forests

MDPI

Article

Mapping Forest Parameters to Model the Mobility of Terrain Vehicles

Tomáš Mikita [1,*], Marian Rybansky [2], Dominika Krausková [1], Filip Dohnal [2], Ondřej Vystavěl [2] and Sabina Hollmannová [2]

[1] Department of Forest Management and Applied Geoinformatics, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic; dominika.krauskova@mendelu.cz
[2] Department of Military Geography and Meteorology, Faculty of Military Technology, University of Defence, Kounicova 65, 662 10 Brno, Czech Republic; marian.rybansky@unob.cz (M.R.); filip.dohnal@unob.cz (F.D.); ondrej.vystavel@unob.cz (O.V.); sabina.hollmannova@unob.cz (S.H.)
* Correspondence: tomas.mikita@mendelu.cz; Tel.: +420-545-134-021

Abstract: This study aims to evaluate the feasibility of using non-contact data collection methods—specifically, UAV (unmanned aerial vehicle)-based and terrestrial laser scanning technologies—to assess forest stand passability, which is crucial for military operations. The research was conducted in a mixed forest stand in the Březina military training area, where the position of trees and their DBHs (Diameter Breast Heights) were recorded. The study compared the effectiveness of different methods, including UAV RGB imaging, UAV-LiDAR, and handheld mobile laser scanning (HMLS), in detecting tree positions and estimating DBH. The results indicate that HMLS data provided the highest number of detected trees and the most accurate positioning relative to the reference measurements. UAV-LiDAR showed better tree detection compared to UAV RGB imaging, though both aerial methods struggled with canopy penetration in densely structured forests. The study also found significant variability in DBH estimation, especially in complex forest stands, highlighting the challenges of accurate tree detection in diverse environments. The findings suggest that while current non-contact methods show promise, further refinement and integration of data sources are necessary to improve their applicability for assessing forest passability in military or rescue contexts.

Keywords: forest passability; terrain vehicle; off-road vehicle; military operation; TLS; HMLS; UAV; DBH

check for updates

Citation: Mikita, T.; Rybansky, M.; Krausková, D.; Dohnal, F.; Vystavěl, O.; Hollmannová, S. Mapping Forest Parameters to Model the Mobility of Terrain Vehicles. *Forests* **2024**, *15*, 1882. https://doi.org/10.3390/f15111882

Academic Editor: Kim Calders

Received: 24 September 2024
Revised: 16 October 2024
Accepted: 21 October 2024
Published: 25 October 2024

1. Introduction

Forest stands are a significant part of the landscape and, depending on natural conditions, are represented differently across continents and within individual countries. For example, in Europe, forests cover an average of 34.8% of the total area, with the highest forest coverage in Nordic countries (up to 50%) and lower coverage in Central and Southern Europe (around 30%). Within European Union countries, forest coverage even reaches 38.3% [1].

Forests provide a series of both tangible and intangible services to society and human well-being, ranging from the production of raw materials and regulation of water flows to the protection of soils and conservation of biodiversity [2].

In addition to these services, forest stands and individual trees can also pose an obstacle, for example, when using forestry machinery, during rescue operations, or for the passage of military equipment. During military operations, forests are—next to the terrain condition—an important object for analyzing visibility, concealment, and movement. Densely forested areas can make movement difficult and may slow down or stop wheeled and tracked vehicles, including tanks. Large trees are usually spaced far enough apart to allow vehicles to pass, but this gap is often filled with smaller trees or bushes that must be considered. Smaller trees are usually closer together and do not offer a gap for vehicles; however, depending on their diameter, they can be knocked over by large, tracked vehicles. Trees that have been knocked over tend to pile up and can block vehicles following behind. Trees large enough to stop wheeled vehicles are usually too close together to allow passage [3].

Overcoming vegetation using off-road vehicles depends on several factors related to tree stability. Some studies addressing tree stability are based on particular terrain tests focused on wind impact on the mechanisms of root and stem failure [4–8].

Rybansky [3] confirmed the passability of different vehicles as a function of vehicle speed and tree height based on field tests. In the case of tracked vehicles, even trees with DBH greater than 20 cm can be overcome.

Thus, determining not only the exact tree position but also the DBH of trees is crucial for vehicle navigation in forest stands. Although various methods are used in forestry practice to determine forest stand inventories, ranging from ground surveys and diameter measurements to data collection using various ground or remote sensing methods, determining the exact tree position and DBH at the level of large forest stands is still challenging.

Traditional tree DBH measurements generally use a wheel ruler, diameter tape and caliper, and other tools for measurement [9]. The localization of single trees with sub-meter precision can be determined using a GPS (GNSS) instrument [10,11], or other electronic device for accurate relative localization, using a distance measurement to several points with known coordinates (e.g., the Haglöf PosTex Measuring Instrument, produced by Haglöf in Langsle, Sweden) [11].

In recent years, scholars from various countries have attempted to measure the DBH of trees in various ways, with different results, with the best results being achieved using terrestrial laser scanning (TLS) or ground photogrammetry methods. The advantage of these methods is in determining not only the DBH, but also the position and condition of individual trees [12–16]. Much progress has been made by using mobile laser scanning (MLS). Data collection using MLS can be 5 times to almost 60 times faster than TLS [17]. In forestry applications, mobile laser scanning systems can be mounted on a vehicle [18,19], but increasingly, they are being carried by a person; this method is known as handheld mobile laser scanning and is used with another approach, so called simultaneous location and mapping (SLAM) [20,21].

In addition to ground-based methods, aerial data collection using both aircraft and UAVs have been developed in recent years. The location of trees can be determined from RGB orthophotos [22], as well as from point clouds generated from stereophotogrammetric processing [23,24]. Better results are achieved using airborne laser scanning (ALS) methods, which, thanks to multiple reflections of laser pulses, penetrate under the tree canopy and thus allow a better representation of the forest structure [25,26].

Surveys of forest areas using laser scanners involve various scanning platforms. ALS technology holds tremendous potential for forest inventory. It offers suitable parameters for collecting data, enabling the modeling of specific stand parameters, such as the number of trees, their height, crown size, and stem volume, over a large geographic area [27,28]. Diameter distribution in forest stands can be reconstructed from ALS data using the area-based approach (ABA) [29,30]. While effective in even-aged stands with simple unimodal distributions, complex forest stands require direct diameter measurements. Stem diameters can be directly measured in high-density point clouds acquired with unmanned airborne laser scanning (ULS or UAV-LiDAR) [31–34].

