

Method of developing the maps of passability for unmanned ground vehicles

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Abstract. The paper presents the methodology for developing passability maps that may be used for planning the movement of unmanned ground vehicles (UGVs). They were based on a standardised spatial data base in the scale of 1:25 000, created and used by the military forces and a high resolution digital terrain model. Maps were generated for square shaped primary fields. 5 sizes of such fields were used (side length 25, 50, 100, 200 and 500 m). Basing on the ground cover and terrain formation, for each primary field the index of passability (IOP) is calculated, being the terrain resistance coefficient. The obtained maps were compared to each other. As the presented methodology is completely automated, an analysis of the passability maps generation time depending on the size of the primary field was conducted. The obtained results demonstrated that maps that are most useful for planning UGV routes are those generated with use of the smallest primary fields (25 m), as they visualise the most terrain obstacles. The generated maps may be recorded in the UGV memory. As far as completely autonomous structures are concerned, this will enable the algorithms implemented in the vehicle, with the support of other sensors, to determine the optimal route of the UGV.

1. Introduction

The sense and utilization of unmanned vehicles is enormous. We can find a lot of various ways of their utilization, both in the civil and military area. Development of autonomous unmanned ground vehicles brings a key issue to be solved – determining the precise position of a vehicle in the area [1-3] and finding the optimal route to move.

Another perspective of interest are the particular factors limiting the speed of the vehicle over the terrain elements. For off-road terrain, it is of particular interest which factor caused the vehicle to be unable to traverse a terrain unit, a condition known as “NO-GO”. There are several Cross-Country Movement (CCM) models, which are developed for the navigation of military vehicles – e.g. see [4-7][21]. The outputs of these models can be in the form of a map or digital Global Positioning System (GPS) navigation implemented in an off-road vehicle.

The NATO Reference Mobility Model (NRMM) [4] is the Army model and simulation standard for predicting vehicle mobility. The NRMM is a comprehensive computer model that predicts vehicle speed performance on roads, trails, and cross-country in all weather conditions, including terrain conditions associated with winter. The motion resistance is used in combination with other resisting forces (e.g., vegetation, slope) to determine the maximum possible force controlled by speed. Model outputs are velocities traveling up- and down-slope, average velocity, and a numerical code related to the speed-controlling algorithm. The CCM models calculate (accumulate) the proportion of the terrain



where speed-made-good is limited by selected factors – see e.g. [8-13] or complete factors: slope gradient, soil conditions, vegetation, hydrology, roads, scenario, weather, etc. – see [14-17].

The aim of this paper is to discuss the issues related to the development of passability maps for Unmanned Ground Vehicles (UGV). Due to the fact that such vehicles are very often used by the military forces, the maps were generated with use of a terrain objects database used and generated by the army. This database contains information about land cover and terrain formation, which, pursuant to military reference standards, directly influence the capability of the vehicle to move in the given terrain. It was the direct intention of the authors for the resulting map to be generated in a completely automated and direct way (without any unnecessary processing), with use of the data contained in the topographic spatial database. The authors set a research task consisting in such selection of the relevant parameters of the generated map that would make it optimally suitable for predicting the influence of the geographic environment on the movement of the UGV. This influences the functional properties of the developed map, which in turn determines the possible scope of its application. These parameters are connected with the accuracy of the map, which manifests itself in the time needed by the computer system to develop such map.

2. Method

2.1 Study area

Maps of passability have been generated in the area in the province located in the eastern part of the Czech Republic – Olomouc Region. The selection of this area was dictated by the fact that it is an area with a variety of terrain features that affect passability (Figure 1). The area occupies approximately 64 km² and encompasses large watercourses (the Morava river and the Trusovický Potok), as well as vast areas of forests (17% of the analyzed area). In this area, there are both large terrain slope gradient levels - up to 10 degrees and extensive plains. It also includes the provincial capital (Olomouc). The density of the road network is variable and depends on the degree of land use.



