Tandem forest Values - Final report

Call: Tandem Forest Value: Forest resources, wood-based value chains and wood construction

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Sites of Research: Finnish Geospatial Research Institute FGI
Swedish University of Agricultural Sciences SLU

Research Themes: Digitalisation of forestry, tree quality and individual tree inventory using new methods and technologies

Project title: Estimating Forest Resources and Quality-related Attributes Using Automated Methods and Technologies

Reporting period FGI : 1.4.2020-31.12.2022 (extended from 31.3.2022)
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Popular science summary

Forest inventory, which records not only basic attributes (i.e., stem volume and biomass), but also information about forest quality (i.e. tree species and wood quality), provides the fundamental reference data for all decision-making that are relevant to human interventions in forest ecosystems, ranging from sustainable management at the landscape scale to harvest planning in forest stands and optimization of wood supply to advanced manufacturing processes. High benefits can be obtained if the quality of individual trees, indicated by attributes such as stem curve, size distribution, height of the lowest dead branch, crown base height and maximum branch diameter can be characterized, and if accuracy and spatial coverage of volume estimations can be improved. Biodiversity values can be preserved and increased by the supply of maps to forest managers.

The project covered a wide range of solutions. A sensor system was specifically designed for measurements of Nordic forests. The data needed for the project were collected and prepared at established and new test sites. In further work, analysis methods were developed for extraction of information from sensor data. Methods were developed for estimation of tree attributes from ground-based mobile laser scanning. These methods could further be used to supply airborne remote sensing methods with high-precision reference data. Tree species specific stem diameter distributions were estimated using airborne multispectral laser scanning. Based on the above described work new tools were developed for high-precision forest inventories in the Nordic countries and for decision support in logistics and wood supplies to industries.

The project has been successful for the exchange of knowledge between Finland and Sweden, and has also included active involvement of forest managers in the research, including participation in reference group meetings, data collection campaigns, seminars, and excursions. The results from the project are valuable as a foundation for further research towards high-precision forestry in the Nordic countries.

Goals

- Development of a hardware for mobile laser scanning that allows collection of a point cloud, that can provide accurate field reference and enables quality determination of standing trees.
- Development of a processing chain for the developed hardware and information system allowing each tree in the field to be measured with the same accuracy as with the current manual field inventory techniques providing location, shape and volume for each tree.
- Combining mobile laser scanning field reference with high resolution airborne laser scanning and photography providing forest inventories for small areas, and with national laser scanning, multispectral airborne laser scanning and single photon laser data for regional and national scale generality.
- Using harvester data to provide size-distribution of trees for area-based calibration.
- To solve tree species extraction and tree quality related technologies providing added value for species-specific high-quality estimates of standing trees.

The work in the project was implemented in altogether six (6) work packages to manage the project and make the responsibilities visible. We report the research and development done in each WP below and list the communication, mobility and publications at the end of the report. During the project we had planning and reporting meetings, mobilities, joint field work in Finland and Sweden in close collaboration with industrial partners to foster the use of new technologies and findings and transfer of knowledge and best practices.

The project has contributed 31 journal publications or manuscripts, and one master’s thesis. Numerous papers in this set, as well as the data collected and experiments done in the project, will be part of PhD qualifications of Mika Pehkonen, Olli Winberg, Jesse Muhojoki, Valtteri Soininen, Lassi Ruoppa, Einari Heinaro, Arvid Axelsson and Raul de Paula Pires.

The key findings

- We built a multispectral airborne laser scanner (ALS) system that was tested and demonstrated in the project for the first time. The novel data was also used for developing the fusion and georeferencing research and algorithms for the developed dual-wavelength MLS and MS ALS use for tree quality data.
- We developed and validated an algorithm for dynamic linking of MLS and ALS data. The algorithm uses time windows and matches tree position patterns supported by tree size similarities to perform automatic co-registration of the data sources.
- The measurements of tree stems stored in the harvester were linked to tree crown segments derived from the ALS data that was used for prediction of tree stem attributes. We could predict stem estimates accurately without any manual field references needed.
- We demonstrated stem curve and volume derivation from standing trees for advanced forest inventory needs, and implemented a method to derive branch structure from the trees. We tested these new approaches on backpack and handheld MLSs the first time.
- Branch extraction research resulted in a method for quality estimation of trees to derive quality measures like number of branch whorls per stem, detection of low growing branch

whorls and angles of branches. Stem quality variables taper, sweep and lean can be estimated by using stem profile detection methods.

- We improved tree species detection and detection of sub-dominant trees with new methods using multispectral laser scanning data.
- We could develop a procedure to measure and track stems/logs from standing trees to sawmill and log X-ray to correlate external and internal qualities and timber assortments.

We established joint approaches to field work and measurement practices and shared many valuable lessons learned in both countries related to conditions, data acquisitions, processing and industrial needs and practicalities. The research and collaboration continues within the research programs UNITE Flagship and Mistra Digital Forest, and on other projects. The work continues to pursue digitalization of forestry to improve forest planning, management and operations with advanced quality indicators. This also fosters biodiversity conservation, as more holistic data and objective computational approaches allow us to analyze and distribute species specific quality related information (both economical and ecological), and decide and act based on that knowledge.

Work done and results by work packages

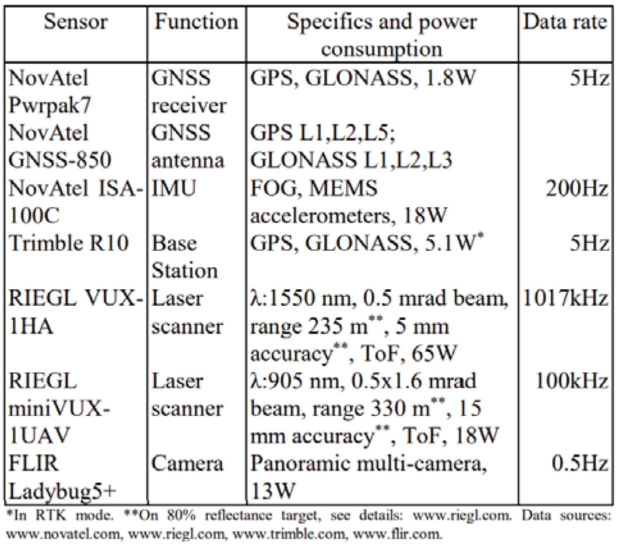
WP 1: Development of dual-wavelength MLS system (lead FGI, prof. Antero Kukko)

Task 1.1 Development of the dual-wavelength backpack MLS system for canopy measurements

In the task we developed a dual-wavelength backpack laser scanning system for forest quality assessment. Design criteria were to have full visibility for forest floor/ground for micro-topography but simultaneously full canopy capture. The geometric requirements for the ranging accuracy and point cloud precision were set at millimeter level. Further functionality was required to be able to collect quality reflectance information to explore and implement robust tree species detection. The dual-wavelength capability was implemented using Riegl miniVUX-3UAV (905 nm) and VUX-1HA (1550 nm) laser scanners tightly coupled with NovAtel Pwrpak7 GNSS and ISA-100C IMU. The final setup is seen in Figure 1, with an exception that the 905 nm scanner used in sweden 2021 was miniVUX-1UAV, which provides 100kHz pulse rate instead of the 200kHz permitted by the miniVUX-3UAV. Based on the field experience and handling during the project, further development of the carrier has also taken place, and the scanners are adjusted to operate more vertically, roughly 15 degrees, to permit good stem and canopy visibility in the data. The backpack has a foldable telescopic support leg to permit stationary initialization and system setup, for which a rugged tablet computer is used. The system weighs about 15 kg, and can be operated about 2 hours per single LiPo battery set.

Figure 1. a) Akhka-R4DW backpack dual-wavelength (905 nm + 1550 nm) laser scanning system, and b) three wavelength (532 nm + 905 nm + 1550 nm) helicopter scanning system was developed in the project and used for forest plot surveys, here in October 2021 in Hällefors region, Sweden.

Table 1. Akhka-R4DW system components. Backpack can also be fitted with a panoramic camera.



Sensor	Function	Specifics and power consumption	Data rate
NovAtel Pwrpak7	GNSS receiver	GPS, GLONASS, 1.8W	5Hz
NovAtel GNSS-850	GNSS antenna	GPS L1,L2,L5; GLONASS L1,L2,L3	
NovAtel ISA-100C	IMU	FOG, MEMS accelerometers, 18W	200Hz
Trimble R10	Base Station	GPS, GLONASS, 5.1W*	5Hz
RIEGL VUX-1HA	Laser scanner	λ:1550 nm, 0.5 mrad beam, range 235 m**, 5 mm accuracy**, ToF, 65W	1017kHz
RIEGL miniVUX-1UAV	Laser scanner	λ:905 nm, 0.5x1.6 mrad beam, range 330 m**, 15 mm accuracy**, ToF, 18W	100kHz
FLIR Ladybug5+	Camera	Panoramic multi-camera, 13W	0.5Hz

*In RTK mode. **On 80% reflectance target, see details: www.riegl.com. Data sources: www.novatel.com, www.riegl.com, www.trimble.com, www.flir.com.

The 3D measurement capability is achieved with two precision profiling mobile laser scanners using kinematic operation mode (Table 1). High density data is obtained with VUX-1HA at up to 1017kHz pulse repetition and 250 lines per second scanning rates. In addition to the 3D location of each measured point, also information of the surface reflectivity, signal amplitude and echo length is recorded. The scanning performance of miniVUX-3UAV is somewhat more moderate at 200 kHz pulse repetition rate and 100 lines per second scanning, but reasonable for backpack and other slow velocity applications in terms of obtained point density for multispectral data fusion. Both scanners, and the system layout, provide 360 degrees FoV (Field of View) to map the surroundings in cross-track scanning. To achieve that the secondary scanner is tilted about 30 degrees in the backpack rig to enable full FoV past the optics of the VUX1HA (See Figure 1a). The primary scanner to provide the accurate 3D data is in a position for nominally vertical scanning. However, the mount on the backpack is slightly tilted forwards while operating in practice. Mapping is carried out in walking, typically 3-5 km/h speed, depending on the forest density, terrain slope and ruggedness. This gives along-track scan line spacing of 3.3-5.5 mm for VUX-1HA, and 8.3-13.8 mm for miniVUX-3UAV. Angular resolutions corresponding to the scan settings applied were 1.5 mrad and 3.1 mrad, respectively. Scanner elevations above the ground were about 1.9 m and 2.3 m (194 cm tall operator). With the 1017 kHz Pulse Repetition Frequency the maximum range was about 235 m. With this system we collected data from Stora Enso test sites in southeastern Finland and Hällefors region in Sweden and Evo research forest in southern Finland.