The objective of this study is to evaluate the feasibility of using various non-contact data collection methods, specifically HMLS, UAV-SfM, and UAV-LiDAR data collection, for tree detection in terms of the ability to correctly detect the location of trees and subsequently estimate DBH, and then to propose a methodology for assessing forest stand permeability based on tree distance and DBH for forestry or military vehicles.

2. Materials and Methods

The Podivice research plot is located on the southeastern edge of the Březina military training area, west of the village of Podivice (Figure 1), about 40 km northeast of Brno city. It is a mixed stand approximately 40–60 years old, dominated by oak and spruce, with a mixture of pine, larch, beech, hornbeam, birch, aspen, and other deciduous trees. The stand features a relatively rich structure with both height and spatial differentiation. The specific area of interest covers approximately 0.3 hectares. In the area of interest around the skidding lane, the position of the trees was surveyed using tachymetry with a total station in the WGS UTM coordinate system, zone 33N. The diameter at breast height (DBH) of the trees was also measured using a diameter tape. For trees with multiple trunks (polycormons), the DBH was not measured, only the number of trunks was determined. In total, 331 trees were surveyed (91 coniferous, 240 deciduous). The statistical values of DBH for tachymetrically surveyed trees are presented in Table 1.

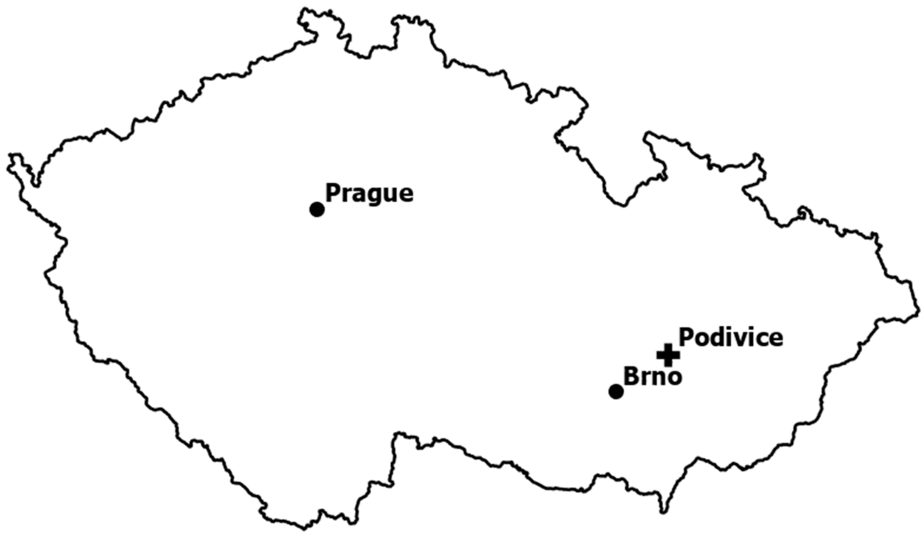

Figure 1. Location of research plot.

Table 1. The statistical values of DBH for tachymetrically surveyed trees.

Number of Trees	Maximum (m)	Minimum (m)	Mean (m)	Std. Dev.(m)
331	0.55	0.04	0.19	0.09

2.1. UAV RGB Imaging

The forest stands were imaged using a UAV DJI Mavic 3 Enterprise equipped with a 20-megapixel RGB camera from an altitude of approximately 60 m. Flight planning was performed using the DJI Pilot 2 app, which allows for the setting of appropriate image overlaps both within and between flight lines. Specifically, an 85% overlap was utilized both within rows and between rows to ensure high-quality alignment of the images for the subsequent creation of the photogrammetric point cloud. Reference points, surveyed using the GNSS RTK method in the WGS UTM zone 33 N coordinate system, were used for referencing the images and for the created model. AGISOFT Metashape software was used to process the images using the SfM algorithm. For further processing, a point cloud with a density of about 2000 points per square meter and an orthophoto with a resolution of 0.02 m was created.

2.2. UAV-LiDAR Scanning

The forest stands were also scanned using a DJI Matrice 350 UAV equipped with a Hovermap ST-X LiDAR. This scanner incorporates the latest LiDAR sensing technology to offer high-density point clouds with exceptional coverage, featuring a sensing range of up to 300 m and more than a million points per second with advanced SLAM technology for processing. LiDAR scanning was performed from an altitude of 70 m with a flight path distance of 60 m, and the data were processed in Emesent Aura software. This produced a point cloud with an average density of 570 p/m^2. Thanks to the use of RTK GNSS on the UAV, the resulting data were already georeferenced to the WGS UTM zone 33 N coordinate system.

2.3. Terrestrial Hand-Held Mobile Scanning

The same device was used for ground scanning, where the data were collected by passing through the forest along the skidding lanes to best capture the surrounding trees. The data collection trajectory is shown in Figure 2. This resulted in a point cloud with an average density of 7400 p/m^2, but a density of over 100,000 p/m^2 around the trajectory. The resulting point cloud was again georeferenced based on reference points to the same coordinate system.

