THE USE OF CELLULAR AUTOMATON FOR TERRAIN MODELING

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Abstract
Terrain modeling methods implemented in geographical information systems differ from geodetic presentation of contour lines on topographic maps. These are often treated as a reliable source of information about the surface of terrain. Despite the sometimes substantial complexity of various algorithms used to create DTM, the results are mostly restricted by conditions regarding the type and range of the required data, or by the aim of modeling. In this paper the method of DTM generation with the logic of contour lines interpolation is presented. In practice, this is a process of improvement of a TIN by smoothing the modeled surface. In accordance with geodetic approach the heights interpolated on the sides of TIN triangles are treated as correct representation of the real surface and the smoothness of the model is achieved within the triangles. The method concerns modeling triangles such a way that gives the model smooth what would make it similar to the surface of the real site. The task is solved in a manner consistent with the logic of cellular automata. In its first phase the algorithm works sequentially, and then it leads to smoothness of the model in an iterative way.
In the article the problem of terrain modeling is pointed out and geodetic method of contour interpolation and its adaptation to the form of cellular automata are highlighted. The method called TMCA – Terrain Modeling Cellular Automata – is described and tested. The attached example illustrates the approach to build a DTM.

Introduction

Modeling of terrain surface is an important preparative step for many three-dimensional spatial analyses. Often, along with terrain models, or instead of them, the surface models have to be performed. Recently 3D models of the site with objects existing on them become more and more popular (Yuan et al., 2008).
In accordance with its nature the models of terrain present it in a simplified manner and have some discontinuities, gaps, or unnatural peaks due to lack of data or their errors. This needs the use of various tricks to correct errors (Dakowicz & Gold, 2002; Hengl et al., 2004). Final shape of the model corrected such a way has a decisive influence on the results of hydrographic or geotechnical simulations (Peralvo, 2004) or – in many other cases – reflects the quality of the other investigations (Tang et al. 2001; Weng, 2002). Also, the selection of appropriate spatial data sources and methods of interpolation (approximation) may lead to the model more or less expressing the reality. It is crucial in engineering and hydrographical applications (Nico et al., 2005; Wise, 2000).

Usually one of the two alternative methods of representation of modeled surface is in use – an irregular network of spatial triangles (TIN) or squared mesh usually identified with GRID model. Various analyses had been made that show the pros and cons of both representation forms (Droy, 2008; Liu & Hu, 2009). The TIN model is mostly used in studies performed in the vector space, and GRID – in a raster space. Sometimes, for the purposes of the raster applications direct conversion of triangles to the raster is performed, but usually one of approximation methods is applied. Repeatedly the weakness of different interpolation methods had been pointed out, and researches were looking for more effective solutions. In the work (Wyczałek, 2009) I showed that some methods are also sensitive to the effects of errors of the points lying in a certain distance from interpolated cell. In seeking the best solutions one can not disagree with Droy (2008) and other authors who associate the accuracy of the spatial development with the density of source data. Describing the history of the emergence and development of the TIN Mark (1997) referred to surveyor's way of thinking 'with triangles' as a primary source of its strengths. Although surveyors did not confirm this reasoning, however there were often proved that the numerical models developed on the basis of direct geodetic measurements (GPS, Total Station) or its graphic implementation in the form of contour map truly reflect the terrain (Nico et al., 2005). A number of interpolation solutions were created strictly for the best use of these data (El Shami & Bango, 2006; Mukherji, 2007). Recently one can get better models based on alternative methods of measurement, such as LiDAR or aerial photogrammetry (Baltsavias, 1999; Hoehle, 2009; Yuan et al. 2008) as well as dense GPS/RTK (Kumar et al., 2008), tacheometric or range (Whitaker, 2001) measurements.
Assuming special advantages of TIN representation, in this paper the development of a method for its efficient conversion to raster format have been undertaken. To do this, classical TIN has been compared with geodetic method of contour line interpolation, what became a base for development of the algorithm. In practice, a solution similar to the method of learning cellular automata (CLA) had been obtained. In the next chapter geodetic interpolation method and its adaptation in raster space are described. Chapter 3 discusses the solution of cellular automaton and presents clear practical example. At the end conclusions and discussion of future research are formulated.

