FEATURE-BASED ENHANCEMENT OF MULTI-RESOLUTION TOPOGRAPHIC SURFACE

Lukáš Brůha[1], Jan Kolář[2]

[1]Lukáš Brůha, Charles University in Prague, Faculty of Science, Department of Applied Geoinformatics and Cartography. Albertov 6, Prague, lukas.bruha@natur.cuni.cz.

[2] Jan Kolář, Grifinor Project, jan.kolar@grifinor.net.

Abstract

Many representations of topographic surface providing graphical, three-dimensional, multi-resolution model of entire planet have been developed. However, current solutions to such a representation of topographic surface suffer from the lack of geometric flexibility and accuracy on boundaries with models of other geographic features. Therefore, this work focuses on a more functional representation of a multi-resolution topographic surface. For this sake we introduce a simplification algorithm, which is designed to build the multiple LOD database of features. The method utilizes the Global Indexing Grid (GIG) as a paging mechanism. For any position of the observer within the 3D virtual environment, the indexing structure determines the position-dependent LOD of currently visible features and underlying terrain. The simplification algorithm guarantees for any observer position the preservation of topological relations between simplified geometries of features in the position-dependent LOD visualization of the Earth surface. Based on the precomputed classification of the elevation points and multiple LOD database of features, the surface is reconstructed using constrained Delaunay triangulation at run-time.

***Keywords**: Virtual Earth,Global indexing, Position-dependent LOD, Topological consistency*

INTRODUCTION

A three-dimensional (3D) representation of terrain, or topographic surface in general, is an important element in planning, civil engineering and mapping. It has a similar importance as the mapping plane has in two-dimensional (2D) cartography.

It provides the defining surface in terms of which other features can be geographically referenced (georeferenced). Many representations of topographic surface providing graphical, 3D, multi-resolution model of entire planet have been developed, for example Crawford et al. (2003) or Cignoni et al. (2003). These works allowed for a new way to explore data related to any location on Earth at arbitrary scale and perspective. Applications for scientific communication, education, news presentation, proved to be useful in practice through commercial products such as GeoFusion or Keyhole, later of which became a basic 3D map used worldwide by broad public as Google Earth.

The current solutions nevertheless suffer from lack of geometric flexibility on boundaries with models of other geographic features, such as buildings or roads, which are connected to the terrain's surface. The precise representation of such boundaries on the surface is essential for any analytical processing traditionally provided by 2D-based geographic information systems (GIS).

Therefore, this work focuses on a more functional representation, which would support geometrical changes of the topographic surface in connection to other geographic features of various kinds. We want to avoid terrain representations based on a recursive subdivision of a regular grid, because it is a core concept that restricts having arbitrary polygonal edges on the surface. We further want to minimize the need for pre-computed patches of the surface and thus improve the ability to adapt to new features. This would make the surface representation more flexible for editing, and would support a distributed management of the surface model. The surface topology reconstructed only at run-time using Delaunay triangulation is one approach, which can also address the topological issues of the surface on the boundaries between different levels of detail (LOD), as Figure 4 suggests. For these reasons we adopt results achieved in Kolář (2006) as a basis for this work, and we suggest a new terrain representation that allows to populate the surface with new geographic features that support multiple LOD.

Related works on feature-based terrain enhancement

Increased demand for 3D GIS applications stressed the structural complexity of pure 3D solutions. In order to avoid it several solutions utilize the simpler 2D topology as far as possible, e.g. Gröger and Plümer (2005). For example, an integrated TIN / tetrahedronized irregular network (TEN) model presented by Penninga (2005) uses TEN representation only for features like bridges, which cannot be modeled by 2D TIN. Such 3D models are then put on top of the TIN using the footprint of the feature. 2D footprints in 3D space are also considered to ensure the topological consistency of 3D models, e.g. 3D city models obtained by extrusion in Ledoux and Meijers (2011). Although these works allowed for 3D visualization, they do not support multiple LOD.