In 2021 we were able to acquire Riegl VQ-840-G laser scanner suitable for airborne laser scanning and use with very large UAVs. The scanner provides 3D point data and reflectance at 532 nm wavelength. This expectedly adds a lot of information on foliage and chlorophyll, which we can exploit in tree species detection and separation of stem and branches from foliage in automated methods, among other things. We built a three wavelength ALS system that could be operated in a helicopter (Figure 1b) for high density forest data. This system was operated in test sites in Finland and Sweden. Unfortunately, the VQ-840-G failed in Sweden so that the sites there were covered only with data from scanners at 905 nm and 1550 nm.

We developed a process for fusing the point cloud data from the scanners into a single data so that each 3D point has two or three reflectance values corresponding to the number of scanners used in each system. Fusion is based on the 3D distance thresholding so that points too far away from each other are not used. The close range nature of measurements of the backpack allow very dense pseudo color point cloud data to be then used for analysis and pointwise classification (Kaijaluoto et al., 2022) or three species classification, such as a method presented in Hakula et al, (submitted). Additionally, the method supports computation of pointwise reflectance ratios, NDVI and such indices to support classification and detection tasks.

Task 1.2 GNSS-IMU positioning for dual-wavelength MLS: geometrically correct data

Deep learning methods based on convolutional neural networks have shown to give excellent results in semantic segmentation of images, but the inherent irregularity of point cloud data complicates their usage in semantically segmenting 3D laser scanning data. To overcome this problem, point cloud networks particularly specialized for the purpose have been implemented since 2017 but finding the most appropriate way to semantically segment point clouds is still an open research question. In our study (Kaijaluoto et al. 2022) we attempted semantic segmentation of point cloud data with convolutional neural networks by using only the raw measurements provided by a multiple echo detection capable profiling laser scanner. We formatted the measurements to a series of 2D rasters, where each raster contains the measurements (range, reflectance, echo deviation) of a single scanner mirror rotation to be able to use the rich research done on semantic segmentation of 2D images with convolutional neural networks. Similar approach for profiling laser scanners in forest context has never been proposed before. A boreal forest in Evo region near Hämeenlinna in Finland was used as an experimental study area. The data was collected with FGI Akhka-R3 backpack laser scanning system, georeferenced and then manually labeled to ground, understorey, tree trunk and foliage classes for training and evaluation purposes. The labeled points were then transformed back to 2D rasters and used for training three different neural network architectures. Further, the same georeferenced data in point cloud format was used for training the state-of-the-art point cloud semantic segmentation network RandLA-Net and the results were compared with those of our method. Our best semantic segmentation network reached the mean Intersection-over-Union value of 80.1% and it is comparable to the 80.6% reached by the point cloud -based RandLA-Net. The numerical results and visual analysis of the resulting point clouds show that our method is a valid way of doing semantic segmentation of point clouds at least in the forest context (Figure 2). The labeled datasets were also released to the research community.

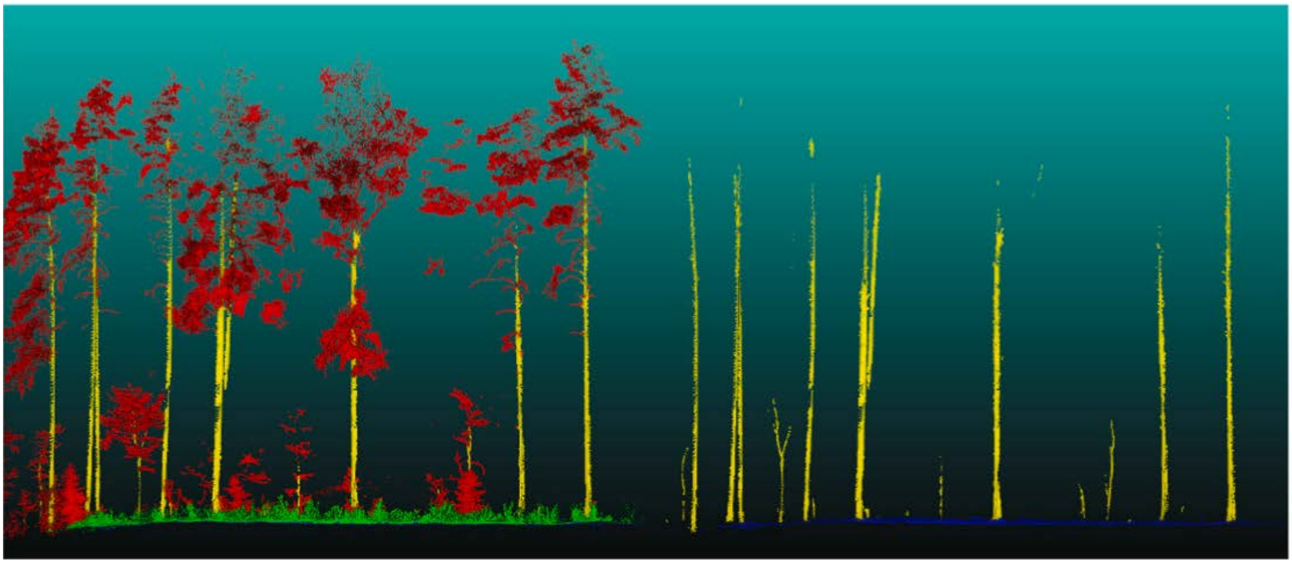


Figure 2. Deep Learning could provide means for real-time stem detection that can be exploited both in fast data registration and pose estimation, but also assessing the stem quality parameters, i.e. stem curve, knottiness, and possible defects.

For matching reference trees with laser scanning-derived tree maps, we developed a new coarse-registration method. In the proposed algorithm, the locations of some distinct objects are detected from the point cloud data, and a rotation- and translation-invariant feature descriptor vector is computed for each of the detected objects based on the relative locations of the neighboring objects. Subsequently, the feature descriptors obtained for the different point clouds are compared against one another by using the Euclidean distance in the feature space as the similarity criterion. By using the nearest neighbor distance ratio, the most promising matching object pairs are found and further used to fit the optimal Euclidean transformation between the two point clouds (Figure 3). Importantly, the time complexity of the proposed algorithm scales quadratically in the number of objects detected from the point clouds. We demonstrated the proposed algorithm in the context of forest inventory by performing coarse registration between terrestrial and airborne point clouds. To this end, we use trees as the objects and perform the coarse registration by using no other information than the locations of the detected trees. We evaluated the performance of the algorithm using both simulations and three test sites located in a boreal forest. We showed that the algorithm is fast and performs well for a large range of stem densities and for test sites with up to 10 000 trees. Additionally, we showed that the algorithm works reliably even in the case of moderate errors in the tree locations, commission and omission errors in the tree detection, and partial overlap of the data sets. We also demonstrated that additional tree attributes can be incorporated into the proposed feature descriptor to improve the robustness of the registration algorithm provided that reliable information of these additional tree attributes is available. Furthermore, we showed that the registration accuracy between the terrestrial and airborne point clouds can be significantly improved if stem positions estimated from the terrestrial data are matched to stem positions obtained from the airborne data instead of matching them to tree top positions estimated from the airborne data. Even though the 2D coarse registration algorithm was demonstrated in the context of forestry, the algorithm is not restricted to forest data and it may potentially be utilized in other applications, in which efficient 2D point set registration is needed. For more details, see Hyyppä et al. 2021.

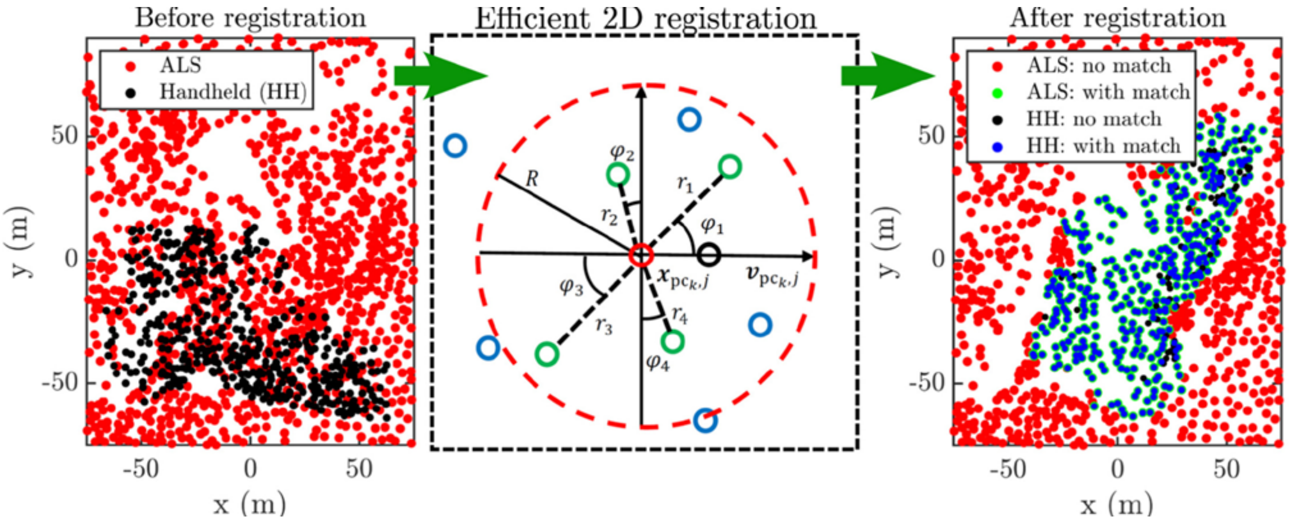


Figure 3. The principle of the coarse registration method developed.

Other solutions to improve positioning inside canopies include integrating additional sensors other than a LIDAR to the IMU, such as cameras (Mostafa et al. (2018)), and algorithms to improve the IMU solution during poor GNSS availability (Tang et al. (2022); Dai et al. (2019)). While these methods can alleviate the IMU drift, the algorithms do not prevent the drift completely, but only slow it down, and the hardware-based solutions increase the cost and weight of the sensor platform and they can have other limitations, such as cameras requiring reasonably good lighting conditions and visibility. However, the same challenges are presented by the fractal nature of the objects.

One potential and yet unexplored method at the start of the project to mitigate these positioning challenges in forest canopies was to use high-definition maps (HD map). A HD map in our approach is essentially a 3D map, eg. point cloud, providing detailed and accurate global context information on the environment (Liu et al. (2020)). HD maps have been used extensively in self-driving cars for the past decade. The data for HD maps are usually collected with a LIDAR and/or cameras attached to mapping vehicles, typically cars, but also drones, helicopters and satellites. However, their use in a forest environment has been limited due to difficulties in acquiring a HD map, attributed to lack of stable and well defined structures such as buildings, street signs, and roads in the road environment. However, tree stems and their locations could be used for positioning improvement in forest canopies.

