PROCEDURES AND SOFTWARE FOR HIGH QUALITY TIN BASED SURFACE RECONSTRUCTION

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ABSTRACT:

Algorithms and software for correct reconstruction of the terrain surface by using data acquired by digitization of existing maps have been developed. The software enables efficient high quality formation of DTM by using contour data, but also using data from other data sources and it properly handle different types of terrain data (mass points, contours, breaklines, structure lines, cliff lines…). TIN and Bézier triangular surface patches are used for surface reconstruction. Special attention is dedicated to the problem of respecting all implicit information about terrain surface that are contained within contour data. Experiments have been carried out in order to test the quality of the procedures and the software. DTMs were created using actual terrain data. Using these so-called "true" DTMs contours were generated. The aim was to use generated contours and some supplemental data (points and breaklines) as an input to various well known interpolation methods in order to test their capabilities for surface reconstruction. The results of these experiments demonstrated that the quality of terrain surface reconstruction from contours using developed procedures and software is better, or at least as good as the quality achieved by using procedures and methods implemented within standard GIS/DTM software. Developed procedures and software were extensively used within project of building country-wide DTM using data obtained by digitization of existing topographic maps. Large DTMs were also created within many orthophoto production projects. Processing of large amount of data provided objective estimation of efficiency and quality of different numerical procedures implemented within the software.

1. INTRODUCTION

1.1 Motivation

The ultimate goal in terrain surface reconstruction using sampled data set is, of course, to obtain the best possible model of the terrain surface. Ideally, this process should be efficient and it should be possible to obtain high quality digital terrain surface model using as an input all kind of data, in terms of:

1. Data sampling strategies (mass points in random and regular spacing, contours, breaklines, structure lines, cliff lines, profiles…), and
2. Accuracy (different accuracies for different data sets).

Software that implements these procedures should be easy to use, and the quality of the reconstructed terrain surface should not depend to a large extent on the experience and skills of the software user. Under "quality" we consider how digital model of the surface represents the real terrain surface

Of course, one should have in mind well-known fact that it is not the interpolation or surface reconstruction method that is decisive for the DTM quality, but the quality of input data in terms of data density, accuracy, distribution, form, completeness, etc. However, even nowadays when we have various powerful techniques for DTM data acquisition, such as LiDAR, which can provide point data sets with high accuracy and density, there are still cases where data density and distribution is not optimal, or we have to deal with heterogeneous data (in terms of density, distribution and form). Therefore, interpolation and surface reconstruction procedures should be able to use all the information contained within available DTM data sets, otherwise optimum results will not be achieved.

1.2 Standard procedures for digital terrain surface modelling

It is well known that digital surface modelling can be done by using TIN based or grid based approach, or approach that will be some mixture of these two. Also, it is well known that both of these approaches have certain advantages and disadvantages. One of the most important ones is the ability to model all possible terrain forms (peaks, bottoms, ridges, streams, breaklines, cliffs, overhangs…). For grid based models this is very difficult and it can be achieved only by introduction of additional features (lines and spot heights) into standard grid data model. Good example of the software that uses this approach to satisfy requirements from above is the famous SCOP software.

Key issue for grid based models is the interpolation of heights at grid points, since it is rarely the case that we have data sampled completely at desired grid points. Different methods and procedures were developed to interpolate heights at grid points. Some of these procedures are general, and some are tailored specifically for certain types of data sets.

General type procedures usually respect only point data sets with more or less uniform distribution of points. These

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interpolation methods can be categorised as moving surfaces (inverse distance weighted, moving plane…), variational methods (thin plate spline, thin plate spline with tension, regularised spline with tension, regularised spline with tension), geostatistical methods (variations of kringing, collocation or linear prediction using LSQ adjustment), multiquadratic method, finite elements methods, and others (Mitáš, 1999; Hardy 1990). There are a lot of implementations of these methods. Most of these methods are implemented within standard GIS software (ArcGIS, GRASS, Geomedia…).