Figure 1. Study area

2.2 Used data

In the presented methodology for the development of land passability maps, a topographical database based on a Digital Landscape Model (DLM) was used. Models of this type are the backbone of national spatial information infrastructures created in various countries. An example of such a national database is BDOT10k (*Baza Danych Obiektów Topograficznych - Database of Topographic Objects* in scale 1:10 000, covering the territory of Poland) and used in this article database DMU 25 (Digitální

model území - Digital Model of Area, which is the database for territory of the Czech Republic). Another interesting example is the OpenStreet map. This is open source database, which covers the whole world. The model used in these examples assumes storage of terrain objects as vector data. Depending on the spatial characteristics of the objects, it will be collected in the form of closed polygons (so-called area objects), broken lines (line objects), and singular points (point objects).

The maps of passability generated for UVG, are developed mainly for military purposes; therefore in experiments, the DMU, a standardized vector spatial database, was used. In terms of detail, it is equivalent to a topographic map at scale 1:25 000. In its conceptual model, there are 170 thematic categories, grouped into nine thematic layers: boundaries, terrain relief, physiography, transport, development, hydrography, vegetation, aviation content, and industry. This is a standard, general geographic elaboration, used by the Czech Republic Armed Forces (as well as others NATO Forces), whose data organization is very precisely defined in the Digital Geographic Information Exchange Standard (DIGEST) as a product of Defence Geospatial Information Working Group (DGIWG). It imposes a unified way of organizing data and developing the database on all compilers. The study carried out used this compilation as the primary source of data on land cover elements. The terrain formation data was derived from the DMR4 (*Digitální model reliéfu 4. Generace – Digital Model of Relief of 4. generation*), on the basis of which a numerical model of land slopes was also generated. Used digital terrain model stores information about relief in form of grid in 5 m by 5 m size.

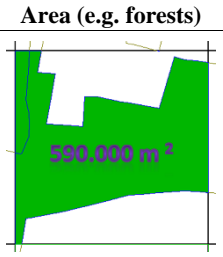
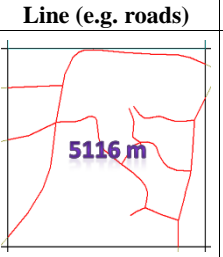
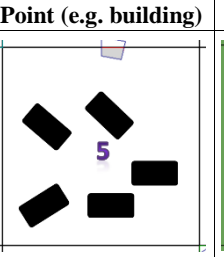
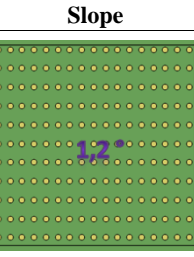
2.3 Processing data

The main assumption for the conducted research was to refer passability to a square-shaped primary field. For each field was calculated Index of Passability (IOP) for the surface area of the whole square. IOP is an estimate reflecting the degree of limitation of vehicular speed by land cover elements. In this study, this index is determined on a continuous scale and decreases from 1.0 (easily passable terrain – GO terrain) to 0.0 (impassable terrain – NO GO terrain). In order to do so, grids of squares of different side lengths (25, 50, 100, 200 and 500 m) were generated at the analyzed area. For each of them, the information about elements of land cover were obtained in an automated way, with use of a specially written software application (Table 1):

- for surface object classes (e.g. forests, lakes, built-up areas) – the total surface area of each area found in the given primary field;
- for linear objects (rivers, roads, railways, contours) – the total length of the linear object located within the given primary field;
- for singular objects (buildings, enclosures) – the number of objects located within the given primary field.

Apart from that, a digital terrain inclination model was generated for the analyzed area. It was created with use of DMR4. Each primary field was assigned the land denivelation parameter defined as the average slope, calculated from all points of the digital model of land inclinations located in the area of the given primary field.

Table 1. Exemplary visualisation of data in used data model

Area (e.g. forests)	Line (e.g. roads)	Point (e.g. building)	Slope
			

The developed data model constituted the basis for generating land passability maps. They were created with use of the method based on the Vegetation Roughness Factor (denoted as VRF). VRF is a

numerical evaluation reflecting the degree of the speed limit related to the movement of vehicles through the different types of land cover.

