



CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

**SAFETY MAPPING OF THE
VEGETATION ALONG THE
TRANSPORT INFRASTRUCTURE**
CERTIFIED METHODOLOGY

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Safety mapping of the vegetation along the transport infrastructure

Certified methodology

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1. Objectives of the methodology

The main aim of the methodology is to create a comprehensive procedure enabling the mapping of vegetation along the transport infrastructure using unmanned aerial vehicles (UAVs). Based on the methodology, it is possible to perform repeated mapping of vegetation along roads and to obtain up-to-date information on the exact position and height of each tree, its distance from the transport infrastructure and optionally on its state of health. The data could be used for long-term vegetation records and for listing of tenders focused on maintenance of greenery, etc. Furthermore, the procedure would allow user to detect potentially dangerous trees in the vicinity of any transport infrastructure. At present, information on vegetation is obtained by ground field measurement, which is inefficient in terms of time, personnel and economics, and often insufficiently accurate method of data acquisition. The creation of a methodological standard will enable the mapping of vegetation and the subsequent exchange of data between individual local transport infrastructure administrations. The usability of the standard grows with the need for transport infrastructure managers to perform measurements repeatedly and archive the outputs in a form that would allow comparison of different periods.

The methodology describes all steps leading to successful mapping of greenery, i.e. data acquisition using a suitable camera (sensor) located on an unmanned aerial vehicle, basic processing of scanned UAV data, detection at the level of individual trees and obtaining the required information about the vegetation.

2. Description of the methodology

Vegetation near the transport infrastructure is currently a much-discussed topic. Planting trees along roads can improve traffic conditions by mitigating the side effects of climatic influences, especially of wind, snowdrifts, and the sun (protection of drivers from glare and prevention from overheating of the road). However, these stands can also be a safety risk, for example in the event of a vehicle colliding with a tree or in the event of parts or whole trees falling into the road itself. In 2018, according to statistical data from the Police Presidium of the Czech Republic, a total of 104,764 accidents occurred in the Czech Republic. One-fifth of them were collisions with a fixed obstacle, such as a pillar, a pillar of a traffic sign, a bollard, a wall, a tree, and a barrier. Collisions with trees has a low share in the total number of accidents (2.5%). However, these collisions are the most serious in the category of fixed obstacles according to the number of people killed. Last year, 73 people lost their lives in a collision with a tree (Police Presidium of the Czech Republic, 2019).

The presented methodology aims to map the vegetation along the roads, using unmanned aerial vehicles (UAV), which is rapidly developing. UAV are an effective tool for data collection and analysis that compete with satellites and aircraft due to their high operational flexibility and high spatial image resolution (Matese et al., 2015). They can also be used in forestry, where remote sensing can effectively provide spatially representative characteristics of the studied forest stands, and thus complement existing ground measurements (Wallace et al., 2016).

The methodology description is divided into six subchapters, in which the procedure of data acquisition and processing is described, followed by a demonstration of the results. To use the methodology, basic knowledge in the field of remote sensing is necessary, as well as processing UAV data and know-how of suitable software to obtain the required spatial information.

2.1 Data acquisition and preparation

Data acquisition by drones can be done using two types of UAVs. The most popular are the so-called multicopters (rotary-wing), which can be found in countless designs. The second type are fixed wings. Multi rotary-wings (copters) are maintained in the air by the tensile force due to the torque generated by the engines. Multicopters offer higher spatial resolution at the expense of coverage. On the contrary, the flight time and flight speed of the helicopters is usually lower than of the wing types. The principle of different speed of air flow above and below the wing profile is used for the movement of the wings, which leads to a decrease in pressure above the wing and at the same time to an increase of pressure under the wing. Fixed wings can offer scanning of larger areas, but the spatial resolution can be reduced.

Both types of UAVs are suitable for mapping vegetation along the transport infrastructure. Multicopters can be chosen for areas of several hectares or distances of hundreds of meters. On the contrary, for larger units or higher distances, it is more appropriate to use the wing type. The choice of device depends on the habitat conditions, topography, legislative restrictions and capabilities of the user. It is also up to the user to choose a commercial or freely available system. The use of a commercial system is ideal for inexperienced users because the control system and the device are ready for immediate use. On the contrary, free systems offer greater variety of use, but at the same time require a certain degree of expertise. A detailed comparison is offered, for example, by Moudrý et al. (2018).

Part of the preparation is a planning of the flight mission, which must follow certain principles and valid national legislation. In Czech Republic, the operation of UAVs is regulated by ICAO aviation regulations, namely Regulation L2 - Rules of the Air and its Attachment X. In May 2019, new European legislation concerning unmanned aerial vehicles was adopted. Commission Implementing Regulation (EU) 2019/947 entered into force on the twentieth day following that of its publication in the Official Journal of the European Union, applicable from 1 July 2020 and available on the website of the European Aviation Safety Agency (<https://www.easa.europa.eu>).

During the preparation of the flight mission, it is necessary to choose a suitable overlay of images. To achieve good results, the flight should take place at a height of 70-90 m above the surface with 70-80% longitudinal and transverse overlaps. Higher overlap represents higher demands on flight time consumption and later computing capacity. When planning the flight level, it is necessary to consider objects on the surface and add their height to the height of the topography. To achieve sufficient sharpness of images, it is important to choose a suitable horizontal speed of the device (typically 4-8 m.s⁻¹ for helicopters and 10-12 m.s⁻¹ for wings) and sufficient lighting conditions of the captured scene. Weather conditions and icing are important factors that can negatively affect the flight mission. To achieve optimal sharpness, the wind speed in gusts should not exceed 5 m.s⁻¹ and 8 m.s⁻¹. Many selected applications can be used to plan a flight mission, such as DJI Pilot (Android and iOS), Mission Planner (Windows), Pix4Dcapture (Android and iOS), UgCS (Windows, Mac OS, Linux).

2.2 UAV data processing

The photogrammetric method Structure from Motion (SfM) is suitable for obtaining the required information from images. According to Lisein et al. (2013), by using the photogrammetric method in the field of precision forestry it is possible to monitor the structure of the vegetation and its development during repeated flight mission. The method is based on classical photogrammetry, i.e. obtaining three-dimensional information from two-dimensional images. It is established on finding identical points

based on local extremes in images with central projection. Identical points are found in overlapping images, from which information of spatial orientation is obtained. Gradually, the image is reconstructed, and a 3D point cloud is created based on the Multi View Stereo (MVS) method. Each point of such cloud contains information about X, Y and Z coordinates. Subsequently, the relationship between the coordinates of the points and the coordinates of the object is found. By using the image correlation, the point cloud is compressed, from which it is possible to perform a 3D reconstruction of objects. The concentrated point cloud is shown in Figure 1, where the object of interest is the highway with the surrounding accompanying vegetation. There is a whole range of software using SfM and MVS methods, from commercial solutions it is e.g. Agisoft Metashape or Pix4Dmapper, from freely available it is Bundler, VisualSFM, SFMtoolkit, MicMac.