Works on data management of poly-lines at multiple resolutions, or scales, are usually associated with 2D cartography. Douglas and Peucker (1973) devised a basic poly-line simplification algorithm applicable for a single, isolated poly-line. The algorithm, however, can easily cause topological conflicts when applied to a set of neighboring poly-lines. This led to development of methods for simultaneous simplification of poly-lines by Berg et al. (1998), Kulik et al. (2005), Dyken et al. (2009), or Meijers (2011). The solution in Kulik et al. (2005) is based on algorithm of Visvalingam and Whyatt (1993) enhanced by the possibility to moderate the simplification process by the semantic influence of the map ontology, and removed the dependency of the simplification result on the order of the poly-lines input, which is an inherent property in Berg et al. (1998). Meijers (2011) identifies poly-lines influenced by a given simplification with help of an auxiliary kd-tree data structure, which facilitates fast access to the influenced poly-lines. In contrast, Dyken et al. (2009) avoids the overhead associated with the management of auxiliary data structures by encoding the poly-lines neighborhood relationships using unconstrained edges from the underlying triangulation. The existing solution however do not support variable intensity of geometry simplification for specified spatial domains.

The main objective of this paper is to introduce a simplification method for a set of poly-lines, that would allow for increased level of geometry simplification with increasing distance from the observer in 3D graphic scene. Such method should guarantee, that all the poly-lines will preserve their mutual topological relationships at all LODs for arbitrary position of the observer. For the sake of definition of such multiple LOD environment, we adopt the space indexing and paging method by Kolář (2006). Since Delaunay triangulation is the basic concept in our surface representation, we can use the method by Dyken et al. (2009) for testing of relationships between poly-lines. We want, however, to avoid the re-triangulation of the approximate set of poly-lines after removal of every point by maintaining a list of points that block the point removal similar to Meijers (2011). The formal definition of the solution is given in the following section. Experiment results are presented in Section 3 and followed by discussion and conclusions.

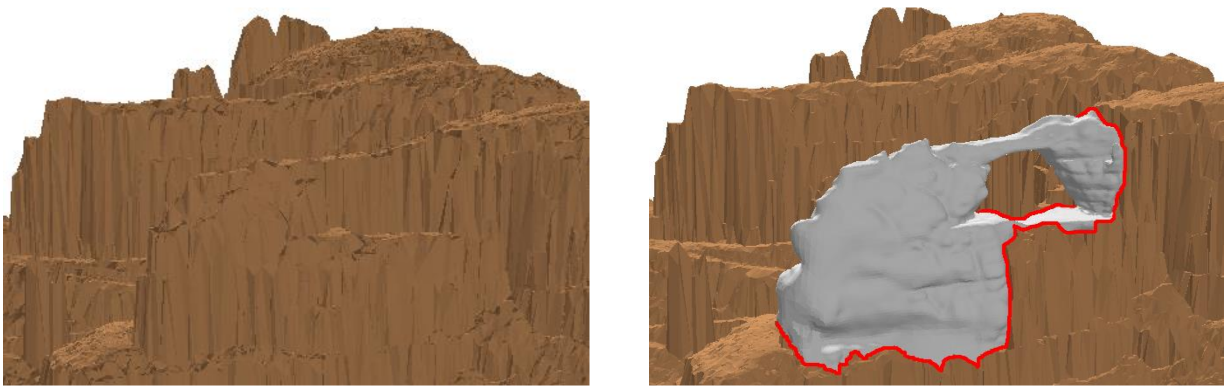

Figure 1. An illustration of the footprint concept. (Left) The view on the rock city in the National Park České Švýcarsko. The 2.5D TIN terrain model acquired by airborne laser scanning techniques is not able to represent complex nature of the area. (Right) 3D mesh object of České Švýcarsko, sandstone rock arch, modeled from terrestrial laser scanner data, integrated with the 2.5D model of surrounding rock city through the footprint depicted by the red line.

FORMALIZATION OF THE METHOD

Footprints

The provision of a topographic surface representation capable of accommodating any geographic feature that can influence its shape relies on the concept of *footprint*. The footprint is defined here as an outline of the geometry resulting from the intersection between the Delaunay triangulation of topographic surface and the geometry of the feature in 3D space, see Figure 1. An example of a footprint is shown in Figure 1, and it can be understood as the link between the topographic surface and an independently modelled feature. The footprint's building element is a poly-line P, which is a finite, non-empty sequence of m points p in $\mathbb{R}^3$

$$p(x, y, z) \in P = \{p_1, \dots, p_m\} \mid P \subseteq R^3 \wedge P \neq \emptyset \quad (1).$$

