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Photogrammetric approach to automated checking of DTMs

Marketa Potuckova

Abstract
Geometrically accurate digital terrain models (DTMs) are essential for orthoimage production and many other applications. Collecting reference data or visual inspection are reliable but time consuming and therefore expensive methods for finding errors in DTMs. In this paper, a photogrammetric approach to automated checking and improving of DTMs is evaluated. Corresponding points in two overlapping orthoimages are found by means of area based matching. Provided the image orientation is correct, discovered displacements correspond to DTM errors. Improvements of the method regarding its reliability are discussed. Thresholds for image matching parameters are applied. A topographic database can be used for eliminating areas where mismatches might occur. Experimental results based on coloured aerial images at the scale of 1:25 000 and DTM derived from 5 m contour lines are reported.

1. Introduction

National mapping agencies and private photogrammetric companies dealing with orthophoto production have high demands for the quality of digital terrain models (DTMs). It is not exceptional that orthoimages are produced in two or three year's intervals. DTMs have to be updated at the same rate. In some countries DTMs with a nation-wide coverage are available only in a form of contour lines digitized from topographic maps. Such DTMs must also be updated; their overall accuracy must be improved in some cases. Therefore the methods for checking and possible correcting of DTMs are required. Measurement of single points by GPS or manual measurement in stereoscopic models are accurate and highly reliable methods but at the same time they require a lot of time and resources.

Several approaches to automatic checking and correcting DTMs can be found in the literature. Regarding photogrammetry, two methods were studied:

1. the method based on finding corresponding points in overlapping orthoimages and deriving height corrections from measured parallaxes (Norvelle, 1996, Skarlatos and Georgopoulos, 2004)
2. the backprojection method which principle is to find conjugate points in an original stereopair of aerial images. A new position of a point on the ground is calculated from found image co-ordinates and known orientation parameters (Schenk et. al, 2001).

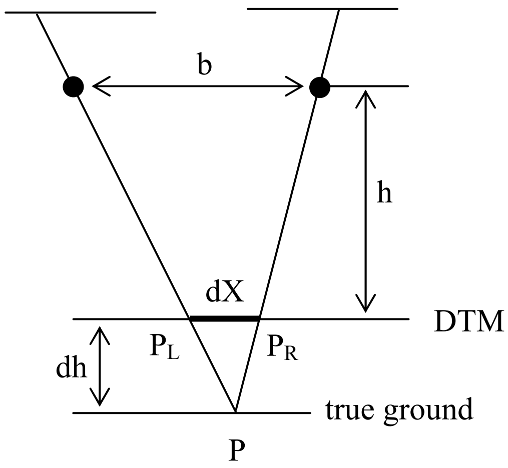
The goal of this paper is to investigate improvements of the first method, especially how to avoid errors in matching that cause introduction of new outliers to the corrected DTM. The proposed procedures are tested and results evaluated by means of reference data. The investigation concerns single point accuracy only. It does not evaluate the capability of a model to describe the real terrain (modelling accuracy).

2. Methodology

The applied methodology is based on the DTM editing technique called ‘Iterative Orthophoto Refinements (IOR)’ method (Norvelle, 1996). The corresponding points in two overlapping orthoimages derived from an erroneous DTM show parallaxes that are used for calculating DTM corrections. The parallaxes are found automatically by image matching.

2.1 Height corrections

The geometric relation between a correction of a DTM and a found parallax between corresponding points in the left and right orthoimages is shown in Fig. 1. Mathematical expression of this relation is given by formulae 1 and 2. The second part of the formula 2 does not have a big influence especially for lower flying heights (Höhle and Potuckova, 2005).



$$\frac{dh}{dX} = \frac{h + dh}{b} \qquad (1)$$

$$dh \approx dX\,\frac{h}{b} + \left(dX\,\frac{h}{b}\right)^2 \frac{1}{h} \qquad (2)$$

dh ...... *DTM correction*
dX ..... *measured parallax*
h .... *flying height*
b .... *distance between projective centers (base)*

Fig. 1: Relation between a correction dh of the DTM and a horizontal parallax found by means of matching corresponding points P_L and P_R in the overlapping orthoimages.

