XXIV

Meeting of Serbian Surveyors

Kladovo, Đerdap upon Danube, Serbia, 24-26 june 2011.

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INTERNATIONAL SCIENTIFIC CONFERENCE & XXIV MEETING OF SERBIAN SURVEYORS

PROFESSIONAL PRACTICE AND EDUCATION IN GEODESY AND RELATED FIELDS

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PROCEEDINGS

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INTERNATIONAL SCIENTIFIC CONFERENCE
AND
XXIV MEETING OF SERBIAN SURVEYORS

PROFESSIONAL PRACTICE AND EDUCATION IN GEODESY AND RELATED FIELDS

PROCEEDINGS

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INTERNATIONAL FEDERATION OF SURVEYORS
UNIVERSITY OF LJUBLJANA - FACULTY OF NATURAL SCIENCES AND ENGINEERING
BELGRADE UNIVERSITY COLLEGE OF APPLIED STUDIES

MINISTRY OF SCIENCE AND
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FACULTY OF NATURAL
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Invitation Paper

TERRAIN SURFACE MODELING USING TRIANGULAR SPLINE PATCHES

Željko Cvijetinović[1], Dragan Mihajlović[1], Miloš Vojinović[1], Momir Mitrović[1]
[1] Faculty of Civil Engineering, University of Belgrade, Department for Geodesy and Geoinformatics, Belgrade, SERBIA, E-mail: zeljkoc@grf.bg.ac.rs, draganm@grf.bg.ac.rs, milosv@grf.bg.ac.rs, mitrovic@grf.bg.ac.rs

Summary: *Algorithms and software for digital terrain modeling using TIN based surface model are presented in the paper. Processing of all types of terrain surface data are supported: mass points, local extrema, contours, breaklines, structure lines, fault lines, etc. TIN topology and Bézier triangular surface patches are used for terrain surface reconstruction. Special attention is dedicated to the problem of respecting all implicit information about terrain surface that are contained within the input data. This is especially important in cases when terrain surface has to be reconstructed by using mostly contour data, since there are a lot of additional information that are implicitly contained within the data of this type. The software also contains functions for efficient verification of collected terrain data and DTM. Special consideration is given to the numerical procedures and algorithms aiming at providing contours and other outputs of DTM analysis of cartographic quality as required by many surveyors and their clients. The results of experiments demonstrated that the quality of terrain surface reconstruction from contours and/or other data 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.*

Keywords: *Terrain, TIN, DTM, Surface, Algorithm*

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 data sampling strategies (selective, systematic, progressive, composite, contours, profiles), and accuracy (different accuracies for different data sets).

Ideally, software that implements these procedures should be efficient. Also, it 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. The “quality” here refers to the exactness of the terrain surface model parameters, i.e. how closely it models 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. There are techniques for DTM data acquisition, such as LiDAR, which can provide point data sets with high accuracy and density. However, 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. Also, terrain surface model should be accurate not only in terms of heights, but also in terms of other surface parameters, such us first and second surface derivatives, curvature, etc.

1.2. Standard procedures for digital terrain surface modelling

Digital terrain surface modeling can be done by using TIN based or grid based approach, or approach that will be some mixture of these two. 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 interpolation algorithms usually work well with point data sets with more or less uniform distribution of points. These interpolation methods can be categorized 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 ([11], [7]). 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 ([15]). In the past, various solutions were formulated 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 ([10]). There is also a method based on finite differences that aims at producing hydrologically correct DTM ([9]). 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 ([1], [8], [12], [15], [17], [6]). The idea is to use these elements (peaks, pass points, bottoms, streams, ridges) latter on as additional data for interpolation.

