University of Sopron

Theses of doctoral dissertation

INVESTIGATION OF THE FORESTRY APPLICATIONS OF POINT CLOUDS AND SURFACE MODELS DERIVED FROM AERIAL REMOTE SENSING DATA

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Subject of the Dissertation

Over the past decades, various remote sensing techniques have increasingly gained ground in forestry research, and shortly thereafter in practical forest management as well, owing to their rapid development. By now, numerous methods have emerged—some still in an experimental phase, others already applied in practice—that aim to determine dendrometric parameters of forest stands as well as terrain characteristics using airborne or terrestrial remote sensing techniques. The advancement of these methods is particularly valuable in the context of climate change, as the rapid changes associated with it cannot be adequately tracked using classical methods alone. Forest stand parameters play a key role in estimating above-ground carbon stocks, while terrain characteristics are essential for understanding site conditions and, consequently, for selecting appropriate forest stand types. Therefore, their accurate determination and continuous monitoring are indispensable for understanding and effectively utilizing the climate change mitigation potential of forests.

In summary, the dissertation consists of two main parts. First, the author presents the feasibility, classification, and processing possibilities of point clouds and surface models generated from UAV-based aerial photogrammetric surveys. This is followed by an analysis of large-scale, high-resolution terrain models derived from airborne laser scanning conducted with light aircraft, taking forestry site conditions into account.

Objectives of the Research

The primary aim of the research is to develop various methods and procedures for processing data acquired through airborne remote sensing, both in terms of dendrometric applications, terrain modelling and analysis. The detailed research objectives are as follows:

1. Development of a workflow for generating terrain models based on the photogrammetric processing of aerial images acquired under leaf-off conditions, including an assessment of the impact of data acquisition and processing parameters on accuracy, and the formulation of recommendations for optimal settings.

2. Development of a method capable of selectively identifying and smoothing potential gross errors in terrain models.

3. Development of a canopy modelling and processing workflow based on the photogrammetric processing of aerial imagery acquired under leaf-on conditions, aimed at achieving the highest possible accuracy in individual tree detection, along with the determination of optimal workflow parameters through the analysis of their impact on accuracy.

4. Investigation of the possibilities and limitations of stem position detection using photogrammetric point clouds derived from leaf-off aerial surveys.

5. Investigation of the applicability of landform classification using a two-step Topographic Position Index (TPI) analysis, and the development of a model for the objective selection of the required analysis parameters.

6. Derivation of slope-, aspect-, and landform-related thematic layers from large-area terrain models generated from airborne laser scanning point clouds, followed by their comparison at

forest compartment level with the corresponding data of the National Forestry Database.

Methodology of the Research

1. Analysis of point clouds and surface models generated by UAV-based photogrammetry

For the investigations, the author designated four sample plots (100 × 100 m) in mature forest stands with mixed species composition. Within these plots, reference data were collected using static terrestrial laser scanning, with particular regard to terrain, stem positions, and diameter at breast height (DBH)

Aerial imagery was acquired over the selected sample plots using a DJI Mavic 2 Pro UAV at three different flight altitudes (80, 100, and 120 m), with 90% forward and 90% side overlap, under both leaf-on and leaf-off conditions. By filtering the acquired imagery to simulate overlaps of 80% and 70%, multiple combinations of flight parameters were generated, from which point clouds were produced using photogrammetric software.

A dedicated processing workflow was developed for the point clouds, incorporating various noise filtering, thinning, and classification steps. This workflow enables the generation of terrain models from leaf-off datasets and canopy models from leaf-on datasets. As part of the terrain modelling workflow, a targeted smoothing procedure was developed to mitigate gross errors in raster models caused by residual point noise that may persist after filtering.

Using the canopy models, individual tree detection was carried out through a two-step local maxima search followed by inverse watershed-based canopy segmentation. In addition, stem detection based on point clustering was performed on leaf-off point clouds generated from imagery with the highest overlap.

For the results obtained from different combinations of data acquisition and processing parameters, the author applied SHAP analysis to evaluate the extent and direction of their influence on the accuracy and error characteristics of the final outputs.

