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Failure prediction in automatically generated digital elevation models

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Abstract

Developments in digital photogrammetry have provided the ability to generate digital elevation models (DEMs) automatically and are increasingly used by geoscientists. Using overlapping imagery, dense grids of digital elevations can be collected at high speeds (150 points per second) with a high level of accuracy. The trend towards using PC-based hardware, the widespread use of geographical information systems, and the forthcoming availability of high-resolution satellite imagery over the Internet at ever lower costs mean that the use of automated digital photogrammetry for elevation modelling is likely to become more widespread. Automation can reduce the need for an in-depth knowledge of the subject thus rendering the technology an option for more users. One criticism of the trend towards the automated "black box" approach is the lack of quality control procedures within the software, particularly with reference to identifying areas of the DEM with low accuracy. The traditional method of accuracy assessment is through the use of check point data (data collected by an independent method which has a higher level of accuracy against which the DEM can be compared). Check point data are, however, rarely available and it is typically recommended that the user manually check and edit the data using stereo viewing methods, a potentially lengthy process which can negate the obvious speed advantages brought about by automation. A data processing model has been developed that is capable of identifying areas where elevations are unreliable and to which the user should pay attention when editing and checking the data. The software model developed will be explained and described in detail in the paper. Results from tests on different scales of imagery, different types of imagery and other software packages will also be presented to demonstrate the efficacy and significantly the generality of the technique with other digital photogrammetric software systems.

Keywords: Digital photogrammetry; DEM; Accuracy; Classification; Strategy parameters

1. A brief introduction to digital photogrammetry and DEMs

The definition of photogrammetry most widely used is that of Slama (1980, p. 1) who states that "Photogrammetry is the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena". In essence, spatial information is obtained from pairs (*stereopairs*) of overlapping images (terrestrial, satellite, or aerial) once knowledge of the position and orientation of each image is obtained.

There is now a new era in photogrammetry known as digital photogrammetry (DP). With DP, processing is carried out using digital imagery (either scanned film-based imagery or imagery captured with a digital camera) on a workstation or high-performance PC. Many of the tasks in the photogrammetric workflow have now been successfully automated which is seen by

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many as the primary advantage of such systems (Heipke, 1999; Saleh, 1996). The use of standard off-the-shelf components in the hardware (as opposed to the specialised, high precision optical and mechanical parts in earlier systems) has reduced the price of digital photogrammetric systems (DPSs), widened the user base, and increased the number of potential applications. The level of user training now required to produce accurate data is greatly reduced, and DPSs offer a much greater degree of functionality.

One of the processes that have been successfully automated is the generation of DEMs. To do this, the software automatically finds common or conjugate points on two overlapping images and, with a knowledge of the position and orientation of the two images, 3D co-ordinates in the object space can be obtained. The DEM is usually generated in a regular user-defined grid format. The generation process can be carried out at high speeds with typical collection rates of 150 points per second. This allows an inexperienced user to achieve in 10 min what previously took a trained and experienced photogrammetrist 6 or 8 h on an analytical plotter.

Fundamental to the automatic generation of DEMs is the process of image matching. This is the process of finding conjugate points in the two images and is done in one (or a combination) of two ways — area or feature based. Area-based matching, as the name suggests, matches small areas or patches in each digital image using cross-correlation or least-squares matching techniques. Feature-based matching identifies objects such as the edges of buildings, roads, etc., which are visible in both images. However, the process of image matching can be problematic because both methods are prone to failure in certain areas (Heipke, 1995). Area-based techniques have difficulty in regions with monotonous, uniform textures, such as man-made features or areas of sudden elevation change, and feature-based techniques suffer in monotonous regions with few features. When the software encounters such areas, it usually finds an incorrect match for the conjugate points which results in erroneous elevation values. An example of this type of failure can be seen in Fig. 1.