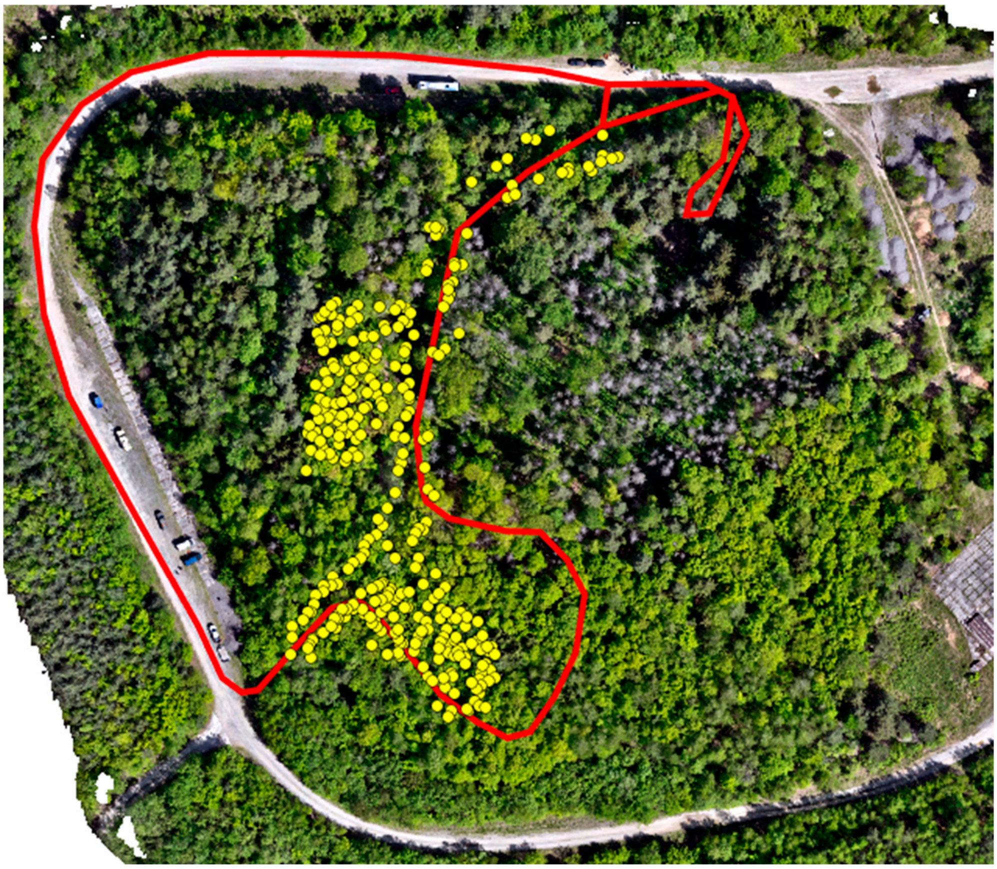

Figure 2. HMLS trajectory and location of measured trees above orthophoto background.

2.4. Data Processing

LiDAR 360 software (GreenValley International, Inc., Berkeley, CA, USA) was used to process all point clouds. In LiDAR 360, tree segmentation begins with the detection of individual trees within the point cloud, using parameters such as height, point density, and spatial distribution. The software employs segmentation algorithms like region-growing, which groups nearby points with similar heights and positions, often applied to identify tree trunks and crowns. Additionally, the supervoxel method divides the point cloud into small 3D regions (voxels) representing different parts of the tree, such as the trunk or canopy. After segmentation, key tree attributes such as DBH (diameter at breast height), height, and crown shape are calculated for further analysis.

The ALS Forest module was used to detect trees from UAV data. First, both point clouds (from RGB imaging and UAV-LiDAR) were subsampled, all outliers were removed, and all ground points were classified. After data pre-processing, individual tree segmentation was performed, and canopy position and tree height were calculated.

The HMLS data were subjected to a similar pre-processing procedure: only segmentation was performed in the TLS Forest module, and again, individual trees, their heights, and DBHs were detected.

2.5. Data Evaluation

Further processing and the evaluation of the data were performed in ArcGIS Pro 3.3 software, where the positions of detected trees, their total number, and in the case of HMLS data, also the DBHs of individual trees, were compared. Additionally, the data from the UAV were compared—specifically, the number of detected trees and their heights. As part of the field measurement, the heights of the trees were not recorded, and therefore it was not possible to compare the accuracy of the heights with trees measured in the field.

The DBH comparison was performed on a narrower selection of trees, as some of them were not captured by HMLS. Due to the nature of the forest, only 176 trees could be assigned based on the closest distance, as only trees automatically detected by HMLS that were within 2 m of the field-measured trees were selected (Figure 3). Deviations and basic statistical characteristics were calculated for these trees. Height differences were only calculated for automatically detected trees; due to the small number of trees detected from the UAV data, the assignment was performed manually based on similar tree heights in the vicinity.

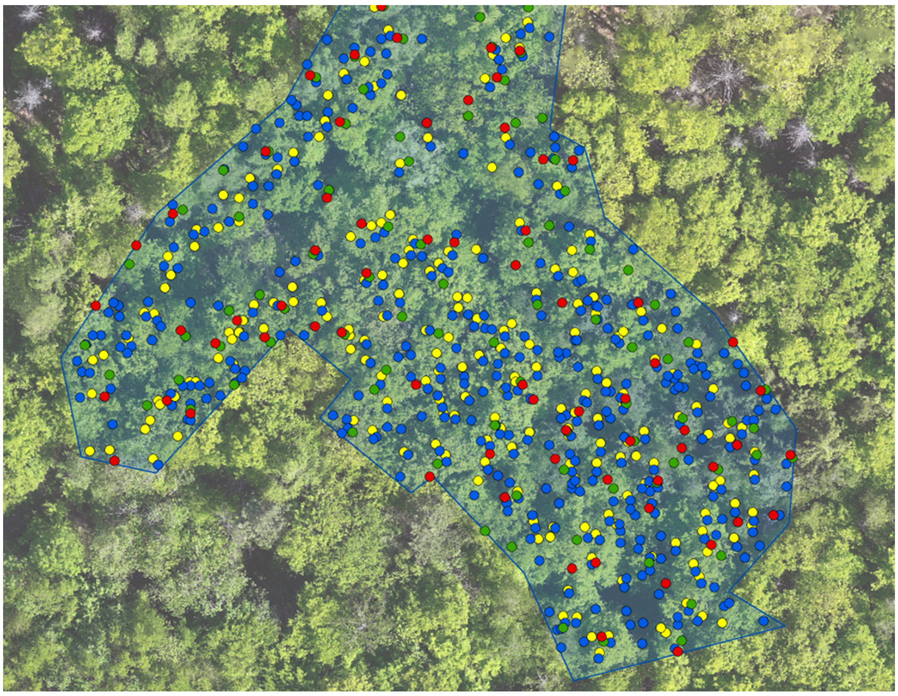

Figure 3. Location of tachymetrically measured trees (yellow) and detected trees (blue—HMLS, red—RGB-UAV, green—UAV-LiDAR).

2.6. Forest Passability Analysis

The resulting passability map was created based on a combination of the maximum possible tree thickness that a vehicle could overcome and the distance between trees that a vehicle could pass through. In the case of tracked vehicles, even trees with DBHs larger than 20 cm can be overcome [3].

A simple map of forest stand passability can be created based on prior tree detection. In this method, barriers to passability are determined based on the prior mapping of tree locations and their DBH. It is also possible to define additional barriers, such as terrain obstacles (e.g., uprooted trees, rock outcrops, or ditches).

Another method for calculating the passability of forest stands is the use of Cost Distance analysis, where the distance from trees with a higher DBH is calculated and the distance is then reclassified according to the vehicle's width (e.g., 3 m). Subsequently, a cost surface is calculated, where areas with distances from trees greater than 3 m are assigned a low value (e.g., 1), and barriers or smaller distances are assigned a high value (e.g., 1000). Based on the determination of a starting point and a target destination, the optimal route is then automatically calculated.