TIN based method can be used for these purposes as well. Firstly, TIN DTM is created and afterwards grid heights can be interpolated using this DTM. This approach provides easy handling of feature specific linear terrain data. Any GIS and DTM software that is based on TIN can be used to interpolate grid heights using this approach.

One particular type of data is particularly interesting – data set that consists of contours with additional spot heights. Such data set is mostly obtained by digitization of existing maps. General type interpolation methods can be used for these data sets, but the results can be less then optimal, because these methods are not able to use all the information available (Schneider, 1998). There were lot of attempts to handle this information properly. Interpolation in the direction of the steepest slope is one of the first methods that appeared. Method that is designed to calculate terrain surface aspect and to include it into finite elements method interpolation is also described in literature (Inaba, 1988). There is also a method based on finite differences that aims at producing hydrologically correct DTM used (Hutchinson, 1996). Spot heights, contours, stream and ridge lines can be used as an input for this method. Special group of methods is those that aim at automatic extraction of specific geomorphological elements using contour data (Auman 1990; Heitzinger, 2001; Peng 1996; Schneider, 1998; Thibault, 2000, Gold 2000). The idea is to use these elements (peaks, pass points, bottoms, streams, ridges) as additional data for latter interpolation methods.

However, almost all of these methods aim at calculating heights at certain points, i.e. they are interpolation methods. Only few of them are actually methods that build DTM that can be subsequently used and analyzed. One such exception is a method that incorporates geomorphological elements extracted from contour data into DTM built and handled by SCOP software (Heitzinger, 2001). This approach uses TIN based terrain feature extraction as a preprocessing tool, whereas grid based DTM is a final product.

The method that will be presented in this paper is based on the idea to have strictly TIN based DTM that can be built from all available DTM data types (mass points, contours, breaklines, structure lines, cliff lines…). It is up to the software to properly handle all the information, explicit or implicit, that are contained within data sets. Also, DTM should provide high quality digital terrain surface. Therefore, linear representation of the terrain surface using triangular faces of the TIN is regarded as insufficient. Instead, Bézier triangular surface patches are to be used for surface reconstruction (Farin, 1993; Pfeifer, 2002). It will be demonstrated latter in the paper that this approach is also useful for high-quality interpolation of heights for points in areas where data distribution is low, and also for data verification.

2. DEVELOPMENT OF THE PROCEDURES FOR TERRAIN SURFACE RECONSTRUCTION

As it was already stated, the procedures are based on building TIN DTM, whereas Bézier triangular surface patches are to be used for surface reconstruction.

General algorithm for building DTM is presented in the following diagram (Figure 1).