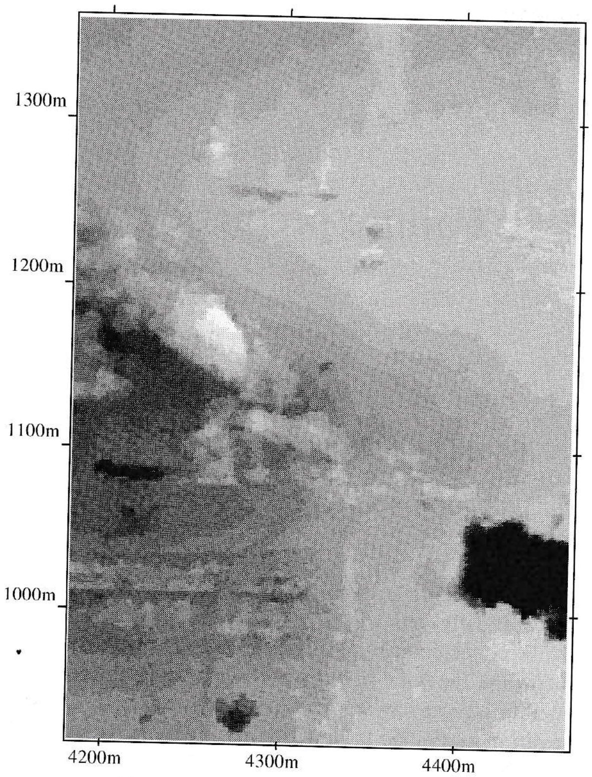

Fig. 1. Raster image of failed DEM.

It can be seen from Fig. 1 that the DEM generation algorithm has failed in a large section of the DEM (denoted by the black area on the right side). The reason for this failure is probably a lack of image content, as there are no sudden elevation changes in the area. From examination of the raster image, it would appear that there are no other problem areas of data, but it is impossible to tell how accurate the information is without comparing it to some other measure of the surface.

The usual method to assess the accuracy of the DEM is either quantitatively by comparing it with checkpoints (points collected by an independent data source with a higher order of accuracy) or qualitatively by the user (Heipke, 1995). Qualitative testing involves interactive editing of points that do not appear to lie on the surface (the DEM is overlaid on a stereomodel of the surface) through the use of stereo vision on a DPS. This can be lengthy process and, as with previous technology, requires expertise and experience to carry out accurately and efficiently.

The collection of checkpoint data prolongs the expense of the ground survey process and is not always practicable. If checkpoint data are available, global measures of the DEM accuracy can be obtained by comparing the elevation of the checkpoint with the elevation of the DEM at the same planimetric position. The most widely used global measure of accuracy is the root-mean-square error (r.m.s.e.) (Li, 1988) where r.m.s.e. $=\sqrt{(\Sigma dh^2)/n}$, where dh is the residual at each check point, and n the number of checkpoints.

A frequent criticism found in recent literature is the lack of quality control procedures in modern DP software. The technology allows for an answer, i.e., a DEM to be generated with ease, but provides little help in assessing the quality of the output (Cooper, 1998). As Heipke (1999, p. 81) states "... most of the ... algorithms have only little knowledge about when they work correctly and when they fail".

2. The strategy parameters used in DEM generation

Many DPS software manufacturers allow the user a degree of control over the automatic DEM generation process with a set of strategy parameters. These are user-definable values that control the acceptance and quality control functions in the software. Parameter definition allows the user a degree of control over the algorithm such that the nature of the resulting DEM can be changed (i.e., different levels of interpolation can be used). Zhang and Miller (1997) suggest that the parameters are functions of terrain-type, signal power, flying height, x and y parallax, and image noise level. In theory, a correct set of parameters will provide an accurate DEM with only successfully correlated points included and unsuccessful points rejected from further DEM processing. An incorrect set may result in filtering successful points and the inclusion of badly correlated points (known as false fixes) or simply failure to find correlated points (Gooch et al., 1999).