Fig. 1 Point cloud showing motorway with surrounding vegetation, source: own

According to the research of Wallace et al. (2016) in areas with relatively low vegetation involvement, the SfM photogrammetric technique can be used to describe not only objects on the surface but also the terrain. A digital terrain model (DTM), representing the relief of the earth's surface, and a digital surface model (DSM) showing all natural and artificial elements that are associated with the terrain (e.g. trees, buildings and vegetation) can be generated from a classified point cloud. The difference between DTM and DSM is shown in Figure 2.

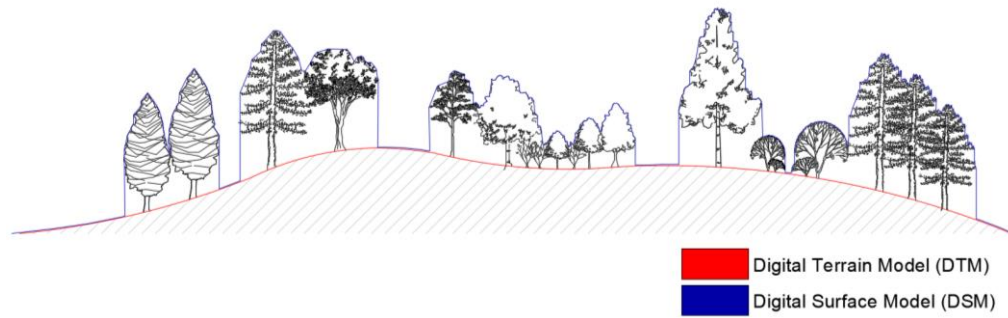


Fig. 2 Illustration of DSM and DTM, source: own

When creating DTM through photogrammetric methods from data obtained from the flight, the terrain must be visible in the images. In case of covered terrain, it is more appropriate to replace this model with another digital model that was created separately. In the Czech Republic, a good substitution can be Digital Terrain Model of the Czech Republic of the 5th generation (DMR 5G). This model was created from data acquired by laser scanning for the entire territory of the Czech Republic and is provided for a fee by the Czech Office for Surveying, Mapping and Cadastre (ČÚZK). More information can be found on the official website of ČÚZK (<https://geoportal.cuzk.cz>). Information on DMR 5G sheet prices is included in Chapter 5, Economic Aspects.

Another output obtained from photographs is orthorectified photomosaic. Images are converted into a map view using orthogonal projection and digital surface model to remove geometric distortion. The creation of a mosaic is important for optical assessment of the accuracy of the detection of individual vegetation peaks and for visual inspection for deciduous vegetation, which may be more difficult to identify in the winter. Photomosaic is also necessary for the calculation of vegetation indices for the assessment of health status.

2.3 Vegetation mapping

2.3.1 Treetop detection

During the process of vegetation mapping, it is necessary to determine the tops of individual trees at first. It can be achieved by analysing a standardized digital surface model (nDSM), which is created by subtracting the digital terrain model from the digital surface model. The result is a digital model representing the height of vegetation in the plain. Subtraction of two rasters can be performed in any GIS or remote sensing software.

The nDSM values can be adjusted to eliminate low height objects that could create noise in the digital image. The determination of the minimum height depends on the user of the methodology and the requirements of the analysis (typically it is a suppression of a height lower than 3 m). Subsequently, it is appropriate to apply a low-frequency filter to nDSM, such as the Filter tool in the ESRI ArcGIS environment, in order to eliminate the

possible detection of multiple tops on one tree. This phenomenon is very common due to the detailed resolution of UAV data.

The detection of individual trees and shrubs then takes place through focal statistics tools (e.g. the Focal Statistics tool in ArcGIS). For proper detection, it is necessary to select the appropriate shape and size of the kernel ("floating window" of focal statistics). The size of the kernel should correspond to the average size of the crowns in the given locality. With an improperly selected size, more or fewer peaks per tree can be detected.

The output is a point layer with treetops with X and Y coordinates, which is created by a combination of the *Raster Calculator* tool (using the conditional function *Con* (n nDSM '== ' Focal Statistics ', 1)) and the *Raster to Point* tool in ArcGIS. Visual inspection and manual adjustment are appropriate for maximum accuracy.

2.3.2 Determination of vegetation heights

For each point, i.e. for each detected tree, it is necessary to add the Z coordinate which represents the height of the stand at the given point. This information can be assigned to individual trees, for example, using the *Extract Values to Points* tool in ArcGIS. The values are from the modified nDSM layer and in the existing point layer new column is created with object height values.

2.3.3 Calculation of the distance of trees from the transport infrastructure

To map the distance of trees from the transport infrastructure a layer with a linear feature showing the road is necessary. Around these lines, an area within a specified distance can be defined using, for example, the *Buffer* tool in ArcGIS. The buffer zone covers any distance from the road axis towards the roadside according to the user's interest. Based on requirements, the buffer zone can determine the risk zone in which the fall of vegetation could cause damage. By setting the buffer distance, the user determines whether a tree will be evaluated as potentially dangerous if it could fall to the centre of the road or only to the curb.

Determination of the tree distance, either to the axis of the road or to the buffer zone, can be done using, for example, *Near* tool in the ArcGIS environment. The *Near* tool uses the point layer of trees and the polygon layer of road boundaries. As in the previous step, also this tool fills the existing point layer with a new column indicating the shortest distance between the specified elements.

2.3.4 Health condition of vegetation

Vegetation indices form an extensive subcategory of so-called spectral indices and are commonly used as a basis for assessing the health of vegetation. Vegetation indices

are often based on information obtained from sensors sensing at four different intervals of the electromagnetic spectrum, namely blue radiation 400–500 nm, green 500–600 nm, red 600–760 nm and near-infrared 760–900 nm. In the case of a professional camera with a higher spectral resolution, it is possible to work with vegetation indices using other parts of the electromagnetic spectrum, such as the Red Edge (700–750 nm), etc. As most vegetation indices are based on the same spectral bands, they are closely correlated (Klouček et al., 2018). For this reason, the methodology recommends (a) Greenness Index (GI) for RGB cameras and (b) Standardized Differential Vegetation Index (NDVI) for multispectral cameras, which equally represent a compromise between the complexity of the calculation, interpretability of results and are also an established indicator of health status of vegetation also outside the remote sensing community. The pair of recommended vegetation indices, together with the computational equations, is presented in Table 1.

Tab. 1 List of potentially usable indices for distinguishing vegetation health

| Vegetation index | Formula |
|--|--------------------------------------|
| Greenness Index | $GI = \frac{GREEN}{RED}$ |
| Normalized Difference Vegetation Index | $NDVI = \frac{NIR - RED}{NIR + RED}$ |

The designations GREEN, RED and NIR represent individual spectral bands

The assessment of health status within the methodology is based on an object-based classification approach using vegetation indices calculated from detailed RGB and multispectral UAV images. For this purpose, it is advisable to first create planar objects representing crowns from the identified treetops (point objects), for example, by creating a buffer zone (*Buffer* tool). In the defined zones, it is possible to calculate the average value of the vegetation index (*Zonal Statistics* tool), which enters the object classification process. The exact size of the packaging zone cannot be clearly defined, as it directly depends on the average size of the treetops in area of interest. Values from 0.5–1 m are recommended.