We developed a HD map-based method to correct the drifts in the trajectory of a 2D MLS backpack dual wavelength laser scanner system in boreal forest environments. A high-density HD map was acquired using an ALS system. Recent advancements allowed us to accurately determine the tree stem locations from the airborne laser scanner (ALS) data and obtain stem curves (Hyyppä et al. (2022)), whereas previously ALS data has typically been adequate only for locating tree tops. ALS, and more often also UAV LS, allows capturing data from a large area several orders of magnitude faster than is possible with an MLS system and it does not suffer from the obstruction of the GNSS signal. However, ALS is impaired by canopy obstructing the stems and by a longer scan distance, and thus cannot measure stem and branch properties, essential for stem quality assessments, with the same accuracy and precision as MLS.

In this application targeted for assessing the quality of trees, the hypothesis was that it could be beneficial to combine ALS and MLS data for information extraction, and to constrain the GNSS-IMU based MLS trajectory solution for global consistency. Thus, in our approach, the HD map contained both the locations of the tree stems (center of tree stems) detected from ALS and the ALS points classified as ground points. The stem locations detected from MLS were matched to those in the HD map using the efficient coarse registration technique presented in (Hyyppä et al. (2021)). Using the HD map and the information on matching tree pairs, we formed a factor graph (Kschischang et al. (2001)) and optimized the trajectory using Georgia Tech Smoothing And Mapping (GTSAM) software (Dellaert et al. (2022)). We used two factor graphs for the optimization, one utilizing the two-dimensional tree locations from the HD map to correct the trajectory in xy-direction and a second one using the ground points for height correction. This was allowed due to IMU errors being significantly lower in roll- and pitch angles, than in yawn angle and xyz position, due to gravity giving a constant reference force. With the method we can currently achieve about 20-50 cm accuracy in global tree location in comparison to the ALS data used as the HD map reference. This allows for unique ITD, and advances for e.g. harvest planning and route optimization. It is to be noted that the estimation includes the error propagated in the ALS as well. The results will be published in Muhojoki et al. (2023), and the work continues to improve the optimization.

For fine registration we developed a discrete overlap search (DOS) method to find correspondences in the point clouds to solve the low-overlap problem in the wide-baseline point clouds. The proposed automatic method uses potential correspondences from both original data and selected feature points to reconstruct rough observation geometries without external knowledge and to retrieve precise registration parameters at data-level. An extensive experiment was carried out with 24 forest datasets of different conditions categorized in three difficulty levels. The performance of the proposed method was evaluated using various accuracy criteria, as well as based on data acquired from different hardware, platforms, viewing perspectives, and at different points of time. The proposed method achieved a 3D registration accuracy at a 0.50-cm level in all difficulty categories using static terrestrial acquisitions. In the terrestrial-aerial registration, data sets were collected from different sensors and at different points of time with scene changes, and a registration accuracy at the raw data geometric accuracy level was achieved. These results represent the highest automated registration accuracy and the strictest evaluation so far. The proposed method is applicable in multiple scenarios, such as 1) the global positioning of individual under-canopy observations, which is one of the main challenges in applying terrestrial observations lacking a global context, 2) the fusion of point clouds acquired from terrestrial and aerial perspectives, which is required in order to achieve a complete forest observation, 3) mobile mapping using a new stop-and-go approach, which solves the problems of lacking mobility and slow data collection in static terrestrial measurements as well as the data-quality issue in the continuous mobile approach. Furthermore, this work proposes a new error estimate that units all parameter-level errors into a single quantity and compensates for the downsides of the widely used parameter- and object-level error estimates; it also proposes a new deterministic point sets registration method as an alternative to the popular sampling methods. For more details, see Pohjavirta et al. 2022.

WP 2: Field sites and data acquisition (Lead SLU, assoc. Prof. Johan Holmgren and FGI, prof. Juha Hyyppä)

Task 2.1 Swedish test sites, applicable field reference and collection of remote sensed data

Siljansfors Research Park is a research facility in central Sweden within the Swedish University of Agricultural Sciences and owned by the forest company Stora Enso. It is situated in the central part of Sweden (Lat. 60º 53´ N, Long. 14º 24´ E) and was established in 1921. At this site we used field plots with tree coordinates and manually measured tree attributes. The field inventory was conducted by personnel at the research park and financed by Stora Enso. In addition, ALS data was collected with dual wavelength RIEGL VQ-1560i with green and near-infrared laser light and approx. 20 returns/m2, a system selected because of suitability for tree species classification. The ALS data collection was also financed by Stora Enso. We also collected ground-based terrestrial laser scanning (TLS) data and measured tree quality variables (branch positions) for sample trees. This work was performed by SLU researchers and field personnel at the Research Park. Results from the project were presented during an excursion in 2022 (one year postponed because of the pandemic) for the 100 years anniversary of the Research Park.

Forest test site Remningstorp (Lat. 58°30′ N, Long. 13°40′ E) is located in southern Sweden. There are 36 field plots with a size of 80m-by-80m with position and stem diameter measured for all trees. These plots were measured with manual field inventory 2021, TLS, and with high-resolution (> 500 points/m2) ALS from a helicopter. The entire test site was measured with ALS in 2019 and in 2022. A systematic grid with 200 m internode distance, consisting of 10 m radius field plots with manual measurements of tree positions and stem diameters was updated 2021/2022. A special inventory was conducted with transects of field measurements near forest roads. The forest near the roads on the test site was laser scanned with a mobile laser scanner mounted on a car.

A test site was established in a forest owned by Stora Enso near Hällefors (Lat. 59º 46´ N, Long. N 14º 31´ E). Two types of field plots were allocated in forest stands planned to be harvested: small plots with 7.5 m radius and large rectangular plots (100m-by-15m). The small plots were scanned with very high precision TLS. The large plots were also scanned with mobile laser scanners (one back pack system built at FGI and one handheld system). The test site was also scanned with an airborne laser scanning system built by FGI, using two different wavelengths.

The harvester operating in the forest stands was equipped with a special satellite navigation system that could be used to measure the harvester's position with cm-precision. The data from this system was fused with the harvester's data giving relative coordinates of the harvester head using internal sensors. It was therefore possible to save tree positions in the production files, thus establishing a link to stem measurements by the harvester. The high-precision measurements of tree positions made it possible to link harvester data and remote sensing data. Sample trees were also marked for identification. Cameras were mounted at sawmill intake in order to link remote sensing data, harvester data, and sawmill data (laser data of stem shape and X-ray data of internal stem properties).

Task 2.2 Finnish test sites, applicable field reference and collection of remote sensed data

The study was conducted on 14 test sites that were located in the Southeastern part of Finland in the Lappeenranta region (61°03′ N 28°11' E). The study area was located in a managed forest in the boreal forest zone, and Norway spruce (Picea abies) was the dominant tree species on all of the test sites. The stands were selected from the operative wood procurement plan of the industrial partner, Stora Enso oyj (Helsinki, Finland), together with the company's wood buyers from the South-Karelian district. We placed 2-5 circular sample plots with a 12-m radius evenly around each stand, the number of plots depending on the stand size (i.e., roughly one plot per hectare, but with a minimum of two, and a maximum of five plots per stand). In each plot, 6-10 sample trees were selected around the plot center. A total of 479 sample trees were selected. A large majority of the spruces at the test sites were mature and managed, and therefore, the lower parts of their trunks were not severely occluded by branches or needles as can be seen from Figure 4.

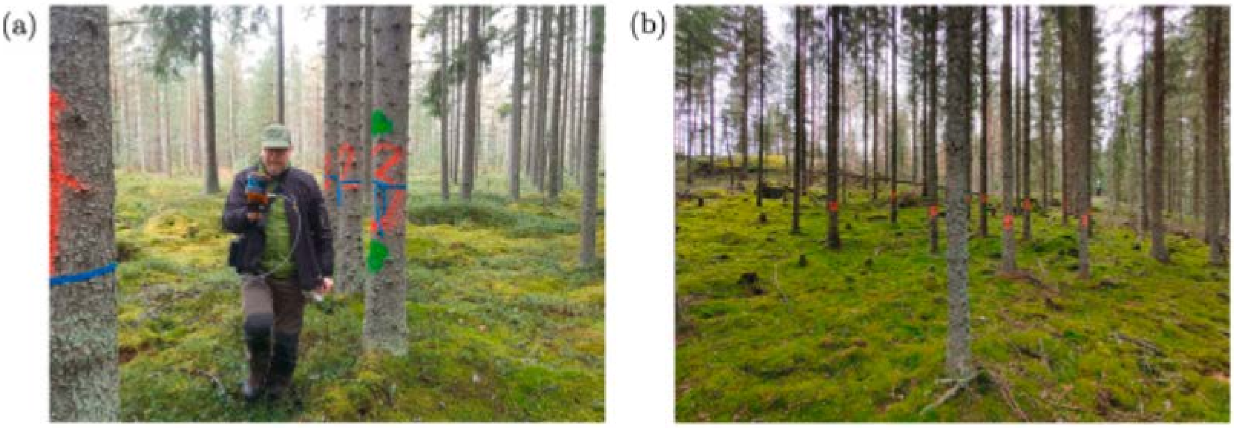


Figure 4. Mapping of a managed spruce forest site in Lappeenranta. Each stand had 2-5 plot areas that were collected with TLS, handheld MLS and backpack MLS, which usually covered a larger proportion of the stands.

To collect dense ALS point clouds of the forests on the 14 test sites, we used a FGI-developed laser scanner system known as HeliALS-DW that was mounted on a helicopter. A similar system could be mounted on a UAV as well. The HeliALS-DW system incorporated a Riegl VUX-1HA and miniVUX-1UAV scanners (Riegl GmbH, Austria) and a GNSS-IMU positioning system based on a LITEF UIMU-LCI inertial measurement unit (IMU), a NovAtel Flexpak6 GNSS receiver and GGG-

703 antenna. The ALS measurements were conducted individually for each test site in October 2020. For each test site, the flight trajectory of the helicopter was planned to consist of multiple perpendicular flight lines forming a 2D rectangular grid with a flight line separation of 50 m. The flight speed of the helicopter was 9.5 m/s, whereas the flight altitude was approximately 80 m above the ground level corresponding to 50–60 m above the forest canopy.