The ERDAS Imagine OrthoMAX software (ERDAS, 1994) uses an area correlation-based algorithm with 14 strategy parameters. A full list of the strategy parameters and their default values are shown in Table 1 and from the descriptions, it is not always obvious what the parameters mean, or what effect each would have on the resulting DEM. Smith and Smith (1996, p. 523) state that the "... parameters are written in a technical language and, even if the basic image matching technique is understood, it does not always help in determining the use of all the parameters as many are obviously software-dependent". Other DPSs use different sets of parameters and other terminology. For example, the Match-T product has 28 parameters (Smith and Smith, 1996) while the Phodis TS software from Carl Zeiss uses just two. Loodts (1996) criticises the use of "... uncontrollable 'magic' strategies ..." in automatic DEM algorithms, but provides no details upon how to specify and control the parameters.

The correct choice of parameters should accept all of the successfully correlated points and filter out the unsuccessful. The wrong choice can have a detrimental effect on the accuracy (Gooch and Chandler, 1998). Fig. 2 shows a DEM of the same area shown in Fig. 1 but generated using the default strategy parameters and a different minimum threshold value (0.6 rather than 0.5 as in Fig. 1). With the new minimum threshold setting, the software has successfully correlated many more points and there is no large failed area as in Fig. 1. This simple example highlights the criticality of selecting the correct values for the strategy parameters.

A few studies have been carried out on the strategy parameters used in the OrthoMAX software. Smith (1997) carried out an extensive study of the parameters on two sets of aerial imagery. He isolated areas with different land-cover types on the imagery and then systematically varied the parameters, with the aim of optimising them with respect to accuracy. The results indicate that the manipulation of the parameters can have a significant effect. For example, in one residential area, changing the Minimum and Maximum Template

Table 1
Default strategy parameters and their default values (adapted from ERDAS, 1994)

Parameter	Value
Minimum threshold	0.6
Noise threshold	0.4
Maximum parallax (x)	5
Minimum template size	7
Maximum template size	9
Minimum precision	0.5
Rejection factor	1.5
Skip factor	2
Edge factor	2.5
Start RRDS	4
End RRDS	0
y-Parallax allowance	0
Resampling	Bilinear
Post-processing	On

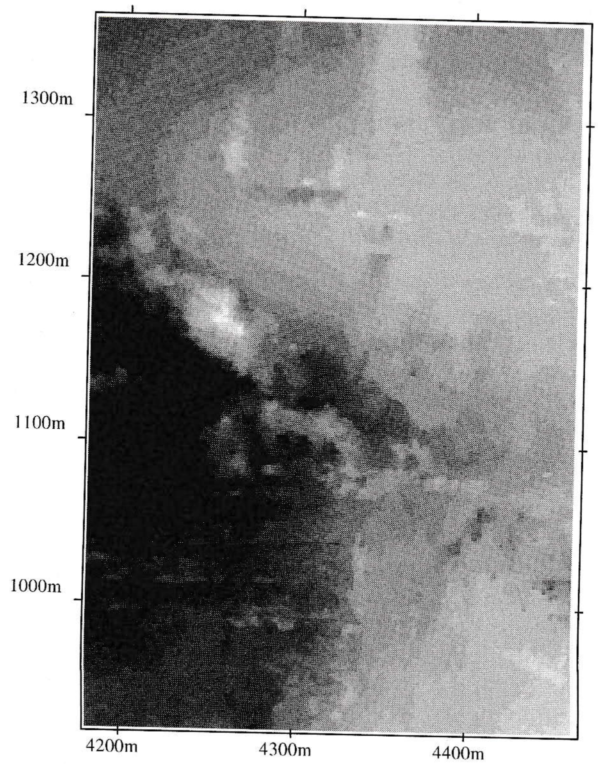

Fig. 2. Successfully correlated DEM.

sizes from the default values of seven and nine pixels to five and 20, respectively, improved the mean error of the DEM from −0.218 to −0.081 m. Similarly, changing the Maximum Parallax parameter from the default value of five to 10 in an area of open Moorland improved the mean error from −0.061 to 0.006 m. Overall, Smith reported that the software was well suited to smooth, textured surfaces and that areas with sudden elevations changes reduced the accuracy. He suggests that the test results could be applied to other data sets, but makes no recommendations as to how they could be applied to close-range-type applications such as medical and architectural imagery.