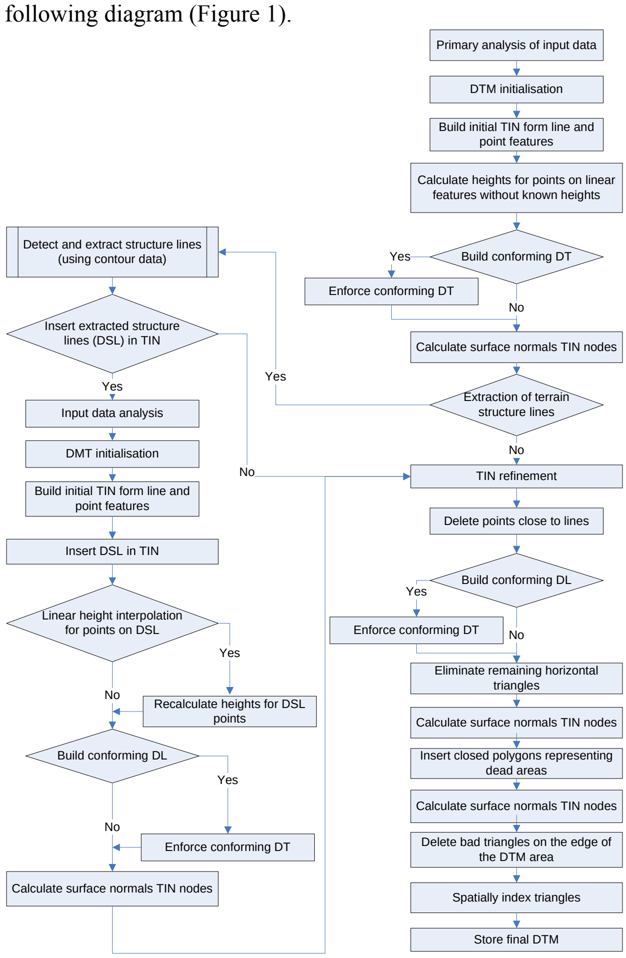

Figure 1. Algorithm of building TIN DTM with optional detection and extraction of structure lines

As it can be seen from the diagram DTM is based on Delaunay triangulation (DT). User can choose between constrained (CDT) of conforming DT. It is allowed to have linear features with no valid heights for points in input data set. Examples for these are streams obtained by digitization of existing maps or boundaries of areas where interpolation should not be done (buildings for example). Software will calculate heights for these points later. These linear features also contain valuable information and therefore should be used for building DTM. There are also options for TIN refinement which aims at obtaining equiangular triangles of the TIN. This is achieved by inserting additional points into TIN (Shewchuk, 2001). Using this option some problems in surface reconstruction can be solved and obtained digital surface has much better characteristic (better surface normal estimation and no undesired undulation of the surface).

If input data sets contain contour data, user can choose option of automatic detection and extraction of terrain specific geomorphological elements from contour data (structure lines and characteristic points). There are several algorithms implemented. After detected structure lines (DSL) and points are extracted from contours, heights for all these new points are assigned. There are also two options for this. One is to calculate heights from DTM obtained in the previous stages, i.e. from DTM built using data without DSL. This is done using standard DTM interpolation methods (linear interpolation using triangular faces, bicubic Bézier triangular surface patches, or quintic Bézier triangular surface patches). The other option is to use linear interpolation along DSL between ending points which are normally positioned on contours (points with known heights).

2.1 Software implementation

These procedures are implemented within SurfIng software. SurfIng is a complete solution for DTM data processing and analysis. It can operate autonomously or as a MapSoft module with high level of integration with other modules. MapSoft is GIS software with extensive support to large scale mapping, specifically tailored for handling cadastral and topographic surveying maps. Various surveying data acquisition techniques are supported, as well as all the spatial data analysis functions required by surveyors. Software keeps the data within standard RDBMS using geo-relational data modeling approach, so the project size is practically unlimited. SurfIng provides all standard DTM analysis: height interpolation, profile and crossection interpolation, contour interpolation, volume calculations, 3D terrain visualization, data conversions, etc.

The software design enables processing of the data without requirement to start several commands to process data in several steps, i.e. all the required steps are implemented as internal procedures within the general software algorithm and software makes decisions about necessary procedures based on the data. Of course, user has to specify some processing parameters at the beginning of the processing. Surfing's dialog with advanced options for building DTM with optional detection and extraction of structure lines (and points) is shown in Figure 2.