For the object classification itself, it is suitable to use the thresholding method, which includes the average values of pre-calculated vegetation indices in the buffer zones around the detected trees. Thresholding can be performed in any GIS or remote sensing software. This classification approach excels in its simplicity and easy interpretability, but care must be taken to select the correct threshold. The method is based on finding a threshold value, or values, distinguishing different stages of vegetation health. It is thus possible to distinguish individually detected trees into a predetermined number of health categories (from healthy trees, through stress, to dry trees). The number of categories and their classification scale (legend) is directly dependent on the needs and assignment

of a specific analysis. Thresholding can be performed manually, when the user finds the desired value or automatically using implemented algorithms, such as the Natural Breaks tool (Jenks) in ArcGIS, etc.

2.3.5 Resulting database

The final output of the methodology is a database containing information on the location of the stand (X and Y coordinates), its calculated height in meters (Z coordinates), the shortest distance to the adjacent transport infrastructure and health status. The following two subchapters present variants of database modification and a possibility of supplementing the database with information on whether a possible tree fall could affect the safety of traffic.

2.3.6 Identification of potentially dangerous trees

Based on accurate information about the position and height of individual trees, it is possible to determine whether the trees could interfere with the road. Any treetop whose height exceeds its distance to the roadside can be considered a potentially dangerous tree. The selection can be made from an existing point layer, e.g. with the *Select* tool in ArcGIS.

When detecting treetops, technical road objects that are higher than the specified minimum height can be identified, such as toll gates and high traffic signs or masts. These objects are usually part of the communication buffer zone, so the *Near* tool assigns them a zero value. It is appropriate to supplement the selection of potentially dangerous trees with the condition that the value of the distance itself is also higher than zero, which will exclude technical objects from the resulting database.

2.3.7 Database modifications

Based on the field survey, two possibilities for expanding or refining the resulting database of potentially dangerous trees were defined. These variants were subsequently tested and validated.

Database refinement variant

During road construction, the terrain is modified, and the surrounding area is often at a different altitude than the body of the transport infrastructure itself, see Figure 3. In case the vegetation near the road is on a slope, it can affect the tree fall. It is possible to adjust the calculated treetop height by the difference in altitudes between the nearest point at the road buffer zone and the top of the tree itself (h_1-h_2). Doing so it is possible to consider the surrounding terrain and its configuration. A similar principle can be used for underpasses and overpasses, where can be a significant difference between the height of the terrain and the height of the surface. The refinement is based on the created

layer of trees and extends it by a column with information about the difference in altitude of the road and of the tree trunk. Subsequently, it is possible to re-compare the height of the trees (but reduced by the difference of the mentioned heights) and their distance from the transport infrastructure.

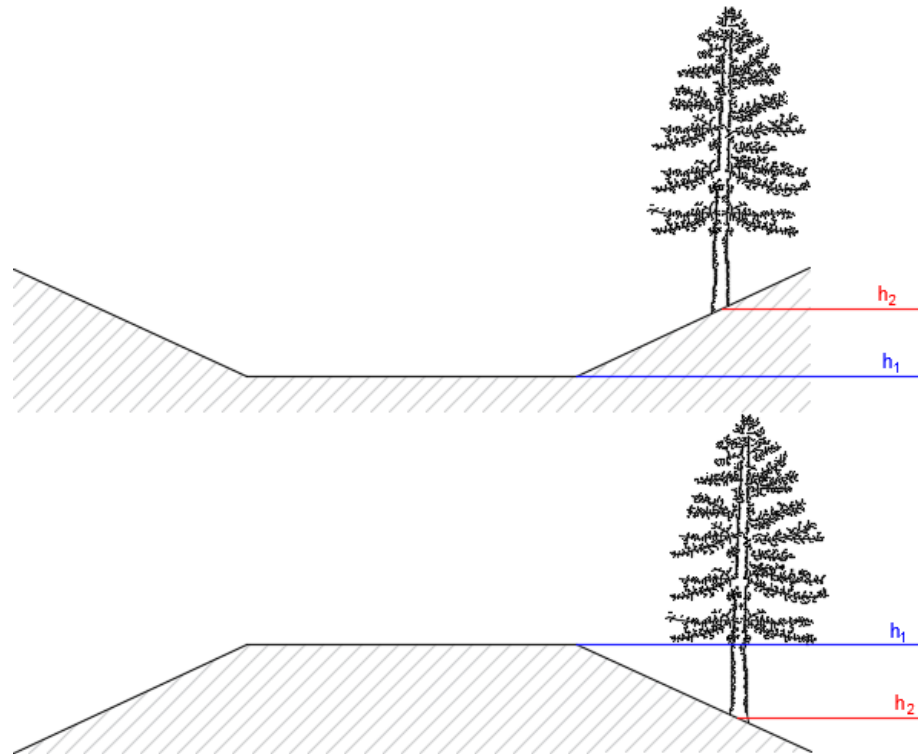


Fig. 3 Representation of the difference in altitude of the road and the surrounding terrain, source: own

Another option of the database refinement is the use of the difference between vegetation indices for two monitored periods calculated using map algebra tools (Raster Calculator). The largest decrease in the value of the vegetation index (for example, GI or NDVI) indicate newly weakened trees.

Database complement for maintenance needs

In the resulting database, it is also possible to record information about the location of the stand with respect to the side of occurrence and the mileage of the road. Such information is advantageously used as a basis for defining the vegetation to be removed. If it is necessary to manually create a waypoint stationing, it is possible to use, for example, the *Split line at point* tool, which can be used to split the communication line at a specified point (mileage), and then the *Generate points along with line* tool. It is advisable to set the distance to 1 m.

You can then use the *Near* tool to reassign the mileage to the previously identified dangerous trees. The side on which the vegetation is located can be determined, for example, by dividing the buffer zone into right and left parts and then attaching the membership information to one of the created packaging zones (*Spatial Join*).

2.3.8 Software requirements

Parts of the methodology of UAV data processing and tree detection itself can be processed both in commercial (ESRI ArcGIS, Harris ENVI, ERDAS IMAGINE, PCI Geomatics, etc.) and in freely available programs (QGIS, GRASS GIS, SNAP, R, etc.). Except for R, the mentioned software does not differ much and with their use comparable results can be achieved. R software requires more advanced knowledge of creating commands and their scripting according to the rules of the programming language. Before using any software, it is always advisable to study its user manual in detail, and especially the recommended parameters of the tools used.