The calculation should be repeated several times in order to clear all the discrepancies between the orthoimages and a DTM. The method does not give any information regarding where the correction should exactly be applied (Skarlatos and Georgopoulos, 2004). In the following text, a found correction is assigned directly to a grid point.

2.2 Matching strategy

The corresponding points in two overlapping orthoimages are found by means of area based matching, namely cross-correlation and least squares matching (LSM).

Because the goal is to find points on the terrain and not on the surfaces rising above the terrain, it is better to avoid such points in advance before DTM corrections are sought. A topographic database or digital topographic map can be used for this purpose. A query whether a point is inside a polygon corresponding to e.g. a house or forest area can be sent to a database. In case of a small area and a digital topographic map, a raster solution can be applied. The layers of the map containing areas that are going to be excluded are converted into a raster with a sufficient ground sampled distance. A colour different to a background is given to polygons corresponding to excluded areas. If a grid point falls within the areas with a different colour, it is eliminated from the matching procedure. Fig. 2 shows an example of such solution. A buffer zone around areas to be excluded can be created in order to avoid cases when the matched point is close to high objects and therefore a calculated correction is influenced by their height.

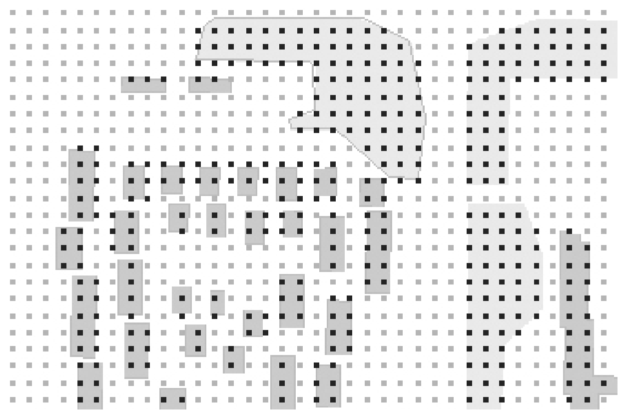


Fig. 2: Raster approach to excluding points on surfaces rising above the terrain. DTM points within built up and forest areas will not be used for deriving DTM corrections.

Based on previous experience (Höhle and Potuckova, 2005, Potuckova 2004), the following thresholds for similarity measures and one geometric constrain are applied in order to minimize outliers in matching:

- minimal value of normalized cross-correlation coefficient
- precision of shift parameters of LSM
- matching along epipolar lines

Setting tough thresholds for similarity measures eliminates a lot of outliers but at the same time the amount of points where the checking method can be applied decreases considerably. Therefore, two other approaches were tested.

Assuming that the found height correction should be almost the same when choosing a template from the left orthoimage and a search window from the right orthoimage and vice versa, the matching is carried out twice and the differences in the found corrections are evaluated.

Finding DTM corrections directly in the grid points can course problems if the conditions for matching are not sufficient at this point (low contrast, a single object raising above the terrain, etc.). Therefore matching in several points well distributed in the neighbourhood of the grid point is performed. The histogram of the obtained corrected heights is evaluated. An interval of a width of $\pm 3\sigma$ with highest occurrence of points is found. A value of a standard deviation σ corresponds to an expected accuracy of the corrected model. A final corrected height assigned to a grid point is calculated as a mean of the heights belonging to the interval. These two approaches are referred as an L-R and a histogram method in the following text.

