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MONITORING OF FOREST HAULING ROADS WEARING COURSE DAMAGE USING UNMANNED AERIAL SYSTEMS

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Abstract

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Currently, a large part of the forest roads that were built using the bituminous surface technology in the second half of the last century have been worn out. This means that forest owners and forest managers urgently need to determine the amount and extent of this damage and establish a suitable repair plan, which demands both time and staff. The aim of the study is to verify whether it is possible, and with what precision, to detect the damage of the wearing course by means of unmanned aerial systems, which would facilitate and accelerate this process and possibly make it cheaper. A 3D model of a forest road was created using photos of the current state of a damaged part of a forest road. The aerial photographs were taken by an unmanned aircraft. To verify the accuracy of the model, cross sections of the road surface were surveyed tachymetrically and compared with the cross sections created in the 3D model in ArcMap, from photogrammetric pointcloud using aerial photographs from the unmanned aircraft. The RMSE of the values of the control points in the 3D model cross sections compared to the values of the points in the tachymetric measurement of the cross sections reached to within 0.0198 m. The results of the tested road section showed that the unmanned aerial systems can be used to detect the forest road surface damage with the difference in accuracy being up to 2 cm compared with the accuracy of the current tachymetric methods. Based on the results we can conclude that the used method is appropriate for detailed monitoring of the condition of the asphalt wearing course of forest roads and allows for a precise and objective localization and quantification of damage.

Keywords: forest road, unmanned aircraft, UAS, UAV, wearing course, 3D model

INTRODUCTION

As reported by Najafi *et al.* (2008), construction of forest roads and timber harvesting has always been the two most expensive activities in forestry and forest engineers have been trying to reduce the costs of forest road construction and the transport process for decades. Murray (1998) also added that the design of forest roads in general and the creation of project documentation of forest road networks are highly time-consuming and professionally challenging. In addition, the way a forest road network is designed and constructed ultimately affects the planning and other activities for foresters managing the forest estates (Kirby *et al.* 1986). Krc and Begus (2013) confirmed that the design and construction of the forest road network is the key to successful forest management. They pointed out that forest roads are not solely used for forest management, but they also have social and recreational functions. There is still another function, more and more presently pressing, and that is the necessary access to forests for fire fighters in case of fires (Najafi and Richards 2013). It follows the statement made by

Aricak (2015) that the sustainable management of forest ecosystems requires a high-quality infrastructure of forest roads, despite the possibly negative environmental impact of the forest road network construction. The forest management of the Czech Republic manifests a constant effort to improve the quality of the forest access roads, both by the construction and maintenance of the forest road network which serves not only for timber transport. Currently, we can already say that its density approaches the optimum (Žáček 2010). As the forest road network was predominantly built in the second half of the last century, and the surface of the forest roads were designed for a life span of 20 years at least, the time is now coming when most of the financial resources intended for forest roads will have to be used for the repair and reconstruction of the existing forest road network rather than to build new roads. However, this is a worldwide trend, as illustrated by the focus on a broad range of recently published papers on forest roads and forest access; Yang *et al.* (2014) mentioned that the increasing proportion of funding needed for the maintenance and repair of forest roads arises not only for the reason of quality infrastructure for timber transport, but also for the requirements of the general public concerning high-quality forest roads for recreational purposes. Similarly, Potočnik *et al.* (2005) published his opinion that in the conditions of public access to the forest ecosystem and the use of the forest road network for recreational purposes the requirements for common maintenance of the forest roads are higher. Hand in hand with the increasing requirements, the forest managers need fast and high-quality information about the current condition of forest roads, so that they can make decisions and work with the finances budgeted for their forest road network administration (Yang and Regan 2013). The authors recommended using the method referred to as AHP (Analytic Hierarchy Process) to make the correct decisions on the use of the funds for the repairs and maintenance. This method is intended to help forest managers make decisions quickly and easily. However, the decision-making process is often affected by data that are monitored visually and only subsequently recorded in the database. Pellegrini *et al.* (2013) drew attention to the fact that forest district managements spend approximately the same amount of money on the maintenance of the forest road network each year. As the resources are often limited, it is necessary to optimize the expenses and set priorities to achieve the desired objectives. They noted that the current objectives are not only based on economics, but also on environmental and socio-economics, aimed primarily at the recreational use of the forest. Due to these differing requirements, it is necessary to provide the forest district managers with a tool that would take account of all these different requirements and allow for a comprehensive solution to forest road network management. The authors (Pellegrini *et al.* 2013) used a combination of tools, AHP and GIS (Geographic information System), to create a supporting decision-making system, which would be used for decisions on forest road network maintenance based on its current condition and the current needs of the forestry sector. The system also partially works on the principle of a visual field assessment. In this case, we could assume the time-consuming collection of data on each road and the need for human labour to record the data in the database system. However, this is currently quite a commonly used system for the inventory of forest roads, but the data is often of a technical character only. An example of such a procedure is, e.g. the system of the British Forestry Commission organisation, where each forest sector administrator in the framework of their work records the occurrence of damage and events on the forest road network by a photo with GPS (Global Positioning System). These are immediately sent to the responsible worker at the offices of the forest district, who evaluates the data and saves them in the GIS system. The data is then available to all workers in the forest district. This system requires all of the workers to have at least a partial knowledge of the software environment of GIS.

