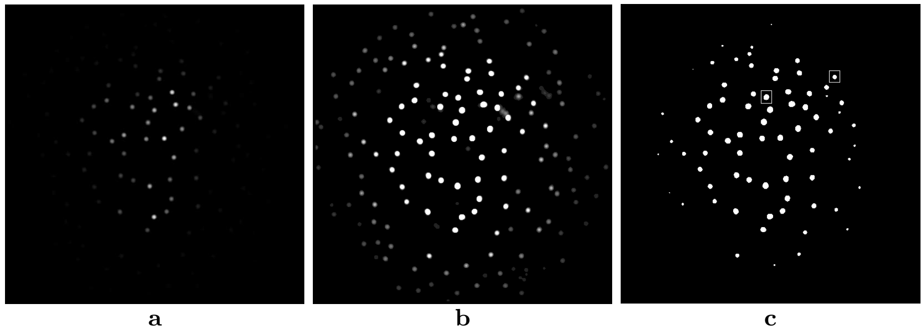

Fig. 2. (**a**) Data of Fig. 1b fuzzified up to the limit with respect to an expected thickest tree. (**b**) Image **a** with enhanced contrast. (**c**) Image **a** thresholded at 3% of its maximum giving 72 candidates for trees. Selected example trees are marked with rectangles: upper-right – difficult *tree08*, lower-left – easy *tree37*.

border and was scanned from only one side (Fig. 3a08). The data set was complemented with the results of measurements made with the software of the laser scanner and with the manual DBH measurements. However, these results were available only for the trees in the central part of the measured region, so for the *tree08* the ground truth data were unavailable.

4 Segmentation

The segmentation of the tree stand into single trees is the easiest at a height well above the ground and below the tree crowns. Such a height differs between tree species, however in the case of our data it extended from about 0.5 to 4.0 m above the mean ground level. Therefore, the breast level was a reasonable candidate height for the segmentation. A thick layer as described in Sect. 3 has been taken.

The main idea is to treat the number of measurement points projected onto the horizontal plane Oxy as the histogram, that is, the experimental approximation of the probability density function, of the presence of a tree surface. The trees are the largest objects in the data cloud so they should prevail in the histogram. In fact, in the global histogram the local histograms for single trees are nearly separated. Let us concentrate on a single tree (yet not localised). To find the location of the tree stem, not its surface, the histogram can be fuzzified with the fuzzifying function in the shape of the positive part of an inverted paraboloid, with the support half-diameter not smaller than the the maximum expected tree diameter. Then, it is guaranteed that a tree manifests itself in the fuzzified histogram as a single paraboloid because this process is the *limit fuzzification* of the histogram [6] with respect to a single tree. Consequently, to find all the trees it is enough to fuzzify the image like the one in Fig. 1b up to the limit with respect to an expected thickest tree, and to find maxima in the resulting image like that in Fig. 2a. Each significant maximum corresponds to one tree. A simple thresholding can give a satisfactory segmentation into regions belonging to separate trees. In more difficult cases, the watershed method could be applied. The points which project themselves onto the region belonging to one maximum belong to one tree. The histogram does not have to be of large resolution: several centimetres per pixel are enough.

5 Verticalization

The trees are not exactly vertical. This makes the projections of the data points belonging to a layer of 1 m thickness lie far from the expected nearly-circular shape. This was not detrimental in the process of segmentation, while in the calculation of the diameter the inclination of the trees should be compensated for, if a thick layer of the data is to be used. In the case of the trees having the data points from many sides, as *tree37*, a thin layer can be used. However, for the trees with less data points, like *tree08*, a thick layer can be necessary.

The data points segmented out for a single tree were projected on the vertical planes and fuzzified. The dominating straight lines were found. The angles of these lines were used to recalculate the data points to the coordinate system parallel to the stem axis thus found. The centre of rotation was at the mid-height of the data layer.

6 Measurements of the diameter at breast height

To determine a circle it is enough to know its three points to form three equations for three parameters of a circle. Three points (three pixels) are called the *elemental subset* for a circle [14]. If an elemental subset is used to vote for a geometrical figure in the HT, then it can vote for a full set of parameters of this figure. In general, the subsets of the cardinality equal or smaller (never larger) than that of the elemental subsets are used as voting subsets in HT. The smaller the cardinality of the voting subset, the more complex the geometrical figure is plotted in the parameter space. Not all the parameters of a figure sought must be found at once. For example, if only the centre of a circle is of interest, then the elemental subset can be just two points, but complemented with the directions of the normals to the circle in them.

In the cited literature on LIDAR measurements of trees it is always assumed that a cross-section of a tree is circular. This is not the case in general. When a circular tree is not vertical, its horizontal section is an ellipse. Further, a simple observation indicates that trees are not regular objects (see Fig. 3b08 and b37. The next more complex approximation of a horizontal tree section, after a circle, is an ellipse. In [15], Chapt. 5.4.3-5.4.5, a number of versions of the HT for circles and ellipses have been described. Some of their basic features are compared in Tables 1 and 2. It has been taken into account that the centre of the figure sought is of primary interest and the other parameters are easy to find in the further, simpler accumulation steps.