Butler et al. (1998) tested the OrthoMAX software on a set of imagery of a gravel riverbed with a flying height of just 2.2 m. Because of the scale of the imagery, the authors had difficulty in obtaining sufficient check data of a higher order of accuracy. They therefore optimised the parameters with respect to the software's estimates of precision and the minimisation of the level of interpolation in the DEM. They found that improved precision (as estimated internally by the software) did not always lead to a more successful or accurate DEM. The exact effects could not be quantified, however, because of the quality of the check data. This work highlighted the need for alternative methods for assessing data quality, particularly when close-range imagery is used, as the availability of check data is limited and the cost of obtaining data of a higher order of accuracy is significantly increased.

A series of tests were carried out on the strategy parameters used in the ERDAS Imagine OrthoMAX software using a variety of imagery with vastly different scales and image content than carried out in prior work. The aim of the tests was to quantify the effect of varying the strategy parameters on the accuracy of the DEM. The data sets used in the study included:

- 1 : 45,000 scale imagery of a dry river bed in Spain captured using a Kodak DCS420 digital camera.
- 1 : 13,000 scale imagery of a rural and residential area scanned at 30 μm.
- 1 : 6,000 scale imagery covering a wide variety of land-cover types captured with a Zeiss RMK A metric camera.
- 1 : 70 scale imagery of a simulated riverbed constructed in a laboratory. The imagery was captured using a Kodak DCS460 digital camera.

A prerequisite for each data set was that check data was available, thus enabling the parameters to be optimised with respect to accuracy. Optimisation of the parameters was carried out using a "trial and error" approach because two optimum parameter settings did not always combine in a positive manner. The process was thus time consuming and not practicable in a production-type environment.

Table 2 shows the effect of changing the strategy parameters on five different DEMs. DEMs 1–4 were derived using the same set of imagery (1 : 13,000 scale photography) whilst DEM 5 was generated using a set of 1 : 6,000 scale imagery. These results are typical of all of the results encountered and demonstrate that the specification of the strategy parameters is critical and can have a significant effect on the accuracy of a DEM in certain areas (areas 2–5 in the example). It was not immediately obvious from the testing as to what caused the parameters to have large effects only on selected areas.

The results of these tests showed no evident link with landcover type as suggested by Smith (1997) and, more importantly, alterations to the strategy parameters affected only certain checkpoints. This result was obtained after examination of a close-range data set (1 : 70 scale) of a simulated riverbed (the check data was collected using a physical profiling rod). The results showed that in three of the four test areas, alterations to the strategy parameters had little or no effect on the resulting r.m.s.e. of the DEM, whilst in one test area, every parameter change had a significant effect. Closer examination of individual residuals showed that all of the points with the largest residuals were located at just one end of one of the profiles, and that changes to the overall r.m.s.e. were due to varied height estimates at these locations only.

This result was then confirmed using previous data sets for which large improvements in the r.m.s.e. were achieved. By removing the checkpoints with the largest residuals from the r.m.s.e. calculations, the r.m.s.e. was subject to much less variation.