As regards the use of GPS technology, Abdi *et al.* (2012) published a paper on the accuracy and usefulness of this technology in the forest environment in relation to the mapping of forest roads; and they noted that due to the relatively small cost, this is a frequently used method for the inventory of the forest road network. However, they added that this method can also be inaccurate in the forest. Rodriguez-Perez *et al.* (2007) pointed out that the use of GPS in the forest ecosystem introduces problems related to signal reception under the forest canopy, including the visibility of satellites in a given territory at the time of measurement.

Coulter *et al.* (2006) were convinced that the best method to set the maintenance plan of a forest road network is a combination of heuristic analysis, analysis of financial costs and impacts on the environment, and "expert judgment". They are one of the few authors who add a certain degree of the experience of the staff responsible for the forest road network condition to the otherwise mostly exact method of decision-making. Their approach shows that it is possible to incorporate the hardly assessable environmental benefits and expert judgement, based on the professional workers' experience, into the decision-making process regarding the efficient use of the annual forest road network maintenance budget. They also used the AHP method within the process of decision-making. In their study, they applied the maintenance plan they proposed in a specific example, 225 km of forest roads in the administration of the Oregon State University College of Forestry, with an annual budget of $250,000 for their maintenance. It should be noted that the roads in question have an unsealed wearing course.

The collection of field data can always be described as time-consuming, especially if the data is obtained from a large territory and not from one place, the collection can be physically demanding as well. Operational decision-making within forest road network management needs the data from a large territory to be obtained quickly and, what is more, the data must be accurate (e.g. true to ground measurements) and their measurement frequently repeated. Remote sensing data provides great potential to meet these requirements. Azizi *et al.* (2014) reported that the most developed method for the monitoring of the forest road network at the present time is LiDAR (Light Detection and Ranging). This is a method of remote measurement of distance based on the calculation of the speed of the laser beam pulse reflected from the object monitored, which is primarily used to produce a DTM (Digital Terrain Model). However, because of an accuracy of one to two metres, this method is mainly used in the field of forest road management to determine the layout of forest roads in the forest (Azizi *et al.* 2014; White *et al.* 2010).

Saito *et al.* (2013) introduced the possible usage of the LiDAR method for an automatic design of the forest road network that takes into account negative cardinal points for the layout, such as sites where landslides are imminent. Based on an accurate DTM (Digital Terrain Model) created using the LiDAR data, the locations of draining structures on the forest roads can also be laid out and the erosion resulting from the construction of forest roads can be reduced (Aruga *et al.* 2005). Aricak (2015) created a DTM using a commercial satellite imagery system GeoEye-1. The images are then processed in software, ERDAS and ArcGIS, to determine locations prone to erosion as a basis for a design of a forest road network.