2.4 Verification of tree heights by ground measurement

As mentioned in subchapter 2.2 UAV data processing, a suitable commercially available basis for calculating the vegetation height in areas with dense vegetation is DMR 5G. To verify the accuracy of the procedures, the trees were measured in-situ with an altimeter. The tree height calculated from digital processing was compared first with the difference between the digital terrain and digital surface model according to the survey and then the same difference while replacing the DTM with the DMR 5G (ČUZK).

HAGLOF Vertex IV, a digital ultrasound hypsometer, commonly used in forestry, was used to measure the heights of trees. The measurements took place in the campus of the Czech University of Life Sciences in Prague and focused on both coniferous and deciduous trees. Vertex IV works on the principle of trigonometric functions using a so-called transponder, which is an ultrasonic generator and an ultrasound signal receptor. Transponder is usually placed in the breast height (1.3 m), and thanks to the signal reflection, the distance is measured. The height of the object is calculated from two angles and distance. The optimal distance from the measured object is usually the one that corresponds to the height of the object. The accuracy of such measurement's ranges from 0 to 0.5 m. A total of 18 trees were measured, 3 coniferous and 15 deciduous. The predominance of deciduous trees is mainly due to the ten individuals in linden alley along a road. The measured heights were then converted to a point layer for each tree and compared with digital models, see Table 2.

Tab. 2 Comparison of measured and calculated vegetation heights

| Tree number | Height according to vertex | Calculated height (DMR 5G) | Difference between DMR 5G height and measured height | Calculated height (DMR from the raid) | Difference between DMR from the raid and measured height | Tree type |
|-------------|----------------------------|----------------------------|--|---------------------------------------|--|--------------------------|
| 1 | 13,0 | 13,0 | 0,0 | 11,3 | -1,7 | cherry tree |
| 2 | 13,9 | 13,3 | -0,6 | 11,1 | -2,8 | cherry tree |
| 3 | 12,8 | 12,8 | 0,0 | 10,7 | -2,1 | linden tree in the alley |
| 4 | 13,5 | 13,8 | 0,3 | 11,7 | -1,8 | linden tree in the alley |
| 5 | 14,8 | 14,3 | -0,5 | 12,3 | -2,5 | linden tree in the alley |
| 6 | 14,3 | 14,2 | -0,1 | 12,0 | -2,3 | linden tree in the alley |
| 7 | 14,2 | 14,5 | 0,3 | 12,7 | -1,5 | linden tree in the alley |
| 8 | 11,6 | 11,9 | 0,3 | 9,9 | -1,7 | linden tree in the alley |
| 9 | 9,9 | 10,6 | 0,7 | 8,6 | -1,3 | linden tree in the alley |
| 10 | 13,5 | 13,4 | -0,1 | 11,1 | -2,4 | linden tree in the alley |
| 11 | 20,5 | 19,3 | -1,2 | 17,8 | -2,7 | oak |
| 12 | 19,4 | 16,7 | -2,7 | 15,2 | -4,2 | oak |
| 13 | 16,8 | 17,6 | 0,8 | 15,9 | -0,9 | oak |
| 14 | 16,3 | 14,0 | -2,3 | 12,4 | -3,9 | pine |
| 15 | 19,5 | 19,5 | 0,0 | 18,0 | -1,5 | pine |
| 16 | 16,0 | 14,2 | -1,8 | 12,2 | -3,8 | spruce |
| 17 | 15,0 | 11,8 | -3,2 | 10,2 | -4,8 | maple |
| 18 | 10,8 | 11,1 | 0,3 | 9,8 | -1,0 | maple |
| ∅ | 14,8 | 14,2 | -0,5 | 12,4 | -2,4 | - |

On average, the calculated height of the tree based on digital models was in both cases lower than the height measured, for DMR 5G only by 0.5 m, while for the digital terrain model from the UAV flight mission even by 2.4 m. The height determined on the basis of the digital terrain model obtained by laser scanning is higher than the heights of the trees according to the digital terrain model from the UAV flight mission. The underestimation of the height of the trees calculated from the digital relief model according to the UAV flight mission compared to the heights measured by the vertex corresponds to the conclusions found by the authors Ganz et al. (2019).

2.5 Summary scheme

Figure 4 shows a simplified workflow diagram from the data acquisition by the drone to the creation of the resulting database containing vegetation information.

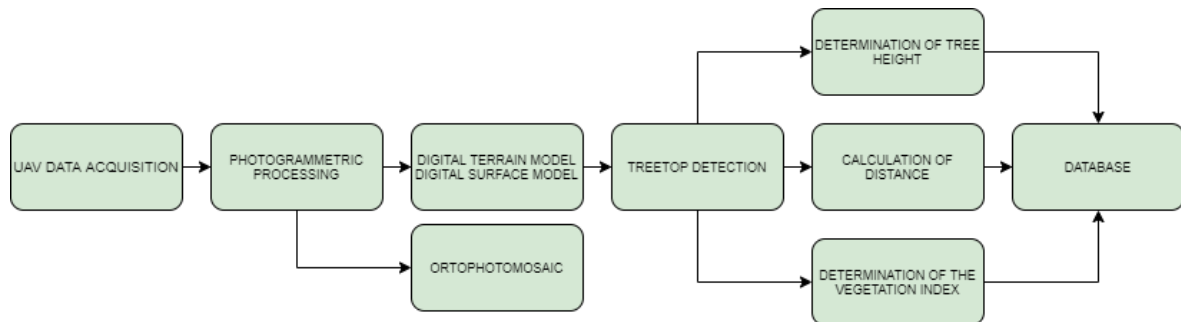


Fig. 4 Summary scheme of data processing, source: own

2.6 Specific example of data processing

Below is a specific example of the application of the proposed methodological procedure in a selected locality of interest together with a summary scheme leading to the described results. The place of interest is the section of the D6 motorway in the range of 9.0 to 13.5 km. The vegetation along the highway is relatively heterogeneous, some parts of the section are densely covered by vegetation, other parts are open landscape without vegetation or with scattered woody plants. In the evaluated section with the width of 300 m are mostly deciduous trees, mature coniferous trees occur at the cemetery Malé Přítočno and the end of the section. Part of the section is crossing the motorway with road III/0069 and the railway between Pavlov and Unhošť stops. Another intersection of the D6 highway is with the I/61 road near Malé Přítočno. There are also information signs, toll gates and noise barriers along the road. Vertical view of the orthophoto mosaic in the part of the section of interest where the overpass of the road I/61 is located, shows Figure 5.



Fig. 5 Vertical view of orthophoto mosaic of D6 motorway section, source: own

The UAV flight mission took place in October 2019. The location was captured by a standard digital camera in the visible spectrum (RGB) and a multispectral five-channel sensor (MicaSense RedEdge-M). Orthophoto mosaics and digital models were created by photogrammetric processing from the data obtained by the sensor carried by the unmanned vehicle, see Figure 6.