Weight of footprint points. To take into account importance of different parts of footprints every point p is assigned a *weight* ω. The weight can be inferred from the geometrical importance like in Douglas and Peucker (1973) or consider the semantic influence like in Kulik et al. (2005). The weights corresponding to points of P constitute the non-empty sequence W of weights ω.

$$\omega \in W = \{\omega_1, \dots, \omega_m\} \mid W \neq \emptyset \quad (2).$$

Footprint definition. Then the formal definition of footprint F is a non-empty set of pairs of poly-lines and weights' sequences, which reads

$$F = \{(p_1, W_1), \dots, (p_s, W_s\} \mid F \neq \emptyset \quad (3).$$

The method requires that every feature provides one footprint F.

Paging of footprints

The main aim of paging procedure is to associate every footprint's point only with a page on appropriate LOD, which means coupling the point with corresponding Global Indexing Grid (GIG) cell from one appropriate GIG level. The basic idea is to gradually decimate the geometry of footprints.

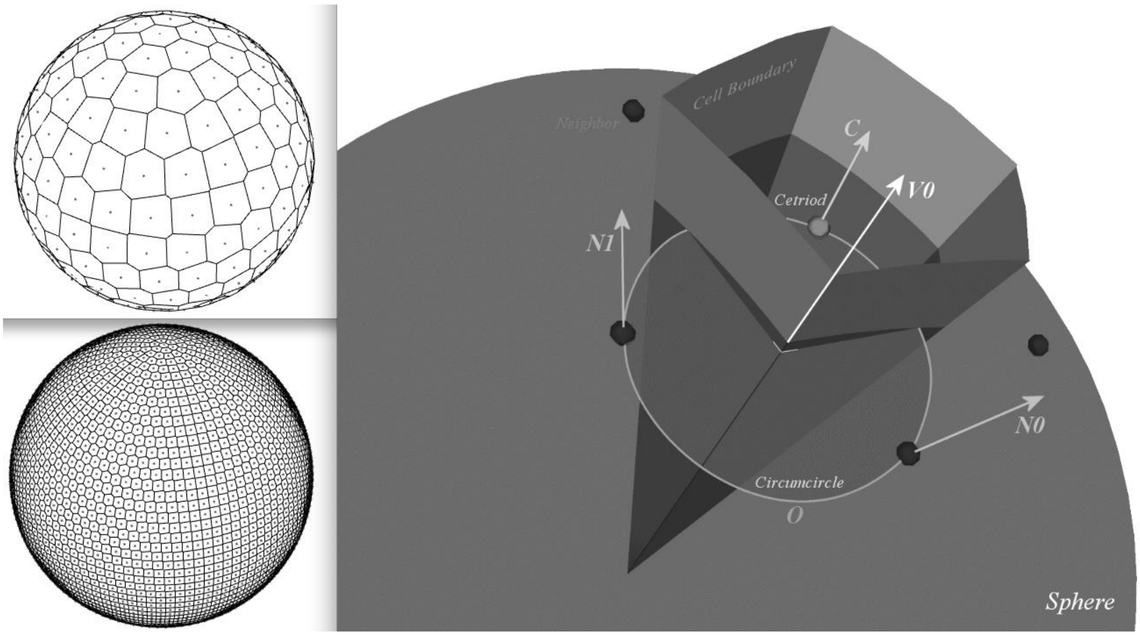

Figure 2. (Left) GIG centroids and GIG scheme at subdivision levels 16 (top) and 64; (Right) graphical representation of GIG cell, and of the cell's vertex vector relationship to neighboring centroids.

Global indexing. The mechanism for management of multiple LOD is fundamental for formalization of our method. As mentioned in Introduction we extend the work by Kolář (2006), which introduced GIG as the basis for a global topographic surface supporting multiple LOD. Important is the concept of GIG cell, see Figure 2. The GIG cell is a set of all vectors having an angular distance from a given centroid C smaller than from any other centroid. All vectors with equal distance to C and to another centroid constitute the cell boundary, and the vertex V_0 in Figure 1 has an equal distance to C and to two other neighboring centroids. GIG thus represents discrete global grid system, which is based on Voronoi diagram on a sphere.