3. Results

3.1. Tree Position Detection

A total of 350 trees were geodetically surveyed in the selected segment around the skidding lane. Using HMLS data segmentation, 643 trees were detected in the same area, 128 trees were detected from UAV-RGB data, and 157 trees were detected from UAV-LiDAR data (Table 2).

Table 2. Number of detected trees.

Data	Number of Trees
Tachymetrically measured trees	331
HMLS	643
UAV-RGB	128
UAV-LiDAR	157

The low number of trees detected from both UAV data methods is due to the nature of the stand and canopy involvement. Conversely, the very high number of trees detected from HMLS data is due to the amount of understory and branches in the lower levels of the tree canopy and especially at the edge of the skidding lane. Furthermore, the shortest distance of the detected trees from the reference trees was also evaluated; unsurprisingly, the best results were obtained for the HMLS data (Table 3).

Table 3. Distance from reference (tachymetrically measured) trees.

Distance (m)	HMLS	UAV-RGB	UAV-LiDAR
Mean	1.06	2.54	2.17
Min	0.11	0.09	0.12
Max	3.86	10.54	8.17
Std.Dev.	0.69	1.66	1.36
RMSE	1.26	3.03	2.56

3.2. DBH Estimation

Due to the large number of trees detected, it was necessary to filter out some trees based on the closest distance and greatest match when comparing DBHs. Finally, DBHs were compared for only 176 trees, and an RMSE of 0.057 m was achieved. The results are included in Table 4.

Table 4. Comparison of DBHs (difference of measured and detected trees from HMLS).

DBH Comparison	Deviation (m)
Mean	−0.029
Min	−0.174
Max	0.111
Std. Dev.	0.049
RMSE	0.057

The highest deviations in DBH (more than 0,1 m) were found mainly for trees at the edge of the skidding lane, where the incorrect assignment of identical trees may have occurred.

3.3. Tree Height Estimation

As tree heights were not measured during the field measurements, only the heights of the nearest detected trees were compared. Thus, the relative differences of the nearest trees between all three data collection methods were calculated. The data show that, overall, the largest differences are between trees detected by HMLS and both UAV data collection methods with RMSE (4.86 m and 4.44 m, respectively). Based on these results, possible causes of these errors were sought. In the case of HMLS, the greatest differences were found in deciduous trees with dense canopy cover, where the laser pulses did not reach the upper canopy stage. In contrast, the highest differences between UAV-LiDAR and UAV-RGB were found in cases of dry spruce trees, where the SfM method could not find enough points and trees were not detected in many places (Table 5).

Table 5. Comparison of tree height.

Height Difference (m)	UAV-LiDAR × HMLS	UAV-LiDAR × UAV-RGB	UAV-RGB × HMLS
Mean	2.32	1.03	−1.28
Min	−0.50	−2.3	−15.2
Max	15.50	11.7	6.5
Std. Dev.	4.27	2.21	4.25
RMSE	4.86	2.44	4.44

3.4. Forest Passability Analysis Results

Based on defining the distance from trees with a diameter greater than what a certain type of vehicle can overcome, along with the vehicle's width, it is possible to easily create a passability map for navigation in the terrain (Figure 4). By identifying obstacles such as thicker trees and other terrain features, it is possible to easily calculate the optimal route for vehicle passage through forest stands (Figure 5).

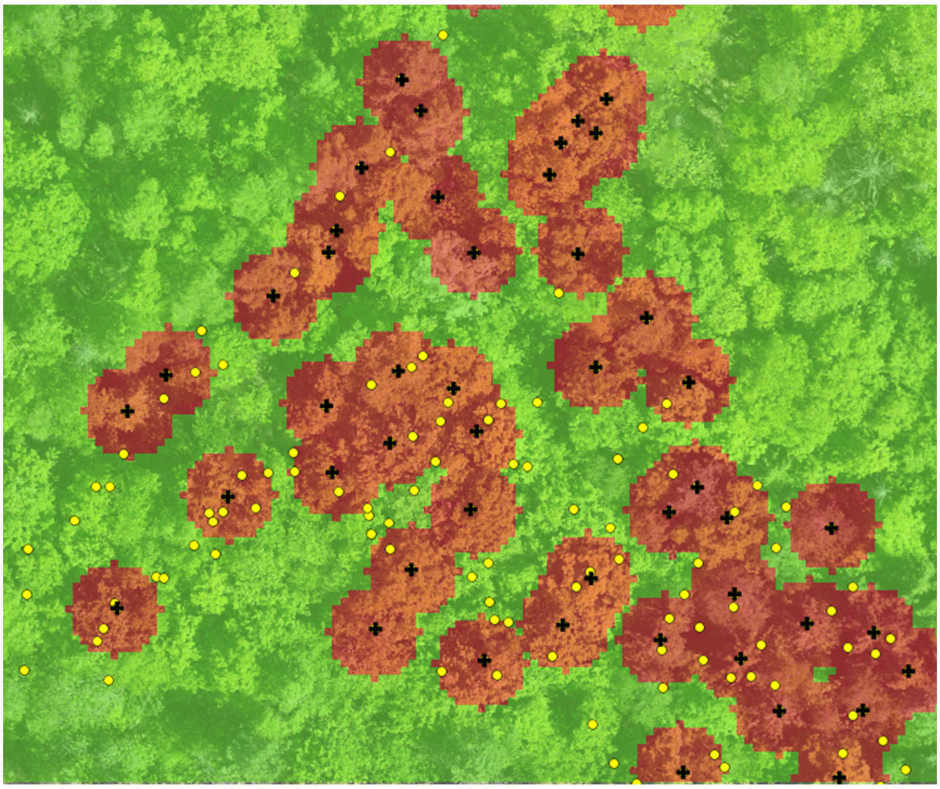

Figure 4. Forest stand passability based on distance from trees with higher DBH (red—unpassable, green—passable).