3. Test of the method

Obtained results are based on a dataset consisting of a DTM, a stereopair of aerial images, and reference points. The test covers approximately 2.1 km^2 of both built up and opened land areas in the southern part of the town of Aalborg, Denmark. The terrain is mostly flat or slightly rolling. The heights vary between 3 m and 65 m. The XY-coordinates are based on the coordinate system UTM/EUREF89 and heights to the Danish national vertical datum DVR90. In order to be able to evaluate results of the applied method, all the calculations were carried out only in the points where the reference values had been measured. Reference data were collected neither on the top nor in the closest neighbourhood of houses and vegetation. Therefore it was not necessary to use a topographic database for eliminating points on surfaces as mentioned in general matching strategy in the chapter 2.2.

3.1 Data description

The DTM is based on 5 m contour lines digitised from topographic map sheets 1:50 000. A 10 m square mash regular grid was derived afterwards. According to information from the National Survey and Cadastre in Copenhagen, the maps reflect the situation from 1984/85. The accuracy of heights is quoted to 2 m or better but in steep slopes it can rise up to 10-20 m (Geodata-info, 2005).

Coloured aerial photographs at the scale of 1:25 000 were taken with a wide-angle analogue camera RMK Top 15. Scanning was performed with the resolution of 21 µm. Orientation parameters of the two overlapping images were obtained by means of relative and absolute orientation in the photogrammetric workstation (ISDM™, Z/I Imaging). Some of the control points were measured by means of GPS, some were determined by means of aerotriangulation of a block of 6 images covering larger area. The final internal accuracy of absolute orientation of the model was rather high, RMS_{XY}=0.1 m, RMS_Z=0.2 m in the 18 control points.

Orthoimages with ground sampled distance of 0.5 m were derived in the program Base Rectifier™ of Z/I Imaging. Both orthoimages cover only the model (overlapping) area. In order to minimize errors from interpolation, the distance between anchor points of 2 pixels (1 m) was set. Bilinear interpolation was used.

Reference points were measured semiautomatically using the software package ISDC™ of Z/I Imaging. The low flight images at the scale of 1:3 000 were used for this purpose. Orientation of the images was carried out by means of aerotriangulation with GCPs measured by GPS (RTK, accuracy of 2 cm in each co-ordinate). Based on heights of the check points, a standard deviation $\sigma_{Z\_ori} = 8$ cm was achieved. Each reference point was measured twice with a standard deviation of a mean value of $\sigma_{Z\_meas} = 3$ cm. It gave a standard deviation of a single reference point of $\sigma = (\sigma_{Z\_ori}^2 + \sigma_{Z\_meas}^2)^{1/2} = 9$ cm. Such accuracy is about four times better than an accuracy that can be achieved from imagery 1:25 000 ($\sigma = 0.1‰h = 0.4$ m). Theoretically, almost 22 000 points in the grid of 10 m could be measured in the test area. As mentioned before, houses, areas of high vegetation, and areas with very low contrast and textures were avoided. All together only 10 390 points were measured. It corresponds to 47% of the test area.

The comparison of the DTM with reference values is summarised in Tab.1. The RMS error of 1.4 m is even better than quoted accuracy of 2 m. 1.6% of points where a difference to reference value is grater than 3RMSE can be considered as outliers.

Number of points	10 390
RMSE	1.4 m
Mean	0.3 m
σ	1.4 m
Δh_{min}	-10.9 m
Δh_{max}	7.2 m
Number of outliers $\lvert\Delta h\rvert < 3RMSE$	165 (1.6%)

Tab. 1: Comparison of a given DTM with reference data.

Except of mentioned programs for orientation of images, orthoimage derivation, and measurement of reference points, self-developed MATLAB® routines were applied in order to perform all the calculations concerning the methodology described in the chapter 2.2.

3.2 Results

The calculation was done in several steps in order to tune the whole procedure and achieve the most satisfactory results. For the matching purposes the coloured orthoimages were converted into greyscale images by means of the function 'rgb2gray' of MATLAB's Image Processing Toolbox.