Terrestrial laser scanning data was obtained from the sample plots using a Leica RTC360 3D time-of-flight laser scanner (Leica Geosystem AG, Switzerland) with 1550 nm wavelength. Three scanning stations were established around the sample trees (one in the middle, and two on the opposite sides of the tree group), adjusted in each case to maximize the vertical laser-point coverage on the stems, i.e., to minimize the effect of occlusion, and scanner distance on point density and coverage

All stands were also recorded with a ZEB Horizon (GeoSLAM, UK) hand-held laser scanner (HHLS). Each of the stands was covered by walking patterns containing several loops in order to provide multiple possibilities for loop closure detection and subsequent drift elimination.

The sample trees were marked in the forest, and the sawlogs bucked from them were also marked and hauled to the Honkalahti sawmill in Joutseno (Stora Enso oyj) as a separate batch. At the sawmill, the feeding of the logs into an industrial X-ray log tomographer was videoed and used to link the X-rayed data to specific sample trees.

Another test site in Finland was our research infrastructure SCAN FOREST. The SCAN FOREST research infrastructure brings forth the vision that within the next 30 years the society will be able to understand the functions of forest ecosystems in a comprehensive manner. To solve this challenge, the development of external tree architecture obtained using terrestrial laser scanning (TLS), mobile laser scanning (MLS) and airborne laser scanning (ALS) will be linked to wood density and its variation and used to quantitatively understand tree growth allocation. The key technologies needed to achieve the goals include annually acquired TLS and MLS data combined with high-quality multispectral ALS data with point density of several hundreds, or even thousands of points per m^2. By adding multi- modal and -temporal dimensions and linking these to the existing theories on tree physiology, SCAN FOREST users can reliably build the missing link from external structural observations to the internal wood quality properties. The SCAN FOREST will include approximately 10,000 individual trees measured with laser scanning at an unprecedented level of detail. For method development and for validation of the targeted solutions, about 2,000 trees will be measured with wood density samples using X-Ray microdensitometry at a 3-year interval.

WP 3: Extracting information from MLS (Lead prof. Juha Hyyppä)

Task 3.1: Processing of MLS georeferenced point cloud data into site map, stem curve, stem volume, and height

Before the project, mobile laser scanning had yet to be demonstrated for deriving stem curve and volume from standing trees with sufficient accuracy for supporting forest inventory needs. We tested a new approach based on pulse-based backpack mobile laser scanner (Riegl VUX-1HA) combined with in-house developed SLAM (Simultaneous Localization and Mapping), and a novel post-processing algorithm chain that allows one to extract stem curves from scan-line arcs corresponding to individual standing trees (Figure 5). The post-processing step included, among others, an algorithm for scan-line arc extraction, a stem inclination angle correction and an arc matching algorithm correcting for the drifts that are still present in the stem points after applying the

SLAM algorithm. By using the stem curves defined by the detected arcs and tree heights provided by the pulse-based scanner, stem volume estimates for standing trees in easy (n = 40) and medium (n = 37) difficult boreal forest were calculated. In the easy and medium plots, 100% of pine and birch stems were correctly detected. The total RMSE of the extracted stem curves was 1.2 cm (5.1%) and 1.7 cm (6.7%) for the easy and medium plots, respectively. The RMSE were 1.8 m (8.7%) and 1.1 m (4.9%) for the estimated tree heights, and 9.7% and 10.9% for the stem volumes for the easy and medium plots, respectively. Thus, our processing chain provided stem volume estimates with a better accuracy than previous methods based on mobile laser scanning data. Importantly, the accuracy of stem volume estimation was comparable to that provided by terrestrial laser scanning approaches in similar forest conditions. To further demonstrate the performance of the proposed method, we compared our results against stem volumes calculated using the standard Finnish allometric volume model, and found that our method provided more accurate volume estimates for the two test sites. The findings are important steps towards future individual-tree-based airborne laser scanning inventories which currently lack cost-efficient and accurate field reference data collection techniques. For more details, see Hyyppä et al. 2020a.

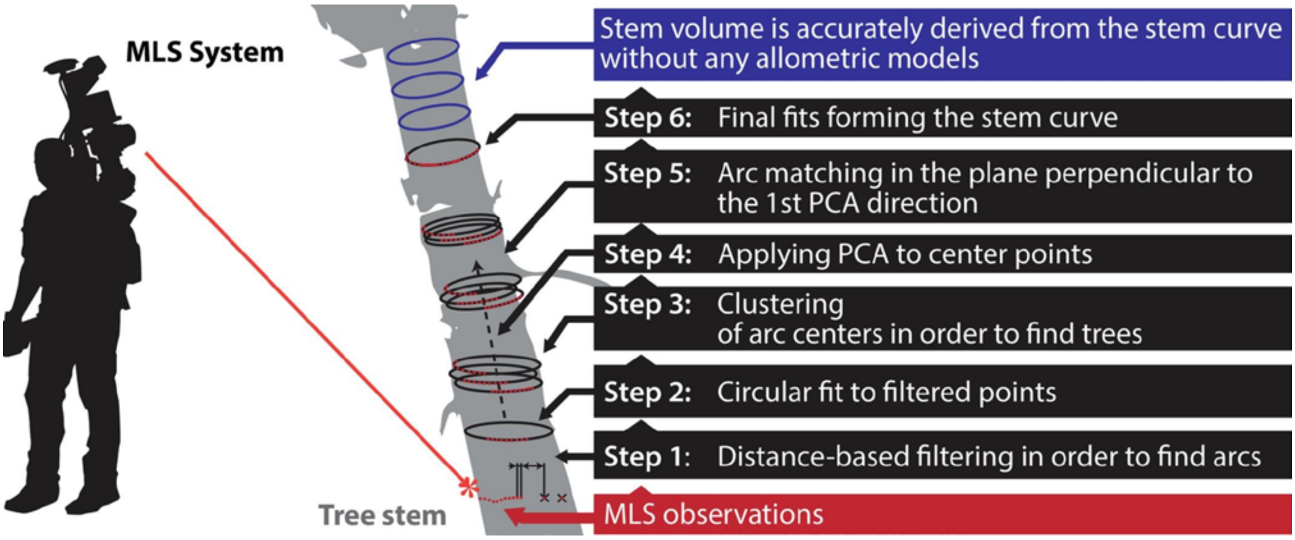
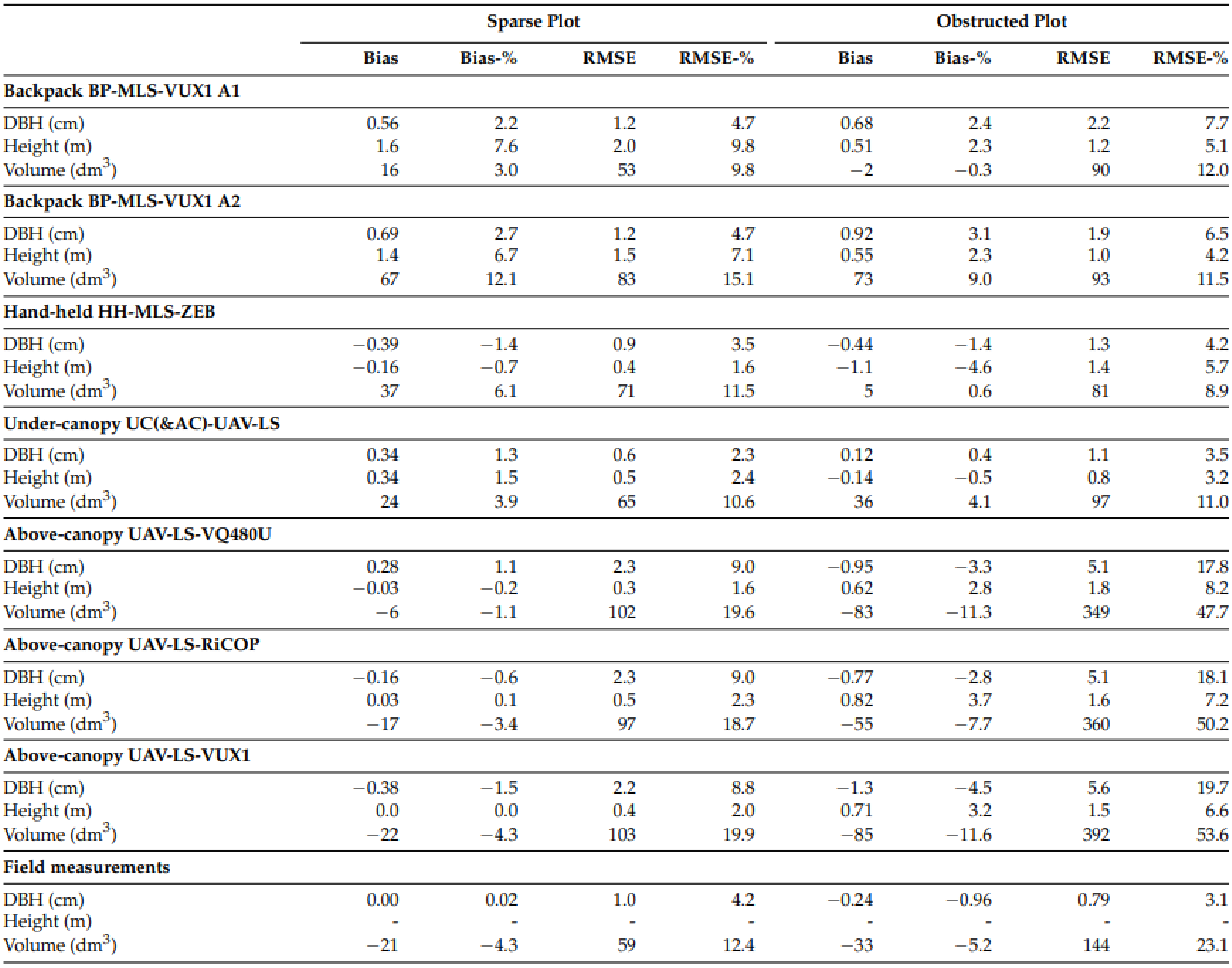


Figure 5. The developed concept of processing MLS data to provide accurate stem and stem curve assessment.