Geodetic-cartographic method of contour line interpolation

The aim of geodetic-cartographic interpolation method is an exact representation of terrain by contour lines on the basis of relatively small group of measured points. In addition to numerical representation surveyor uses his/her experience and knowledge about different geological forms in order to express local characteristics of terrain on the map. To help further interpolation the measurements are supplemented by additional information in the form of sketch containing *skeletal lines* (e.g. ridges or valleys) and *edges* (break lines, jumps). After defining these lines on a map and connecting other neighboring points together the area is divided on triangles looking like the TIN. The interpolation is performed along the sides of all triangles and then the nearest points of the same height are connected with curved lines. The aim for all the contour lines is to pass by the interpolated points on the sides of triangles.

The deflection of the contour line between the points depends on the degree of diversity of local forms and is determined in the subjective way. The principle is employed that contour lines should cross the skeletal lines at right angles, while all remaining lines they cross at the angles depending on local inclination of the terrain. On the edge lines the terrain form collapses what should be reflected by the break of contour line. Due to the significant slopes in some places, certain areas (scarps, ditches) are marked with the symbol instead of contours.

Terrain representation by contour lines is such reliable, that many authors create DTM on the basis of topographic map (e.g. Wise, 2000, Franklin, 2000) and some, such as Gousie & Franklin (2005) suggest their densityfication by secondary interpolation between them before running next steps to create DTM.

The adaptation of geodetic-cartographic interpolation method

The above described graphic interpolation method substantially competes with analytic methods of terrain modeling. One can say that it is a way of smoothing out of an irregular set of flat triangles, which, in the TIN model adjoin together along straight lines. As a result the triangular sections of land are not flat and along lines of contact they retain mathematical conditions of surface continuity (first derivative equal to zero). Moreover, at the skeletal lines there is zeroing the second derivative, what reflects by horizontal tangential to the profile.

Such described method of interpolation one can adopt to create digital terrain model based on regular grid of squared cells. Each cell will have height calculated on the basis of the closest lying *pickets* (e.g. measured field points) and lines connecting them. It is proposed to do interpolation along rows of cells with reference to the heights calculated for points on the sides of triangular mesh.

The interpolation procedure is therefore as follows:

Create a grid of squared cells in the area of interest and assign the heights of pickets to the cells lying just over them;

Calculate the heights of cells on the sides of triangles by linear interpolation between their vertices;

Determine the heights of the remaining points using curves, ensuring for selected sides conditions of zeroing the first and second derivative.

The algorithm has a weakness resulting from the adoption of the method for spinning curves, which should respect the different conditions when connect together along the horizontal or slope lines, and also – have variable flexibility. The selection of the degree of bending of a line is determined by the certain range of subjectivity related to the lines modeled ridges and valleys. To automatize this operation it is proposed to extend the scope of the marking them in the field with different lines for various types of ridge (valley), as a *sharp*, *moderate*, *mild* or *flat*. This additional information can be better utilized by the modeling procedure.

A useful way of practical implementation of this algorithm can be cellular automaton – the mathematical algorithm which iteratively set out a state of individual cells of regular grid based on the state of surrounding cells in the previous step.