Each class of objects found in a given data model was assigned a resistance coefficient, provided that classes of objects which facilitate the passability of troops, it takes the value in the range (0, 1> (e.g. roads, tracks and open area), classes identified as hindering (limiting) passability were assigned the index of VRF (I_{VRF}) in the range <-1,0) (waters, forests, built-up areas, etc.), while classes of objects that do not affect passability (neutral) were assigned a coefficient of 0 (these are mainly single objects or cartographic elements such as descriptions or contours).

The index of passability (IOP) assigned to the whole primary field was calculated with use of the following algorithm:

- Due to the fact that information on land cover for each primary field is stored in the database in different units and that it has different numerical ranges, prior to the start of the analysis they are normalised to the range from 0 to 1, pursuant to the formula (1).

$$V' = \frac{V - V_{min}}{V_{max} - V_{min}} \cdot (new_max - new_min) + new_min \quad (1)$$

where V is an input value and the V' – normalized value of input. Consequently, $[V_{min}, V_{max}]$ is the interval of input data and $[new_min, new_max]$ is a new data range $[0, 1]$.

- Indices of passability for all primary fields were calculated with use of the following formula:

$$IOP_i = A_i^{n1} \cdot I_{VRF}^{n1} + L_i^{n2} \cdot I_{VRF}^{n2} + N_i^{n3} \cdot I_{VRF}^{n3} + \quad (2)$$

where:

- IOP_i is the index of passability of primary field with i index.
- For area objects, A_i^{n1} is a normalized area (within i primary field) of $n1$ feature class.
- For linear objects, L_i^{n2} is a normalized length (within i primary field) of $n2$ feature class.
- For singular point objects, N_i^{n3} is a normalized quantity (within i primary field) of $n3$ feature class.
- I_{VRF} is the Vegetation Roughness Factor of $n1, 2$ or 3 feature class.

Formula (2) takes into account all object classes that are contained in the analyzed databases. The obtained indices of passability are then again normalised to a constant range from 0 to 1, pursuant to the formula (1).

A detailed description of the method presented above is provided in [6, 7]. In order to apply the methodology described above, it was necessary to assign a terrain resistance coefficient to each class of objects contained in the used database (DMU 25). The coefficient was assigned individually to a specific class of objects – see Table 2.

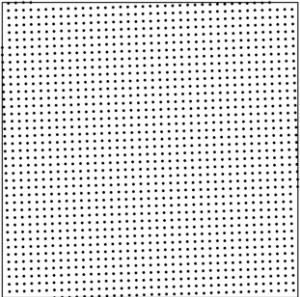
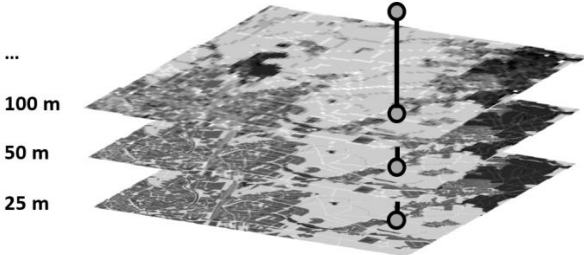
Table 2. Sample VRF (I_{VRF}) values, source: own study

Facilitating		Hindering		Neutral	
<i>Object</i>	<i>I_{VRF}</i>	<i>Object</i>	<i>I_{VRF}</i>	<i>Object</i>	<i>I_{VRF}</i>
Roads	0.7	River	-1.0	Monument	0
Footpath	0.4	Swamp	-0.8	Tree	0
Firebrake	0.3	Forest (area)	-0.8	Chimney	0
Tunell	0.2	Orchard	-0.5	Forest (point)	0
Open areas (without area objects)	0.5	Slope	-0.4	All cartographic elements (eg. labels)	0

As a result of the application of the above algorithm 5 passability maps were created (for sizes of primary fields – 25, 50, 100, 200 and 500 m). In order to compare the content of these maps, the grid (in size 200 by 200 m) of control points were placed in the test area (Table 3A). For each of these points, data were obtained about the passability of the primary field where the given control point was

located (Table 3B). This operation was performed for all generated maps. Thus, each control point was assigned 5 indices of passability. In order to analyse the correlations between the generated maps, Pearson correlation matrices were calculated for the indices of passability obtained for all control points. Calculations were performed separately for each size of the primary field. Basic statistic parameters of the obtained distributions of Indexes of Passability (arithmetic average and standard deviation) were calculated.