However, almost all of these methods aim at calculating heights at certain points, i.e. they are interpolation methods. Only few of them actually 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 ([8]). 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 of building TIN based DTM from all available DTM data types. It is up to the software to properly handle all the information contained within the regardless if they are given explicitly or implicitly. Also, it is required that DTM should provide high quality representation of the terrain surface. Therefore, linear representation of the terrain surface using triangular faces of the TIN is regarded as insufficient. Instead, higher order polynomial surface patches are used for surface reconstruction ([5], [13]). 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. ALGORITHMS AND NUMERICAL PROCEDURES FOR TERRAIN SURFACE RECONSTRUCTION

General algorithm for building DTM is presented in the following diagram (Figure 1). 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. Streams obtained by digitization of existing maps or closed polygons representing areas where interpolation should not be done (buildings) are examples of such linear features. Software will calculate heights for points of these features using the rest of the input DTM data. These linear features contain valuable information and therefore they 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 ([14]). Using this option some problems in surface reconstruction can be solved and resulting digital surface has much better characteristics (better surface normal estimation and no undesired oscillations of the surface).

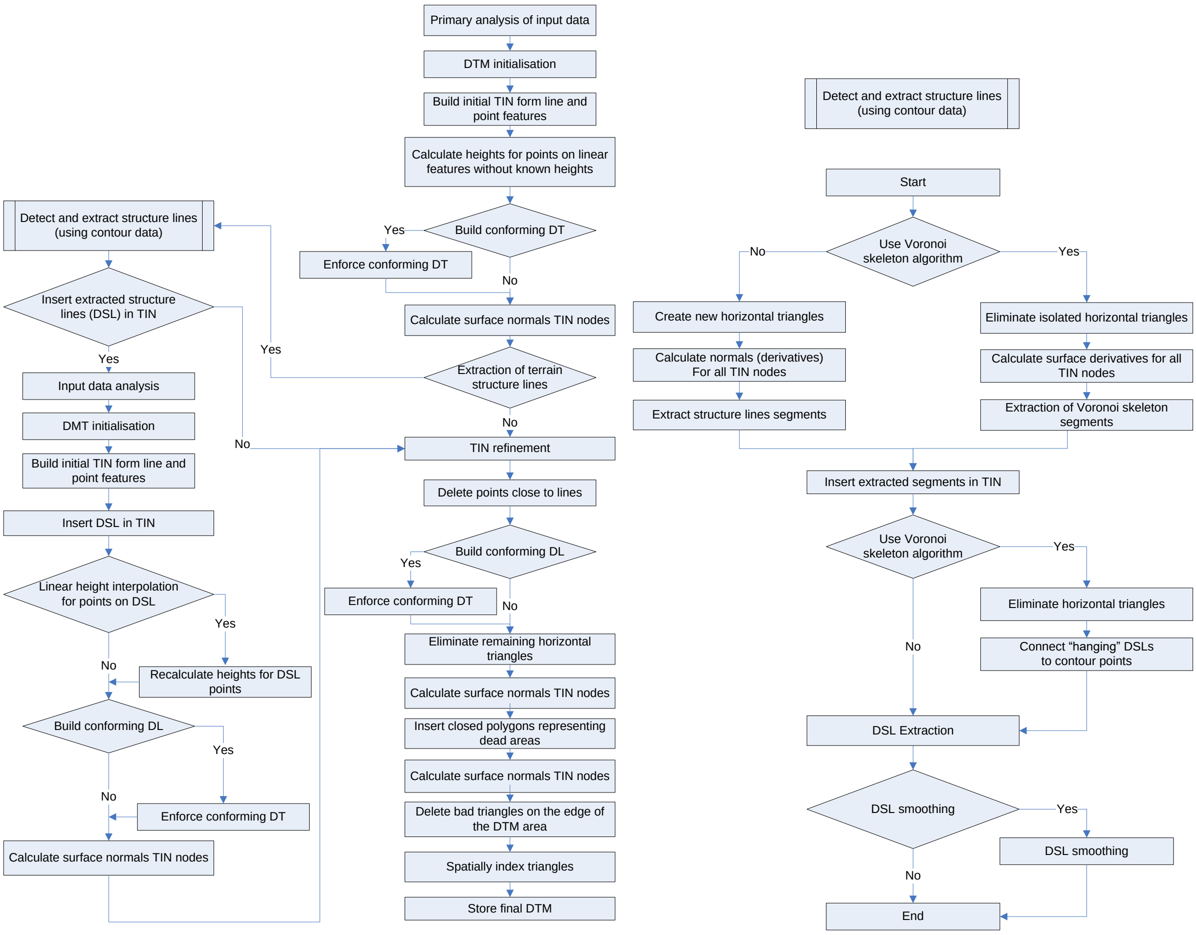


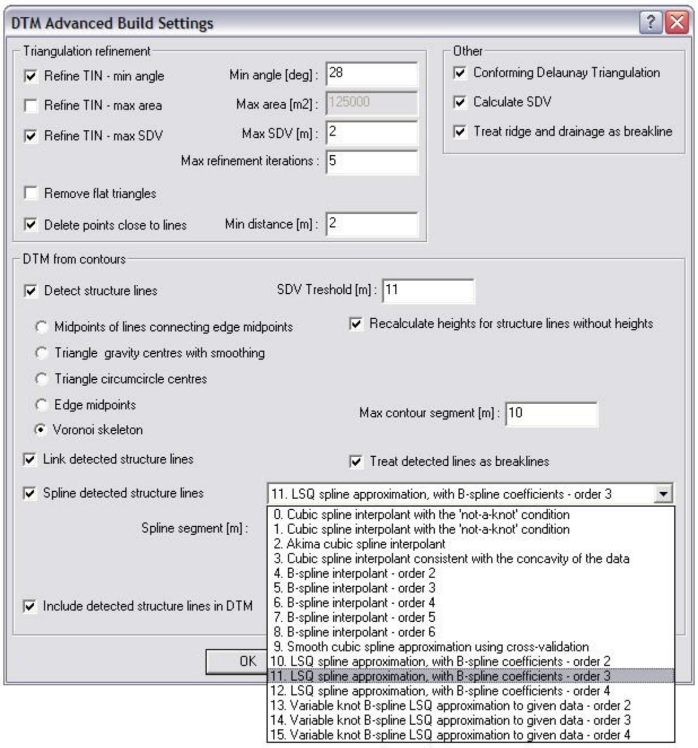
Figure 1: Algorithm of building TIN DTM with optional detection and extraction of structure lines

If input data sets contain contour data, user can choose option of automatic detection and extraction of terrain specific geomorphological features from contour data (structure lines and characteristic points). There are several algorithms implemented (Figure 2). Detailed description of these algorithms and quality of their results is given in [2]. After detected structure lines (DSL) and points are extracted from contour data, heights for all points of these features are calculated. There are 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 SurfIng 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 second option provides slightly better results ([2]).