Implementation of cellular automaton

A cellular automaton is basically a computer algorithm that is discrete in space and time and operates on a lattice of sites (cells). A bi-dimensional, deterministic cellular automaton (CA) can be described as a triple A = (S, N, δ); where S is a nonempty *set of states*, N is the *neighborhood*, and $\delta : S^N \rightarrow S$ is the local *transition rule* – the function for which the argument of δ indicates the states of the neighborhood cells at a given time (t), while its result determines the state of the central cell at the next step (t+1).
The characteristics of neighboring cells do not have to be the only source of data for the transition rule. Its parameters can also be obtained from outside the space of its operations. In the general case it can be assumed that the automaton may consist of a specified number of certain identifiable features. One can further assume that the automation has not only the ability to recognize these characteristics, but also it affects the change of them. By adopting this approach for modeling the surface area it can be established that created DTM is this outer space.
Depending on the state of individual cells of automaton the underlying DTM cells are in the next stage of modeling. This way the automaton not only has a small number of states, but their values describe the status of the progress of creating the model.
The transition rule also runs individual action for each state. Move to the next states goes only if the specified condition of neighborhood is met. The following actions are within the transition rule:

left cell	cen-tral	right cell	The action performed:
0	0	0	– the cell in the DTM space has a value calculated from TIN,
0	1	1	– the cell modified in the base on parameters of the change of slope,
1	2	1	– the height of the cell is calculated from the other side and averaged,
2	3	2	– height is adjusted to neighbors in the von Neumann neighborhood.

The cells lying over pickets and the sides of triangles immediately receive the status code of ‘3’. For the other cells transition to the next state takes place after the end of the previous state. The last stage adopt the behavior of learning automata (CLA), which in an iterative way adjust heights of neighboring cells in order to smooth the model. DTM sends out the signal depicted the degree of local diversity, which is treated by the transition rule as an assessment of its last action.
Completion of the process is based on two alternative criteria – local and global:
locally the indicator of the end (a positive answer) is suitably small height difference between the central cell and the value calculated on the basis of the heights of its neighbors,
global assessment base on the percentage threshold (respectively small) of the change of mean error calculated for all cells.
Local end is indicated by the code of the state of the cell equal to "4", but in other cells automata continue to operate until the global assessment will be met or all local ones will reach the state "4".
The example of using Terrain Modeling Cellular Automaton

For illustration of the method a fragment of a simple artificial terrain model (e.g. two triangles cut from wider area) has been created including:
the ridge line (dashed) – on the left side in the Figure 1;
the valley (dotted line) – in the center;
the ordinary side of the triangle (continuous) – on the right.
The lines converge in a common node at the bottom of the figure.

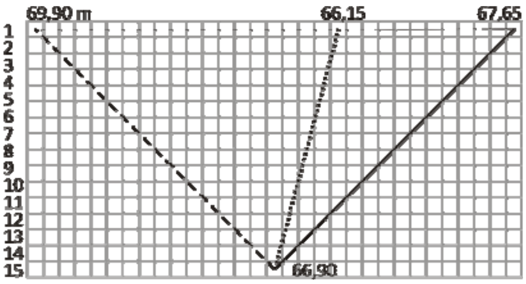

Fig. 1. Part of artificial area for tests of TMCA

Calculations were made according to the above described algorithm. There are two parameters declared for each side of every triangle:
the first (‘s’) means the degree of slope and it is expressed in centimeters/cell,
second (‘r’) declares how many steps should be done to reach original slope of the triangle – the more steps the greater curvature of the surface.
The values of the two parameters should be determined in the process of model calibration. For both sides of each line first parameter should have the same value, but the second can be changed depending on how wide is the area. For ridges and valleys parameter ‘s’ should get value 0.0, and every ordinary line should have slope ‘s’ calculated as a mean value of both neighboring triangles. For earlier suggested four types of ridges and valleys more steps should be declared when it is flat and wide area and less – for sharp edges.
In the presented example first we tested various combinations of declared parameters. Results in one line of cells are presented in Figure 2 for five combinations which include increasing values of ‘r’ at the left triangle (from 1 to 5) and ‘s’ at the right triangle (from -9,0 to -1,0). The other parameters were declared as constant. Straight dotted lines in the graph represent sections of TIN, dashed curves – the result of the first stage of creation the terrain model, continuous curves – heights obtained in the second stage, while the thick dotted line – the result of smoothing the model (stage 4). Vertical axes denote heights above sea level and in our test show how resulting surface can differ from TIN when we declare particular parameters.
Figure 4 presents results of consecutive stages for 5 rows of cells after declaration following parameters:
from the left side: s = -2 cm / cell and a change of the fall: r = 7 steps, what means mild decrease of terrain;
in the center: s = 0 and a change of the fall: r = 3 steps, e.g. moderate valley;
terrain raising toward the right side: s = 5 cm / cell, a fall change: r = 4 steps.