Table 3. A - distribution of the control points in 200 by 200 m grid, B – visualisation of data collection for a control point

A	B
	

3. Results

The indices of passability determined for various primary field sizes were a basis for generating passability maps on various levels of detail. Fragments of maps created for various sizes of square shaped primary fields are presented in Figure 2.

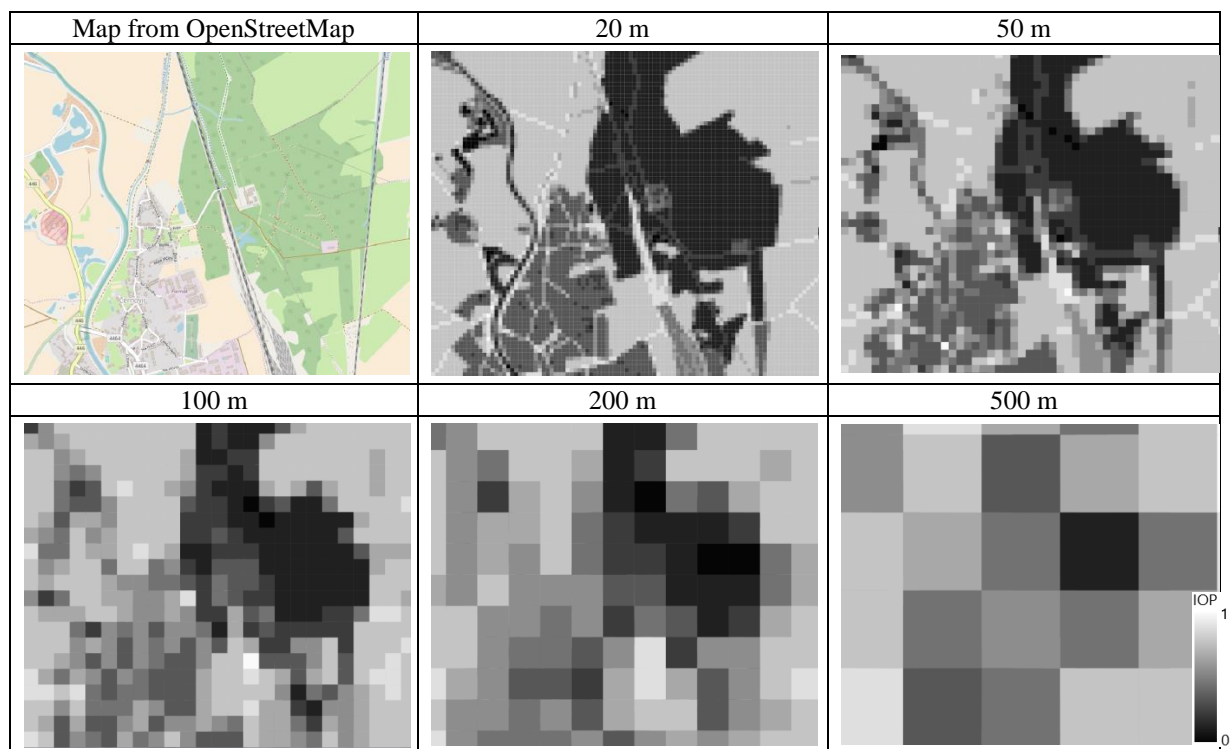


Figure 2. Passability maps on various levels of raster data detail

The Pearson correlation matrices that demonstrate the degree of similarity between individual maps are presented in Table 4. These matrices, together with the basic statistic parameters were generated separately for control points generated in grid in size 200 by 200 m (1576 points on test area).

Table 4. Demonstration of the degree of similarity between individual maps

	Average	Std. dev.	25 m	50 m	100 m	200 m	500 m
25 m	0.61	0.17	1	0.94	0.86	0.83	0.65
50 m	0.62	0.16		1	0.92	0.87	0.67
100 m	0.62	0.16			1	0.90	0.72
200 m	0.62	0.15				1	0.79
500 m	0.68	0.17					1

The distribution of the generated indices of passability for each tested primary field size is presented in the histograms in Diagrams 1-5 (see Figure 3). They were generated for control points located on test area.