3.2.1 Pixel size

The first problem that had to be solved was choosing a proper template size in order to assure sufficient grey level variations for area based matching. Several calculations with a different template size were carried out and a success was evaluated by means of comparison of corrected DTM heights with reference data. The results are summarised in Fig. 3. The template was moving along an epipolar line ±1 pixel within a search area. The base of the stereopair was rotated about 5 gon with respect to the X coordinate axis. Therefore the size of the search area in the Y direction was set equal to the size of the template plus 2 x 4 pixels. In X the direction the search window had to be wide enough to find the biggest errors in the DTM. Based on Tab. 1 and specifications of the DTM, the biggest error was below 11 m which corresponds to a planimetric shift of 7 m or 14 pixels (considering 60% overlap). The size of the search window in the X direction then corresponds to the template size plus 2 x 14 pixels. It should not be forgotten that the size of the template and search windows has also a direct impact on calculation time.

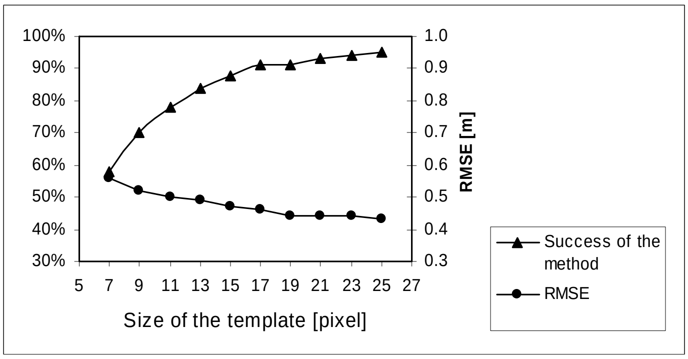


Fig. 3: Dependence of the success of the method on the size of the template. Success of the method was determined by number of points where the difference between a corrected height and a reference height was smaller than 3σ, where σ is an expected accuracy of the corrected model (0.4 m). At the same time root mean square error (RMSE) of the points that fulfilled the criterion was calculated. A template size of 19 x 19 pixel^2 was considered as a good compromise between success of the method and calculation time.

Based on Fig. 3, the template size of 19 x 19 pixel^2 (or 9.5 x 9.5 m^2) and the search window size of 27 x 47 pixel^2 (or 13.5 x 23.5 m^2) was used. This result supported solution can be used as a starting point for other investigations in this area with the imagery of the same or similar parameters. Due to κ angle of the original images, the X-parallax in formula 2 was for practical calculations replaced with a radial displacement $dR=(dX_{LR}^2 + dY_{LR}^2)^{1/2}$, where dX_{LR} and dY_{LR} were the differences in X- and Y- coordinates of the matched points from the left and right orthoimages.

3.2.2 L-R method

Fig. 3 shows that the method of finding DTM corrections is rather successful but new blunders are also introduced. The question is how to distinguish automatically without reference data where the method works and where it cannot work or where blunders might occur. The thresholds for similarity measures as well as matching with a template chosen from the left and in the second calculation from the right orthoimage were applied with the results summarised in the Tab. 2. If an accuracy of matching σ_{LSM}=0.3 pixel (≈0.15 m) which corresponds to a height error of σ_{hLR}=0.25 m is assumed, then the standard deviation of the difference of the derived corrected heights by L-R matching should not exceed $3\sqrt{2}\sigma_{hLR}$=1.1 m (threshold T_{hLR}).

A			B		
L-R method T_{hLR}, T_r, T_{LSM}	Before correction	After correction	L-R method T_{hLR}, T_r, T_{LSM}, T_{dh}	Before correction	After correction
Number of points	8481 (82%)		Number of points	5878 (57%)	
RMSE	1.4 m	0.5 m	RMSE	0.7 m	0.5 m
Mean	0.3 m	0.1 m	Mean	0.1 m	0.1 m
σ	1.4 m	0.5 m	σ	0.6 m	0.5 m
Δh_{min}	-10.8 m	-5.9 m	Δh_{min}	-2.5 m	-2.4 m
Δh_{max}	7.2 m	10.3 m	Δh_{max}	5.3 m	4.4 m
Number of outliers $\vert\Delta h\vert < 1.2$ m	2321 (27%)	229 (3%)	Number of outliers $\vert\Delta h\vert < 1.2$ m	340 (6%)	98 (2%)