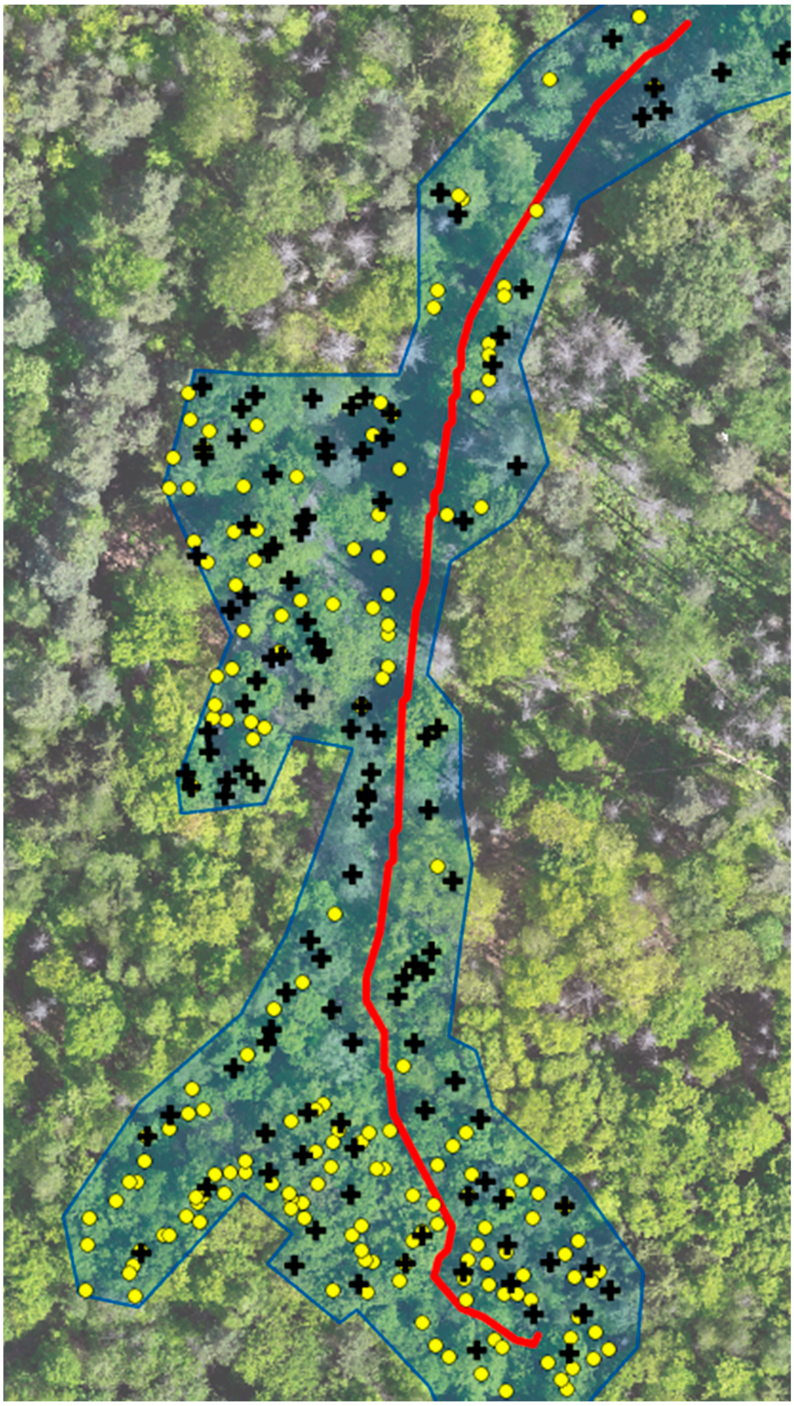

Figure 5. Route planning based on Cost Distance analysis (black crosses—trees with DBH more than 20 cms, yellow dots—smaller trees).

4. Discussion

Terrestrial laser scanning (TLS) for measuring the diameter at breast height (DBH) has become a standard method in forestry research and practice. This method, often used due to its high accuracy and efficiency, has been the subject of many scientific studies and publications [13,14,18,35]. However, TLS-based methods, despite their effectiveness, have certain limitations for DBH measurements. They require multi-station scanning and registration, which is time-consuming and labor-intensive. Furthermore, TLS systems must be transported to the area of interest, posing spatial challenges and often necessitating a field team. The resulting high-density data and the need for multi-station alignment also lead to redundancy and increased hardware demands [36].

In comparison, hand-held mobile scanning provides better tree detection than TLS [17], yet detection rates remain below 100%. Challenges associated with mobile scanning include low data density, complex tree shapes, and point noise [37], all of which significantly impact the detection accuracy, particularly for smaller trees and those near their neighbors, with DBH and proximity both significantly affecting results [18]. These limitations were confirmed in our study, where only 50% of trees were correctly detected, and many trees showed significant variation in DBH determination. However, it is important to note that most studies, including ours, suggest that DBH estimation accuracy is highly dependent on the type of forest stand being examined [18]. The overall lower accuracy of DBH determination using HMLS is primarily influenced by the LiDAR sensor itself, as compared to TLS, it achieves a reflection accuracy of about 1–3 cms. As a result, the output point cloud has a significantly higher noise compared to TLS.

Several studies have explored the use of UAV-based LiDAR for detecting tree trunks in forest stands. However, these studies have predominantly focused on plantations, monocultural stands, or single-layered forests. In richly structured forests, methods such as UAV-LiDAR face significant limitations due to the presence of undergrowth and branches in the lower forest layers. Our results indicate that even with very detailed UAV-LiDAR scanning from low altitudes, it is challenging to reliably capture tree trunks in such environments for direct DBH estimation. Dense canopy structures and the inability of laser pulses to penetrate the ground or reach tree trunks complicate effective segmentation and DBH estimation. Based on the results of this study, it can be concluded that in the case of richly structured forests, it is very difficult to accurately determine the location of trees and DBH using aerial or satellite remote sensing methods. Nevertheless, these parameters are essential for forest passability using terrain vehicles.

The study also included a comparison of tree heights using data from UAV-RGB, UAV-LiDAR, and HMLS. Although tree heights were not measured in the field, studies have found that both UAV-RGB and UAV-LiDAR methods are sufficiently accurate (and in some cases, even more accurate than field measurements) [38–41]. Conversely, HMLS tends to significantly underestimate height. For the purposes of ensuring the passability of forest stands, tree height does not play such a crucial role. However, in the event of a tree falling, it can become entangled with surrounding trees, thus increasing the difficulty for equipment to pass through. Tree height data are also very important because if we do not have data on tree trunk diameter (DBH), we determine this parameter from the correlation between tree height and tree diameter [42–45]. Tree diameters determined in this way then allow us to predict whether or not a tree can handle a given vehicle crossing over the tree [3].

As mentioned above, the issue of data collection and processing for the detection of trees and their breast height diameter has been addressed by numerous authors, focusing on forest stands with various structures. This study was not solely aimed at determining the accuracy of the scanning methods used, but rather at a comprehensive evaluation of their practical usability for the preliminary detection of tree trunk positions and measuring breast height diameter in forests. The main objective was to determine how effectively these methods can identify and map trees in different forest stands to ensure the passability of stands for military and forestry equipment. This capability is crucial for the effective planning and execution of operations, where ensuring the free movement of equipment in various terrain conditions is essential. Accuracy in determining the location of individual trees is very important in terms of the reliability of determining vehicles capable of traversing trees and in terms of selecting vehicles for deployment in military situations, or even rescue vehicles during forest fires. In terms of the ability of vehicles to overcome trees, the selected publications can be used [3,44–49].