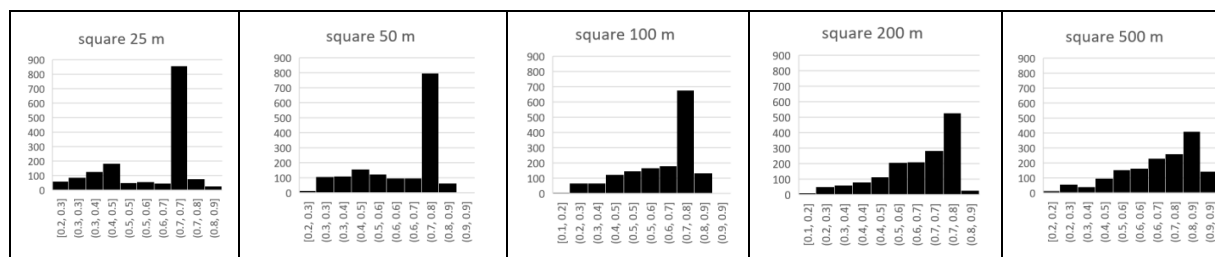


Figure 3. The distribution of the various generated indices of passability

The total map generation time consists of: preparation of the data model (grid of squares) and direct calculation of the index of passability. The results of these operations for the test area (Olomouc province), are presented in Table 5. Calculations were performed on a computer with Intel Xeon e3-1230 v5 3, 4 GHz (4 cores) processor, memory: 8 GB DDR IV. For this hardware configuration, the time of preparation of the data model for 1 square (regardless of its size) is 1.1 s. Calculation of IOP, in accordance with formula (2), for one square takes approx. 0.03 s.

Table 5. Map generating time, source: own study

Square side length	Number of squares in tested area	Time of data model preparation	IOP generating time	Total map generating time
25 m	101869	1 d 7 h 08 min	51 min	1 d 7 h 59 min
50 m	25630	7 h 50 min	13 min	8 h 3 min
100 m	6490	1 h 59 min	3 min	2 h 2 min
200 m	1664	0 h 30 min	1 min	31 min
500 m	289	0 h 5 min	> 1 min	5 min

4. Discussion

Visualisations of the generated passability maps (Figure 2), demonstrate unambiguously that maps created basing on the smallest primary fields (25 m) enable to distinguish a large number of narrow UGV movement corridors. This map shows the course of roads, paths and ducts in forests, which are the key element for the movement of all vehicles (not only UGVs). For larger primary fields (50 and 100 m), the details of the terrain situation gradually disappear. These maps only show a general outline

of terrain barriers. In maps generated with use of the largest analysed primary fields (200 m, and particularly 500 m), the generalisation level is so high that only the largest, consistent impassable areas are distinguishable. These maps are unsuitable for planning the routes of relatively small vehicles such as UGVs due to the high degree of content generalisation. This results from the fact that each individual primary field contains numerous elements that affect passability both in a positive and negative way and the passability of all these elements is “averaged” for the whole field.

The correlation matrices (Table 4) calculated basing on the IOPs obtained for control points in the 200 by 200 m grid, demonstrates that the correlation coefficient between maps diminishes with the increase in differences in the size of primary fields. This is a linear decrease (Figure 4A). However, it should be noted that the correlation coefficients between maps generated for primary fields of similar sizes are very high (e.g. 0.94 between maps based on 25 m and 50 m primary fields and 0.90 between maps based on 100 and 200 m primary fields). This proves that maps generated with use of primary fields of similar sizes are highly similar. The PPC between maps with the highest difference in primary field sizes (25 and 500 m) is low and equals 0.65.