This study aims to find and verify a solution which would be able to replace or make field surveys more efficient, which are often time-consuming and physically demanding and yet provide sufficiently detailed data provided by ground-based measuring instruments as compared to LiDAR or GIS methods. One of such solutions can be the use of unmanned aircrafts, known as UAS (Unmanned Aerial System) or UAV (Unmanned Aerial Vehicle); more specifically, multi-rotor propelled unmanned aircrafts often referred to as copters (as an abbreviation of the multicopter or the multi-rotor copter). The UAS has served mainly for military purposes for decades. However, in recent years, they have also begun to be used outside military use. They can be equipped with thermal cameras, a radar to map the Earth's surface, microwave and ultraviolet radiation sensors, laser spectroscope or biochemical detectors or simply a digital camera. This range of options makes them an extremely effective means for the monitoring of almost anything, from the movement of people to the detection of the size of disasters (floods, fires, explosions of power plants, etc.) and e.g. finding metal or mineral deposits. This issue is currently also in the field of forestry, as we can read in the statement of The U.S. Forest Service (USDA 2015), which stated that the use of the UAS is advantageous for a series of activities in forestry, such as forest health protection, fire suppression, science, assessment of the impact of recreational activities on the forest ecosystem or law enforcement. Although The U.S. Forest Service currently has no official UAS programme in place, they have already done the analysis of appropriate, safe and the cost-effective use of UAS in state forests and will prepare a programme based on the results. The first studies published on the use of UAS in forestry focused on their use for monitoring and the quantification of forest fires. Wing *et al.* (2014) stated in their article that forest fires occur regularly in forest management around the world and affect millions of hectares of forest per year. They added that many applications had already been developed on the basis of remote sensing to assess the damage and consequences caused by forest fires, mentioning them in their publication, such as quantifying the material in a fire site or monitoring the forest stand restoration after the fire. They mentioned the game chipping in the areas of fire occurrence, which provides information about the behaviour and movement of the game in the affected areas. They see big potential in the usage of UAS, in particular because it provides, current information in real time, so each situation can be responded to quickly enough to help moderate the damage. The use of UAS for a different purpose than fire prevention was presented by Pierzchała *et al.* (2014) with the example of the determination of soil erosion from skid trails during logging. In their study, aerial photographs were taken by a multi-rotor UAS and a detailed model of the terrain after logging was done, together with the damaged skid trails. These images were then compared to the photographs taken before the logging by means of LiDAR (Light Detection and Ranging) or ALS (Airborne Laser Scanning) and the magnitude of soil erosion caused by timber skidding was determined. Due to the size of the logging areas and the need to record each terrain damage, like the depth of the soil cut in the creation of the skid trails, the authors found UAS highly appropriate for this purpose. They also stressed the financial advantage of data obtained by UAS compared to LiDAR data, the great variability of these systems, the simple acquisition of images, the subsequent computer processing, and, in particular, the accuracy compared to conventional methods of LiDAR remote imaging. LiDAR data documents can be usually obtained only commercially, by purchasing them, unlike the data obtained using UAS, which are essentially based on the acquisition of data in a specific location. We can also assume that these devices will be more affordable in the near future. The development of UAS use in the field of photogrammetry and remote sensing were discussed in an extensive article by Colomina and Molina (2014). They pointed to the fact that the UAS potential was identified 30 years ago, but technologies that allow the potential to be realised have only been developed in the last five years. This has resulted in the obtained centimetre accuracy of data at very favourable prices. Siebert and Teizer (2014) also mentioned the rapidly growing interest in the use of UAS in the agricultural and forestry sectors, integrated rescue systems, security and guarding services, traffic control and supervision, 3D modelling, and control systems; especially for their low costs, flexibility, manoeuvring options, and a relatively high safety of operation. They noted that UAS in these fields are already able to fully replace satellite systems and manned aircrafts. In addition, they have overcome their disadvantages, such as the lack of flexibility or high purchase costs of satellite or aerial images from manned aircrafts. The current developments in computer visualisation provide far better options for creating 3D models from images taken by the UAS. Images taken by the UAS are often taken from commonly available cameras, which are not specially adapted to record the exact metric data (Turner *et al.* 2012). This drawback is overcome by the processing of the images by means of the SfM (Structure from Motion) method, which allows using the calibration of the camera, position and orientation of disordered and overlapping photos and the 3D geometry of the scene (Lisein *et al.* 2012). It uses the algorithm known by the abbreviation SIFT (Scale Invariant Feature Transform) to extract objects or elements. The algorithm is well suited for the UAS images due to its resistance to the changes in rotation, scale and overlapping (Lingua *et al.* 2009).