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.



DTM Advanced Build Settings

Triangulation refinement

☑ Refine TIN - min angle — Min angle [deg] : 28

☐ Refine TIN - max area — Max area [m2] : 125000

☑ Refine TIN - max SDV — Max SDV [m] : 2

Max refinement iterations : 5

☐ Remove flat triangles

☑ Delete points close to lines — Min distance [m] : 2

Other

☑ Conforming Delaunay Triangulation

☑ Calculate SDV

☑ Treat ridge and drainage as breakline

DTM from contours

☑ Detect structure lines — SDV Treshold [m] : 11

○ Midpoints of lines connecting edge midpoints

○ Triangle gravity centres with smoothing

○ Triangle circumcircle centres

○ Edge midpoints

● Voronoi skeleton

☑ Recalculate heights for structure lines without heights

Max contour segment [m] : 10

☑ Link detected structure lines

☑ Treat detected lines as breaklines

☑ Spline detected structure lines — 11. LSQ spline approximation, with B-spline coefficients - order 3

Spline segment [m] :

☑ Include detected structure lines in DTM

0. Cubic spline interpolant with the 'not-a-knot' condition
1. Cubic spline interpolant with the 'not-a-knot' condition
2. Akima cubic spline interpolant
3. Cubic spline interpolant consistent with the concavity of the data
4. B-spline interpolant - order 2
5. B-spline interpolant - order 3
6. B-spline interpolant - order 4
7. B-spline interpolant - order 5
8. B-spline interpolant - order 6
9. Smooth cubic spline approximation using cross-validation
10. LSQ spline approximation, with B-spline coefficients - order 2
11. LSQ spline approximation, with B-spline coefficients - order 3
12. LSQ spline approximation, with B-spline coefficients - order 4
13. Variable knot B-spline LSQ approximation to given data - order 2
14. Variable knot B-spline LSQ approximation to given data - order 3
15. Variable knot B-spline LSQ approximation to given data - order 4