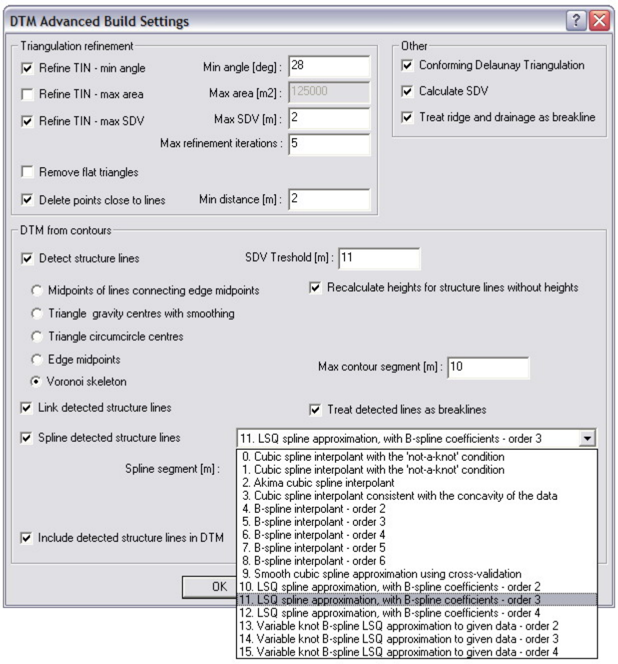

Figure 2. Dialog with advanced options for building DTM

2.2 Surface normal calculation

As it was already stated, it is necessary to use all available information from maps that could improve terrain surface reconstruction. Some of the information is given implicitly by contours (Schneider, 1998). This information could be generated by using rules applied during map making process and by respecting the very nature of contours. Some of these are: limited terrain height in areas bounded by contour(s) of given height(s), existence of terrain form lines in areas where set of contours abruptly change direction, maximum slope direction is perpendicular on contour segments, etc.

SurfIng's algorithm for building high quality DTM is based on TIN and bicubic Bezier's surface patches over triangles. No special data filtering is currently supported, i.e. calculated terrain surface interpolates data points. Therefore, this method is very sensitive to distribution of data points and their height values, so this must be taken into consideration. Also, estimation of surface normals at these points is highly critical, as this has a great influence on calculated terrain surface.

Calculation of surface normals for mass points: Generally, surface uses Akima's method for estimating surface normals, by averaging surface normals of all TIN triangles joining at given data point.

Calculation of surface normals for structure line points: For structure line point normal is located within vertical plane defined by planar position of the structure lines segments at the point (Figure 3, left), and the normal's slope is determined by slopes of the structure line segments (Figure 3, right).

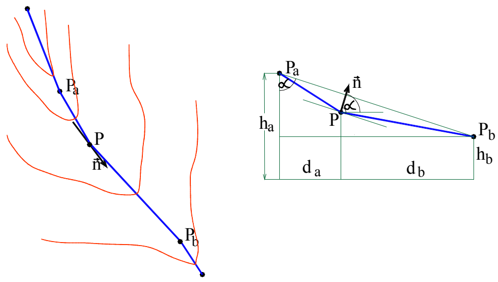

Figure 3. Calculation of surface normals for structure lines points

Calculation of surface normals for breakline points: Each breakline point will have several normals (two normals, except for points where breaklines meets each other). These normals are calculated for the terrain surface for each side of the breakline using Akima's method (Figure 4).

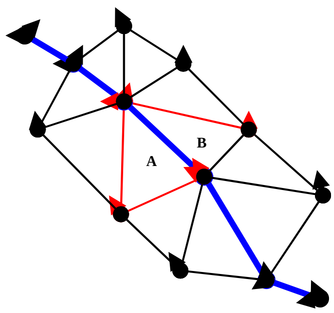

Figure 4. Calculation of surface normals for breaklines points

During calculation of Bézier triangular surface patches in latter stages, smoothness (G^1 continuity) of the digital terrain surface will not be preserved across breaklines.

2.2.1 Calculation of surface normals for contours points:

Methods for calculation of surface normals described above are unsuitable for contour points. Instead, another approach is used. It is based on assumption that direction of steepest slope is perpendicular to the contour. Slope is estimated by calculating profile containing given contour point in the direction of the steepest slope (Figure 5).