In a continuation work (Hyyppä et al. 2020b), we compared six emerging mobile laser scanning MLS) technologies for field reference data collection at the individual tree level in boreal forest conditions (Table 2). The systems under study were an in-house developed AKHKA-R3 backpack laser scanner, a handheld Zeb-Horizon laser scanner, an under-canopy UAV (Unmanned Aircraft Vehicle) laser scanning system, and three above-canopy UAV laser scanning systems providing point clouds with varying point densities. To assess the performance of the methods for automated measurements of diameter at breast height (DBH), stem curve, tree height and stem volume, we utilized all of the six systems to collect point cloud data on two 32 m-by-32 m test sites classified as sparse (n = 42 trees) and obstructed (n = 43 trees). To analyze the data collected with the two ground-based MLS systems and the under-canopy UAV system, we used a workflow based on our recent work featuring simultaneous localization and mapping (SLAM) technology, a stem arc detection algorithm, and an iterative arc matching algorithm. This workflow enabled us to obtain accurate stem diameter estimates from the point cloud data despite a small but relevant time-dependent drift in the SLAM-corrected trajectory of the scanner. We found out that the ground-based MLS systems and the under-canopy UAV system could be used to measure the stem diameter (DBH) with a root mean square error (RMSE) of 2–8%, whereas the stem curve measurements had an RMSE of 2–15% that depended on the system and the measurement height. Furthermore, the backpack and handheld scanners could be employed for sufficiently accurate tree height measurements (RMSE = 2–10%) in order to estimate the stem volumes of individual trees with an RMSE of approximately 10%. A similar accuracy was obtained when combining stem curves estimated with the under-canopy UAV system and tree heights extracted with an above-canopy flying laser scanning unit. Importantly, the volume estimation error of these three MLS systems was found to be of the same level as the error corresponding to manual field measurements on the two test sites. To analyze point cloud data collected with the three above-canopy flying UAV systems, we used a random forest model trained on field reference data collected from nearby plots. Using the random forest model, we were able to estimate the DBH of individual trees with an RMSE of 10–20%, the tree height with an RMSE of 2–8%, and the stem volume with an RMSE of 20–50%. Our results indicate that ground-based and under-canopy MLS systems provide a promising approach for field reference data collection at the individual tree level, whereas the accuracy of above-canopy UAV laser scanning systems is not yet sufficient for predicting stem attributes of individual trees for field reference data with a high accuracy.

Table 2. Accuracies obtained for various kinds of MLS, drone and field measurements at easy and obstructed plots.

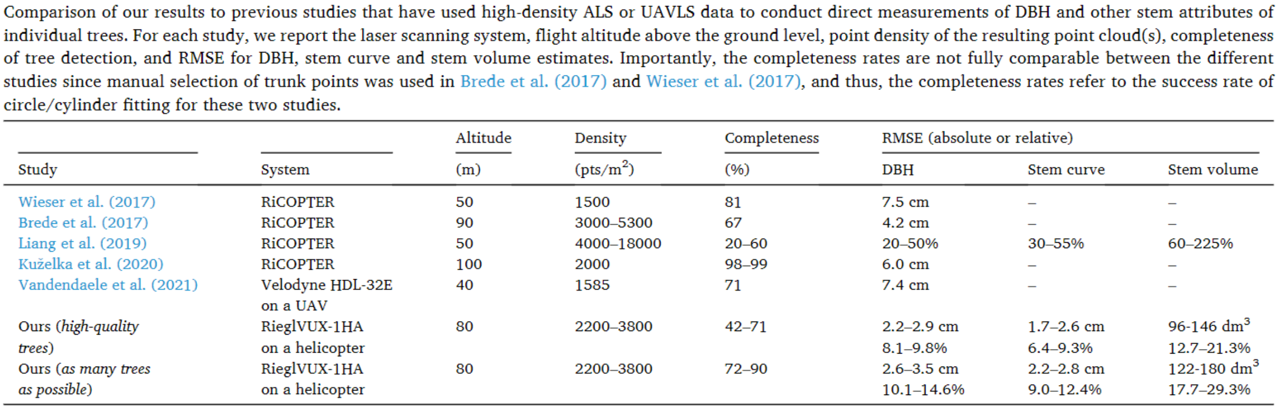


	Sparse Plot				Obstructed Plot			
	Bias	Bias-%	RMSE	RMSE-%	Bias	Bias-%	RMSE	RMSE-%
Backpack BP-MLS-VUX1 A1								
DBH (cm)	0.56	2.2	1.2	4.7	0.68	2.4	2.2	7.7
Height (m)	1.6	7.6	2.0	9.8	0.51	2.3	1.2	5.1
Volume (dm^3)	16	3.0	53	9.8	−2	−0.3	90	12.0
Backpack BP-MLS-VUX1 A2								
DBH (cm)	0.69	2.7	1.2	4.7	0.92	3.1	1.9	6.5
Height (m)	1.4	6.7	1.5	7.1	0.55	2.3	1.0	4.2
Volume (dm^3)	67	12.1	83	15.1	73	9.0	93	11.5
Hand-held HH-MLS-ZEB								
DBH (cm)	−0.39	−1.4	0.9	3.5	−0.44	−1.4	1.3	4.2
Height (m)	−0.16	−0.7	0.4	1.6	−1.1	−4.6	1.4	5.7
Volume (dm^3)	37	6.1	71	11.5	5	0.6	81	8.9
Under-canopy UC(&AC)-UAV-LS								
DBH (cm)	0.34	1.3	0.6	2.3	0.12	0.4	1.1	3.5
Height (m)	0.34	1.5	0.5	2.4	−0.14	−0.5	0.8	3.2
Volume (dm^3)	24	3.9	65	10.6	36	4.1	97	11.0
Above-canopy UAV-LS-VQ480U								
DBH (cm)	0.28	1.1	2.3	9.0	−0.95	−3.3	5.1	17.8
Height (m)	−0.03	−0.2	0.3	1.6	0.62	2.8	1.8	8.2
Volume (dm^3)	−6	−1.1	102	19.6	−83	−11.3	349	47.7
Above-canopy UAV-LS-RiCOP								
DBH (cm)	−0.16	−0.6	2.3	9.0	−0.77	−2.8	5.1	18.1
Height (m)	0.03	0.1	0.5	2.3	0.82	3.7	1.6	7.2
Volume (dm^3)	−17	−3.4	97	18.7	−55	−7.7	360	50.2
Above-canopy UAV-LS-VUX1								
DBH (cm)	−0.38	−1.5	2.2	8.8	−1.3	−4.5	5.6	19.7
Height (m)	0.0	0.0	0.4	2.0	0.71	3.2	1.5	6.6
Volume (dm^3)	−22	−4.3	103	19.9	−85	−11.6	392	53.6
Field measurements								
DBH (cm)	0.00	0.02	1.0	4.2	−0.24	−0.96	0.79	3.1
Height (m)	-	-	-	-	-	-	-	-
Volume (dm^3)	−21	−4.3	59	12.4	−33	−5.2	144	23.1

We further developed the methods to derive reference measurements from drone-type data. Today, high-quality reference tree measurements, including the position, diameter, height and volume, are cumbersome and slow to carry out, but highly needed for forest inventories based on airborne laser scanning. Mobile laser scanning technologies hold the promise for collecting reference data for forest inventories with an extremely high efficiency. Perhaps, the most efficient approach for reference data collection would be to mount a high-resolution laser scanning system on board an airborne vehicle flying at a low altitude above the forest canopy since this would allow recording reference samples of individual trees with the speed of flight. To demonstrate the potential of this technology, we mounted in Hyyppä et al. (2022) an FGI-in-house-developed HeliALS-DW laser scanning system on board a helicopter and collected point cloud data in a boreal forest on three test sites containing a total of 1469 trees. The obtained point clouds incorporated sufficiently many high-quality stem hits for estimating the stem curves and stem volumes of individual trees since the point clouds had a relatively high point density of 2200–3800 echoes/m^2, and the scanner had been tilted by 15° from the nadir to increase the possibility of recording stem hits. To automatically estimate the diameters at breast height (DBH) and stem curves of individual trees, we used algorithms designed to tolerate moderate drifts in the trajectory of the laser scanner. Furthermore, the stem volumes of individual trees were computed by using the estimated stem curves and tree heights without any allometric models. Using the proposed methods, we were able to estimate the stem curves with a root-mean-square error (RMSE) of 1.7–2.6 cm (6–9%) while detecting 42–71% of the trees. The RMSE of stem volume estimates was 0.1–0.15 m^3 (12–21%). We also showed that the tree detection rate could be improved up to 87–96% for trees with a DBH exceeding 20 cm if slightly larger average errors for the stem attributes were allowed. Table 3 compares our results with some of the earlier works. Our results pave the way for using high-resolution airborne laser scanning for field reference data collection by conducting direct measurements of tree stems with a high efficiency.

The work Hyyppä et al. (2022) received the Unite flagship Science Award in spring 2023. To our knowledge the method is the fastest field reference collection techniques in the world for stem curve and volume. The method is 100-times faster than other known field reference techniques (even compared to MLS). There is, however, a need to develop the processing further to be more accurate.

Table 3. Comparison of the method Hyyppä et al. 2022 versus other published methods.



Comparison of our results to previous studies that have used high-density ALS or UAVLS data to conduct direct measurements of DBH and other stem attributes of individual trees. For each study, we report the laser scanning system, flight altitude above the ground level, point density of the resulting point cloud(s), completeness of tree detection, and RMSE for DBH, stem curve and stem volume estimates. Importantly, the completeness rates are not fully comparable between the different studies since manual selection of trunk points was used in Brede et al. (2017) and Wieser et al. (2017), and thus, the completeness rates refer to the success rate of circle/cylinder fitting for these two studies.

		Altitude	Density	Completeness	RMSE (absolute or relative)		
Study	System	(m)	(pts/m^2)	(%)	DBH	Stem curve	Stem volume
Wieser et al. (2017)	RiCOPTER	50	1500	81	7.5 cm	–	–
Brede et al. (2017)	RiCOPTER	90	3000–5300	67	4.2 cm	–	–
Liang et al. (2019)	RiCOPTER	50	4000–18000	20–60	20–50%	30–55%	60–225%
Kuželka et al. (2020)	RiCOPTER	100	2000	98–99	6.0 cm	–	–
Vandendaele et al. (2021)	Velodyne HDL-32E on a UAV	40	1585	71	7.4 cm	–	–
Ours (*high-quality trees*)	RieglVUX-1HA on a helicopter	80	2200–3800	42–71	2.2–2.9 cm 8.1–9.8%	1.7–2.6 cm 6.4–9.3%	96-146 dm^3 12.7–21.3%
Ours (*as many trees as possible*)	RieglVUX-1HA on a helicopter	80	2200–3800	72–90	2.6–3.5 cm 10.1–14.6%	2.2–2.8 cm 9.0–12.4%	122-180 dm^3 17.7–29.3%

Task 3.2: Extracting wood quality variables from MLS

The research of developing branch quality extraction algorithms in ground based laser scanning data resulted in a method published by Olofsson and Holmgren (2023). The algorithm is based on the technique of classifying the data cells positioned in the vicinity of the stems of the trees. Three classes are used: near stem data points, low vegetation points and unclassified points. The data points that are positioned close to the stems have a large probability to be part of a branch, belonging to the tree of investigation. The extraction of branches are then performed using a voting procedure for all possible directions. The angle with the highest number of votes is considered to be the direction of a branch that is attached to the stem of investigation. The stem profile detection method that was used in the classification of the data points is described in an earlier paper by Olofsson and Holmgren (2016). Different quality estimates of the trees can then be assessed once the branch attachments are detected using the algorithms described. Quality measures like for instance number of branch whorls per stem, detection of low growing branch whorls and detection of the angles of branches. Then quality variables taper, sweep and lean of the trees can be estimated by using stem profile detection methods.