Figure 2: Dialog with advanced options for building DTM

2.2. Surface normals and derivatives calculation

As it was already stated, it is necessary to use all available information from input data that could improve terrain surface reconstruction. Some of the information is given implicitly. Data sampled by contour digitization are typical example ([15]). This information could be generated by using rules applied during data acquisition process (mapping and digitization) 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 building TIN topology and calculation of 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. Estimation of surface normals at these points is highly critical, as this has a great influence on calculated terrain surface. Calculation of surface first derivatives using surface normals is straightforward ([2]). Calculation of second derivatives at TIN vertices that are required in case of using quintic Bézier surface patches is based on known first derivatives at TIN vertices ([2]).

Calculation of surface normals for mass points: Akima's method for estimating surface normals is used. This is done simply by averaging surface normals of all TIN triangles joining at given data point. For points marked as local extrema (tops, bottoms) or saddle points it is assumed that normals are vertical.

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 3, left). 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.

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, middle), and the normal's slope is determined by slopes of the structure line segments (Figure 3, right).

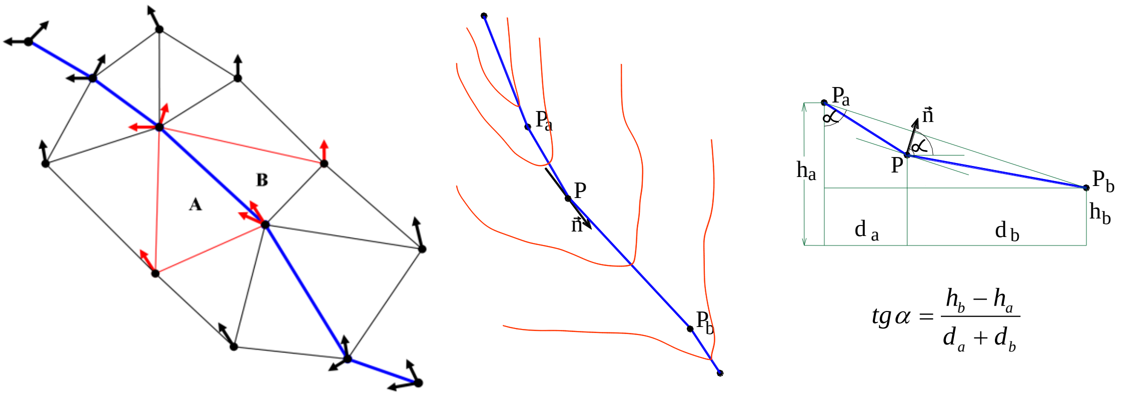


Figure 3: Calculation of surface normals for breakline (left) and structure line (middle, right) points

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 4). 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 ([15]). This method provides much better results for contour data than original Akima's method. Care must be taken in cases where profile changes curvature (Figure 4, right), because the calculated normal will have significant influence on shape of the DTM (note the difference between red and blue option).

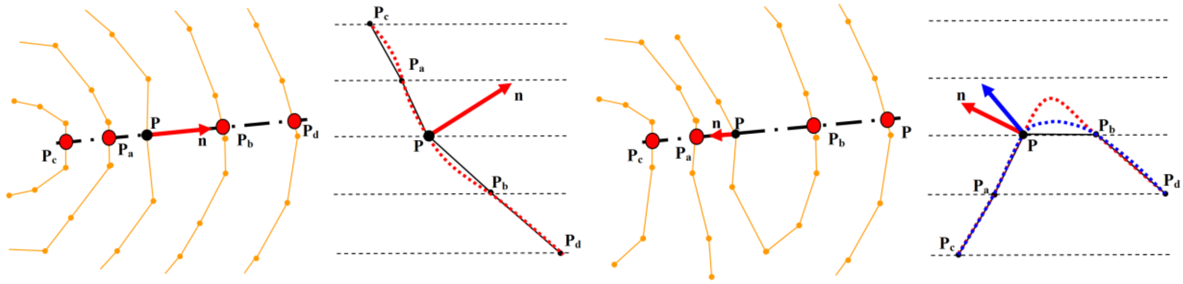


Figure 4: Calculation of surface normals for contour points

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 features using contour data and TIN ([1], [8], [12], [15], [17]). Some of these algorithms that are based on vector data processing techniques are implemented within SurfIng (Figure 2, Detect structure lines option). More detailed explanation of these algorithms can be found in literature ([2], [17], [6], [12]).