Tab. 2: Results of the L-R method. Thresholds for similarity measures were set as following: correlation coefficient $r>T_r$, $T_r = 0.5$; precision of least squares matching σ_{LSM} < TLSM, $T_{LSM} = 0.3$ pixel; difference of two corrected heights obtained for one grid point $\Delta h_{LR} < T_{hLR}$, T_{hLR}=1.1m (part A). To avoid big outliers, only points with a correction dh < T_{dh}, T_{dh} = 1.2 m (≈3σ, see the histogram method) were accepted (part B).

Tab.2A shows that an improvement of DTM was achieved but new, relatively high outliers still appeared. After studying a relation between applied corrections and the achieved differences between corrected DTM and reference values, a new threshold, namely the size of corrections was set. Tab.2B shows that in this case an overall accuracy of the checked area (only 57%) did not improve too much. Nevertheless, the amount of outliers decreased considerably.

3.2.3 Histogram method

Corrected heights were found for 25 evenly distributed points around each grid point. The surrounding points were within a square of 19 x 19 pixel^2 or 9.5 x 9.5 m^2 with a grid point in the centre. A histogram of the corrected heights of the points belonging to one grid point that had passed similarity measures criteria was created. The size of the intervals of the histogram was equal to ±3σ, where σ is an expected accuracy in height of a single point that can be achieved from aerial images at the scale of 1:25 000, taken with a wide angle camera with overlap of 60% and was set to σ=0.4 m (0.1‰h). The overview of achieved results is in the Tab. 3.

Histogram method T_r, T_{LSM}, $T_{\#p}$	Before correction	After correction
Number of points	8973 (86%)	
RMSE	1.4 m	0.4 m
Mean	0.3 m	0.1 m
σ	1.4 m	0.4 m
Δh_{min}	-10.9 m	-6.0 m
Δh_{max}	7.2 m	2.5 m
Number of outliers $\vert\Delta h\vert < 1.2$ m	2400 (27%)	95 (1%)

Tab. 3: Results of the histogram method. Thresholds for correlation coefficient $r>T_r$, T_r = 0.3, precision of least squares matching $\sigma_{LSM} < T_{LSM}$, T_{LSM} = 0.3 pixel, and a number of points within an interval with highest occurrence of points $T_{\#p}$ = 75% were applied.

Similarly to the L-R method, a threshold T_{dh} for calculated height corrections was applied. A value $T_{dh} = 1.2$ m (≈3σ) proved to be rather tough (compare Tab. 4A). By setting a softer criterion $T_{dh} = 3.6$ m (≈6σ), the same result with respect to accuracy was achieved but at the same time the number of points where the method was successful increased as well as the number of corrected outliers (see Tab. 4B).

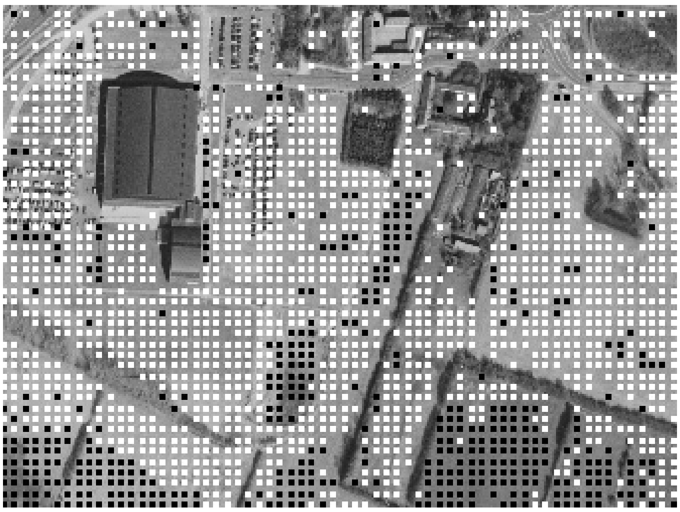
A			B		
Histogram method T_r, T_{LSM}, $T_{\#p}$, T_{dh1}	Before correction	After correction	Histogram method T_r, T_{LSM}, $T_{\#p}$, T_{dh2}	Before correction	After correction
Number of points	7328 (71%)		Number of points	8811 (85%)	
RMSE	1.0 m	0.4 m	RMSE	1.2 m	0.4 m
Mean	-0.1 m	0.1 m	Mean	0.2 m	0.1 m
σ	1.0 m	0.4 m	σ	1.2 m	0.4 m
Δh_{min}	-10.9 m	-2.0 m	Δh_{min}	-10.9 m	-2.2 m
Δh_{max}	2.6 m	2.5 m	Δh_{max}	4.2 m	2.5 m
Number of outliers $\lvert\Delta h\rvert < 1.2$ m	959 (13%)	81 (1%)	Number of outliers $\lvert\Delta h\rvert < 1.2$ m	2238 (25%)	93 (1%)