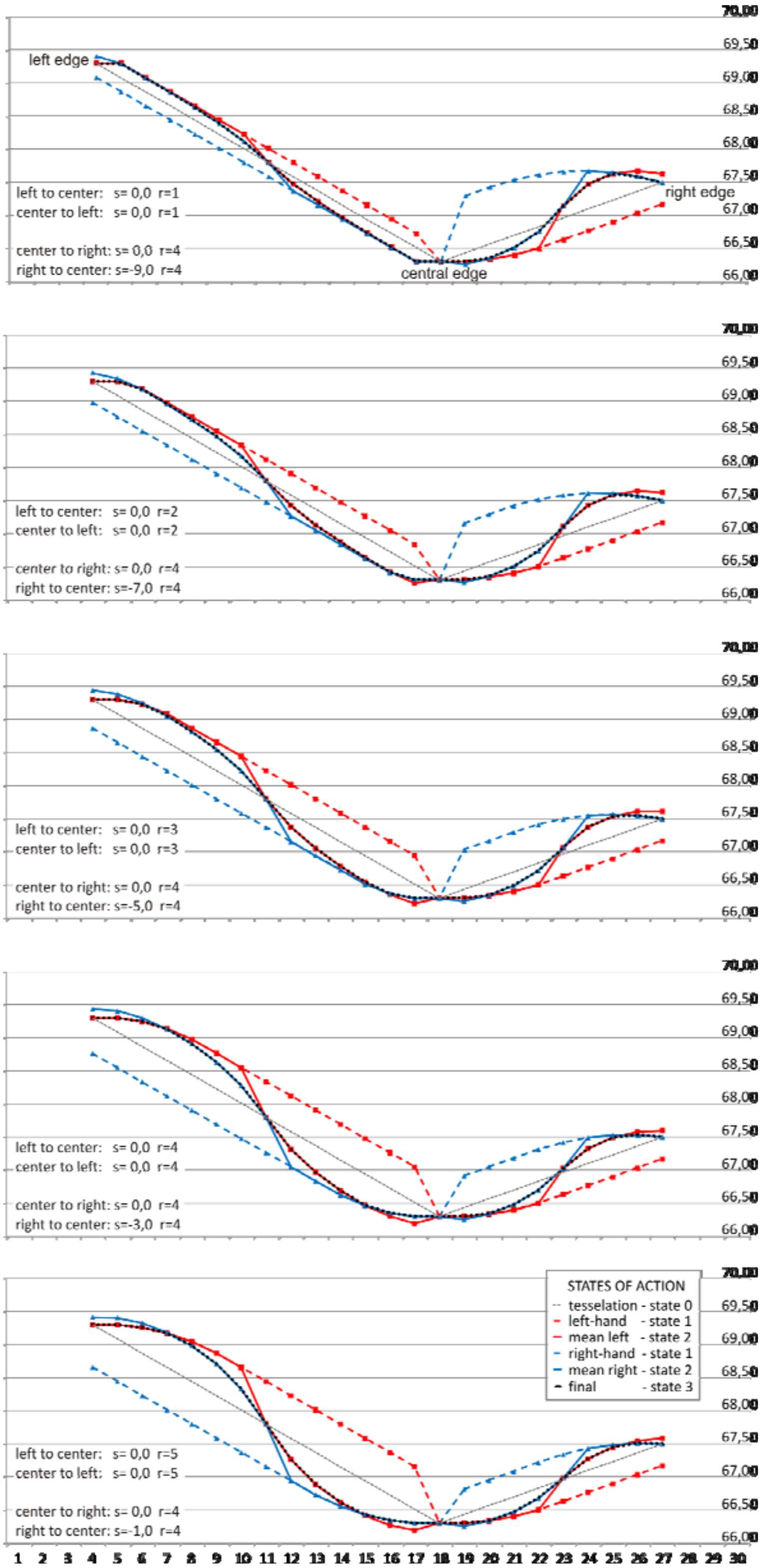

Fig. 2. Cross-sections along first line of cells – the illustration of changes caused by different values of parameters of transition rule.