We employ GIG cells to delimit the partitions of space that correspond to multiple LOD. As for the required number of LODs and the spatial extent to be covered by the GIG cells of every LOD, we get a set Z of LODs L

$$\mathrm{Z} = \{\mathrm{L}^1, \dots, \mathrm{L}^{\mathrm{l}}\} \mid \mathrm{Z} \neq \emptyset \wedge \mathrm{c}^{\mathrm{i}} \in \mathrm{L}^{\mathrm{i}} \quad (4).$$

where L^{i} corresponds to the finest LOD, L^{i} to the coarsest LOD, see Figure 2 (left).

GIG queries play important role during data processing. The nearest-centroid (NC) GIG method utilized as a hash function assigns an arbitrary point $p(x,y,z)$ to a unique GIG cell c based on the proximity to the centroid

$$\mathrm{NC}(\mathrm{x}, \mathrm{y}, \mathrm{z}) = \mathbf{c} \mid \mathrm{C} \in \mathbf{c} \quad (5).$$

When all neighbors of processed cell are required for the cell c, the NN query returns all adjacent cells

$$NN^i(c^i) = \{c_1^i, \dots, c_j^i\} \mid NN^i \subseteq L^i \quad (6),$$

where j is the index of the last neighbor cell.

The four-nearest-neighbors (*4NN*) query, which yields the four nearest GIG cells to the observer's camera position, is employed during the reconstruction of the 3D graphic scene with feature-enhanced topographic surface. It delimits the spatial domain, for which data need to be retrieved and visualized.

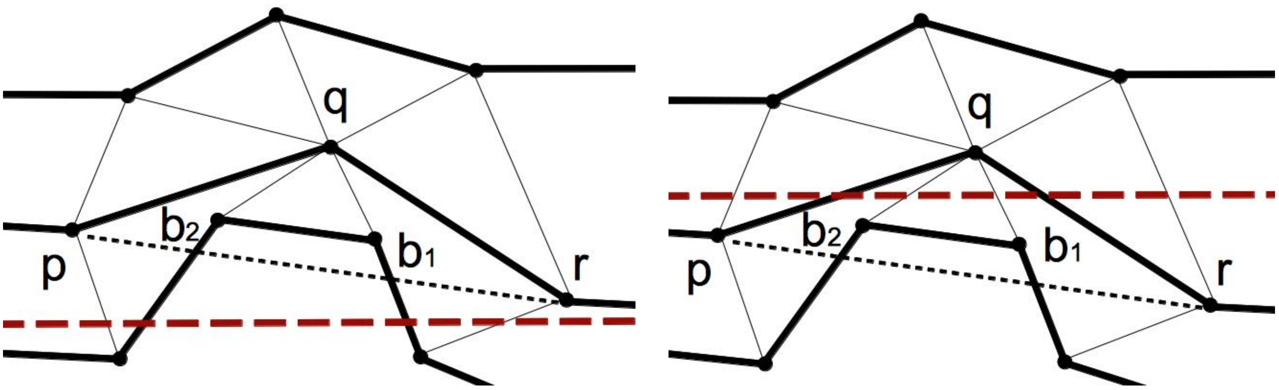

Figure 3. The geometry of the point q neighborhood. Removal of the point q, resulting into the new (p, r) segment, causes two new intersections. Thus q must be kept to avoid the change of topology. However, in case the blocking points b_1 and b_2 would be simplified, it would also allow for removal of q for the first case (left). In the second variant (right), the blockers b_1 and b_2 lies in the GIG cell different then the point q. Therefore, in the (right) case the point q will always be preserved to prevent from introduction of the topological error, when the cell with q is on coarser LOD. The boundary between GIG cells is depicted by the red fine dashed line.

Removable points. Testing the non-intersecting removal utilizes constrained Delaunay triangulation (CDT) constructed against the tangent plane of the concerned GIG cell's centroid. The CDT has the footprint poly-lines as input, and edges of the triangulation provide information about connected points. The removal condition test uses two lists of points connected to the candidate for removal q. The first list S starts with point p and proceeds counter-clockwise around q ending with point r. The complementary second list T starts with r and proceeds counter-clockwise to p.