Table 2
r.m.s.e. (m) results from five different areas generated with six different sets of strategy parameters

Area	Parameter set *a*	Parameter set *b*	Parameter set *c*	Parameter set *d*	Parameter set *e*	Parameter set *f*
1	3.466	3.354	3.327	3.242	3.234	3.568
2	1.538	1.671	10.952	1.495	1.527	1.793
3	2.542	3.738	2.529	2.287	3.271	3.532
4	3.59	9.845	1.912	3.339	3.12	2.267
5	2.034	6.03	2.658	2.078	1.87	1.932

3. The failure warning model

Using the finding that the strategy parameters only affect points with the highest residuals, a software model was developed to identify automatically such areas. Such a facility can assist users (in particular, novice users) during the lengthy checking and editing phase of work. Instead of checking the entire DEM, the user could focus on the areas highlighted by the model. By simply subtracting two DEMs of the same area generated using different strategy parameter settings, areas where height estimates are unreliable are highlighted. The areas where the parameters have no effect (i.e., the areas with the lowest residuals) will have a value around 0 m, as illustrated in Fig. 3.

The model was developed in the Spatial Modeller tool in ERDAS Imagine. This is a visual modelling environment that allows generation and customisation of algorithms to manipulate graphical data. The software allows for a wide variety of inputs including raster, numeric, and vector files with output to a similar range of file types.

The algorithm behind the failure warning model (FWM) is simple. It isolates the areas statistically different from 0 m in the difference DEM and the areas where the algorithm has interpolated points on terrain with a sudden elevation change which are also likely to contain significant residuals. This information is then overlaid on an orthophoto of the area, enabling the user to print a hardcopy output to assist when the DEM is checked and edited using the stereo viewing tools. The model does not alter the DEMs in any way; it merely highlights the areas which it suspects as having the highest residuals. Each point on the DEM is given one of three classifications in the output (as illustrated in Fig. 4):

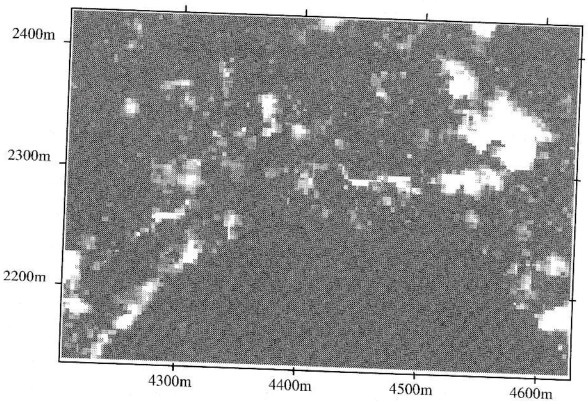

Fig. 3. Difference image between two DEMs of same area. Areas with difference around 0 m are coloured grey, whilst large differences are denoted by white areas.

Fig. 4. Example output from FWM.

0 (*black areas*): Areas where the software has interpolated the elevation in areas where slope angle is varying rapidly.

Unclassified (*orthophoto visible*): The evidence from the data suggests that the height estimate of this point is as accurate as possible.

256 (*white areas*): The points with the lowest accuracy. These are the points that are susceptible to changes in the strategy parameters.

The inputs for the FWM are as follows:

- DEM generated with the default strategy parameters.
- DEM generated with a different set of strategy parameters (four parameters were changed in these tests).
- An orthophoto of the area.

The FWM has been tested on a large number of areas taken from different sets of imagery and has performed consistently well. In the analysis of the results, the output from the FWM was exported in an ASCII format and the point residuals for the three classifications were grouped together into a zone. This enabled the r.m.s.e. of each zone to be calculated. The purpose of this was to determine if the points classified as acceptable had a lower r.m.s.e. than the entire DEM and conversely, if the areas highlighted by the FWM had a higher r.m.s.e. than the entire model. This would indicate that the FWM was highlighting the correct points (those with the largest residuals). For brevity, the results from the tests on six areas of one of the sets of imagery are presented in Fig. 5.