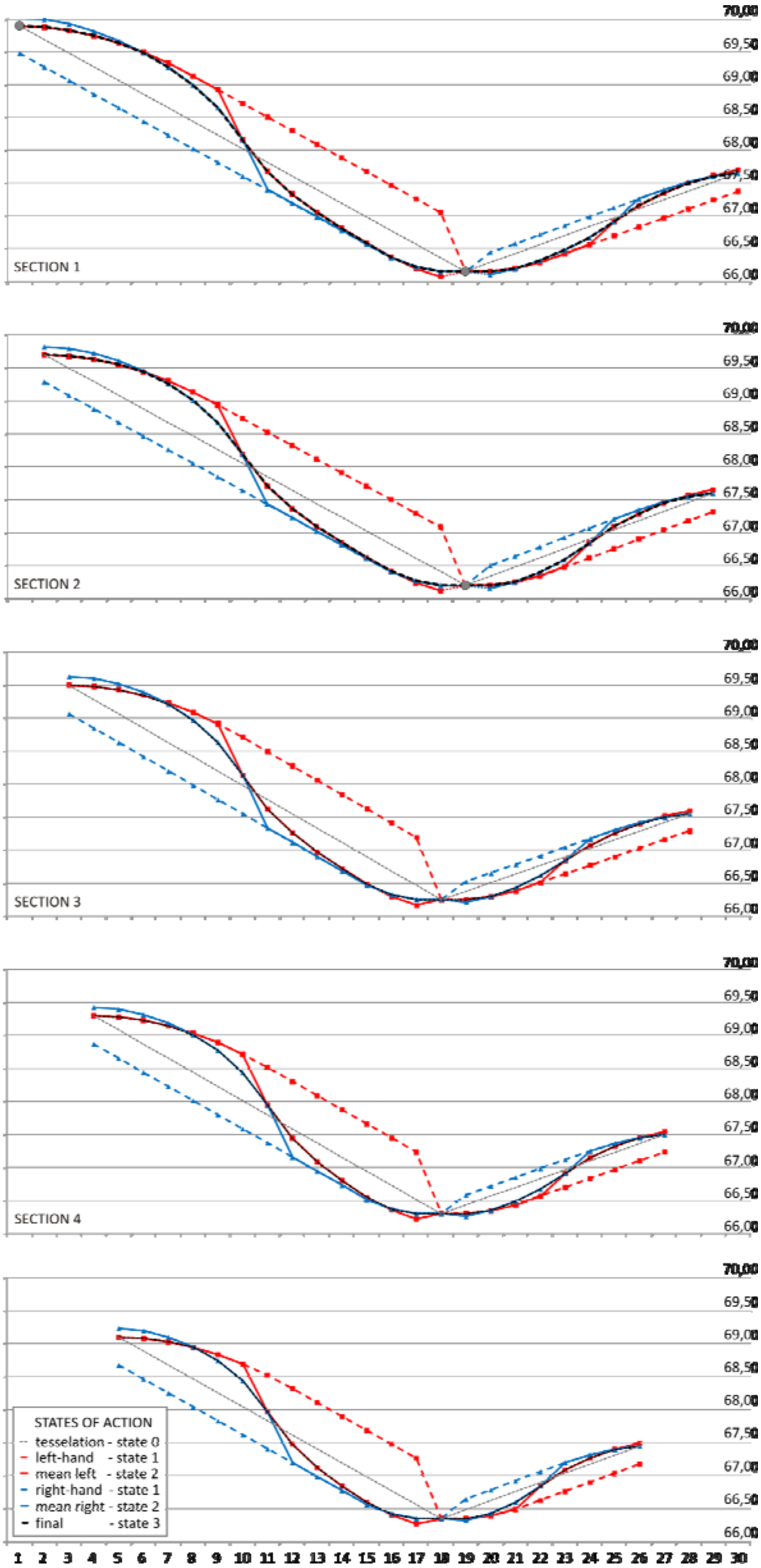

Fig. 3. Cross-sections along five lines of cells – the illustration of changes caused by interpolated place.

Figure 4 presents results obtained for top 10 rows of cells after stages '0' (tessellation), '2' (averaging) and '4' (smoothing) with comparison to contour interpolation made by surveyor. We can especially see how rough interpolation is smoothed in consecutive steps of automaton. Also we can compare result of automatic approximation with surveyor's interpolation what shows some differences caused by different assessment of flatness of central valley.

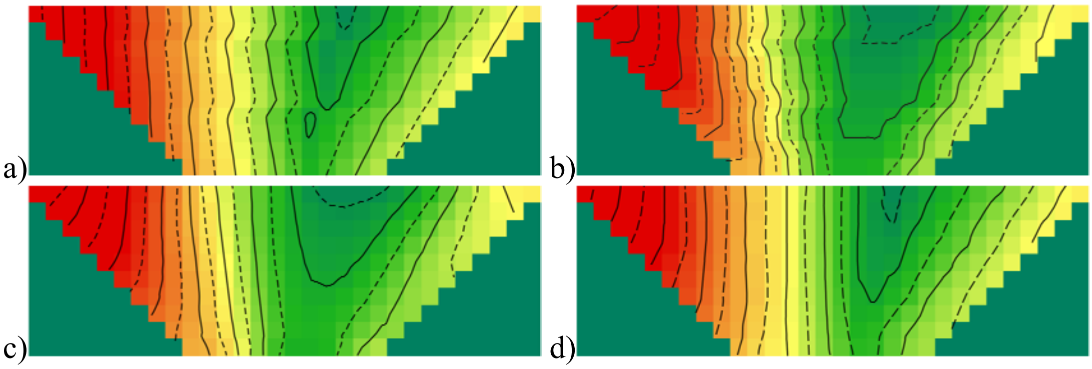

Fig. 4. Results of selected stages of terrain modeling: a) after tessellation, b) stage 2 (averaged), c) stage 4 (smoothed) and for comparison d) contour interpolation by surveyor, who decided, that valley in the center is thinner than in modeling by TMCA.

Conclusions

The new approach to terrain modeling has been presented as the implementation of geodetic (topographic) contour line interpolation method, which is still the best data source for traditional DTM modeling algorithms. The model is built on the basis of TIN triangles by smoothing the surface and providing continuity in their joints. It is assumed that – with the exception of the discontinuity – the slopes in the joints of TIN triangles obtain average value of their slopes. However, if the contact is marked as the ridge or valley, then its slope is equal to zero. The line comes up to the slope of TIN gradually, and the number of degrees depends on the degree of recognized undulations of the site. The next modeling phase results of averaging heights among neighboring cells.

The whole process takes place in a manner similar to the method of cellular automata cooperating with its environment (e.g. recognizing it and changing), which in this case is DTM. In the last phase automaton operates in interactive mode, learning itself how big should be the scope of correction of the surface in order to its smoothing.

The first attempt was made on a spreadsheet that serves possibility to visualize current results of actions taken, and the statistical evaluation of the accuracy and convergence of the process. Results presented here served as an inspiration to write a computer program, which is currently at the phase of testing. An important element in the development of the method is selfcalibration of the automata in order to obtain the best approximation to the actual surface. With this the sensitivity analysis is linked in order to early and effective detection of anomalies in source data. These issues are the subject of further work on the presented method.

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