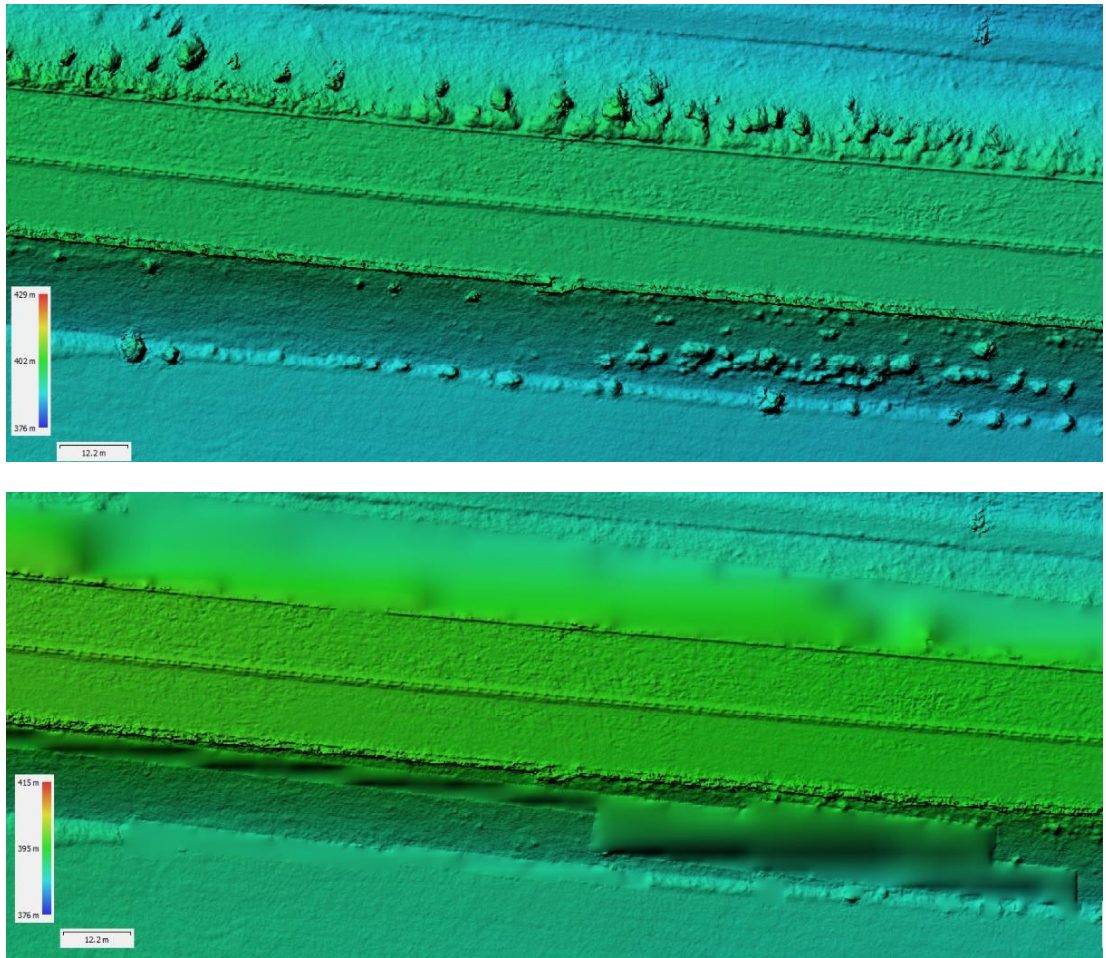


Fig. 6 Illustration of DSM (top) and DTM (bottom) of the D6 motorway section, source: own

Based on digital models, the above described methodological procedure was verified. To obtain the height of the objects themselves, a digital terrain model was subtracted from the digital surface model, thus creating a normalized Digital Surface Model (nDSM), which was further processed in ArcGIS software, see Figure 7.

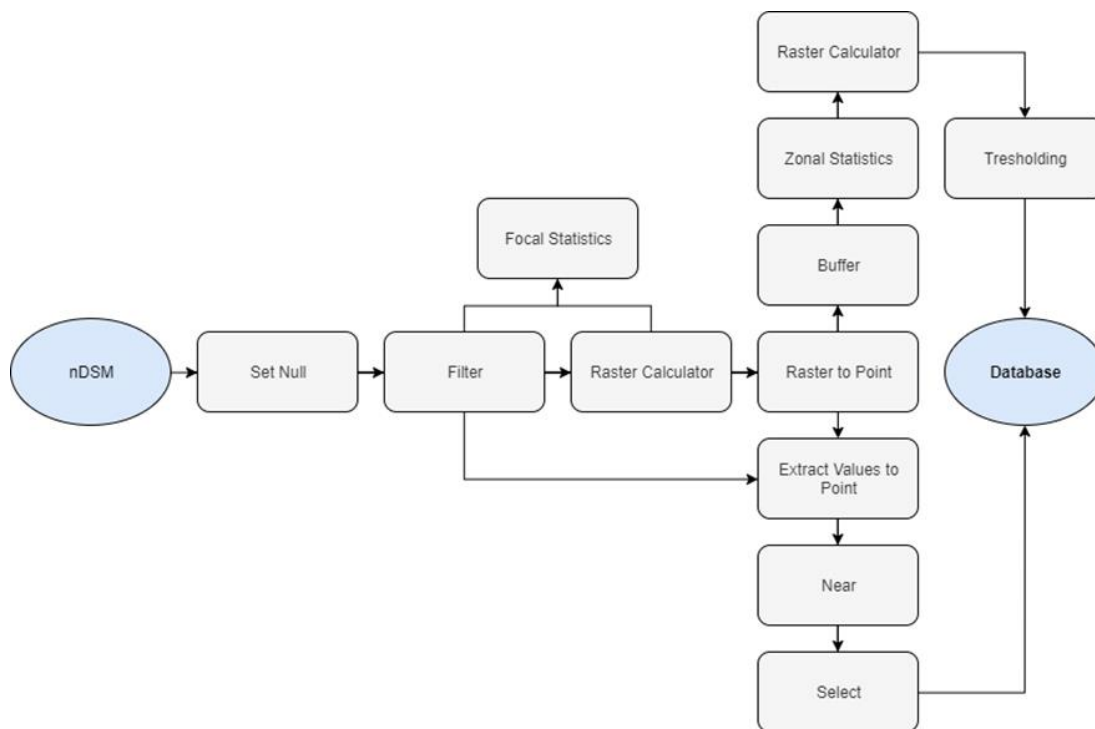


Fig. 7 Scheme of tools used in ESRI ArcGIS software, source: own

Before the treetop detection, normalized surface model was modified. Values of nDSM lower than or equal to 5 were replaced by a value of 0, as trees with a lower height are not considered dangerous according to the field survey. However, the value depends on the user and the location. Then, the modified nDSM was smoothed by a low-frequency filter, and then focal statistics was used to delimit the tops of objects higher than 5 m. Each raster cell represents one tree top and the value of the cell obtained by focal statistics corresponds to the value of the cell from the adjusted nDSM (*Raster Calculator*). Points were created from these cells using *Raster to Points* and to each point heights were assigned from the smoothed nDSM (*Extract Values to Points*). The penultimate step is to calculate the distance of treetop points from the infrastructure. In this case, the distance from the road verges in both directions was calculated. To remove erroneously detected treetops which are part of the traffic structure (toll gates, traffic signs higher than 5 m, etc.), a buffer zone was created around the axis of the road with a size according to width, a number of lanes and road verges width. The stand distance was calculated with the *Near* tool. All detected treetops are part of the database and potentially dangerous trees can be selected depending on their height and distance from the buffer zone (*Select*). If their height is greater than the distance, these trees can be described as potentially dangerous.