2. Analysis of terrain models derived from airborne laser scanning using light aircraft

Within the framework of the SoilSense project, two sample areas have been designated to date: one in the Dudlesz Forest and the other within the administrative boundaries of Réde, covering a total area of more than 3,000 hectares. These sample areas also formed part of the author's doctoral research, in which high-resolution terrain models derived from airborne laser scanning using light aircraft were analysed. From these models, slope, aspect (exposure), and landform categories were derived.

For landform classification, a two-step Topographic Position Index (TPI) analysis was carried out. To determine the required analysis radii, an empirical model was developed that objectively selects these parameters based on the spatial resolution of the model and the local characteristics of the terrain.

Using the derived thematic raster datasets, the author reviewed the relevant records in the National Forestry Database for the forest compartments located within the two sample areas. Since the "variable" category is not clearly defined in the Forest Management Guidelines, the author examined the feasibility of deriving mathematical classification rules by statistically analysing the proportions of subcategories within each forest compartment (frequency, stability, and Shannon entropy).

Results

1. Processing of surface models and point clouds generated by UAV-based photogrammetry

For most combinations of flight parameters, the acquired imagery resulted in successful image matching. However, image alignment failed in 20% of cases under leaf-off conditions and in 39% of cases under leaf-on conditions, thus reducing the actual number of usable parameter combinations per sample plot accordingly.

The average error of the terrain models is primarily influenced by flight parameters, followed—at a somewhat lower level—by the scale of ground point classification, while the impact of noise filtering procedures is also non-negligible. In the case of gross errors, although these factors remain significant, a clear dominance is observed for the targeted smoothing procedure developed by the author. The resulting deviations indicate an average error of 6 cm and a maximum gross error of 40 cm for the most accurate terrain models.

The accuracy of individual tree detection based on the leaf-on canopy model is only marginally influenced by flight parameters (resulting in differences of only a few correctly detected trees), while filtering procedures have virtually no effect. Instead, the results depend primarily on the selection of processing parameters. The average detection rate of treetops based on local maxima search is 76%, which is slightly improved to 78% when combined with crown delineation using an inverse watershed algorithm. In addition, this approach reduces over-detection by a few percentage points, resulting in an overall improvement in detection accuracy.

Stem position detection performed on the leaf-off point cloud is mainly influenced by two factors: illumination conditions and canopy structure. On the best-performing sample plot, the detection rate exceeded 95%; on two others, it was around 90%, while on the fourth, weakest-performing plot, it reached 68%.

2. Analysis of terrain models and comparison with National Forestry Database records

Due to the differing geomorphological characteristics of the two study areas—the Dudlesz Forest and the Réde forest block—different radii are required for the two-step, TPI-based landform classification. In the former case, optimal radii were found to be 25 m and 100 m, while in the latter they were 30 m and 80 m. This variability is also supported by the analysis of slope and aspect. In the Dudlesz area, the majority of the terrain falls within the 2–5° slope category, whereas in the Réde forest block the dominant category shifts one level higher, to 5–10°. Regarding aspect, the Dudlesz area shows a strong bias toward east–northeast exposures, while in the case of Réde a more balanced distribution can be observed between southwest–west and northeast–east aspects.

By analysing the stand-level distribution of the derived slope, aspect, and landform categories—along with their frequency, stability, and Shannon entropy—several conditions were established for defining the "variable" category. However, even under the most favourable conditions, the agreement with the database records averaged only 63% across the two sample areas. Consequently, no consistent mathematical rules could be derived for this category.

Conclusions

1. Applicability of point clouds and surface models generated by UAV-based photogrammetry

In the case of terrain models, flight altitude and the degree of overlap—along with their combination—have a significant impact on accuracy. These parameters are particularly influential under variable illumination conditions and dense canopy structures. Among the point cloud processing steps, reliability-based filtering and the scale of ground point classification proved to be the most decisive factors. Based on the results, the highest accuracy can be achieved with a flight altitude of 100 m, 80% forward and 90% side overlap, filtering of the lowest-confidence points, and a 9 m ground point classification scale, complemented by the targeted smoothing method developed by the author, which effectively reduces the extent and magnitude of gross errors.