The method was evaluated using ten sample trees at the Siljansfors research park, where the branch whorls were measured using manual field inventory and by comparing those measurements with the estimation results from the laser scanner data.

The output of the task is a paper by Olofsson and Holmgren (2023) and prototype code that was used to evaluate the methods.

For MLS data we developed a density-based clustering method for branch extraction (Figure 6). The density-based clustering (DBSCAN) -based branch detection method can be divided into the following stages:

1) Denoising point cloud
2) Segmentation and extraction of points belonging to trunk of the tree
3) Removal of trunk points
4) Determining disconnected components of the remaining point cloud
5) Post-processing of disconnected components to remove clusters not corresponding to individual branches
6) Estimation of geometric features (growing location, diameter and insertion angle) of each branch

The first step in processing point clouds of individual trees was denoising. To reduce the amount of noise and enhance extraction of relevant features, a heuristic denoising based on local point density was applied to the point cloud as part of the analysis. The assumption is that noisy points are uniformly distributed in space and that they have smaller local point density than points which arise from actual hits of the measurement laser in different parts of the tree. Local point density for a point is defined as the number of points in a sphere of fixed radius centered at the point. Having computed local point density for each point with some fixed neighborhood radius, noisy points were filtered out by setting a threshold on the local point density values. By trial and error, the radius of the spherical neighborhood was chosen to be 7 cm and the threshold value used for the local point density was the 20th percentile over all spherical neighborhoods for each point. This kind of denoising is computationally time-efficient and takes only seconds for a coarse point cloud of an individual tree with over one million points. An interesting observation about this denoising method was that in addition to removing noisy points, it also removed foliage from the point clouds of trees, leaving mostly the woody parts for further analysis. The effect of foliage removal was desired, since it made it easier to analyze the branching structure of the trees. For more details, see Winberg et al. (in-review).

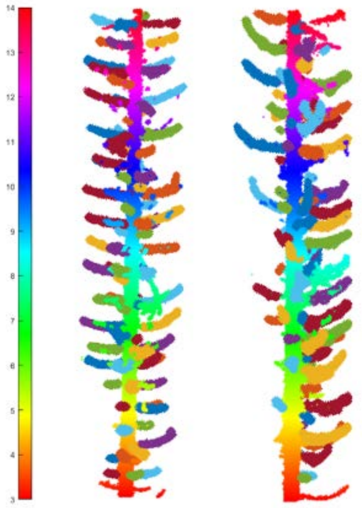


Figure 6. Example output of the branch extraction, illustration based on data from a handheld MLS system from a test plot in Lappeenranta.

WP 4: Methods for extracting information from ALS for species-specific size distribution (Lead SLU, Dr. Eva Lindberg)

Task 4.1 Tree level

We have used multispectral airborne laser scanning for automatic delineation of individual trees and for identification of tree species. The laser measurement of tree crown shape and height distributions of laser measurements were used for classification of tree species. The use of both wavelengths (i.e. green and near-infrared) improved the tree species classification compared with the use of only one wavelength. The method was validated using field inventory data from Siljansfors Research Park and maps were presented on site during the 100 years anniversary of the research park. The results have been published (Axelsson et al. 2022).

In the Evo test site in Finland we studied for the first time the feasibility of tree species classification using high-density point clouds collected with an airborne close-range multispectral laser scanning system – a technique that has previously proved to be capable of providing stem curve and volume accurately and rapidly for standing trees. To this end, we carried out laser scanning measurements from a helicopter (see Figure 1) on 53 forest sample plots, each with a size of 32 m × 32 m. The plots covered approximately 5500 trees in total, including Scots pine (*Pinus sylvestris L.*), Norway spruce (*Picea abies (L.) H.Karst.*), and deciduous trees such as Downy birch (*Betula pubescens Ehrh.)* and Silverbirch (*Betula pendula Roth*). The multispectral laser scanning system consisted of integrated Riegl VUX-1HA, miniVUX-3UAV, and VQ-840-G scanners (Riegl GmbH, Austria) operating at wavelengths of 1550 nm, 905 nm, and 532 nm, respectively. A new approach was developed for individual tree detection and segmentation from the dense point cloud data. After individual tree segmentation, 249 features were computed for tree species classification, which was tested with approximately 3000 trees. The features described the point cloud geometry as well as single-channel and multi-channel reflectance metrics. Both feature selection and the tree species classification were conducted using the random forest method. Using the developed tree detection algorithm, trees in the dominant and co-dominant categories were found with detection rates of 89.5% and 77.9%, respectively, whereas suppressed trees were detected with a success rate of 15.2%–42.3%, clearly improving upon the standard watershed segmentation. The overall accuracy of the tree species classification was 73.1% when using geometric features from the 1550 nm scanner data and 86.6% when combining the geometric features with reflectance information of the 1550 nm data. The use of multispectral reflectance and geometric features improved the overall classification accuracy up to 90.8%. Classification accuracies were as high as 92.7% and 93.7% for dominant and co-dominant trees, respectively. (Hakula et al., submitted)

Task 4.2 Tree branch level

We have used projection of very high resolution ALS data as input to neural networks, which could identify tree species. The projections depict branch geometry of trees in order to identify tree species. The methods will be validated using the Hällefors test site and reported as part of a doctoral thesis and also at the IUFRO congress 2024 in Stockholm (de Paula Pires et al. in preparation).

WP 5: Towards high precision forest inventory in the Nordic countries (Lead FGI, prof. Juha hyyppä, SLU, Dr. Eva Lindberg)

Task 5.1 Individual-tree-level wood quality-based national forest inventory

We implemented a novel architecture and implementation for an information system capable of processing, storing and visualizing forest resources from large areas at the level of individual trees. The system was implemented at www.metsakanta.com under CSC services (Figure 7).The system uses ALS data with a point density of 5 pts/m^2 as its primary data source. The ALS data originates from the national laser scanning programme that collects laser scanning data from entire Finland. The presented system consists of a data pipeline and an information system forest. The data pipeline is utilized for detecting, post-processing and storing individual trees from ALS data. The data pipeline leverages MATLAB Engine API for Python for parallelizing individual tree detection. The pipeline stores the detected trees in a PostGIS database and visualizes them using raster map tiles rendered with Mapnik. The digital twin of forests was implemented as a web application leveraging the client-server architecture. The client application utilizes Leaflet for visualizing individual trees on a 2D map whereas the server application was developed with the Django framework. The performance of the information system was also evaluated. From the computational perspective, it was concluded that the system could be scaled to handle individual tree level forest data from entire Finland/Sweden. However, availability of suitable reference data is currently the most significant bottleneck for scaling the system to the entire Finland/Sweden. It remains to be seen when such reference data becomes available, and therefore enabling all the national ALS data to be processed at the level of individual trees. See Hyyppä et al. 2023 for more details of tree-based forest information system as a cloud service. The cloud service works from a mobile phone, tablet, or computer. More than 100 million trees over 5 m in height are in the test database (both Finnish test sites Lappeenranta and Evo have been implemented in Metsakanta.com). The SW was developed in collaboration with user needs of UPM, Stora Enso, Terratec, Metsäkeskus, National Land Survey and Terrasolid. More than 50 test users have been working with the system. The information system received the First Unite flagship Impact award in spring 2022. The award was evaluated by a Finnish industry representative.

The developed software can be tested https://metsakanta.com.

Karttatasot Tilastot Ohjeet

Tilastoja valitsemaltasi alueelta

Puita
1 498 kpl

Pinta-ala
4,346 ha

Yhteenveto alueen puista

TUNNUSLUKU	YHTEENSÄ	MÄNTY	KUUSI	LEHTIPUU
Maksimipituus (m)	35,41	33,87	35,41	31,57
Keskipituus (m)	24,64	21,59	25,34	23,93
Maksimiläpimitta (cm)	53,46	53,46	53,44	44,61
Keskiläpimitta (cm)	27,89	24,67	28,78	26,47
Tilavuus (m³)	1 251,84	121,82	965,6	164,41
Biomassa (t)	597,39	55,07	458,19	84,13
Pohjapinta-ala (m²)	99,86	10,55	75,18	14,13
Runkoluku (kpl)	1 498	188	1 066	244

Tunnusluvut hehtaaria kohti

TUNNUSLUKU	YHTEENSÄ	MÄNTY	KUUSI	LEHTIPUU
Runkoluku (kpl/ha)	344,67	43,26	245,27	56,14
Tilavuus (m³/ha)	288,03	28,03	222,17	37,83
Biomassa (t/ha)	137,45	12,67	105,42	19,36
Pohjapinta-ala (m²/ha)	22,98	2,43	17,3	3,25

Figure 7. An example of the metsakanta.com interface.

Reviewing forest carbon sinks is of the utmost importance in efforts to control climate change. Study by Soininen et al. (2022) focuses on reporting the 20-year boreal forest growth values acquired with airborne laser scanning (ALS) (Figure 8). The growth was examined on the Kalkkinen research site in southern Finland as a continuation of several earlier growth studies performed in the same area. The data for the study were gathered with three totally different airborne laser scanning systems, namely using Toposys-I Falcon in June 2000 and Riegl VUX-1HA and miniVUX-3UAV in June 2021 with approximate point densities of 11, 1360, and 460 points/m2, respectively. The ALS point cloud was preprocessed to identify individual trees, from each of which different features were extracted either for direct or indirect growth measurement. In the direct method, the growth value is predicted based on differences of features, whereas in the indirect method, the growth value is obtained by subtracting the results of two independent predictions of different years. The growth in individual tree attributes, such as growth in height, diameter at breast height (DBH), and stem volume, were calculated for direct estimation. Field reference campaigns were performed in the summer of 2001 and in November 2021 to validate the obtained growth values. The study showed that long-term series growth of height, DBH, and stem volume are possible to record with a high-to-moderate coefficient of determination (R2) of 0.90, 0.48, and 0.45 in the best-case scenarios. The respective root-mean-squared errors (RMSE) values were 0.98 m, 0.02 m, and 0.17 m3, and the biases were −0.06 m, 0.00 m, and 0.17 m3. The direct method produced better metrics in terms of RMSE-% and bias, but the indirect method produced better best-fit lines. Additionally, the mean growth values for height, diameter, and stem volume intervals were compared, and they are presumed to be usable even for forest modeling.

