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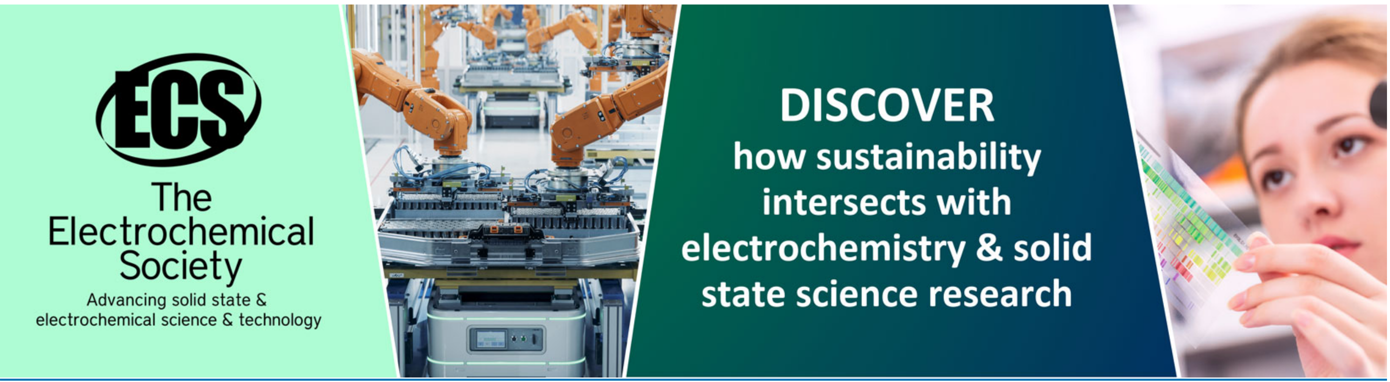

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A tree canopy height delineation method based on Morphological Reconstruction—Open Crown Decomposition

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Abstract. For the purpose of forest management, high resolution LIDAR and optical remote sensing imageries are used for treetop detection, tree crown delineation, and classification. The purpose of this study is to develop a self-adjusted dominant scales calculation method and a new crown horizontal cutting method of tree canopy height model (CHM) to detect and delineate tree crowns from LIDAR, under the hypothesis that a treetop is radiometric or altitudinal maximum and tree crowns consist of multi-scale branches. The major concept of the method is to develop an automatic selecting strategy of feature scale on CHM, and a multi-scale morphological reconstruction--open crown decomposition (MRCD) to get morphological multi-scale features of CHM by: cutting CHM from treetop to the ground; analysing and refining the dominant multiple scales with differential horizontal profiles to get treetops; segmenting LiDAR CHM using watershed a segmentation approach marked with MRCD treetops. This method has solved the problems of false detection of CHM side-surface extracted by the traditional morphological opening canopy segment (MOCS) method. The novel MRCD delineates more accurate and quantitative multi-scale features of CHM, and enables more accurate detection and segmentation of treetops and crown. Besides, the MRCD method can also be extended to high optical remote sensing tree crown extraction. In an experiment on aerial LiDAR CHM of a forest of multi-scale tree crowns, the proposed method yielded high-quality tree crown maps.

1. Introduction

With the development of LiDAR (Light Detection And Ranging) techniques, LiDAR data with high point density are available and a canopy height model (CHM) with high spatial resolution can be derived.

Various crown delineation methods are available for CHM, such as those based on valley-following [1], between-tree shadow identification [2], region-grouping [3], edge detection [4], watershed segmentation [5], and 3D model [6]. Although successful for coniferous forests, the current crown delineation methods for CHM typically work poorly on deciduous tree forests. In a typical crown delineation method for CHM, treetops are first carefully localized and then used as reference points for crown delineation [7]. Although it is relatively easy to detect the treetops of conifers, it is difficult to determine the treetops of deciduous trees. This is primarily due to the fact that deciduous tree crowns have a wider size range and their branches resemble individual trees.

In order to delineate varied-size tree crowns, the CHM is typically smoothed to suppress spurious treetops and then treetops are detected using local maximum filtering with a fixed or variable-size window [8]. However, it is difficult to determine an optimal filter size to retain multi-scale tree crowns for a given forest [9]. In order to effectively detect the tops of varied-size tree crowns, the size of the search window for the local maximum filtering is set to vary with tree height [10]. However, the allometric relationship between tree height and crown width is not always present, and sometimes the relationship is so weak that accurate crown width cannot be obtained with reference to tree height.