The results presented in Fig. 5 show that the FWM has worked well on the imagery used in the test. The points that are classified as OK by the model consistently have a lower r.m.s.e. than the overall model, suggesting that many of the points with the larger residuals have been filtered out. In four of the six areas, the points classified as 0/black (points that the algorithm

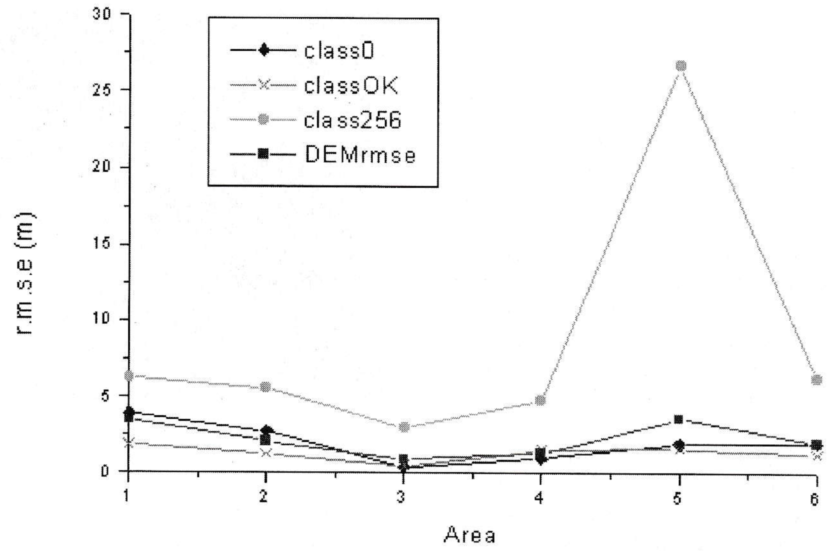

Fig. 5. Accuracy results of FWM output.

has interpolated over sudden elevation changes) had a higher r.m.s.e. than the acceptable points. This was the case for all of the areas classified as 256/white (areas susceptible to changes in the strategy parameters). The difference between the points classified as 256 and the rest of the points can be seen to be significant.

The model was also tested on the Phodis TS DPS from Carl Zeiss Inc.[1] This program uses the TopoSURF algorithm, which in turn uses digital images in a correlation procedure to generate a large number of elevation points, from which a grid-type DEM is then derived (see Footnote 1) The Phodis TS software has two user-definable strategy parameters, the terrain-type parameter (flat, hilly or mountainous) and the smoothing factor (low, medium or high). The output from Phodis is an ASCII file containing the Cartesian co-ordinates of each point in the grid followed by an estimate of the accuracy of each point. This estimation is made on a scale from one to seven, one being the most accurate. This served as a basis for a comparison between the two packages and as a demonstration of the universality of the FWM approach.

Three areas of the 1 : 13,000 scale imagery were used in the testing of the FWM, two with a 5 m grid spacing (areas 1 and 2) and the other with a 10 m spacing. Area 1 covered mainly farmland with small-forested areas; area 2 covered fields, trees, a steep slope, and a large residential area; and area 3 covered rural and residential areas. A DEM was generated for each area with every combination of the two variable strategy parameters. Each DEM was then generated with the OrthoMAX DEM generation software (using identical grid spacings).

The output data from the Phodis software was imported into the Imagine environment for comparison with the ERDAS data and testing of the FWM. The FWM had to be modified for the Phodis output, since the software does not identify which points were interpolated on the DEM. Therefore only classifications of 256 (white) or acceptable could be used. The input for each run of the FWM was therefore a DEM of the area generated using the default strategy parameters, a DEM of the area generated with one or both of the parameters changed, and an orthophoto of the area.

Table 3 shows the average results for the three areas used to test the Phodis software. The results show that the FWM performed significantly better than the Phodis classification system. This is shown by the fact that the points classified as unacceptable, i.e., 256/white, have a significantly higher r.m.s.e. than the points classified as two or seven by the Phodis software. Also, the points classified as OK by the FWM have a lower r.m.s.e. than the points classified as one by the Phodis software. Whilst the Phodis classification of two consistently had a higher r.m.s.e. than the points classified as one, the points classified as seven proved to be somewhat less robust.