The outcome of canopy detection is only minimally affected by flight parameters; therefore, higher flight altitudes and lower overlaps are sufficient, provided that image matching remains successful. Detection accuracy is primarily determined by processing parameters, namely the window sizes used for local maxima search and the maximum crown diameter applied in the inverse watershed algorithm, while the resolution of the raster canopy model is also a non-negligible factor. According to the results, the most favourable detection rate can be achieved with a flight altitude of 120 m, 80% overlap, 0.3 m/pixel resolution, a 3 m search window size, and a maximum crown diameter of 7 m.

Based on the results of stem detection, the optimal flight altitude strongly depends on stand density. In stands with more open canopy structures, a flight altitude of 120 m is sufficient; interestingly, in such cases, lower flight altitudes resulted in reduced detection rates. In stands with denser branch structures and a significant proportion of conifers, altitudes of 100 m and 80 m proved to be more effective. The application of noise filtering resulted in considerable point loss; therefore, its omission is justified, as the objective is approximate stem position detection rather than precise diameter estimation. The most severe limiting factor is the combined effect of dense canopy structure and direct illumination; under such conditions, aerial image acquisition for this purpose is not recommended.

2. Comparison with National Forestry Database records on terrain characteristics

Based on the comparison of database records and model-derived data, it can be concluded that the terrain-related fields (slope, aspect, landform categories) of the National Forestry Database require improvement in both accuracy and structure. The analyses indicate that discrepancies are more pronounced in areas with complex terrain conditions; however, data storage inaccuracies are also present in less dissected landscapes.

The use of modern, nationwide high-resolution terrain models would provide an opportunity to update the database. In this regard, the author formulated several recommendations and evaluated their feasibility and limitations. These include the quantification of the "variable" category, consideration of its elimination, the possibility of introducing multi-category storage supplemented with proportional measures, as well as issues related to the subdivision of forest compartments.

Theses of the Dissertation

1. The author developed a processing workflow capable of deriving photogrammetric point clouds, terrain models, canopy surface models, as well as stem positions, treetops, and crown dimensions from UAV-based RGB imagery acquired under both leaf-on and leaf-off conditions. A sensitivity analysis of the workflow parameters was conducted, and recommendations for their optimal values were provided.
2. For specific outputs of the above workflow, the author determined the optimal flight parameters (flight altitude, forward and side overlap) for forestry data acquisition using a DJI Mavic 2 Pro UAV.
3. A targeted smoothing algorithm was developed which, in contrast to conventional methods applied uniformly across the entire model surface, can identify and selectively remove non-real surface anomalies (e.g., stumps, noise-induced false depressions) remaining after ground point classification and noise filtering. Based on its detection principle, the method is also suitable for identifying pits and stockpiles.
4. The author demonstrated that the detection of treetops as local maxima on raster surface models can be significantly improved when combined with canopy segmentation based on an inverse watershed algorithm. The integration of these two methods enables more accurate estimation of stem numbers.
5. It was demonstrated that stem positions can be determined with an accuracy exceeding 95% under optimal conditions (diffused illumination, more open canopy structure) using high-density photogrammetric point clouds generated under leaf-off conditions, particularly in mature forest stands where thinning operations aimed at increment enhancement have already begun.
6. An empirical model was developed that enables the objective determination of parameters for two-step Topographic Position

Index (TPI) analysis, taking into account local terrain characteristics.

7. The author reviewed the terrain-related data (slope, aspect, landform categories) of the National Forestry Database and, based on this assessment, formulated recommendations for improving both their content and storage methodology.

List of publications related to the dissertation

Theses and degree projects

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SZÁSZ B., CZIMBER K., KIRÁLY G. (2024): Digitális domborzatmodell-elemzés a Dudlesz-erdő területén a SoilSense projekt keretein belül. In: CZIMBER K. (szerk.): Erdészeti Tudományos Konferencia 2024. Soproni Egyetem Kiadó, Sopron

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