Recently, multi-scale analysis techniques have been used to overcome the issues caused by multi-scales of tree crowns in crown delineation. For example, in one proposed crown delineation method [11], a series of scaling functions over a continuum of scales of the 2D Mexican hat wavelet is employed, and from its correlation with the CHM, treetops of multi-scale crowns are detected; and in a method proposed by [12], a series of 3D crown models with similar shapes and increasing sizes is employed to extract varied-size crowns from their correlation values with the CHM.

An alternative and possibly more efficient approach to analyse the existing tree crown scale levels of the target forest is needed, and a scheme to effectively utilize the scale levels for crown delineation should be explored. For these two targets, an innovative method is proposed in this study, which effectively determines dominant scales and delineates varied-size crowns from CHM, based on Multi-Scale Analysis,.

2. Methodologies

The method proposed in this paper is composed of four steps: (1) automatic calculation of feature scales, getting the dominant sizes of the structuring element (SE) for the following morphological analysis; (2) multi-scale analysis, employing a multi-scale crown horizontal-cutting tool for pre-selecting treetops with morphological opening or reconstruction-open operation; (3) Integration of treetops from feature levels, to integrate the multi-scale treetops of every pre-selected feature scale to the final treetops under certain constraint conditions; (4) watershed segmentation, to produce and refine the segmentation map of crowns with a watershed segmentation method.

2.1. Feature scales calculation

The 3D shape of a typical tree crown is usually considered as a half ellipsoid with outmost branches attached [13]. According to this rule we select a tree crown from an actual test CHM to display the principle of feature scale calculation, as shown in Figure 1b. Morphological opening can remove 'foreground' objects that are smaller than the SE in an image [14], so the mean values curve of difference images between a series of opened images with a progressively increasing SE diameter (DSOPSE) was used to reveal the dominant scales from its local minimums, whereas DSOPSE cannot adjust parameters automatically in complex canopy structures.

The purpose of this part is to calculate the dominant SE scales of morphological erosion on the self-adjusted contour surfaces of CHMs (SESCS), as shown in figure 1. First, a denary logarithm operation is applied to the height range $\boldsymbol{R}$ of CHM, to get the height-log-value's nearest integer less than or equal to itself. Then, ten to the integer power is calculated to get a new range $\boldsymbol{R_{10}}$. And then, if the ratio of $\boldsymbol{R} / \boldsymbol{R_{10}}$ is smaller than 1.2, bigger than 1.2 and smaller than 2.4, bigger than 2.4 and smaller than 6, the contour level step $\boldsymbol{R_{step}}$ is determined by dividing $\boldsymbol{R_{10}}$ by 10, 5, 2 respectively. Contour levels $\boldsymbol{L}$ then can be correspondingly confirmed automatically by $\boldsymbol{R_{step}}$ between minimum and maximum of CHMs starting with the minimum plus a correction to $\boldsymbol{R_{step}}$ (figure 1a and 1b).

In order to determine the scale range and feature scale levels, a series of disk SEs with increasing diameters was employed in morphological erosion (figure 1d) on each binary plane between two adjacent contour levels (figure 1c). When the binary plane contains no valid value, the scale of the SE is selected as one of the feature scales for the following MOCS and MRCD methods. All binary contour planes, except the lowest level, result in a set of scales. After eliminating the repeated ones, these scales are refined to ascending dominant scales in ascending order automatically. In addition, the region lower than the minimum contour level is of no use for canopy extraction, and can be taken as an invalid area for the following segment.