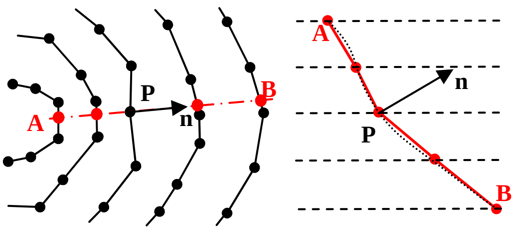

Figure 5. Calculation of surface normals for contour points

Profile is calculated using intersection between neighboring contours and the profile line. Slope could be estimated by using smooth curve set through given point and all intersecting points, or simply averaging slopes for upper and lower contour profile intersections. The similar approach is proposed in (Schneider, 1998). This method provides much better results for contour data than original Akima's method.

2.3 Extraction of specific geomorphological elements from contour data

The second problem that is typical for TIN based terrain surface reconstruction using contour data is related to regions with flat triangles. It is well known, that these regions are actually implicating that there are some special terrain forms (local minimum and maximum, ridge, drainage, saddle). There are several published algorithms for automatic extraction of specific geomorphological elements using contour data and TIN (Auman 1990; Heitzinger, 2001; Peng 1996; Schneider, 1998; Thibault, 2000). Some of these algorithms based on vector data processing techniques are implemented within SurfIng (Figure 2, Detect structure lines options). Explanation of and algorithm based on Voronoi skeleton can be found in literature (Cvijetinović, 2004; Thibault, 2000; Gold, 2002).

Extracted line segments are connected and smoothed (line interpolation or approximation). After that, heights for their points are calculated. As it was said, there are also two options for this. One is to calculate heights from DTM obtained in the previous stages, i.e. from DTM built using data without DSL. This is done using standard DTM interpolation methods (linear interpolation using triangular faces, bicubic Bézier triangular surface patches, or quintic Bézier triangular surface patches). The other option is to use linear interpolation along DSL between ending points which are normally positioned on contours (points with known heights). The last option usually gives the best results. DSL with proper heights are inserted into TIN built using data from initial data set.

The final objective of the procedures described above could also be to obtain geomorfological elements that would enable DTM generalization and also data reduction, if needed. For example, it is possible to build new DTM by using obtained TIN DTM to interpolate semi-regular (similar to progressive and composite sampling) grid of heights. These grid points and characteristic terrain forms (characteristic points, structure lines, breaklines, DSL) can be used to build new DTM without significant loss of the quality (Figure 6). Contour points will be excluded from this DTM.

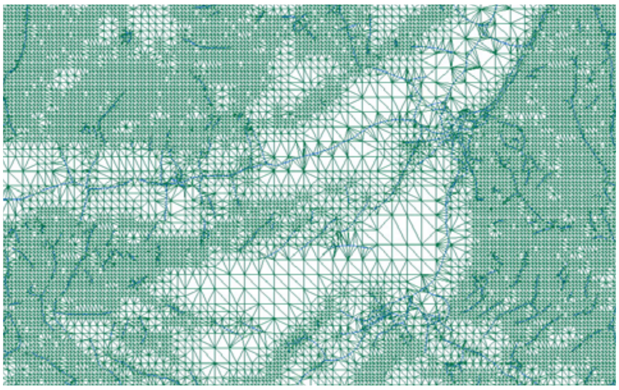

Figure 6. DTM obtained from interpolated grid with some grid nodes eliminated and with DSL included

2.4 Functions for calculation of digital terrain surface

Before final DTM surface is calculated, user can select the following options:

1. TIN refinement (elimination of skinny long triangles) by inserting additional points into TIN (Shewchuk, 2001);
2. Removal of TIN points too close to breaklines and structure lines;
3. Enforcement of conforming Delaunay triangulation;
4. Removal of remaining horizontal triangles (if possible);
5. Removal of bad triangles (skinny, long, or extra large triangles) on the DTM border.

The purpose of these functions is to eliminate badly shaped triangles which are problematic for construction of Bézier patches and for TIN based DTM processing in general. During the first option (TIN refinement) special attention is dedicated to calculation of heights for new points. Usually, interpolation using bicubic Bézier triangular surface patches is used. The exception is in areas where differences between triangular faces and Bézier triangular surface patches are over specified threshold. In these cases, linear interpolation using triangular planar faces is used.