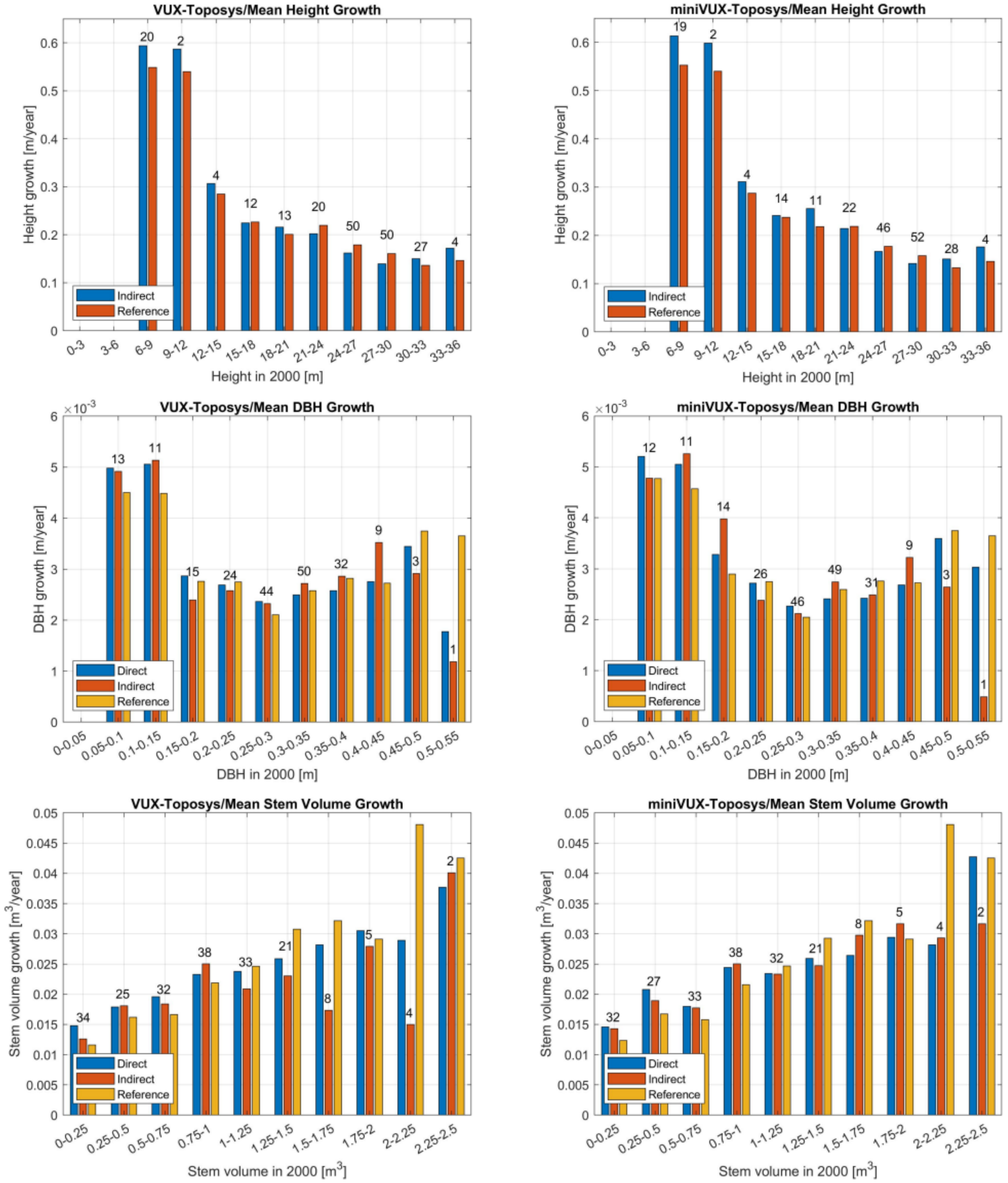


Figure 8. Obtained growth statistics when using 20 years long change detection with ALS. Soininen et al. 2022

Task 5.2 Micro-topography modeling

For modeling micro-topography, ground elevation models were produced for the test site using ALS and MLS data with various resolutions. In addition, stones were detected and maps were demonstrated for people from forest companies (Figure 9) . These maps could potentially be useful to prohibit soil damages during logging operations and for optimizing forest machine paths to reduce fuel consumption.

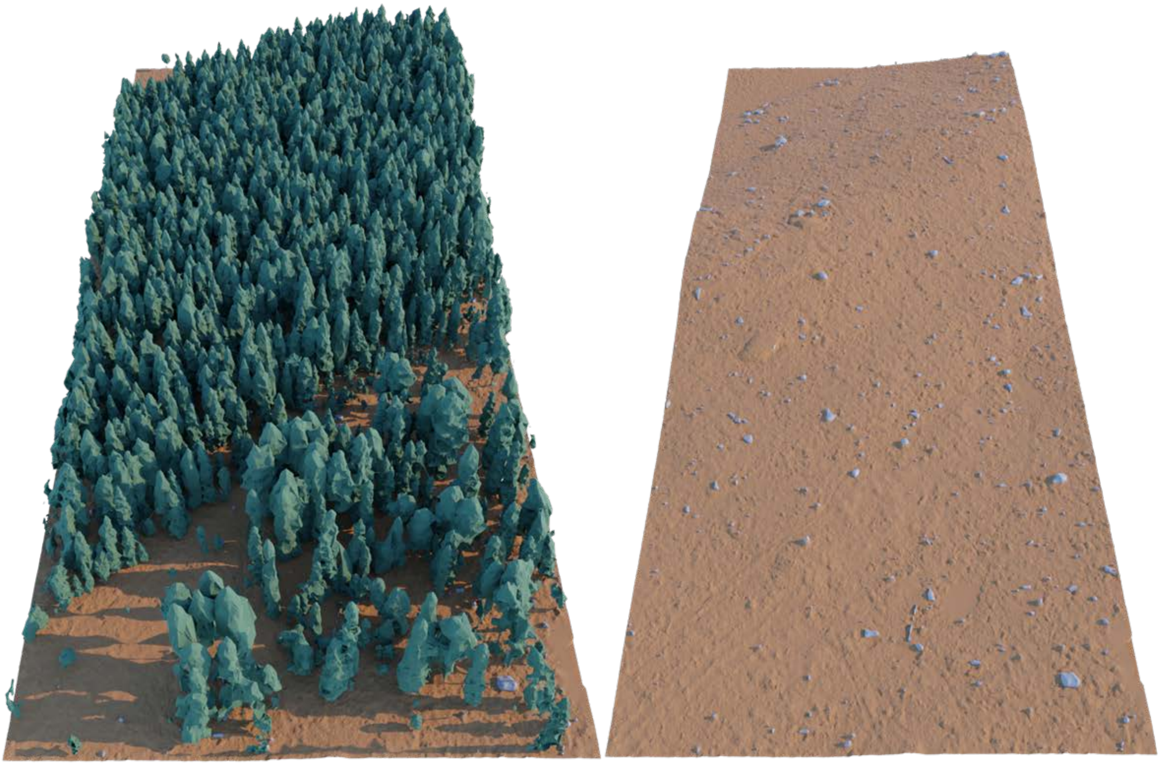


Figure 9. Left: Trees, ground, and stones modeled using high-resolution data from airborne laser scanning. Right: the same models but without trees.

Task 5.3 Detection and assessment of sub-dominant vegetation/undergrowth

We have developed a new method to detect both overstory and understory trees from dense ALS data. The method includes 1) a new symmetrical structure detection algorithm (SSD) for 3D ITC segmentation of dominant trees, by detecting the symmetrical structure of the trees, and 2) removing points of dominant trees and mean shift clustering of the low vegetation. It was tested on a boreal forest in Sweden and the performance was compared 1) between plots with different stem density levels, vertical complexities, and tree species composition, and 2) using ALS data, terrestrial laser scanning (TLS) data, and merged ALS and TLS data (ALS + TLS data). The results suggest that the SSD algorithm can successfully separate laser points of overstory and understory trees, ensuring the detection and segmentation of low vegetation in forest (Huo et al 2022).

Task 5.4 Mapping of prominent tree individuals

Initial work has started in the form of field surveys of prominent trees at the SLU test site, the watershed Krycklan, Vindeln, northern Sweden. A systematic inventory of field plots with individual tree positions is already available for the test site. This will be used for validation of tree species classification, but there are too few trees with unusual tree species (e.g., aspen and willow) to create models for those species. Further developments and validations are planned in cooperation with Stora Enso during a two year post doc research. The PostDoc will analyze patterns of biodiversity from remotely-sensed data, in particular dense ALS data, including trees with high biodiversity value.

Task 5.5 Validation of biodiversity and micro-topographic mapping products on harvester

Topographic maps and maps with biodiversity indicators have been produced from dense ALS data. The biodiversity indicators were derived based on a commonly used method in Sweden for field assessment of ecological values. The maps of biodiversity indicators were validated by forest managers by comparing the results with field assessment using two different methods: the Swedish Forest Biologists field method and subjective assessments of the ecological values in each stand. The validation was done in cooperation with Södra, a forest owner association in southern Sweden with more than 52 000 members. No validation has however yet been done by harvester operators. The validation of biodiversity maps will continue also after the project, in cooperation with Stora Enso, using a test site in central Sweden.

WP 6: Information for decision support cases in logistics and wood supply to industries (Lead SLU, Assoc. Prof. Johan Holmgren)

Task 6.1 Case study: Information extraction from sensor data fusion

We used a high-precision laser scanner mounted on a car to collect reference data and compare with traditional reference data collected with manual field measurements. The system was mounted on the car in order to produce data suitable for tree stem measurements: with approx. 30 degrees angle relative to the horizontal plane to have cross stem measurements from the same scanning revolution and also laser measurements on the ground. Algorithms were developed specifically to make use of data from the special sensor setup. In addition, estimates of stem diameters using data from the system were validated using manual field measurements and TLS measurements in order to understand how the errors depend on the distance to the sensor (i.e., distance to the road). The results were reported in de Paula Pires et al. (2022). We have also developed and validated an algorithm for dynamic linking of MLS and ALS data. The algorithm uses time windows and matches tree position patterns supported by tree size similarities to perform automatic co-registration of the data sources. The algorithm and source code has been published with open access (Olofsson & Holmgren, 2022). The concept of using a combination of ALS and MLS for estimation of tree stem attributes has been validated at the Remningstorp test site and will be reported in a publication (de Paula Pires et al. 2023) and presented in the summer 2023 at an international conference (IGARSS 2023).