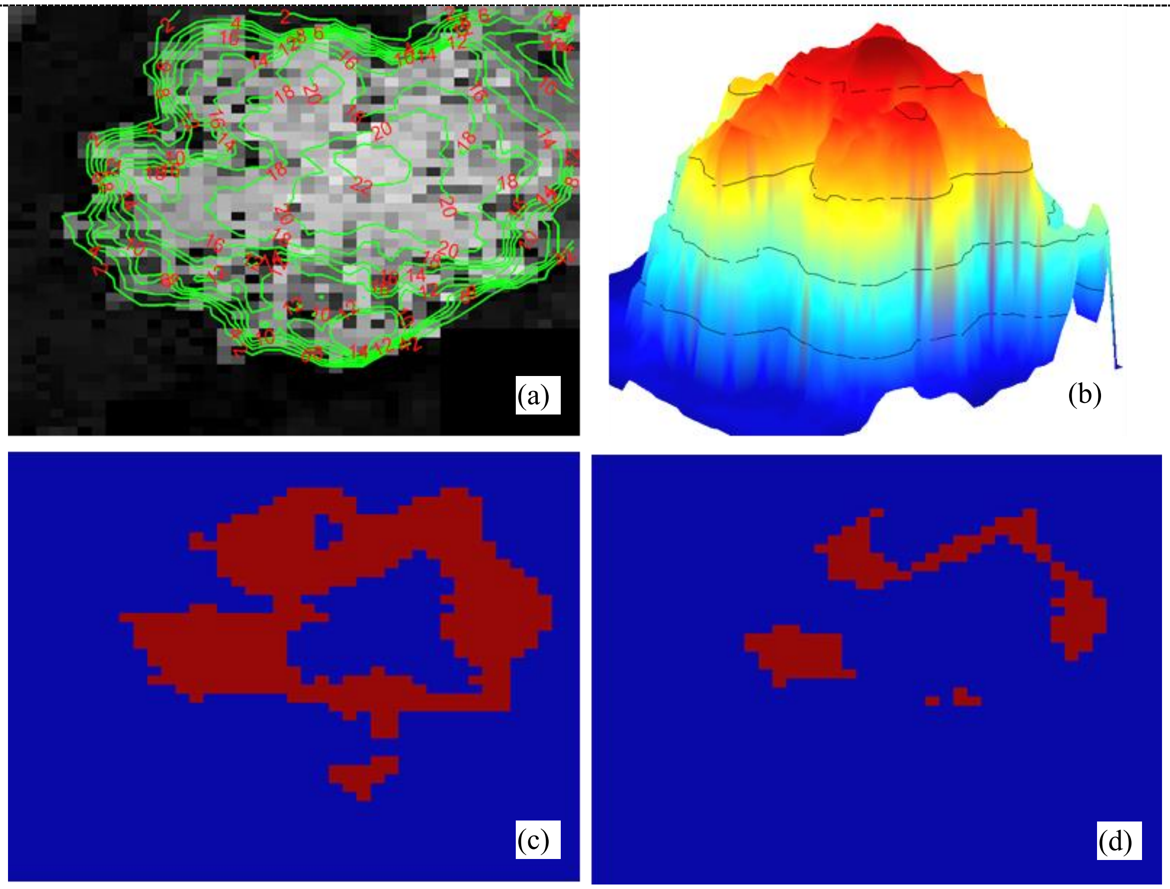

Figure 1. Self-adapted feature dominant scale calculation of a CHM.(a) 2D shape of a CHM with contours; (b) 3D shape of a CHM with contours; (c) binary contour surface of two adjacent levels; (b) erosion on binary contour surface

2.2. Multi-scale analysis

The multiple tree crown SE levels previously obtained by self-adjusted feature scale calculation were used to design a crown horizontal-cutting tool for slicing the crown into many layers from top to bottom and generating a set of pre-selected treetops. Morphological opening crown segmentation (MOCS) and morphological reconstruction--open crown decomposition (MRCD) were selected for analyzing multiple-scale crown properties. A MOCS with an SE includes two successive operations: erosion and dilation with the same SE, as shown in figure 2b. In the erosion operation with a disk SE of diameter ***d*** pixels, each pixel of focus is superimposed by the center of the SE, and its value is replaced with the minimum value of the pixels superimposed by the SE. In the following dilation operation, each pixel of the eroded surface is superimposed by the center of the SE and its value is replaced with the maximum value of the pixels superimposed by the SE. As a result, each side of the eroded surfaces is dilated by $(d-1)/2$ pixels and the layers not smaller than the SE in the original surface are restored. Comparing the 3D (figure 2b) and vertical profile (figure 2d) of a tree crown under MOCS with the original one (2a), the tops and some side surfaces smaller than SE were all removed, because neither erosion nor dilation is an invertible transformation in 3D direction.