This study evaluates whether the UAS method is sufficiently accurate to compete with the current methods of ground-based surveys such as tachymetry, which is used to detect damage on the wearing course of forest roads, and thus attempts to verify whether it is possible to use UAS for surveys on the current state of the sealed wearing course of forest roads.

MATERIAL AND METHODS

The site and the description of the forest road section investigated

To verify the possible application of the UAS for the monitoring of the forest road network wearing course damage, a section of the main forest road "Šibrnka" was chosen in the Training Forest Enterprise Masaryk Forest Křtiny of the Mendel University in Brno. The forest road wearing course surface was made from penetration macadam and was built in 1978. The technology of penetration macadam was largely used for the reinforcement of forest roads in particular in the second half of the last century, when an extensive construction of the forest road network took place in the Czech Republic. During this forty years of construction, the density of forest roads in the Czech Republic increased from 5 m.ha^{-1} to 16 m.ha^{-1} (Beneš 1978). Due to the fact that the life of the wearing course is commonly

1: *The current state of the damaged surface* designed for 20 years at least, the time has now come for their reconstruction. The investigated section of the forest road was 500 metres long and was already extensively damaged (Fig. 1). Longitudinal drainage consists of a double-sided longitudinal ditch of a trapezoid shape. The test section of the forest road is surrounded by a spruce stand of the third age class. The branches of the surrounding spruce stand do not reach over the forest road.

Taking the aerial photos for the creation of the 3D model and geodetic surveying of the current state of the road wearing course

The photos were taken by a multi-rotor unmanned aircraft type hexacopter DJI S800 Spreading Wings mounted with a gyro stabilized DJU Zenmuse Z15 gimbal with a Sony NEX 5r camera, sigma lens with a fixed focal length of 19 mm. The camera photo sensor size was APSC (24 × 16 mm) and the resolution was 16 Megapixels (4912 × 3264 pixels). Aerial photos were taken on 10th September 2015, at noon, when the best light conditions were expected. The unmanned aircraft was remotely controlled from the ground through an RC transmitter. The pilot followed the UAS during the entire flight. The aircraft was moving at a speed of approximately 1 m/s and at a height of 4 to 6 m above the road axis, photos were taken, including its surroundings, under a vertical angle of approx. 45°. The camera took photos with a frequency of 60 frames per minute with the longitudinal overlap of about 90 %, which means that each point of the test section was captured on nine frames at minimum. To put the surface model and the subsequent ortophoto mosaic into the coordinate system of the uniform trigonometric cadastral network (the national grid S-JTSK) accurately, it was necessary to use a special template and fluorescent colour to indicate and survey 15 control points with geodetic precision; a further 15 points were indicated and surveyed in order to verify the horizontal accuracy of the model.

In total, 703 images (aerial photographs) were taken by the UAS in the test section with a length of 500 m. They were then processed in AGISOFT PhotoScan professional into the form of an orthorectified RGB (RGB colour model) of the image with a resolution of 1cm and a stereo photogrammetric 3D point cloud with an average density of 3.2 point per 1 cm^2 (see Fig. 2). The AGISOFT application was also used for a comparison of the horizontal accuracy of 15 geodetically surveyed points. The stereo photogrammetric point cloud was then processed in ArcGIS Desktop 10.3 using 3D Analyst and Spatial Analyst extensions. The first step was to define the boundaries of the forest road width based on the manual identification of the road shoulders above the orthophoto picture. Next, the stereo photogrammetric point cloud was interpolated using linear interpolation into a form of a continuous raster 3D model of the forest road. Due to the computational complexity of further analyses, the resulting model was generalised to a resolution of 1cm, although the data density would allow for an even higher resolution.