The comparisons implies several conclusions. Bearing in mind the quality of the data it can not be expected that all the points in a pair or a quadruple

Table 1. Comparison of the features of HT for circles. PS: parameter space. Expectations on the robustness inferred merely from the features of the method.

No.	Voting subset	Figure in PS	Remarks on the data	Exp. robustness
1	1 point	cone	raw points can be used	high
2	1 normal	line	projected on a plane, fuzzified	moderate
3	2 points	line	raw points can be used	low
4	2 normals	point	projected on a plane, fuzzified	low/moderate

Table 2. Comparison of the features of HT for ellipses

No.	Voting subset	Figure in PS	Remarks on the data
1	2 points with their normals	line	projected on a plane, fuzzified
2	4 points	line	raw data can be used

appear to lie very near to the circle of ellipse to be found, or that they lie at the same side of its border. Therefore, the stability of the result of finding the figure plotted in the parameter space can be low, adversely influencing the robustness of the whole method. Finding the normal to the figure border can be difficult unless the the data are fuzzified, which makes it possible to find the normal as the gradient of the intensity of a resulting image. Fuzzification necessitates for projecting all the points onto one plane. This process reduces the number of data and the resulting processing time, but with the simultaneous loss of information. Decrease of the quality of the voting process in the parameter space must be compensated with the *weak fuzzification* [6]. Finally, the more points in one voting set, the larger the number of all possible sets and hence the longer the processing time. The processing time increases also with the complexity of the figure plotted in the parameter space.

In the present preparatory study the methods 1 and 2 from Table 1 have been used. These are the method of Kimme [12] and Illingworth and Kittler [9], respectively. The other methods will be tested in the next stages of the work.

7 Results and discussion

For the segmentation, images with resolution of 10 cm/pixel were formed from the *thick* data set. For the limit fuzzification with respect to a single tree, the fuzzification function in the form of an inverted parabola, as advised in [6], was used, with the support of 11 pixels, that is, 110 cm. No tree was expected to have a larger diameter, so one single maximum was detected for each tree. The fuzzified image was thresholded at 3% of the maximum for these data. In this way, 72 tree candidates were found, as shown in Fig. 2.

For the verticalization of the *thick100* data set, the image resolution was 2 mm/pixel. The angle resolution was 1°. The paraboloidal fuzzification function with the support of 31 pixels, that is 6.2 cm was used. Inclination angles of the stem appeared to be up to ±15°.

Table 3. Results for *tree37*. Besides the results calculated with the methods from Tab. 1, No. 1 and 2, the manually measured result (ground truth) and result calculated with the software of the LIDAR (L. soft) were available.

method	Manual	L. soft	HT cone		HT line	
data set			*thin004*	*thick100*	*thin004*	*thick100*
result [mm]	238	221	248	248	232	232
error [%]	0.0	-7.1	4.2	4.2	-2.5	-2.5
time [s]			68	1552	8	8

Table 4. Results for *tree08*. Only the results calculated with the methods from Tab. 1, No. 1 and 2, were available; the ground truth was unknown.

method	HT cone		HT line	
data set	*thin004*	*thick100*	*thin004*	*thick100*
result [mm]	356	364	332	360
time [s]	17	372	8	14

For the diameter measurements the resolution and the fuzzification function were the same as for the verticalization. The measurement results are shown in Tables 3 and 4. The *thick100* data were verticalized, while the *thin004* ones were obviously not. Times of calculations are given for an Intel®Core™2 Duo Pentium at 2.4 GHz.

In general, the results obtained should be validated on a large set of ground-truth test data, with the properly formulated measure of correctness of the results (discussed for example in [2]). The results shown here are preliminary and can be treated only as an encouraging feasibility study.

The segmentation results seem very satisfactory at this stage. Simple thresholding of the limit fuzzification results should be a sufficient method in most cases, while the watershed segmentation can be used in case of necessity.

Among the verticalization results, from 8 to 11% of angle measurements were erroneous (7 to 10 in 90). It is expected that better results could be attained if the images with only the vertical edges of the tree were used instead of the the raw images, fuzzified.

The breast diameter measurements of the *tree37* with the methods presented here seemed to be slightly better than those received with the software package provided together with the LIDAR, with the HT with lines performing the best. For the more difficult *tree08* the ground truth data were not available, so it can only be stated that the result for the HT with lines for the data set *thin004*, having much less measuring points, is far from the cluster of the other results. This indicates than this method can be less robust in difficult cases.