Table 3
Phodis classification and FWM results model for Phodis data

Phodis 1	Phodis 2	Phodis 7	FWM OK	FWM 256
1.419 m	3.618 m	1.510 m	1.301 m	5.893 m

[1] Carl Z. web page. http://www.czi.com.

4. Discussion

The work presented has highlighted the many disadvantages of parameter optimisation. Although significant improvements in the r.m.s.e. were achieved in some areas, this was only after extensive testing and regeneration of the same model. The large number of strategy parameters used in OrthoMAX means that testing every parameter combination is clearly impracticable.

The data and results from this study show the extreme variability of the software in certain areas, and the importance and criticality of the strategy parameters. Whereas the parameters have proved to have a significant effect in certain areas of an image, the results have shown that manipulation of the parameters has little if any effect in areas well suited to the matching algorithm. Improvements in accuracy in these areas are likely to be marginal through manipulation of the strategy parameters.

The tests in this study were all carried out on data with checkpoint information. If checkpoint data are not available, optimisation of the parameters becomes extremely difficult, as every model must then be checked manually. Butler et al. (1998) demonstrated that improvements in strategies, such as matching success, are not always accompanied by an improvement in the accuracy of the DEM.

This research has also highlighted the criticality of the location of the checkpoint data. The United States Geological Survey suggest that check data should be "well distributed" and "representative of the terrain" with a "... minimum of 28 points per DEM ... required to compute the r.m.s.e., which is composed of a single test using 20 interior points and eight edge points" (United States Geological Survey, 1996) (Section 2.1.4). If all of the checkpoints lie in areas well suited to the algorithm used, the result is likely to be good and not subject to much variation. Any accuracy figure derived from the data is not likely to reflect any problem areas in the DEM. Conversely, if one or more of the checkpoints lie in ill-suited areas such as near to tall buildings or on man-made monotonous surfaces, derived accuracy results will be poorer and will not reflect the accuracy of the successful sections of the DEM. Whereas this is an obvious observation, and is countered in part by the required use of 28 checkpoints as opposed to, for example, 10 points, this research has questioned the suitability of using the r.m.s.e. as a measure of DEM accuracy. Should the organisation generating the DEM choose the location of the checkpoints or should it be the client using the DEM? If the producer of the DEM has the choice, it would be easy to select 28 points from areas well suited to the algorithm. Should the checkpoints all lie in areas well suited to automated methods, in areas prone to problems, or a mixture of the two? Selective sampling measures such as r.m.s.e. can never represent the true accuracy of dense DEMs such as those generated by digital photogrammetry.

The FWM approach outlined in this paper provides an alternative approach to parameter optimisation. Instead of attempting the lengthy process of optimisation, the strategy parameters are used to identify areas where the software is likely to fail and areas where the residuals are likely to be highest. This can be used as a guide when the DEM is checked, and is of value particularly to the novice user. Time spent during the editing phase is reduced to a minimum, thus increasing the profitability of a project. It answers some of the criticisms raised by Cooper (1998) and Heipke (1999) by increasing the level of quality assessment procedures used in the software. As it is a software-based assessment process, it could easily be incorporated into an existing DPSs, thus providing another internal quality assessment procedure.

The approach has proved to work successfully in practice and has been tested on a wide range of image scales. It consistently highlights areas of DEMs with large residuals and results in unclassified areas having a lower r.m.s.e. than that of the whole DEM. Significantly, the approach has been tested on the Phodis TS DEM generation software and proved to be successful, suggesting that the approach can be applied to other DPSs.

5. Conclusions

This paper has highlighted some of the problems and issues surrounding optimisation of strategy parameters used in the automated generation of DEMs. It has shown that the parameter specification can be significant and that a manual optimisation approach is lengthy and subject to a degree of variability. A system has been described that automatically identifies areas likely to contain suspicious residuals, and results have been presented which prove the efficacy of the method. The model has proved successful on different software packages and both close-range and aerial imagery.

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