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 features 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. The 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 7, right). Contours are no longer required and they are excluded from the final terrain dataset and DTM. Another advantage, is that this dataset can be used as input for building DTM using linear interpolation over TIN, but the notorious problem of having artificial flat regions (series of flat triangles) caused by contour data topology will exists no more.

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 ([14]);
2. Removal of TIN points too close to breaklines and structure lines (using specified distance);
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 using these functions is to eliminate all triangles of TIN which are problematic for the construction of Bézier surface patches and for TIN based DTM processing in general. Within the TIN refinement function 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. This indicates that Bézier surface patches results in large DTM surface oscillation. This usually happens because input data are incomplete. 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. Three options for modeling triangular surface patches are supported: plane, bicubic Bézier surface and quintic Bézier surface. All three options provide continuity of the DTM surface. Bicubic Bézier patches proved to be the best option. This option does not provide surface smoothness (C^1 or G^1 continuity) across TIN lines, but it is more than adequate for practical requirements. If surface smoothness is required, quintic Bézier surface patches should be used. Calculation of Bézier triangular surface patches is done by calculation of coordinates of Bézier control points (points P_{ijk}, Figure 5). Process is rather straightforward and details can be found in literature ([2], [5], [13]). Here, only calculation of bicubic Bézier surface is presented.

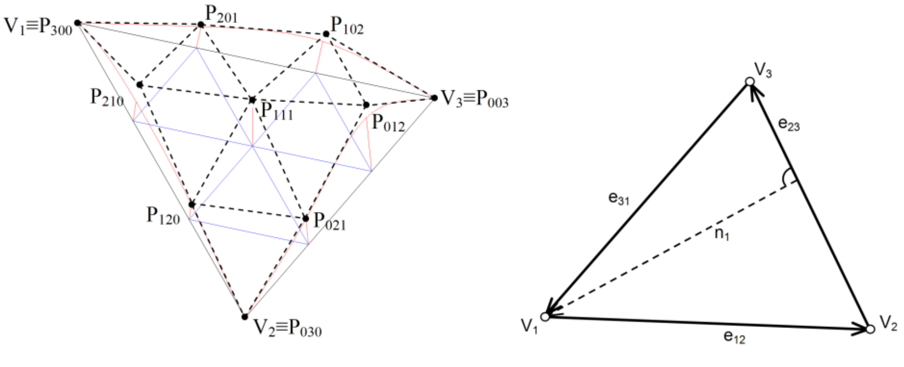


Figure 5: Bézier triangle with control net points (left), and edge and normal vectors (right)

Let us assume that surface patch is presented in a form *f(x,y)=z*. Planimetric coordinates *(x,y)* of Bézier control net points are calculated as:

$$P_{ijk}[x,y] = \frac{i \cdot V_1[x,y] + j \cdot V_2[x,y] + k \cdot V_3[x,y]}{n} \tag{1}$$

For bicubic surface patch $n=3$. Therefore, it is only required to calculate the third coordinate $Z(P_{ijk})=Z_{ijk}=b_{ijk}$ for points of Bézier control net. Since it is required that surface patch interpolates triangle vertices it follows that:

$$b_{300} = S(V_1) \quad b_{030} = S(V_2) \quad b_{003} = S(V_3) \tag{2}$$

For the calculation of *z* values at remaining six control points of Bézier net that are located on triangle edges we can use values of *z* coordinates at triangle vertices and estimated tangent planes defined by normals (derivatives) at these vertices. Therefore, we have:

$$\begin{aligned} b_{210} &= S(V_1) + \tfrac{1}{3}\frac{\partial S}{\partial e_{12}}(V_1) & b_{021} &= S(V_2) + \tfrac{1}{3}\frac{\partial S}{\partial e_{23}}(V_2) \\ b_{201} &= S(V_1) - \tfrac{1}{3}\frac{\partial S}{\partial e_{31}}(V_1) & b_{102} &= S(V_3) + \tfrac{1}{3}\frac{\partial S}{\partial e_{31}}(V_3) \\ b_{120} &= S(V_2) - \tfrac{1}{3}\frac{\partial S}{\partial e_{12}}(V_2) & b_{012} &= S(V_3) - \tfrac{1}{3}\frac{\partial S}{\partial e_{23}}(V_3) \end{aligned} \tag{3}$$