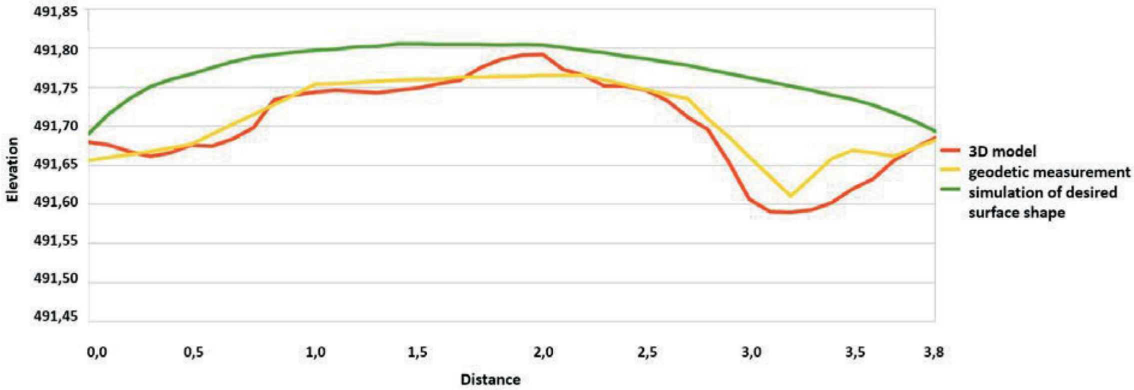
The geodetic survey of control points was carried out using the GPS receiver Topcon Hiper Pro in combination with the Trimble M3 total station. The points were surveyed in the coordinate system JTSK and the Baltic Vertical Datum – After Adjustment. In addition to the control points, the Trimble M3 total station surveyed 17 cross profiles in total within the test section (127 control height points) of the actual state of the damaged wearing surface for a subsequent comparison of the height accuracy to the 3D model created. The comparative cross profiles of the 3D model were created in the ArcMap program, 3D Analyst extension, at the same station places where the cross profiles were surveyed by the total station in the test section of the forest road.