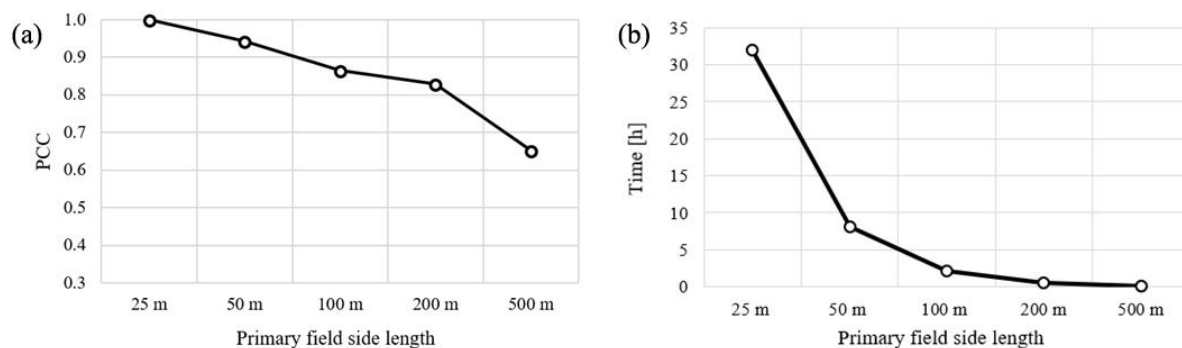


Figure 4. The correlation matrices based on the IOPs between (a) PCC and primary field size (for 25 m fields) and (b) map generating time and primary field size

Figure 3 (25-100 m square) showing the histograms of IOP distribution, clearly illustrate the increase in the number of samples with the index of passability of approx. 0.7. This peak gradually disappears for larger sizes of primary fields (Figure 3, 200-500 m square). The main reasons for the discussed growth are roads that are visualised in passability maps based on the smallest primary fields (25, 50 m). Along with the increase in generalisation that takes place gradually, with the growing size of primary fields, the course of roads becomes less and less visible on the map. This is manifested in the diagram of the distribution of indices of passability for the largest primary fields (200 and 500 m). They do not contain the characteristic increase in the number of primary fields with an IOP = 0.7.

An essential factor that affects the possibility to use the presented methodology, for operational purposes, is the time of generating passability maps of a specific accuracy. The conducted tests demonstrate, that it takes approx. 30 hours for the developed application to create the most accurate map for the smallest primary field (side length 25 m) and an area of 16 km² (Table 5). Increasing the size of primary fields and thus lowering the number of squares in the tested area, shortens the time of generating the resulting map considerably (to only 8 hours for the 50 m primary field, Figure 4B).

5. Conclusions

The presented methodology for the development of passability maps for UGVs is universal and completely automated. The determined index of passability may be calculated with use of any vector spatial database. It offers a possibility to generate primary fields of various shapes and sizes. Finally, different *Vegetation Roughness Factor* coefficients may be selected for specific classes of objects included in the used spatial database. This is quite important for creating passability maps for various types of vehicles and terrain conditions. An example might be a large, heavy vehicle, for which the forest may be a major barrier (then, the “forest” class of objects should be assigned a low VRF, e.g. -

0.8). On the other hand, the forest will not constitute an important barrier for a small vehicle, so a higher VRF may be assigned in this case (e.g. -0.2), as such vehicle may manoeuvre between trees.

The generated passability maps may also be used for planning the movement of UGVs. The operator of an unmanned vehicle may use them as auxiliary materials while controlling the vehicle. Moreover, planned routes of the unmanned vehicles may be placed on such maps. However, the most interesting way to use the generated maps is to record them in the vehicle memory. This is particularly important for fully automated devices, because, with the support of other sensors installed in the UGV, this may enable the algorithms implemented in the vehicle to determine the optimum route independently and thus the vehicle may move across the terrain in a completely automated way.

The conducted tests demonstrated that passability maps based on smaller primary fields are more suitable to be used by UGVs, due to higher level of detail. The smallest primary field used in the discussed analyses was a 25 by 25 m square. Hence, it would be reasonable to generate passability maps based on even smaller primary fields (e.g. 10 by 10 m or 5 by 5 m). This will be the direction of further research. Another element is to increase the number of parameters that are taken into account when determining the index of passability. The currently presented algorithm takes into consideration only terrain cover and relief elements to determine passability. It is planned to expand its scope by considering soil parameters as well as weather conditions [18] and accuracy of data e.g. see [19, 20].

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