This study focused on processing point clouds obtained using UAV-RGB, UAV-LiDAR, and HMLS methods (Figure 6). While the use of multispectral or hyperspectral data could provide more information about the species composition of forest stands, this information is partially redundant for the purpose of passability for forestry and military equipment.

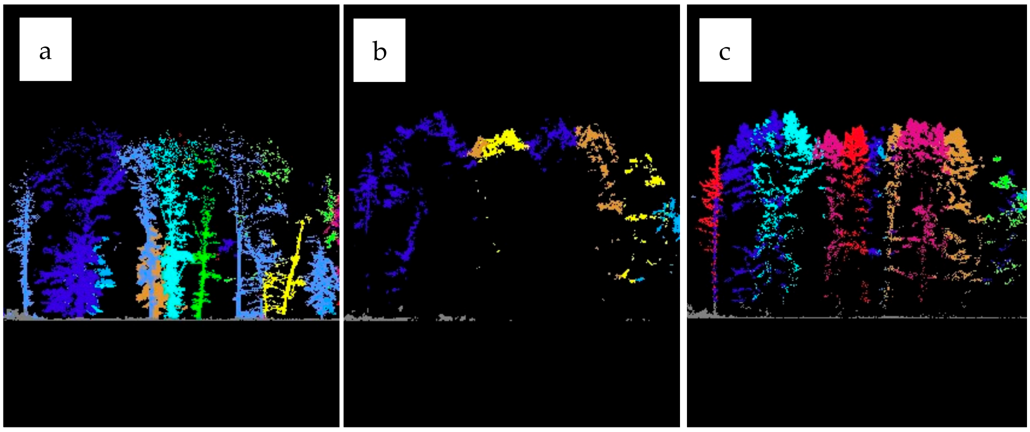

Figure 6. Comparison of point cloud density ((**a**). HMLS; (**b**). UAV-RGB; (**c**). UAV-LiDAR).

More accurate tree detection results were demonstrated with UAV-LiDAR data, where it was possible to capture parts of the trunks of edge trees, thus better determining their positions.

Although the testing was conducted on a very small area, the selected forest stands had a very rich structure, with varying height differentiation and undergrowth of young trees. Such stands are not only difficult to map using conventional terrestrial methods, but also pose challenges for HMLS.

The results suggest that utilizing UAV-LiDAR data for preliminary tree detection and subsequent route planning is an effective mitigation strategy. In deciduous stands, detection accuracy could be further improved by scanning outside the growing season. For detailed route planning, it would be necessary to use HMLS scanning for forestry equipment and to deploy LiDAR sensors directly on military vehicles. This would enable the real-time mapping of tree distances and their breast height diameters during navigation. Such technology could be applied in autonomous vehicles, like TAROS 6x6, which is already equipped with LiDAR sensors and an Inertial Measurement Unit (IMU) (see Figure 7).

Figure 7. TAROS V2 6 × 6 (VOP Cz s. p.) overcoming tree obstacles.

5. Conclusions

The analysis of forest passability for the movement of terrain vehicles involves several key steps, each contributing to a comprehensive understanding of the forest's ability to support such activities. The first critical step is the accurate detection and measurement of trees, specifically their diameter at breast height (DBH) and spatial positioning within forest stands. This study utilized UAV-based LiDAR, RGB imagining, and HMLS to detect and measure these characteristics. The findings highlight the strengths and limitations of each method, particularly in how they handle different forest structures.

The second step focuses on evaluating the effectiveness of these non-contact methods in capturing the necessary details for assessing forest passability. UAV-LiDAR and UAV-RGB methods, while effective in capturing broader canopy structures, show limitations in detecting trees with dense undergrowth or complex canopy structures. Conversely, HMLS provides a higher density of point clouds, enabling more precise detection and DBH measurement, albeit with challenges in areas with dense foliage

By integrating these methods, the study offers a nuanced understanding of the challenges and potential solutions in assessing forest passability for military or rescue purposes. The results underscore the importance of selecting appropriate methods based on the specific forest structure and the operational requirements. Future studies will aim to refine these methodologies, particularly in terms of improving the accuracy of tree height detection and DBH estimation in complex forest environments. This ongoing research is vital for optimizing military logistics and ensuring that forested areas can be navigated efficiently while minimizing environmental impact.

The study results recommend that the optimal method for tree detection involves using UAV-LiDAR data, followed by refinement with HMLS or the deployment of LiDAR sensors on military vehicles for real-time passability mapping. Together, these steps ensure that forest passability can be assessed with higher accuracy, providing critical insights for both military (rescue) planning and forest management. This approach not only supports the movement of terrain vehicles, but also contributes to broader efforts in sustainable forest management by enhancing our understanding of forest structures and dynamics.

Author Contributions: Organization, M.R.; conceptualization and methodology, M.R. and T.M.; measurement, validation, M.R., T.M., F.D., O.V. and S.H.; writing the paper, T.M., M.R. and D.K.; original draft preparation, T.M., M.R. and D.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data were measured and analyzed by the authors of this article.

Acknowledgments: This paper is a particular result of the defense research project DZRO VAROPS managed by the University of Defence in Brno and the specific research project 2024–2026 at Department K-210 managed by the University of Defence, Brno.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Forest Europe. State of Europe's Forests 2020. 2020. Available online: https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf (accessed on 16 October 2024).
2. Reid, W.V.; Mooney, H.A.; Cropper, A.; Capistrano, D.; Carpenter, S.R.; Chopra, K.; Dasgupta, P.; Dietz, T.; Duraiappah, A.K.; Hassan, R.; et al. *Ecosystems and Human Well-Being—Synthesis: A Report of the Millennium Ecosystem Assessment*; Island Press: Wasshington, DC, USA, 2005. Available online: https://edepot.wur.nl/45159 (accessed on 16 October 2024).
3. Rybansky, M. Determination the ability of military vehicles to override vegetation. *J. Terramechanics* **2020**, *91*, 129–138. [CrossRef]
4. Barone, P.M.; Ferrara, C. A posteriori GPR Evaluation of Tree Stability: A Case Study in Rome (Italy). *Remote Sens.* **2019**, *11*, 1301. [CrossRef]
5. Ciftci, C.; Arwade, S.R.; Kane, B.; Brena, S.F. Analysis of the probability of failure for open-grown trees during wind storms. *Probabilistic Eng. Mech.* **2014**, *37*, 41–50. [CrossRef]