2: *3D view of the photogrammetric point cloud*

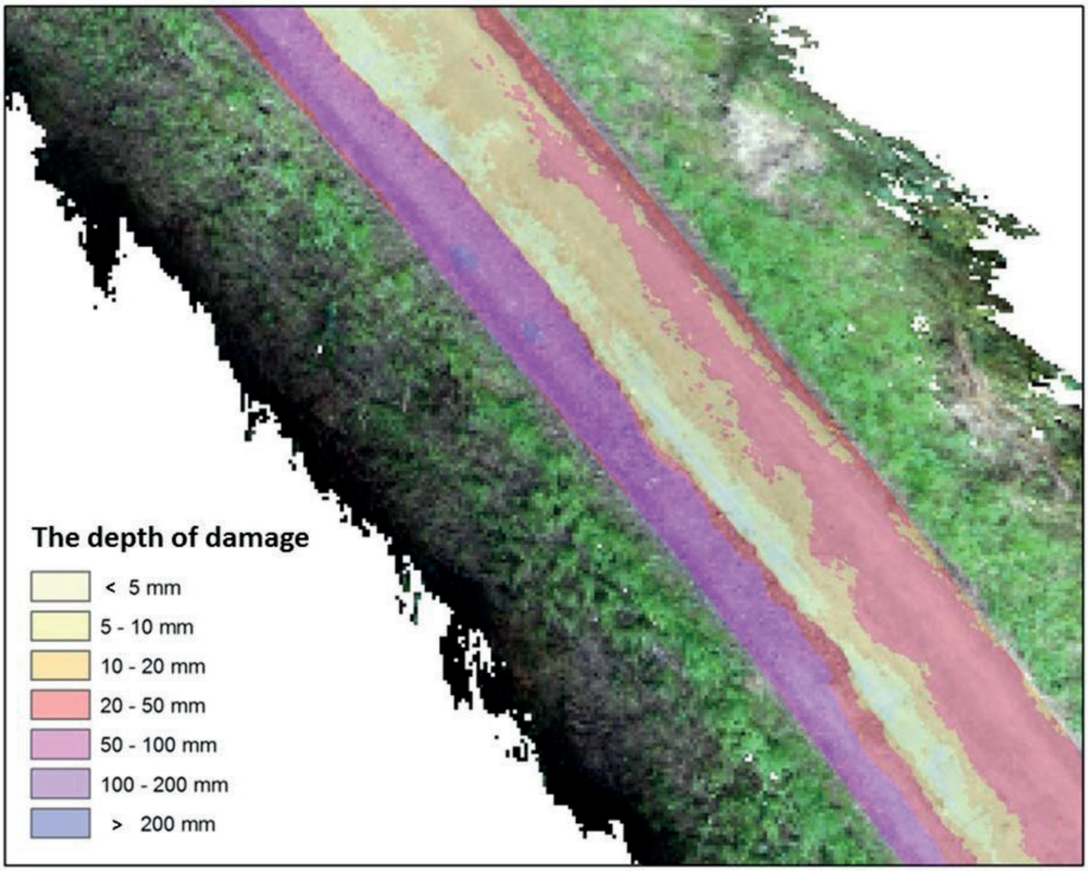
RESULTS

The use of UAS to identify the damage and survey the current state of the penetration macadam wearing course of forest roads and the model of accuracy (Fig. 3) shows only minimum differences between the surfaces modelled from the photogrammetric cloud and the points surveyed. Larger deviations are primarily caused by a smaller number of points of geodetic measurements and the associated generalisation.

The model accuracy was evaluated by comparing the altitudes of the points in cross sections from the 3D model with the altitudes of the control points from the geodetic measurement and the calculation of the basic statistical characteristics and the mean-square error. In addition to showing the 3D model of the current state of the forest road, the 3D Analyst extension of ArcGIS enables us to insert the cross shape of the road surface we created into the 3D model as it was originally built or is designed for repair. This creates a space between the real and the proposed road surface shape and its size gives



3: *An example of a cross section from the 3D model, the geodetic measurement, the 3D model and the desired surface shape*



4: *The depth of damage calculated on the basis of the difference between the simulated and the actual state of the road surface* the volume of the material required to level the damaged road surface into the desired shape. For the purposes of calculating the total amount of material needed for the road repair, the increase in and levelling of the road surface into the original desired cross shape of the road wearing course was simulated and the difference from the 3D model surface shape was used to calculate the total amount of the missing wearing course material (Fig. 3).

The results of the UAS used to monitor the state of the wearing course of forest roads from penetration macadam show that even after photogrammetric processing of photos and subsequent interpolation into DTM and orthophoto, it is possible to directly define the boundaries of the road width and also identify the damage based on visual assessment. In addition to a detailed orthophoto, another output of the processing is an exact digital model of the surface, which allows for automated processing and identification of potholes and other types of surface damage of forest roads, including the determination of the depth of the actual damage (Fig. 4) and the calculation of the amount of material needed for a repair. It was calculated that to repair the damage in the test section of the road with a length of 500 m, the total volume of material needed is 40.46 m^3.

Verification of the accuracy of the 3D model based on the comparison between the cross sections made in the 3D model and the measurements of the forest road

The results of the comparison of the cross sections created, based on the 3D model with the cross sections surveyed by the Trimble M3 total station in the actual road conditions, show that the photogrammetric point cloud of the forest road obtained from the UAS achieves a very high accuracy. We can conclude that the altitude deviations of the points from the cross sections in the 3D model compared to the point altitudes obtained by the total station measurement have an average value of 0.009 m; the maximum deviation reached a value of 0.0306 m; and the root mean square error (RMSE) reached a value of 0.0198 m (Tab. I.); in the case of the positional deviation of the orthophoto and DTM the RMSE was 0.0118 m, which is a precision sufficient for the UAS to be used to determine the magnitude of damage to a forest road surface of penetration macadam.

The overall results of the basic statistical characteristics of the compared groups of control point altitudes are presented in Tab. II.

The graphic comparison of arithmetic means and the overlap of confidence intervals with 95 % probability of the occurrence of the value (Fig. 5) show that these groups are practically the same.