The output is a database of trees with data about the location (X and Y coordinates), its height and distance from the transport infrastructure. Figure 8 shows the result of a detection approach on orthophotomosaic background (top) and on the created digital surface model (bottom), where the green points represents safe trees in terms of

falling onto the transport infrastructure, while the red points represents potentially dangerous trees.

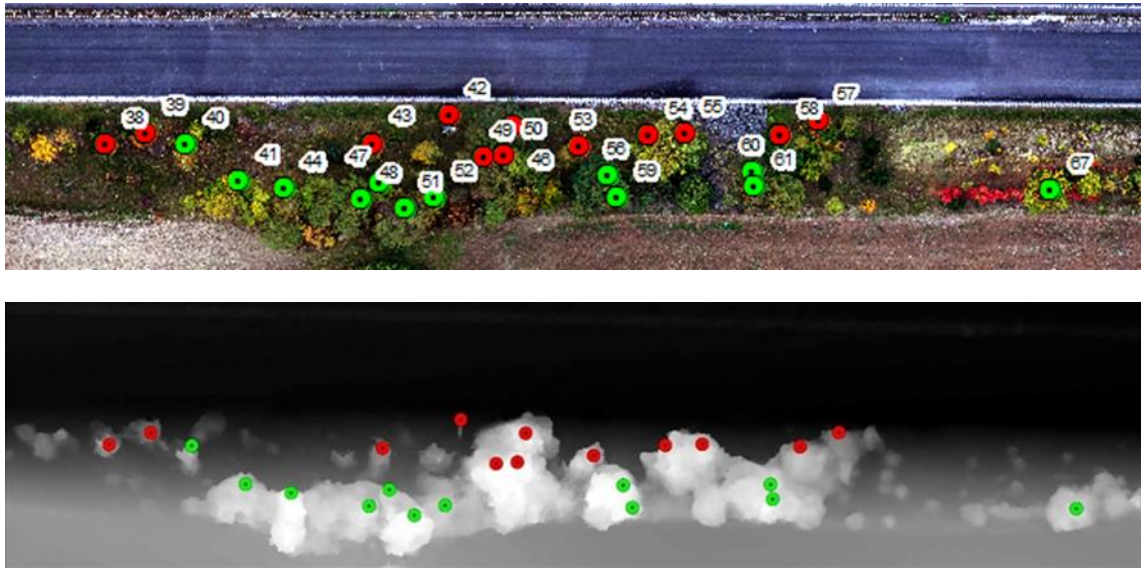


Fig. 8 Representation of the database of the D6 motorway section, orthophoto (top) and nDMP (bottom), source: own

In this example, the vegetation without the colour mark is less than 5 meters high and is therefore not detected. On the contrary, the detected element number 42 (see above) with the designation potentially dangerous is visibly different from other vegetation, because it is a large traffic sign, see Figure 9.



Fig. 9 Detected traffic sign, source: Panorama, Seznam.cz a.s.

Furthermore, the health status of vegetation along the highway was assessed. Below is the classification of trees (Figure 10) according to health status into three categories, where healthy trees are represented by green, slightly weakened by yellow and weakened by red points. The classification was performed using the thresholding

method. Using the *Natural Breaks (Jenks)* algorithm, the boundary of the three predetermined vegetation health categories was selected automatically.

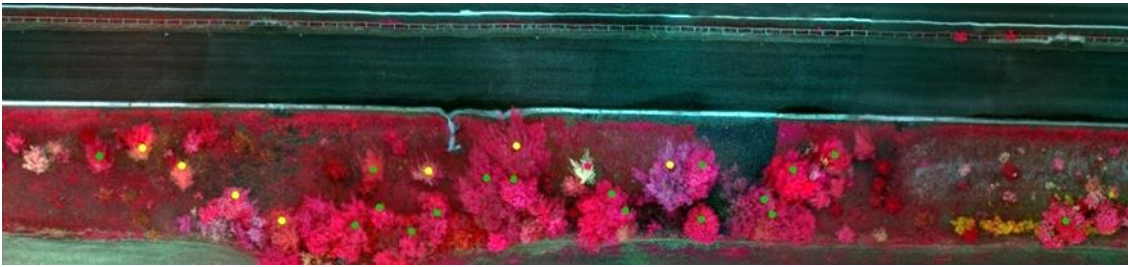


Fig. 10 Representation of the database of the D6 motorway section in false colours, source: own

Outputs for the selected locality of interest are shown in the following database example (see table 3), where the ID corresponds to Figure 8. The presented example demonstrates the usability of the methodology for vegetation mapping and possibly for detection of trees potentially dangerous to transport infrastructure.

Tab. 3 Sample of the resulting database from the locality of interest D6

| ID | X | Y | HEIGHT | DISTANCE | HEIGHT > DISTANCE | HEALTH CONDITION |
|----|-------------|--------------|--------|----------|-------------------|------------------|
| 38 | -763070,672 | -1038511,415 | 6,6 | 5,9 | TRUE | HEALTHY |
| 39 | -763065,869 | -1038514,969 | 5,1 | 4,2 | TRUE | SLIGHTLY WEAK |
| 40 | -763060,491 | -1038522,461 | 5,3 | 5,9 | FALSE | SLIGHTLY WEAK |
| 41 | -763029,082 | -1038523,805 | 6,2 | 11,0 | FALSE | SLIGHTLY WEAK |
| 42 | -763040,704 | -1038523,998 | 5,8 | 1,4 | TRUE | traffic sign |
| 43 | -763054,824 | -1038525,726 | 5,6 | 5,6 | TRUE | SLIGHTLY WEAK |
| 44 | -763055,383 | -1038525,841 | 8,2 | 12,1 | FALSE | SLIGHTLY WEAK |
| 46 | -763041,665 | -1038529,761 | 10,7 | 3,0 | TRUE | SLIGHTLY WEAK |
| 47 | -763045,123 | -1038531,009 | 5,3 | 11,3 | FALSE | HEALTHY |
| 48 | -763026,393 | -1038531,201 | 5,4 | 13,7 | FALSE | HEALTHY |
| 49 | -763023,511 | -1038531,970 | 9,6 | 7,4 | TRUE | HEALTHY |
| 50 | -763039,552 | -1038534,275 | 10,1 | 7,1 | TRUE | HEALTHY |
| 51 | -763035,037 | -1038534,371 | 7,5 | 14,9 | FALSE | HEALTHY |
| 52 | -763013,138 | -1038534,563 | 5,2 | 13,4 | FALSE | HEALTHY |
| 53 | -763003,149 | -1038536,484 | 8,4 | 6,0 | TRUE | WEAK |
| 54 | -762998,250 | -1038538,021 | 9,8 | 4,3 | TRUE | SLIGHTLY WEAK |
| 55 | -763010,545 | -1038539,846 | 10,0 | 4,0 | TRUE | HEALTHY |
| 56 | -762979,617 | -1038542,727 | 8,3 | 10,0 | FALSE | HEALTHY |
| 57 | -762985,380 | -1038542,823 | 5,8 | 2,0 | TRUE | HEALTHY |
| 58 | -763010,353 | -1038543,208 | 7,1 | 4,1 | TRUE | HEALTHY |
| 59 | -762991,046 | -1038546,473 | 8,0 | 13,1 | FALSE | HEALTHY |
| 60 | -762991,431 | -1038548,490 | 7,5 | 9,5 | FALSE | HEALTHY |
| 61 | -762991,483 | -1038548,102 | 7,5 | 11,5 | FALSE | HEALTHY |
| 67 | -763046,275 | -1038563,762 | 5,3 | 11,8 | FALSE | HEALTHY |