6. Dupont, S.; Pivato, D.; Brunet, Y. Wind damage propagation in forests. *Agric. For. Meteorol.* **2015**, *214*, 243–251. [CrossRef]
7. Gardiner, B.; Berry, P.; Moulia, B. Wind impacts on plant growth, mechanics and damage. *Plant Sci.* **2016**, *245*, 94–118. [CrossRef]
8. Giambastiani, Y.; Preti, F.; Errico, A.; Sani, L. On the tree stability: Pulling tests and modelling to assess the root anchorage. *Procedia Environ. Sci. Eng. Manag.* **2017**, *4*, 207–218.
9. Liang, X.; Kankare, V.; Hyyppä, J.; Wang, Y.; Kukko, A.; Haggrén, H.; Yu, X.; Kaartinen, H.; Jaakkola, A.; Guan, F.; et al. Terrestrial laser scanning in forest inventories. *ISPRS J. Photogramm. Remote Sens.* **2016**, *115*, 63–77. [CrossRef]
10. Kaartinen, H.; Hyyppä, J.; Vastaranta, M.; Kukko, A.; Jaakkola, A.; Yu, X.; Pyörälä, J.; Liang, X.; Liu, J.; Wang, Y.; et al. Accuracy of kinematic positioning using global satellite navigation systems under forest canopies. *Forests* **2015**, *6*, 3218–3236. [CrossRef]
11. Qian, C.; Liu, H.; Tang, J.; Chen, Y.; Kaartinen, H.; Kukko, A.; Zhu, L.; Liang, X.; Chen, L.; Hyyppä, J. An integrated GNSS/INS/LiDAR-SLAM positioning method for highly accurate forest stem mapping. *Remote Sens.* **2016**, *9*, 3. [CrossRef]
12. Wezyk, P.; Sroga, R.; Szwed, P. Postex precision positioning of tree trunks on circular inventory plots using the postex device. *Rocz. Geomatyki* **2008**, *8*, 109–118.
13. Calders, K.; Adams, J.; Armston, J.; Bartholomeus, H.; Bauwens, S.; Bentley, L.P.; Chave, J.; Danson, F.M.; Demol, M.; Disney, M.; et al. Terrestrial laser scanning in forest ecology: Expanding the horizon. *Remote Sens. Environ.* **2020**, *251*, 112102. [CrossRef]
14. Wilkes, P.; Lau, A.; Disney, M.; Calders, K.; Burt, A.; de Tanago, J.G.; Bartholomeus, H.; Brede, B.; Herold, M. Data acquisition considerations for terrestrial laser scanning of forest plots. *Remote Sens. Environ.* **2017**, *196*, 140–153. [CrossRef]
15. Kuželka, K.; Marušák, R.; Surový, P. Inventory of close-to-nature forest stands using terrestrial mobile laser scanning. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *115*, 103104. [CrossRef]
16. Valjarević, A.; Djekić, T.; Stevanović, V.; Ivanović, R.; Jandziković, B. GIS numerical and remote sensing analyses of forest changes in the Toplica region for the period of 1953–2013. *Appl. Geogr.* **2018**, *92*, 131–139. [CrossRef]
17. Forsman, M.; Holmgren, J.; Olofsson, K. Tree stem diameter estimation from mobile laser scanning using line-wise intensity-based clustering. *Forests* **2016**, *7*, 206. [CrossRef]
18. Kukko, A.; Kaijaluoto, R.; Kaartinen, H.; Lehtola, V.V.; Jaakkola, A.; Hyyppä, J. Graph SLAM correction for single scanner MLS forest data under boreal forest canopy. *ISPRS J. Photogramm. Remote Sens.* **2017**, *132*, 199–209. [CrossRef]
19. Chen, S.; Liu, H.; Feng, Z.; Shen, C.; Chen, P. Applicability of personal laser scanning in forestry inventory. *PLoS ONE* **2019**, *14*, e0211392. [CrossRef]
20. Mokroš, M.; Mikita, T.; Singh, A.; Tomaštík, J.; Chudá, J.; Wężyk, P.; Kuželka, K.; Surový, P.; Klimánek, M.; Zięba-Kulawik, K.; et al. Novel low-cost mobile mapping systems for forest inventories as terrestrial laser scanning alternatives. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *104*, 102512. [CrossRef]
21. Han, P.; Ma, C.; Chen, J.; Chen, L.; Bu, S.; Xu, S.; Zhao, Y.; Zhang, C.; Hagino, T. Fast tree detection and counting on UAVs for sequential aerial images with generating orthophoto mosaicing. *Remote Sens.* **2022**, *14*, 4113. [CrossRef]
22. Mohan, M.; Silva, C.A.; Klauberg, C.; Jat, P.; Catts, G.; Cardil, A.; Hudak, A.T.; Dia, M. Individual tree detection from unmanned aerial vehicle (UAV) derived canopy height model in an open canopy mixed conifer forest. *Forests* **2017**, *8*, 340. [CrossRef]
23. Mohan, M.; Leite, R.V.; Broadbent, E.N.; Wan Mohd Jaafar, W.S.; Srinivasan, S.; Bajaj, S.; Corte, A.P.D.; Amaral, C.H.D.; Gopan, G.; Saad, S.N.M.; et al. Individual tree detection using UAV-lidar and UAV-SfM data: A tutorial for beginners. *Open Geosci.* **2021**, *13*, 1028–1039. [CrossRef]
24. Holopainen, M.; Hyyppä, J. Possibilities with laser scanning in practical forestry. In *Proceedings of the Scandlaser Scientific Workshop on Airborne Laser Scanning of Forests*; Hyyppä, J., Naesset, E., Olsson, H., Granqvist Pahlen, T., Reese, H., Eds.; SLU, Department of Forest Resource Management and Geomatics: Umeå, Sweden, 2003; pp. 264–273.
25. Heurich, M.; Schneider, T.; Kennel, E. Laser Scanning for Identification of Forest Structures in the Bavarian Forest National Park. In Proceedings of the Scandlaser Scientific Workshop on Airborne Laser Scanning of Forests, Umeå, Sweden, 3–4 September 2003; Hyyppä, J., Naesset, E., Olsson, H., Pahlen, T.G., Reese, H., Eds.; European Association of Remote Sensing Laboratories: Paris, France, 2003; pp. 97–106.
26. Akay, A.E.; Oğuz, H.; Karas, I.R.; Aruga, K. Using LiDAR technology in forestry activities. *Environ. Monit. Assess.* **2009**, *151*, 117–125. [CrossRef] [PubMed]
27. Hyyppä, J.; Hyyppä, H.; Leckie, D.; Gougeon, F.; Yu, X.; Maltamo, M. Review of methods of small-footprint airborne laser scanning for extracting forest inventory data in boreal forests. *Int. J. Remote Sens.* **2008**, *29*, 1339–1366. [CrossRef]
28. Spriggs, R.A.; Coomes, D.A.; Jones, T.A.; Caspersen, J.P.; Vanderwel, M.C. An alternative approach to using LiDAR remote sensing data to predict stem diameter distributions across a temperate forest landscape. *Remote Sens.* **2017**, *9*, 944. [CrossRef]
29. Zhang, Z.; Cao, L.; Mulverhill, C.; Liu, H.; Pang, Y.; Li, Z. Prediction of diameter distributions with multimodal models using LiDAR data in subtropical planted forests. *Forests* **2019**, *10*, 125. [CrossRef]
30. Kuželka, K.; Slavík, M.; Surový, P. Very high density point clouds from UAV laser scanning for automatic tree stem detection and direct diameter measurement. *Remote Sens.* **2020**, *12*, 1236. [CrossRef]
31. Wieser, M.; Mandlburger, G.; Hollaus, M.; Otepka, J.; Glira, P.; Pfeifer, N. A case study of UAS borne laser scanning for measurement of tree stem diameter. *Remote Sens.* **2017**, *9*, 1154. [CrossRef]
32. Pilarska, M.; Ostrowski, W.; Bakuła, K.; Górski, K.; Kurczyński, Z. The potential of light laser scanners developed for unmanned aerial vehicles–the review and accuracy. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *42*, 87–95. [CrossRef]
33. Liu, K.; Shen, X.; Cao, L.; Wang, G.; Cao, F. Estimating forest structural attributes using UAV-LiDAR data in Ginkgo plantations. *ISPRS J. Photogramm. Remote Sens.* **2018**, *146*, 465–482. [CrossRef]