Task 6.2 Case study 2: Prediction of wood product assortments

The measurements of tree stems stored in the production files collected by the harvester were linked to tree crown segments derived from the ALS data. The multi-spectral ALS data could then be used for prediction of tree stem attributes. Predictions of stem volume and tree-species-specific stem diameter distributions were validated at forest stand level using cross validation. The prediction method produced high accuracy estimates without any manual field references needed. The results will be published in a forthcoming publication (Axelsson et al. 2023) and will also be presented at an international conference (SilviLaser 2023).

Task 6.3 Case study 3: Linking MLS, sawmill data and high-density aerial point clouds

We combined the terrestrial point-cloud data (from TLS and HHLS) with the ALS, and X-ray data. Stem and branching information were extracted from the HHLS data using two different algorithms: a newly-developed density-based clustering method combined with cylinder fitting, and the quantitative structure model (QSM). We compared these extracted branching data to X-ray tomography data from the Honkalahti sawmill at individual log level; the variables included knot cluster counts within logs, mean knot cluster volume, and the volume percentage of knot clusters of the total log volume. The comparisons revealed that direct correspondences between the point clouds and X-rayed data are difficult to establish, but using the branching information extracted from the point clouds served as useful predictors of the X-ray features: our testing with a simple Random Forest approach yielded R^2:s of over 0.5. The results are reported in Winberg et al. (in-review), a manuscript of which is submitted to peer-review.

In addition, we collected wood property data from 52 trees in the studied stands, and combined these information (wood age, ring area, latewood percentage and wood density) with the X-rayed branching data. The purpose of the analysis was to shed light on the linkages between the wood properties that are influential to e.g., timber strength (in addition to the knots), and assess the possibilities to predict these properties based on the fused branching data. The results showed that the branching explains up to 40% of ring area and cambial age, but less than 10% of the latewood content and wood density with Norway spruce. Therefore, at least the estimation of growth rate and juvenile wood content could be possible based on the reliably estimated branching data, using the fused data-sets of in-situ point clouds and sawmill data. The results are reported in a preprint Pehkonen et al. (in-review): https://osf.io/984tk/, and has been submitted to peer-review. The methods used in the study are openly reposited in https://github.com/jpyorala/woodGradients. The methods demonstrate our approach to reproduce 2-D stem models of any wood property, to be used for sawing simulation.

We showed that the dense ALS data can support the direct extraction of a partial stem curve, using data from three of our stands in the Lappeenranta region (Hyyppä et al. 2022), using similar arc detection method as previously developed for MLS: on average, 50% of the trees were detected correctly with stem measurement RMSE:s of 1.7-2.6 cm. These results highlight the possibility to assess stand-level stem curve reparametrization, and increase the accuracy of the log breakdown estimation, when combined with predictions of the branching data.

The final step of task 6.3 is to test the combination of the developed methods to extrapolate the branching and wood property models to a landscape with the high-density ALS. The work is undergoing, and initial results of the combined methods will be presented in June 2023 in IUFRO Division 5 conference in Cairns (Pyörälä et al. 2023). An article manuscript is currently being prepared and will be submitted to peer-review during 2023.

In addition, similar tasks will be repeated at a higher level of detail using the data set obtained from Hällefors.

Communication and mobility

In the following we report the communication and dissemination done in addition to publications listed separately below. The COVID-19 pandemic affected critically in the conduct of international collaboration in the project, especially the first 18 months, and extensions for the project period were applied for and granted.

Dissemination of the project results have largely taken place in stakeholder meetings and networks of the project partners. In Finland, a large and significant forest related partnership ecosystem within UNITE flagship, including universities, forest organizations and industry at different levels of management, conservation, logistics and technology, has been reported on the developments and results of the project. In Sweden, the research program “Mistra Digitial Forest” with the Swedish Forest Industries as coordinator has been used for communication of results to stakeholders, and the same research program has also been used for collaboration with other researchers for automation of forest operations.

The research has opened new collaboration with industry. We have also been able to transfer knowledge and develop procedures for stem quality assessments from the standing trees to sawmill measurements.

Presentations

Lindberg, Eva, SLU, 2021, Föreningen Skogen, Excursion, Online.
Lindberg, Eva, SLU, 2021, RIU conference (Skogforsk), Online.
Lindberg, Eva, SLU, 2021, Koliforum, Koli Finland/Online.
Lindberg, Eva, SLU, 2021, Collaboration seminar Mistra Digital Forest and SmartForest, Online.
Lindberg, Eva, SLU, 2021, Mistra Digital Forest conference, Stockholm, Sweden.
Lindberg, Eva, SLU, 2022, Mistra Digital Forest conference, Stockholm, Sweden.
Holmgren, Johan, SLU, 2022, Mistra Digitial Forest conference, Umeå, Sweden.
Olofsson, Kenneth, SLU, 2022, Mistra Digitial Forest conference, Umeå, Sweden.
Axelsson, Christoffer, SLU, 2022, Mistra Digitial Forest conference, Umeå, Sweden.
Hyyppä, Juha, FGI, Finland, 2022,Tandem forest values seminar in Espoo, Finland.
Pyörälä, Jiri, FGI, Finland, 2023, IUFRO Division 5 conference in Cairns, Australia.
Lindberg, Eva, SLU, 2023, Workshop SLU/SE collaboration remote sensing biodiversity, Umeå, Sweden.
de Paula Pires, Raul, SLU, 2023, The International Geoscience and Remote Sensing Symposium (IGARSS), Pasadena, California, USA.

Mobility has taken place between institutions supporting for the project goals in the following ways:

From FGI

Kukko, Antero, SLU, Sweden, 3.10.-8.10.2021, field work in Hällefors in 2021.
Kaartinen Harri, SLU, Sweden, 3.10.-8.10.2021, field work in Hällefors in 2021.
Pyörälä Jiri, SLU, Sweden, 3.10.-8.10.2021, field work in Hällefors in 2021.
Lehtomäki, Matti, SLU, Sweden, was called off due to COVID-19.

To FGI

Ferrari Castanheiro, Leticia, UNESP, Brazil, 4.11.2022-31.10.2023, Laser scanner SLAM solutions for backpack MLS systems.

Spadavecchia, Claudio, POLITO, Italy, 1.9.-31.12.2022, Detection of trees from MLS and ALS data, forest disturbance and AI automation of point cloud processing procedures through machine/deep learning algorithms, map forests and classify tree species and definition of an accurate method of woody biomass assessment.

From SLU

de Paula Pires, Raul, forest company Stora Enso, Sweden, December 2021-January 2022, internship for PhD to obtain practical experience of the implementation of remote sensing methods.

To SLU

Pyörälä, Jiri, FGI, May 2022, Moeleven Valåsen sawmill, Visit to sawmill for meeting Swedish sawmill personnel and taking part in the experimental data acquisition with recording of raw data from X-ray and 3D laser wood measurement system when logs from the Hällefors test site were measured.

Pyörälä, Jiri, FGI, March 2023, Research about stem quality predictions using remote sensing, saw mill experiments, work at SLU, seminar with SLU researchers, visited the Division of Wood Science and Technology at Luleå University of Technology and learning about X-ray computed tomography (CT) scanning of wood. Meeting with the sawmill measurements technology manufactory company RemaSawco to learn how to perform analysis of the sawmill X-ray and 3D laser data collected at the Moelven Valåsen sawmill.

Articles and reports from the project

1. Axelsson, C.R., Lindberg, E., Persson, H.J., & Holmgren, J. (2023). The use of dual-wavelength airborne laser scanning for estimating tree species composition and species-specific stem volumes in a boreal forest. International Journal of Applied Earth Observation and Geoinformation, 118, 103251.

2. Axelsson, C.R., Persson, H.J., & Holmgren, J. (2023). Using harvester and airborne laser scanning data to estimate species-specific stem diameter distributions, Manuscript.

3. Balenović, I., Liang, X., Jurjević, L., Hyyppä, J., Seletković, A., and A. Kukko, 2021. Hand-Held Personal Laser Scanning - Current Status and Perspectives for Forest Inventory Application. Croatian Journal of Forest Engineering, 42(1): 165-183. https://doi.org/10.5552/crojfe.2021.858.

4. Brolly, G., Király, G., Lehtomäki, M., and X. Liang, 2021. Voxel-Based Automatic Tree Detection and Parameter Retrieval from Terrestrial Laser Scans for Plot-Wise Forest Inventory. Remote Sensing, 13(4), 542. https://doi.org/10.3390/rs13040542.

5. Dai, W., Yang, B., Liang, X., Dong, Z., Huang, R., Wang, Y., Pyörälä, J., and A. Kukko, 2020. Fast registration of forest terrestrial laser scans using key points detected from crowns and stems. International Journal of Digital Earth. https://doi.org/10.1080/17538947.2020.1764118.

6. de Paula Pires, R., Olofsson, K., Persson, H.J., Lindberg, E., & Holmgren, J. (2022). Individual tree detection and estimation of stem attributes with mobile laser scanning along boreal forest roads. ISPRS Journal of Photogrammetry and Remote Sensing, 187, 211-224.

7. de Paula Pires, R., Lindberg, E., Persson, H.J., Olofsson, K. & Holmgren, J. (2023). An automatic forest inventory method combining car-mounted mobile and airborne laser scanning, Manuscript.

8. de P. Pires, R., Axelsson, C., Lindberg, E., Persson, H. J., Olofsson, K. & Holmgren, J. (2024). Deep learning-based tree species identification using high-density airborne laser scanning and forest harvester data, Manuscript.

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10. Du, K., Huang, H., Feng, Z., Hakala, T., Chen, Y., and J. Hyyppä, 2021. Using Microwave Profile Radar to Estimate Forest Canopy Leaf Area Index: Linking 3D Radiative Transfer Model and Forest Gap Model. Remote Sensing, 13(2), 297. https://doi.org/10.3390/rs13020297

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12. Heinaro, E., Tanhuanpää, T., Vastaranta, M., Yrttimaa, T., Kukko, A., Hakala, T., Mattsson, T. and M. Holopainen, 2023. Evaluating Factors Impacting Fallen Tree Detection from Airborne Laser Scanning Point Clouds. Remote Sensing, 15(2), 382. http://dx.doi.org/10.3390/rs15020382.

13. Holmgren, J., Lindberg, E., Olofsson, K., & Persson, H.J. (2022). Tree crown segmentation in three dimensions using density models derived from airborne laser scanning. International Journal of Remote Sensing, 43, 299-329.

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25. Olofsson, K., & Holmgren, J. (2023). Stem Quality Estimates Using Terrestrial Laser Scanning Voxelized Data and a Voting-Based Branch Detection Algorithm. Remote Sensing, 15(8), 2082.

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