As mentioned in chapter 2.3.7, the resulting database can be further modified. One possibility of refining the database is to determine the difference between the altitude of the road and individual trees and then adjust the height of the trees by their difference. The altitude of the nearest points on road from each detected tree can be obtained using the *Extract Values to Points* tool, the same as for the trees themselves. Below is one of the possible procedures for using the tools in ESRI ArcGIS, see Figure 11.

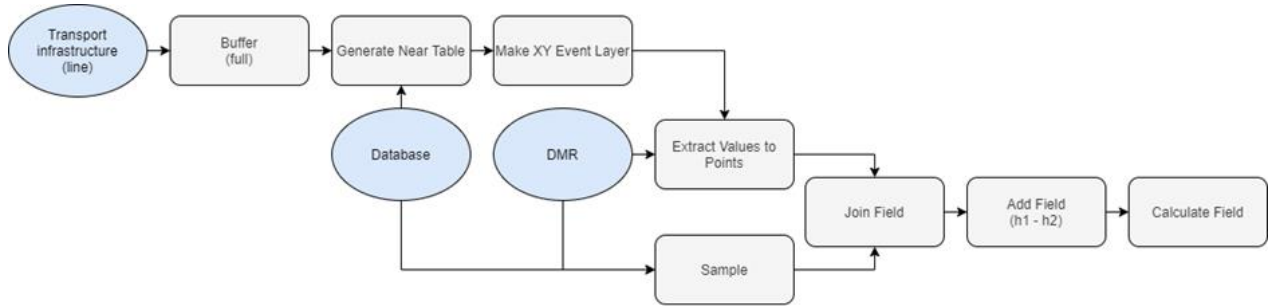


Fig. 11 Simplified database refinement scheme in ESRI ArcGIS software, source: own

Furthermore, it is possible to add data to the database usable in the maintenance of vegetation, specific information on the side of the occurrence of vegetation and its location along the road according to the kilometre marker. The *Generate Points Along Line* tool create points along the line, and the stationing of the entire line can then be calculated from a known kilometre marker. A specific example of a tool sequence using ESRI ArcGIS software is shown in Figure 12.

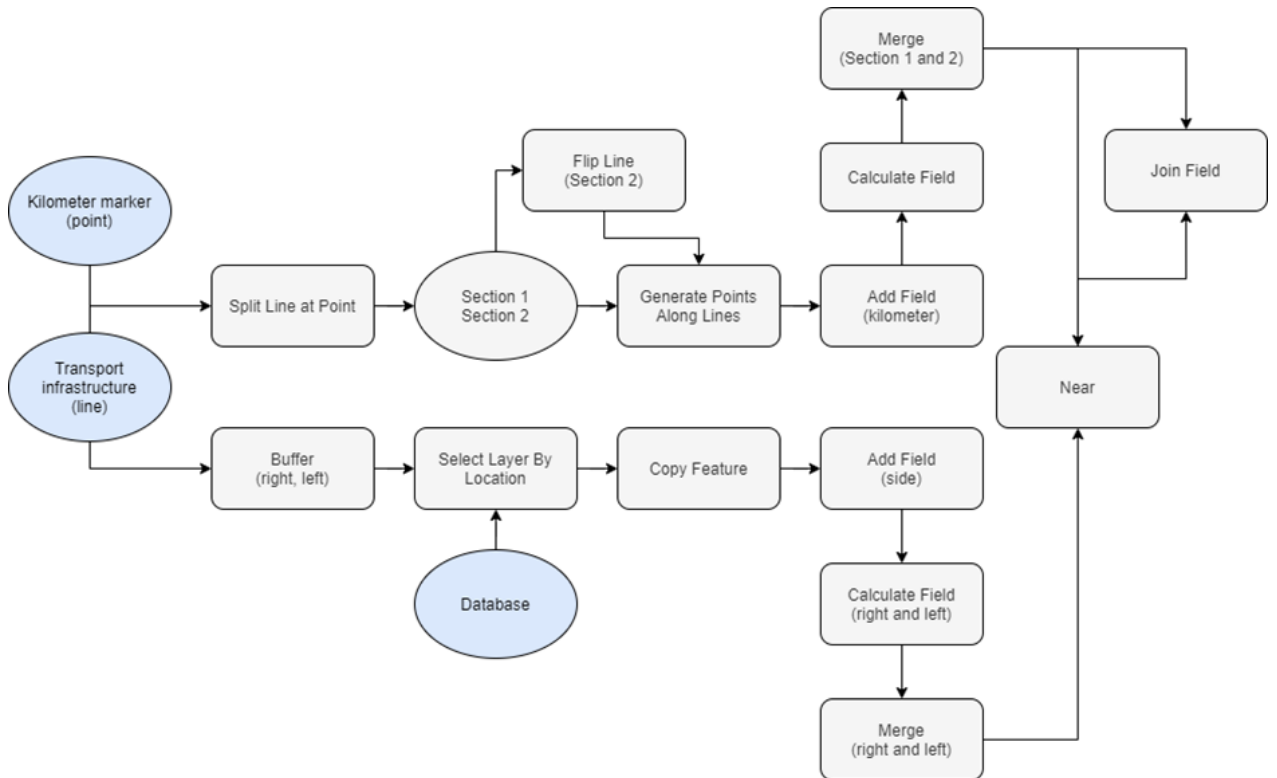


Fig. 12 Simplified database complement scheme in ESRI ArcGIS software, source: own

The settings of the *Generate Points Along Line* tool depend on the user's priorities, a distance of 1 m was used at the specified location. Table 4 shows an example of the final modification of the database.