34. Dalla Corte, A.P.; Rex, F.E.; Almeida, D.R.A.d.; Sanquetta, C.R.; Silva, C.A.; Moura, M.M.; Wilkinson, B.; Zambrano, A.M.A.; Cunha Neto, E.M.d.; Veras, H.F.P.; et al. Measuring individual tree diameter and height using GatorEye High-Density UAV-Lidar in an integrated crop-livestock-forest system. *Remote Sens.* **2020**, *12*, 863. [CrossRef]
35. Hyyppä, E.; Hyyppä, J.; Hakala, T.; Kukko, A.; Wulder, M.A.; White, J.C.; Pyörälä, J.; Yu, X.; Wang, Y.; Virtanen, J.-P.; et al. Under-canopy UAV laser scanning for accurate forest field measurements. *ISPRS J. Photogramm. Remote Sens.* **2020**, *164*, 41–60. [CrossRef]
36. Ryding, J.; Williams, E.; Smith, M.J.; Eichhorn, M.P. Assessing handheld mobile laser scanners for forest surveys. *Remote Sens.* **2015**, *7*, 1095–1111. [CrossRef]
37. Feng, B.; Nie, S.; Wang, C.; Xi, X.; Wang, J.; Zhou, G.; Wang, H. Exploring the potential of UAV LiDAR data for trunk point extraction and direct DBH measurement. *Remote Sens.* **2022**, *14*, 2753. [CrossRef]
38. Ganz, S.; Käber, Y.; Adler, P. Measuring Tree Height with Remote Sensing—A Comparison of Photogrammetric and LiDAR Data with Different Field Measurements. *Forests* **2019**, *10*, 694. [CrossRef]
39. Zhou, X.; Wang, H.; Chen, C.; Nagy, G.; Jancso, T.; Huang, H. Detection of Growth Change of Young Forest Based on UAV RGB Images at Single-Tree Level. *Forests* **2023**, *14*, 141. [CrossRef]
40. Hao, Z.; Lin, L.; Post, C.J.; Jiang, Y.; Li, M.; Wei, N.; Yu, K. Assessing tree height and density of a young forest using a consumer unmanned aerial vehicle (UAV). *New Forests* **2021**, *52*, 843–862. [CrossRef]
41. Rodríguez-Puerta, F.; Gómez-García, E.; Martín-García, S.; Pérez-Rodríguez, F.; Prada, E. UAV-Based LiDAR Scanning for Individual Tree Detection and Height Measurement in Young Forest Permanent Trials. *Remote Sens.* **2022**, *14*, 170. [CrossRef]
42. Rybansky, M.; Zerzán, P.; Brenova, M.; Simon, J.; Mikita, T. Methods for the update and verification of forest surface model. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives*; International Society for Photogrammetry and Remote Sensing: Praha, Czech Republic, 2016; pp. 51–54.
43. Rybansky, M.; Brenova, M.; Cermak, J.; Van Genderen, J.; Sivertun, Å. Vegetation structure determination using LIDAR data and the forest growth parameters. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Kuala Lumpur, Malaysia, 13–14 April 2016; Volume 37, p. 12031.
44. Rybansky, M. Modelling of the optimal vehicle route in terrain in emergency situations using GIS data. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Kuching, Malaysia, 26–29 August 2013; Volume 18, p. 12131.
45. Rybansky, M. *The Cross–Country Movement—The Impact and Evaluation of Geographic Factors*; CERM: Brno, Czech Republic, 2009; p. 113. ISBN 978-80-7204-661-4.
46. Rada, J.; Rybansky, M.; Dohnal, F. Influence of Quality of Remote Sensing Data on Vegetation Passability by Terrain Vehicles. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 684. [CrossRef]
47. Rybansky, M. Determination of Forest Structure from Remote Sensing Data for Modeling the Navigation of Rescue Vehicles. *Appl. Sci.* **2022**, *12*, 3939. [CrossRef]
48. Dawid, W.; Pokonieczny, K.; Wyszyński, M. The application of the methodology to define terrain passability on a detailed level in various configurations. *Aviat. Secur. Issues* **2023**, *3*, 331–352. [CrossRef]
49. Mason, G.L.; Gates, B.Q.; Moore, V.D. Determining forces required to override obstacles for ground vehicles. *J. Terramechanics* **2012**, *49*, 191–196. [CrossRef]