After all available data is included in TIN and TIN is finally processed (refined), surface normals for all TIN nodes are calculated. Surface normals and heights at TIN nodes and TIN edges with attributes are sufficient for calculation of triangular surface patches. This process is rather straightforward (Farin, 1993; Pfeifer, 2002). Bicubic Bézier patches proved to be the best option.

2.5 Functions for DTM data verification

Considering that we usually have to deal with large amount of DTM data it is normal to expect errors within data. Therefore, functions for large errors detection and elimination are required. Some procedures are designed specially for these purposes. All of them were implemented using SurfIng DTM software environment. All of these functions are described in (Cvijetinović, 2004).

Some of the functions for DTM data verification are:

1. Detection of contour with wrong elevation;
2. Visual inspection of DTM surface (contour plots, perspective views);
3. Detection of places where there are significant difference between triangular faces and Bézier triangular surface patches (Figure 7).

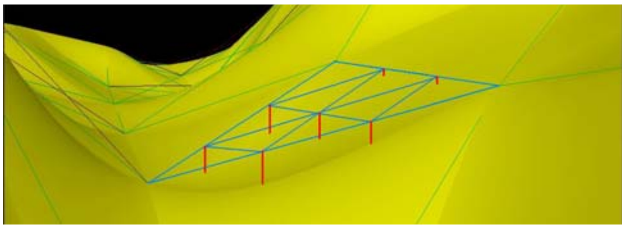

Figure 7. Difference between triangular faces and Bézier triangular surface patches

Contours with wrong heights and triangles where differences between triangular faces and Bézier triangular surface patches are over specified threshold are marked. The last function is quite useful for support to DTM data acquisition since it is efficient in locating areas within DTM with low data density where additional data should be supplied.

All of these data verification options are accompanied by simple correction of detected errors. Data editing is done directly on data that are kept within MapSoft's database.

3. VERIFICATION OF THE PROCEDURES AND THE SOFTWARE

All objectives were successfully achieved and the results were verified through numerous experiments and real applications in practice. Experiments have been carried out in order to test the quality of developed procedures and software. One of the typical test areas is shown in Figure 8. Criterion for selecting this test area was that all important terrain forms and features should be present.

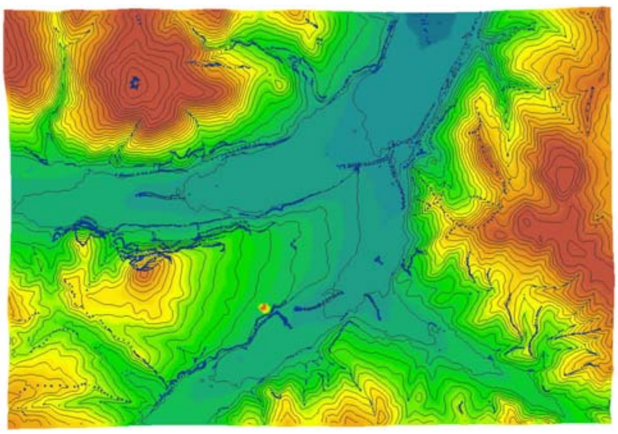

Figure 8. Typical test area used for experimental verification of developed procedures

DTMs were created using actual terrain data (stereocompilation using aerial photogrammetry). Using these so-called "true" DTMs contours were generated by automatic procedures. The aim was to use generated contour data and some supplemental data such as breaklines (Figure 8, in blue) as an input to various interpolation methods. The aim was to test performances of these methods for surface reconstruction. Kriging, i.e. collocation, spline with tension, regularized splines, natural neighbour, TIN based interpolation, Inverse distance weighted, and multiquadratic method are the most common standard interpolation methods tested and compared against the developed method. ArcGIS software was used for these purposes.