Tab. 4: Results of the histogram method including a threshold for obtained DTM corrections. Values T_r, T_{LSM}, and $T_{\#p}$ were set in the same way as in Tab. 3. The threshold for DTM corrections was set as $T_{dh1} = 1.2$ m (part A) and $T_{dh2} = 3.6$ m (part B).

3.3 Discussion

Using L-R and histogram methods, the whole investigated DTM can be divided into two categories:
1. The method works successfully, i.e. all the criteria are fulfilled. Most of the outliers are eliminated. After applying corrections, the overall accuracy of the DTM improves.
2. The criteria are not fulfilled; the points in this category must be checked by means of another method, e.g. manual measurement in stereomodels.

The division has been carried out fully automatically. The result can be displayed graphically (compare Fig. 4).



▫ category 1: corrected DTM points
▪ category 2: points where the method failed

The distance between grid points is 10 m.

Fig. 4: Division of DTM into two categories: 1 – model was checked and improved, 2 – application of another method is necessary. The division is carried out fully automatically.

Applying a size of corrections as a criterion deteriorates the 'correcting' power of the method. On the other hand, it eliminates most of remaining outliers. The points where all criteria are fulfilled except of the criterion for a correction value can be moved to an extra category of points. By means of filtering or visual inspection the biggest outliers can be removed and then the points can be returned to the first group again.

The suggested approaches tried to check as many points as possible. If only a random check is required, templates on grid points can be checked for radiometric measures contrast, entropy, or parameters w and q of the Förstner operator that assure good matching conditions. Only templates fitting the high criteria required for the mentioned measures would be matched. Based on literature and own experience (Schenk et al., 2001, Potuckova, 2004) the number of checked points can decrease down to 10%.

Whether the proposed method is used only for checking or also for an improvement of DTM depends on the data available. The tested DTM was of a lower accuracy than the accuracy that is possible to gain from 1:25 000 imagery. Therefore an improvement was possible.

The histogram method proved to be more successful but it requires much longer computation time (23 more points per grid point were matched comparing L-R method). Improvement of the reliability of both methods could be also achieved by running several iterations.

4. Conclusion

The method of DTM checking based on two overlapping orthoimages was investigated. The attention was mainly paid to procedures that eliminate outliers caused by mismatches in area based matching. Two approaches using several measurements per grid point together with applying rather soft criteria for the normalised cross-correlation coefficient and the precision of least squares matching proved to be successful. More than 80% of investigated points were moved into category 'checked and improved'. Overall accuracy of points within this category improved more than 60%. The number of outliers among these points was also minimised, in the ideal case down to 1%. The whole process can run automatically. At the end the user obtains two files – one with corrected part of a DTM and the second with points where another method must be applied such as manual measurement in stereomodels. A disadvantage of the proposed approach, especially the histogram method, might be the calculating time. Nevertheless, this problem is becoming minor with increasing computer power.

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