Derivatives of the surface S in vertex V in the direction e is calculated as:

$$\frac{\partial S}{\partial e}(V) = \begin{bmatrix} e_x & e_y \end{bmatrix} \begin{bmatrix} \dfrac{\partial S}{\partial x}(V) \\ \dfrac{\partial S}{\partial y}(V) \end{bmatrix} \tag{4}$$

The value of *z* coordinate for the last control point P_{111} (central point of Bézier net) is calculated using additional requirement that triangular surface patch have to fulfill. Usually it is a requirement that surface patch has quadratic precision, i.e. that it is able to represent quadratic surface accurately. This means that, if the rest of nine points of control net lie on a quadratic surface, than point P_{111} also has to lie on that surface. This requirement is fulfilled if the value of Bézier ordinate is calculated as ([5]):

$$\begin{aligned} E &= \frac{1}{6}\left(b_{021} + b_{012} + b_{102} + b_{201} + b_{120} + b_{210}\right) \qquad C = \frac{1}{3}(V_1 + V_2 + V_3) \\ b_{111} &= E + \frac{1}{2}(E - C) \end{aligned} \tag{5}$$

Surface patch can be represented as *S(u,v,w)=f(x,y)=z*, i.e. using parametric representation of points in the triangle plane via barycentric coordinate vector ***u****=(u,v,w)*. With the use of Bernstein's polynomials, triangular Bézier surface patch of order *n* can be represented using the following formulas ([2]):

$$S^n(u,v,w) = \sum_{i+j+k=n} B^n_{ijk}(u,v,w)\cdot \mathbf{P}_{ijk} = \sum_{i=0}^{n}\sum_{j=0}^{n-i} B^n_{ijk}(u,v,w)\cdot \mathbf{P}_{ijk} \tag{6}$$

Bernstein's polynomials are calculated as:

$$B^n_{ijk}(\mathbf{u}) = B^n_{ijk}(u,v,w) = \frac{n!}{i!\,j!\,k!} u^i v^j w^k \tag{7}$$

where

$$0 \le u,v,w \le 1, \quad u+v+w=1, \quad i+j+k=n, \quad i,j,k \ge 0 \tag{8}$$

For correct modeling of the terrain surface across the triangle edges that represents breaklines, modification is necessary for the calculation of Bézier control points belonging to these edges. Instead of using formulas (3), Bézier oordinates for these points are calculated using linear interpolation along breakline edges.

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 ([2]).

Some of the functions for DTM data verification are:

1. Detection of contours with wrong elevation;
2. Visual inspection of the DTM surface (contour plots, perspective views);

3. Detection of places where there are significant difference between triangular faces and Bézier triangular surface patches (Figure 6).

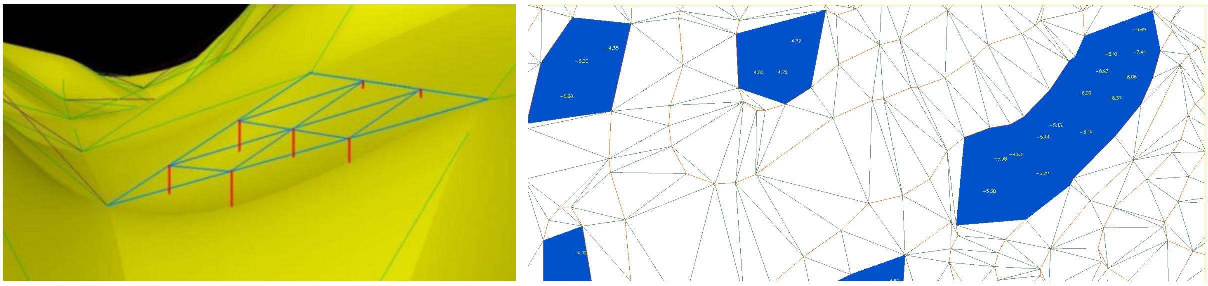


Figure 6: Difference between triangular faces and Bézier triangular surface patches

Contours with wrong heights and triangles where differences between triangular faces and Bézier triangular surface patches are over specified threshold are marked (Figure 6). 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 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.