The results of these experiments demonstrated that the quality of digital terrain surface built by SurfIng using contour data is better, or at least as good as the quality achieved by using standard procedures and methods implemented within standard GIS/DTM software. Table with typical results is shown below (Table 1). Statistics based on differences between original heights (interpolated from true DTM) and heights obtained from contour data using listed interpolation methods are represented.

Method	Grid 25m				
	Average	Max	Min	STDEV	RMSE
TIN - Linear interpolation	-0.56	9.23	-9.07	1.95	2.03
Natural neighbour	-0.54	9.23	-8.35	1.90	1.97
Inverse distance weighted	-0.51	9.23	-9.60	2.78	2.83
Ordinary kriging	-0.55	9.23	-8.79	2.28	2.35
Universal kriging	-0.53	9.23	-8.79	2.35	2.41
ANUDEM	0.60	248.62	-16.63	5.41	5.45
ANUDEM (large errors removed)	0.37	11.91	-11.63	1.92	1.96
Multiquadratic	-0.52	8.74	-8.82	1.85	1.92
Radial Base Functions - Spline with Tension	-0.54	9.48	-8.11	1.97	2.05
Completely Regularised Spline	-0.52	9.23	-9.76	2.73	2.78
SurfIng - with DSL included	-0.52	7.43	-8.81	1.65	1.50

Table 1. Results of comparison of original heights and heights obtained from contour DTMs using various methods

In Table 1 height differences at points in 25m grid are given. It should be noted that SurfIng method is even superior on places where structure lines are located (at structure lines points). Only two methods achieved approximately the same accuracy: ordinary kriging and multiquadratic method. However, it should be noted that ordinary kriging requires significant experience and skill from the user. In Table 1 results for ordinary kriging are rather poor, because inexperienced user was not able to set proper parameters. In the following tests results obtained by ordinary kriging, carried out with more experienced user were better. Spline interpolation methods were even more sensitive to parameter selection. Very large errors in surface reconstruction were quite common, especially in valley regions (Figure 8, blue-green area).

Almost all available methods are able to use just point data (no use of breaklines) and only grid DTM can be calculated. Of course, TIN implementation in ArcGIS was able to use breaklines, but the quality of the reconstructed surface was rather poor, especially in areas with flat triangles, and therefore completely inadequate when contour data are present in input data set.

Interesting conclusions can be drawn from comparison of the results obtained by using SurfIng and the results obtained by using a method designed to handle contour data. It is a finite difference method with drainage enforcement – ANUDEM algorithm (Hutchinson, 1996). The results of this algorithm (Topo To Raster in ArcGIS implementation) were generally good, but large errors were frequent (Table 1).

Additional advantage of the SurfIng software and implemented procedures is a simple specification of parameters for building DTM. Experiments also demonstrated that SurfIng's algorithms when compared to other interpolation methods were highly efficient and accurate for other data sets as well (different types of data, with or without contours).

Developed procedures and software were extensively used within project of building country-wide DTM using data obtained by digitization of existing topographic maps. Large DTMs were also created within many orthophoto production projects. Processing of large amount of data provided objective estimation of efficiency and quality of different numerical procedures implemented within the software.

4. CONCLUSIONS

Results obtained from experiments as well from the practise demonstrate high quality of developed procedures and their software implementation. The software provides valuable framework and platform for further research and development of other methods based on TIN DTM.

One of the main directions for further research is design of filtering procedures. Filtering has two aims. Firstly, filtering should eliminate large errors (points belonging to vegetation and buildings). It is well known fact that there are more and more requirements for filtering of LIDAR data and data obtained from digital photogrammetry using automatic DTM extraction. Current research shows that elimination of erroneous data could be done efficiently by analysis of the TIN DTM. Secondly, filtering should help in calculation of the, statistically speaking, most probable terrain surface. This can be done by using geostatistical methods (kriging, collocation) or some adjustments to correct heights at TIN points.

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