The calculated values of mean square errors of both location and height deviations between the tachymetric measurement and the 3D model from the UAS prove a precision of the method sufficient for the mapping of forest road sealed wearing courses.

DISCUSSION

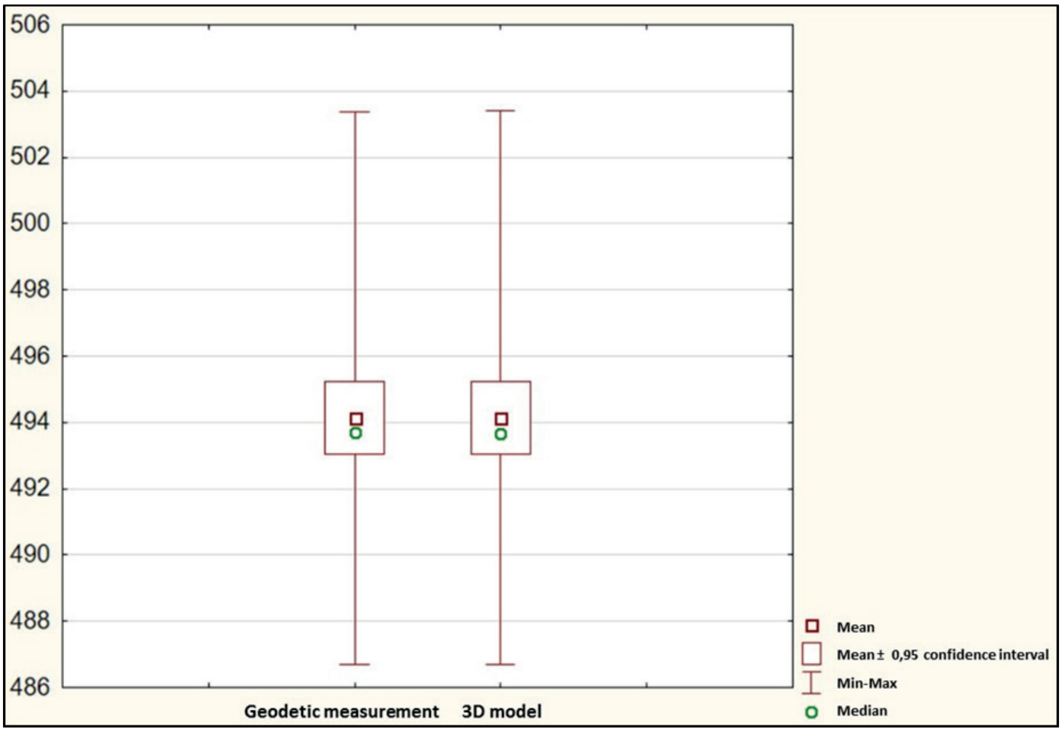
According to our results, the use of UAS should appear as one of the challenges for the logging activities within forestry as reported by Heinimann (2007). Other modern methods of remote sensing, such as aerial LiDAR (Light Detection and Ranging), reach a significantly lower accuracy with a RMSE of 0.103 m and with a lower density of points around 1–10 points per m^2 (Mikita *et al.* 2013). Ahamed *et al.* (2000) presented that the LiDAR accuracy of each point on the ground is approximately 15 cm in the vertical, and 1.0 m in the horizontal. Aricak (2015) stated that with a commercial satellite imagery system GeoEye-1, it is possible to achieve a high degree of resolution with an accuracy of 0.46 m. The

I: *Evaluation of the altitude and location deviations of control points*

	Altitude error	Positional error
Number of control points	127	15
Min	-0.0291	0.0031
Max	0.0306	0.0227
Sum	1.0422	0.1582
Mean	0.0090	0.0105
Standard Deviation	0.0141	0.0052
RMSE	0.0198	0.0118

II: *The basic statistical characteristics of altitude deviations of 3D model control points from the actual state*

	Count	Mean	Confidence interval -95 %	Confidence interval +95 %	Min	Max	Std. deviation
Geodetic points	127	494.1443	493.0565	495.2321	486.6849	503.3707	6.46
3D model from the UAS	127	494.1345	493.0456	495.2234	486.7020	503.3950	6.07