The morphological reconstruction--open operation is an algebraic opening and preserves the shape of the components that are not removed by the erosion [15]. After erosion on original CHMs, the eroded sets are then used as seeds for a reconstruction of the original CHMs. All crown features that cannot contain the SE are removed, the others being unaltered, as illustrated in figure 2c and figure 2 d.

A series of MOCS or MRCD operations with previously calculated dominant SE levels were applied to CHMs, leading to a set of corresponding flat-topped CHMs. The local maxima of these flat-topped CHMs in all dominant SE levels can be used as pre-selected treetops.

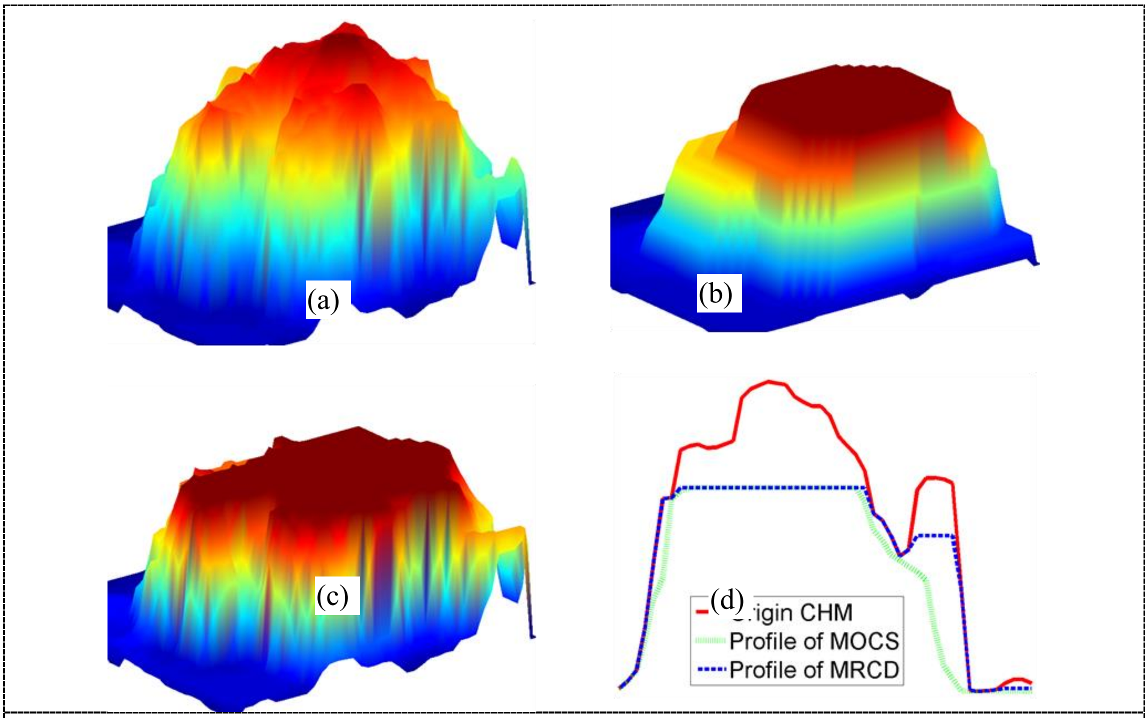

Figure 2. Comparison with MOCS and MRCD operation on a 3D CHM.(a) 3D shape of original CHM ; (b) MOCS operation on CHM with a SE; (c) MRCD operation on CHM with a SE; (d) vertical profiles of CHM under MOCS and MRCD operation

2.3. Integration of treetops from feature levels

To generate a map composed of treetops, the pre-selected treetops of ascending dominant levels from the multi-scale analysis should be first integrated as follows: the treetops of the first scale level were first integrated with those of the second scale level, and the resulting integrated treetops were then integrated those of the third scale level, and so on.