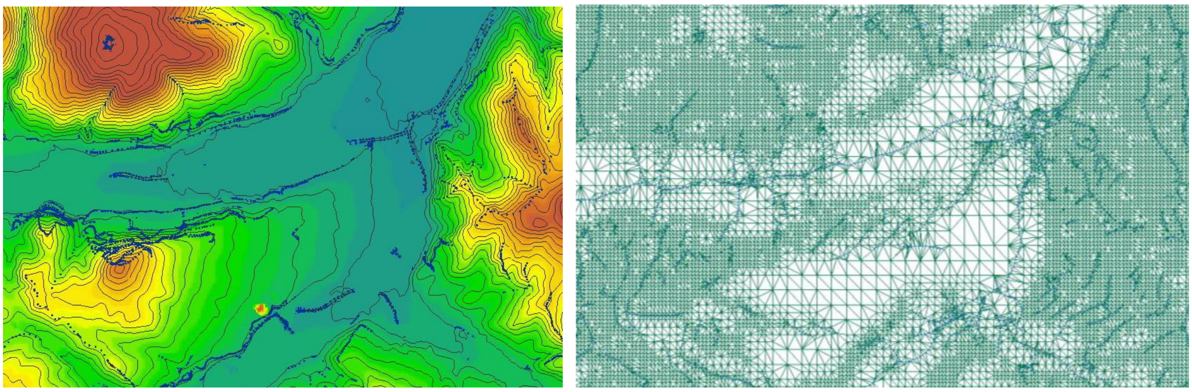


Figure 7: Experimental test area

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 7, lines 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.

Table 1 : Results of comparison of original heights and heights interpolated from contour DTMs

Method	**Grid 25m**					
	Average	Max	Min	Max(abs)	STDEV	RMSE
TIN - Linear interpolation	-0.56	9.23	-9.07	9.23	1.95	2.03
Natural neighbour	-0.54	9.23	-8.35	9.23	1.90	1.97
Inverse distance weighted	-0.51	9.23	-9.60	9.60	2.78	2.83
Inverse distance weighted	-0.51	9.23	-9.60	9.60	2.78	2.83
Ordinary kriging	-0.55	9.23	-8.79	9.23	2.28	2.35
Universal kriging	-0.53	9.23	-8.79	9.23	2.35	2.41
ANUDEM	0.60	248.62	-16.63	248.62	5.41	5.45
ANUDEM (large errors removed)	0.37	11.91	-11.63	11.91	1.92	1.96
Multiquadratic	-0.52	8.74	-8.82	8.82	1.85	1.92
Radial Base Functions - Spline with Tension	-0.54	9.48	-8.11	9.48	1.97	2.05
Completely Regularised Spline	-0.52	9.23	-9.76	9.76	2.73	2.78
SurfIng - with DSL included	-0.52	7.43	-8.81	-0.04	**1.65**	**1.50**

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 7, 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 ([9]). 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 practice 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.

The use of bicubic triangular surface patches for modeling terrain surface is justified because it does not require too much computer processing and also it enables direct calculation of other surface parameters (slope, curvature, etc.). Also it provides better surface visualization using interpolated contours or perspective views. The software and implemented procedures enable building DTM using dataset containing mixture of all kind of terrain data. User does not have to preprocess the data with some other software tools, because the software itself will use numerical procedures appropriate for certain data type.

One of the main directions for further research is design and implementation of filtering procedures. Filtering has two aims. Firstly, filtering should eliminate large errors (points belonging to vegetation and buildings). For example, filtering of LIDAR data and data obtained from digital photogrammetry using automatic DTM extraction. This could be done efficiently by the analysis of the TIN DTM. Secondly, filtering should help in calculation of, statistically speaking, the most probable terrain surface. This could be done by using geostatistical methods (kriging, collocation) or fitting local polynomials to correct heights at TIN nodes.

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