5: *Graph of the confidence interval of the occurrence of the parameter with the significance level* α = *0.05*

LiDAR method can help us update the maps of the forest road network, increase the effectiveness of the forest access, can be used for the planning of harvest processes, e.g., the direction and length of skidding and transport; however, the data processing can be lengthy and the method is not applicable for gaining more accurate and detailed data, as is the case of the wearing course surface damage. Despite the mentioned options of the LiDAR method, it is necessary to have high-quality data obtained by remote sensing of the Earth and work with a large volume of data; their accuracy can be lost by interpolation when creating a DTM. Additionally, the final, relatively large, size of the grid of 1 m (Dehvari and Heck 2013) makes this method applicable rather as a support for the decision-making process AHP and for the assessment of the forest road network as a whole in the context of the transport area. This method is hardly applicable to a determination of the magnitude of damage and the maintenance plan of individual forest roads. We can conclude that although AHP, LiDAR and DTM were created on the basis of remote sensing of the Earth and are quite immaculately developed in the field of forest roads, they only provide approximate data, which ultimately, in the process of investment planning, require data precision by a field survey and a more detailed financial cost analysis. This can be the reason why the use of these methods seems to be "double work" for forest road managers and designers and why they are not frequently used in practice. Contreras *et al.* (2012) tried to take advantage of the DTM model created with LiDAR data to determine the earthwork amount in the design of the forest road layout, and compared its accuracy with the data obtained by the conventional method of a ground-based survey. In their work, they pointed out that in order to achieve the necessary precision in the size of cuts and fills in the case of DTM – it is necessary to use the maximum distance of cross-sections of 1m. If this principle is complied with, the determination of the earthwork amount reaches the required accuracy, comparable with conventional ground-based methods.

Abdi *et al.* (2012) published the horizontal accuracy of GPS for forest mapping as a variable and in their study, values ranged from 6.49 to 88.03 m, depending on the GPS signal or barriers. This is a general problem when using GPS under forest canopies and some authors (Naesset &, Jonmeister 2002) see the solution in a longer observation time period and applying DGPS. Other studies have shown big variable average accuracies due to the different methods and GPS receivers (August *et al.* 1994, Wolniewicz 2001, Rodríguez-Pérez *et al.* 2007).

Compared to the methods mentioned above our results of UAS usage show precision that is usable for monitoring of the forest road wearing course damage. Besides the higher accuracy, the advantages of the UAS photogrammetric data collection can be the lower costs and time consumption compared to the conventional geodetic measurements. Christensen (2015) published an economic analysis for UAS and wildland fire management and stated if this method is implemented and managed appropriately, it could improve the cost effectiveness very well.

Disadvantages are e.g. the complexity of data processing and the need for specific applications for the formation of the photogrammetric point cloud, but also the legislative restrictions, since the use of UAS for this purpose in the Czech Republic requires a flight permit and pilot registration, which is issued by the civil aviation authority. This fact, together with the risk of a plane crash due to collision with the canopy over the forest road, greatly complicates the procedure. To simplify it, we can propose putting a camera onto a telescopic rod, which will be carried manually or transported by means of transport, for example a car, which will significantly accelerate the data collection.

CONCLUSION

The application of UAS to plan road wearing course repairs, as regards to the urgency and also the determination of the costs of individual road repairs, appears as one of a few quite realistic options. Thanks to the speed of the UAS flight when obtaining the aerial imagery of the forest road network, it is possible to map a substantial amount of forest roads in a short time and use the data operatively in the determination of the urgency of repairs. In comparison with the commonly used procedures for the visual assessment of the road damage or the geodetic survey, this method is objective and accurate, eliminating the evaluator's or helper's subjective approach. In comparison with the geodetic survey, this method is significantly faster. The time demanded to take images of 1 km of a road is in the order of tens of minutes. The processing of the images taken by the UAV and their turning into the form of a digital surface model is time consuming (approx. 10 hours); however, except for the necessary manual entry of identical control points, it is fully automated and does not require the user's active intervention.

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