Larger SEs can contain larger crown structures, so the treetops size of larger scale are larger or equal to the smaller scale for both MOCS and MRCD methods, and the treetop shape of MRCD is more sophisticated than that of MOCS, which is similar to the shape of SE. To integrate such different-scale treetops, we need to know whether the fine-scale (smaller scale) treetops are merged to the coarse-scale (larger scale) ones. It is reasonable to assume that a tree crown is circular, whereas a tree cluster is less circular, and this can also be extended to describe treetops. Based on this assumption, comparing the circularity values of the fine-scale, coarse-scale, and merged treetops may facilitate judging the treetops. Circularity (***c***) of a treetop is defined as follows:

$$\mathrm{c} = \frac{A}{\pi\left(\frac{D}{2}\right)^2} \tag{1}$$

Where ***A*** and ***D*** are the area and the equivalent diameter of the treetops, respectively.

The less circular a treetop is, the smaller its circularity value is. Therefore, if the circularity of merged treetops is larger than a supposed threshold value, then the fine-scale and coarse-scale treetop could be integrated and replaced by the merged treetop; otherwise the fine-scale treetops should be retained. When all dominant scale treetops are processed in this way, an actual integrated treetops map is achieved for the following final segmentation.

2.4. Watershed segmentation

According to the similarity between geographic reliefs and tree crown surfaces, the watershed segmentation approach [16] is widely used to segment imagery for tree crown delineation. Indeed, provided that the input image has been transformed so as to output an image whose minima mark relevant image objects and whose crest lines correspond to image object boundaries, the watershed transformation will partition the image into meaningful regions. The watershed approach involves finding local minima as markers, flooding the relief from the markers, and building dams where waters coming from two different minima would merge. In the process of individual tree crown delineation, the watershed segmentation method was implemented on inverted CHMs of crowns with integrated treetops as markers in MATLAB software (R2014a). The resulting segment was removed from the non-vegetation area by a mask generated by setting a threshold from the minimum contour level on CHMs.

3. Experimental Results

Two study areas within the Great Lakes-St. Lawrence forest region were selected to test the methods proposed in this paper. The first study area selected is near Sault Ste. Marie, Ontario, Canada. The forest in the first study area is a mix of varied-size trees, bushes, grasses, and forbs. The forest in the second study area has two obvious layers. The LiDAR data over the two study areas were acquired in August 2009 using a Riegl Q-560 scanner. The flying height of 200 m and two overlapped flight lines resulted in a high point density of about 45 points per m^2. The DSM (digital surface model) and DEM (digital elevation model) of each of the study areas were derived with a grid cell size of 0.15 m by 0.15 m in order to be consistent with the spatial resolution of the digital aerial imagery acquired simultaneously. The difference between the DSM and DEM was the CHM (crown height model) of each study area, which was then smoothed with a 3×3 Gaussian filter to effectively eliminate noises. The CHMs of the first and the second study areas are taken as Dataset I and Dataset II and shown in Figure 3a and 3b, respectively.

The original CHM was manually delineated by an independent researcher to get a reference map for target segment result evaluation. The target segment result maps are shown with boundaries in blue in Figure 3 for Dataset I and II. Visual inspection shows that the two maps are consistent for most tree crown segments, and get more accurate crown boundaries even than manual delineation. To evaluate the result quantitatively, we used three classes of the spatial relationships between the reference and target segment: 'Exact ratio'—If only one reference segment is overlapped by a target segment at least 50%; 'Reference ratio'—The ratio of a reference segment being overlapped by a target segment; 'Target ratio'—The ratio of a target segment being overlapped by a reference segment. The statistics of the four processing flow sheets combined with SESC, DSOPSE, MOCS and MRCD are listed in Table 1. As demonstrated, segmentation combined with SESCS and MRCD has the same Extract-ratio with that of the combination with DSOPSE and MOCS, as well as a higher Reference-ratio and lower Target-ratio than the latter flow. This means that the segment maps of SESCS and MRCD had good performance in tree crown segmentation and achieved more accurate boundaries of crowns than DSOPSE and MOCS.