In general, the 2 mm accuracy in DBH seem to be more than enough for such irregular objects like trees, where the actual cross-section is rarely a regular circle. However, such accuracy is usually treated as a standard in forestry. The

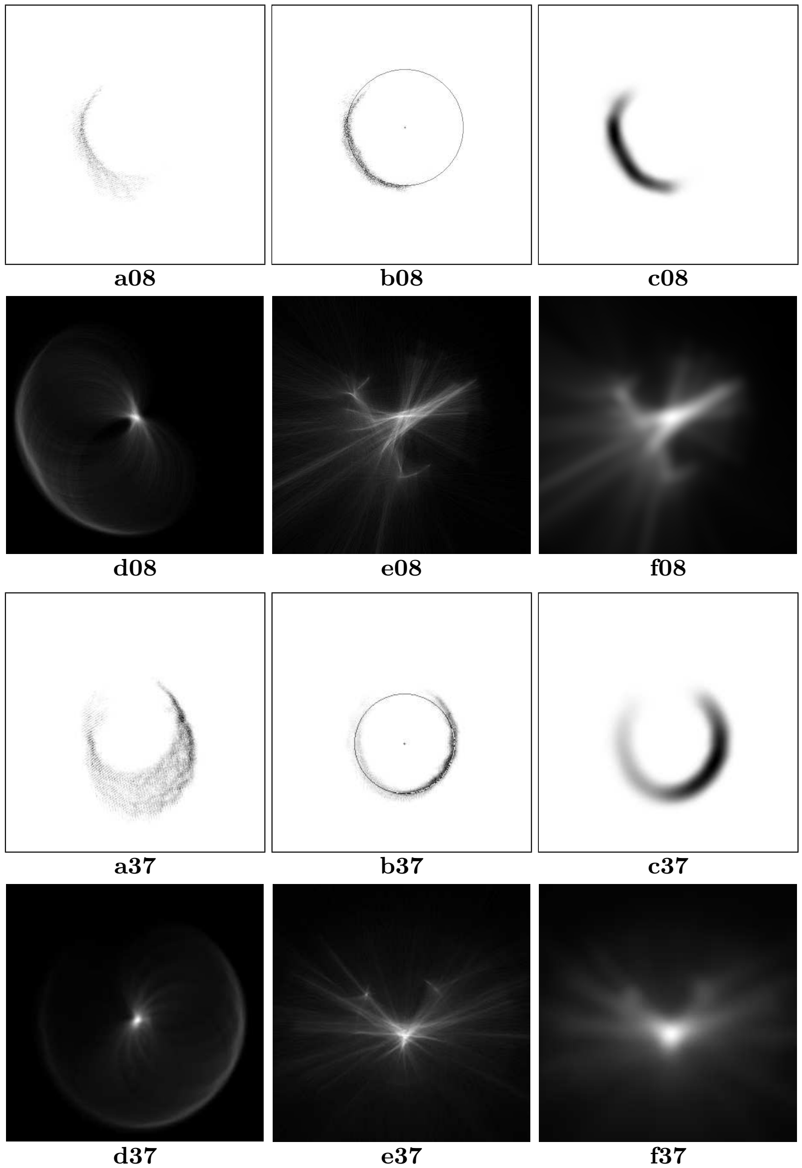

Fig. 3. Calculations for *tree08* and *tree37*, data set *thick100*. (**a**) Raw data points projected on a horizontal plane Oxy; (**b**) Data points of image **a** after verticalization; result calculated from the accumulator **f** is overlaid. (**c**) Fuzzified data of image **b**. (**d**) Accumulator of the HT with circles calculated directly from the data **a** – layer containing the maximum; fuzzification not necessary. (**e**) Accumulator of the HT with normals calculated from fuzzified data **b**; fuzzification is needed due to the presence of many maxima. (**f**) Accumulator **e** fuzzified.

present errors of the methods transcend this standard, so the image resolution of 2 mm seems to be enough in the considered application.

The calculation times for the HT with cones can be reduced if the data are projected on the horizontal plane, as in the HT with lines. This could have little or no influence on the accuracy if the image resolution is sufficiently high.

Trials with more variants of the Hough transform are necessary, including the use of an ellipse as a model of a tree section (see Tabs. 1 and 2).

8 Conclusions

Tree measurements can be speeded up with the use of terrestrial LIDAR-based measurements, but the accuracies attainable with some currently available software seems to be questionable. The presented startup study indicates that the segmentation of the terrestrial LIDAR data into separate trees is not a difficult task, so that the starting points for the analysis of single trees going up from the breast height can be easily found in the cloud of the measuring points. The literature study suggests that the application of more advanced Hough transforms for circle and ellipse detection can lead to better results and quicker calculations of the breast-height diameters.

Using the more advanced methods, including the fuzzy Hough transform-based and other robust techniques seems to be promising, but more work should be done. The impact should be laid upon the development of large benchmark data sets with the known ground truth and on the validation of the existing and new methods against the credible data.

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