Tab. 4 Example of resulting database refinement and complement

| ID | HEIGHT | DISTANCE | HEIGHT > DISTANCE | TERRAIN: h ₁ -h ₂ | HEIGHT + TERRAIN | HEIGHT + TERRAIN > DISTANCE | SIDE | KILOMETER |
|----|--------|----------|-------------------|---|------------------|-----------------------------|-------|-----------|
| 38 | 6,6 | 5,9 | TRUE | -3,1 | 9,7 | TRUE | RIGHT | 12,264 |
| 39 | 5,1 | 4,2 | TRUE | -2,6 | 7,7 | TRUE | RIGHT | 12,258 |
| 40 | 5,3 | 5,9 | FALSE | -2,9 | 8,2 | TRUE | RIGHT | 12,252 |
| 41 | 6,2 | 11 | FALSE | -4,6 | 10,8 | FALSE | RIGHT | 12,245 |
| 42 | 5,8 | 1,4 | TRUE | -0,5 | 6,3 | TRUE | RIGHT | 12,215 |
| 43 | 5,6 | 5,6 | TRUE | -2,6 | 8,2 | TRUE | RIGHT | 12,226 |
| 44 | 8,2 | 12,1 | FALSE | -1,2 | 9,4 | FALSE | RIGHT | 12,238 |
| 46 | 10,7 | 3 | TRUE | -1,1 | 11,8 | TRUE | RIGHT | 12,206 |
| 47 | 5,3 | 11,3 | FALSE | -5 | 10,3 | FALSE | RIGHT | 12,225 |
| 48 | 5,4 | 13,7 | FALSE | -6,4 | 11,8 | FALSE | RIGHT | 12,227 |
| 49 | 9,6 | 7,4 | TRUE | -3,9 | 13,5 | TRUE | RIGHT | 12,21 |
| 50 | 10,1 | 7,1 | TRUE | -3,5 | 13,6 | TRUE | RIGHT | 12,207 |
| 51 | 7,5 | 14,9 | FALSE | -6,5 | 14 | FALSE | RIGHT | 12,221 |
| 52 | 5,2 | 13,4 | FALSE | -5,7 | 10,9 | FALSE | RIGHT | 12,217 |
| 53 | 8,4 | 6 | TRUE | -3,6 | 12 | TRUE | RIGHT | 12,196 |
| 54 | 9,8 | 4,3 | TRUE | -2 | 11,8 | TRUE | RIGHT | 12,186 |
| 55 | 10 | 4 | TRUE | -1,5 | 11,5 | TRUE | RIGHT | 12,181 |
| 56 | 8,3 | 10 | FALSE | -4,8 | 13,1 | TRUE | RIGHT | 12,192 |
| 57 | 5,8 | 2 | TRUE | -0,5 | 6,3 | TRUE | RIGHT | 12,162 |
| 58 | 7,1 | 4,1 | TRUE | -1,4 | 8,5 | TRUE | RIGHT | 12,167 |
| 59 | 8 | 13,1 | FALSE | -6,4 | 14,4 | TRUE | RIGHT | 12,19 |
| 60 | 7,5 | 9,5 | FALSE | -3,9 | 11,4 | TRUE | RIGHT | 12,171 |
| 61 | 7,5 | 11,5 | FALSE | -3,8 | 11,3 | FALSE | RIGHT | 12,171 |
| 67 | 5,3 | 11,8 | FALSE | -6,2 | 11,5 | FALSE | RIGHT | 12,128 |

3. Comparison of novelty of procedures

The presented methodology combines the areas of GIS, remote sensing and forestry and enables the achievement of effective vegetation mapping along the transport infrastructure. The methodology based on the usage of unmanned systems brings an innovative solution that allows the entire process to be automated and applied comprehensively to larger territorial units. The advantage of using the methodological procedure is the application of modern approach and equipment in the form of unmanned aerial vehicles, which are characterized by the speed of data acquisition over a large area, the choice of time resolution and last but not least high spatial resolution, which allows individual detection of individual tree tops.

The scientific literature contains studies focused on the use of unmanned aerial vehicles for forestry use, both by photogrammetry using conventional digital cameras (Lisein et al., 2013; Zarco-Tejada et al., 2014) and by laser scanning (Lin et al., 2011; Wallace et al., 2014), or by comparing the two (Wallace et al., 2016). Another interesting study is the work of Ganz et al. (2019), which compares a photogrammetric method and a laser scanning method based on data obtained from drones and aircraft together with field measurements, which were both indirect through Vertex and direct after tree felling using tape on a tree trunk. Currently published studies confirm the usability of unmanned aerial vehicles for detecting treetops and calculating their height.

The methodological procedure represents a comprehensive practically applicable procedure for current monitoring and repeated mapping of vegetation along with the transport infrastructure, which according to the performed research is not available elsewhere at the time of elaboration of the this methodology and is, therefore, a new methodology. The described methodological procedure can achieve sufficiently accurate results in the detection of vegetation and technical elements in the vicinity of the transport infrastructure.

4. Description of the application of the methodology

The described methodology of tree detection in the proximity of the transport infrastructure is intended mainly for road owners and administrators. It is suitable for obtaining the height, distance and health status of vegetation along the transport infrastructure in large territorial units, both once and repeatedly. This methodological procedure can be used beyond national borders and can be practically applied in other countries with adaptation to local vegetation.

Within the project TAČR Zéta 2 No. TJ02000283: Safety mapping of vegetation along the transport infrastructure, the proposed methodology will be used as a basis for the creation of subsequent user-friendly software usable for the detection and mapping of vegetation along the transport infrastructure.

5. Economic aspects

The presented methodological procedure will enable road owners or administrators to effectively map vegetation along the transport infrastructure and, if interested, to detect potentially dangerous vegetation. Based on the determination of health status, heights of individual trees and their distance from roads using drones, the methodology offers a fast and effective way to obtain information about the condition of the stand and provides the data necessary for its regular monitoring. At the same time, it enables the acquisition of detailed information for announcing potential tenders for the maintenance of vegetation.

The financial demands of a raid by an unmanned system with an appropriate sensor depend on the size of the area of interest. With an area of 1 to 10 ha, the price ranges from 10 to 30 thousand CZK. In the case of linear structures, the area can be determined according to the length of the section of interest and the expected width of the sensor, however, it is advisable to increase the calculated area due to the need for sufficient transverse and longitudinal overlap of images, see chapter 2.1. The stated price is always a subject of a market offer and usually includes the alignment of the ground control points obtained by a geodetic instrument on the surface, as well as the processing of the recorded images into orthophotomosaics and digital models of the surface or terrain. In case of necessity or interest to use already made digital models of terrain or surface, commercially available data sets from ČUZK can be used. In such case, it is necessary to add to the total price the amount for payment according to the area, which represents approximately 30 CZK per 1 km² of the monitored locality. Software equipment is not included in the price, as it is up to the user whether to choose a commercial or freely available software solution.

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Legislation

Zákon č. 13/1997 Sb. Zákon o pozemních komunikacích

Předpis L2 – Pravidla létání; Doplněk X

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Safety mapping of the vegetation along the transport infrastructure

Certified methodology

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