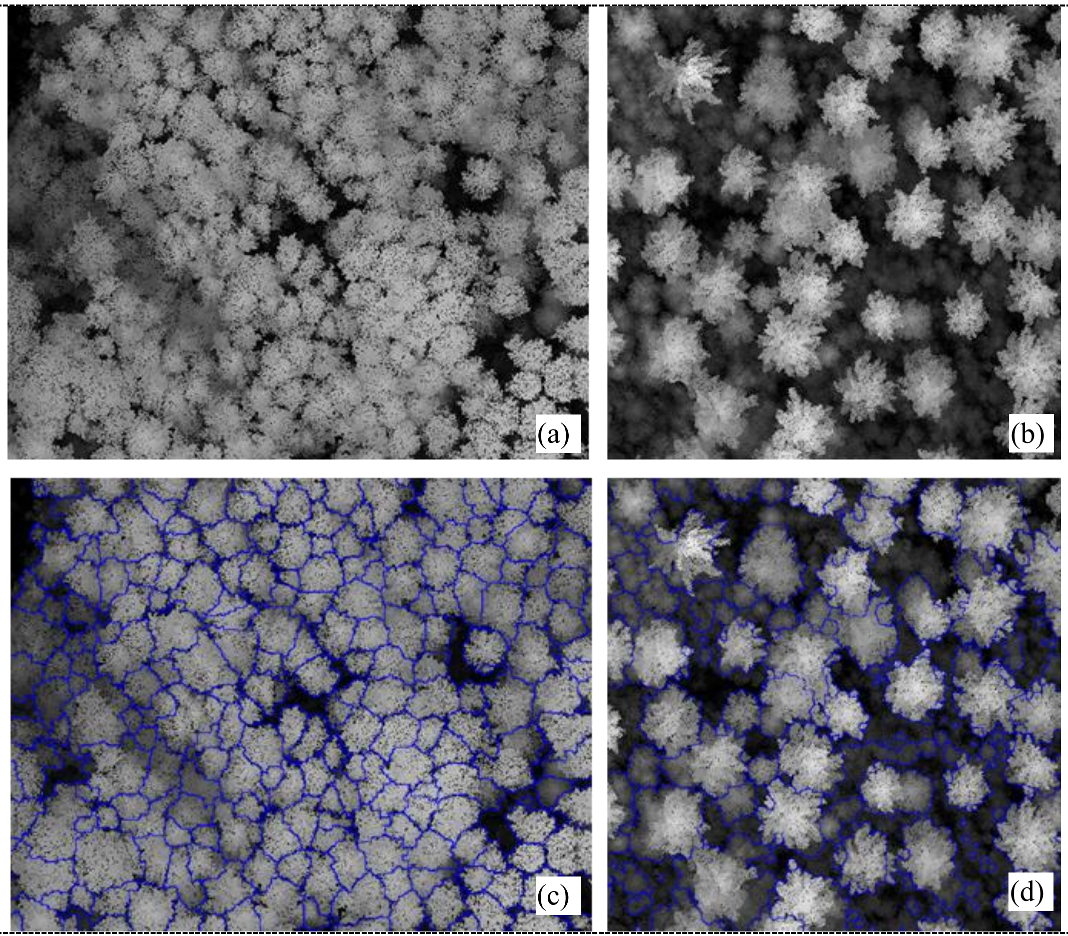

Figure 3. The CHMs of Two test areas.(a) the first area (Dataset I); (b) the second area (Dataset II); (c) the tree crown segmentation map of Dataset I; (d) the tree crown segmentation map of Dataset II

Table 1. The accuracy statistics of the tree crown maps for combinations of SESCS,DSOPSE,MOCS and MRCD

Dominant Scale method	Multi-scale analysis	Dataset	Exact ratio	Reference ratio	Target ratio
SESCS	MOCS	I	0.9912	0.7196	0.4200
		II	1.0000	0.9357	0.5843
	MRCD	I	0.9912	0.7806	0.3189
		II	1.0000	0.9644	0.5805
DSOPSE	MOCS	I	0.9912	0.6768	0.4855
		II	1.0000	0.9464	0.5671
	MRCD	I	0.9912	0.7288	0.4072
		II	1.0000	0.8766	0.5316

4. Conclusions

In this study, a tree crown delineation method for CHM was developed that included self-adjusted feature scale calculation, multi-scale morphological reconstruction--open crown decomposition analysis to generate pre-selected treetops, their integration to get foreground actual treetops, and watershed segmentation to achieve the final tree crown maps. The method was validated using LiDAR CHM over a mixed forest in Ontario, Canada. Compared with manual interpretation, the new method provided a satisfactory individual tree crown map.

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