Removal of q yields a simplified segment (p, r) without any new intersections with other poly-lines only if all $s_i \in S$ hold the same topological position relatively to (p, r) and all $t_i \in T$ have the same but topologically opposite position to (p, r). The left-or-right topological position of an arbitrary point v relatively to segment (p, r) can be expressed by a determinant

$$\det(v) = \begin{vmatrix} x_r - x_p & y_r - y_p \\ x_v - y_p & y_v - y_p \end{vmatrix} \quad (7),$$

where *x, y* are Cartesian coordinates of the CDT plane. Then the non-intersecting removal condition (as in Dyken et al. (2009)) is satisfied when

$$\det(s_i) > 0 \wedge \det(t_i) < 0 \quad (8),$$

or

$$\det(s_i) < 0 \wedge \det(t_i) > 0 \quad (9).$$

Simplification procedure. The objective of the simultaneous simplification procedure is to associate every footprint's point *p* with a cell *c* at just one GIG level L^i . Given a set *Z* of LODs *L*, the outcome of the procedure guarantees that all topological relationships between poly-lines *P* will be preserved in the finally reconstructed footprint-enhanced topographic surface.

Therefore, the a priori knowledge of, what GIG levels form the paging structure, is important, because the cells of the index also delimit the boundaries between different LODs. During the creation of pages by means of geometry simplification algorithm, special care must be paid to preservation of topological consistency at the LOD boundaries.

The key to the topological preservation in the multiple LOD environment (the mixed-scale representation of poly-line, whose detail decreases with increasing distance from the observer accordingly to the applied indexing structure) is rooted in the distinction of two kinds of points, which can block the removal, cf. Figure 3.

First, the points in the processed GIG cell *c*, which results from the *NC* query. Then, such a point *u* can block the removal of *p*, however, it can also be a candidate for a removal. If it becomes a successful candidate, it also enables the removal of *p*.

The second case happens, when the blocking point lies in the neighboring cell resulting from the *NN* query. Then, the decision on removal must be done solely owing to the non-simplified version, because the neighboring cell may be visualized with finer resolution.

To simplify the preconditions, we assume that input data are valid, meaning, they are free of geometric cases like multiple points at one location, intersecting and overlapping poly-lines. Moreover, every point has a weight defined. The process of assigning the portion of footprints' geometry is bound up with the paging mechanism, the GIG cells.

An outline of the procedure follows:

1. As an input, the procedure receives all footprints' poly-lines to be processed.
2. The *NC* function (Equation 5) is utilized to associate all input points with matching GIG cells at all levels as the first step. As the result of this mapping of all input footprints onto the indexing structure, also the list of cells to be processed is retrieved.
3. The processing of all cells *c* starts at the finest LOD and gradually reaches the coarser LODs. At given LOD *i*, the procedure iterates over all cells c^i.
4. For currently processed cell *c*, the CDT with *P* as constraints is built. The CDT domain is given by the union of *NC* and *NN* query on the centroid *C* of *c*.
5. Through comparison of weights ω and threshold value ε corresponding to processed LOD, it is decided, which points should be removed.
6. The decision on removal allowance is based on Equations 8 and 9, in order to prevent from introduction of any new intersection between poly-lines on coarser LODs.
7. Points that can be directly removed are placed to *Remove* list. With every blocked *p* (*p* should be removed, but neighboring polyline prevents from it), the lists of vertices, which *p* is *blocked by* and which *p blocks*, are associated.
8. After initial processing of all points of *c*, on the basis of points from *Remove* list, the particular *blocked_by* and *blocks* lists are iteratively updated, which may allow for removal of previously blocked point. Such a point is subsequently added to the *Remove* list. Every processed point from *Remov*e list is removed from the list and associated with given GIG cell *c*.
9. The processing of the cell *c* ends, when *Remove* is empty.

IMPLEMENTATION AND EXPERIMENT

This section illustrates the functionality of proposed methods on the example of Open Street Map data and complex 3D topographic feature modelled from airborne and terrestrial laser scanner data. For the representation of global surface we use the dataset from Space Shuttle Radar Topographic Mission in the form described in Kolář (2007). The elevation points were separated into three LOD corresponding to GIG levels 100, 500 and 1500. Clusters of elevation points corresponds to GIG cells on appropriate levels of detail.

Open Street Map (OSM) data sets (roads and railroads centerlines, buildings outline) were chosen due to their nearly global coverage. Proposed methodology was tested on European region subset of OSM data.

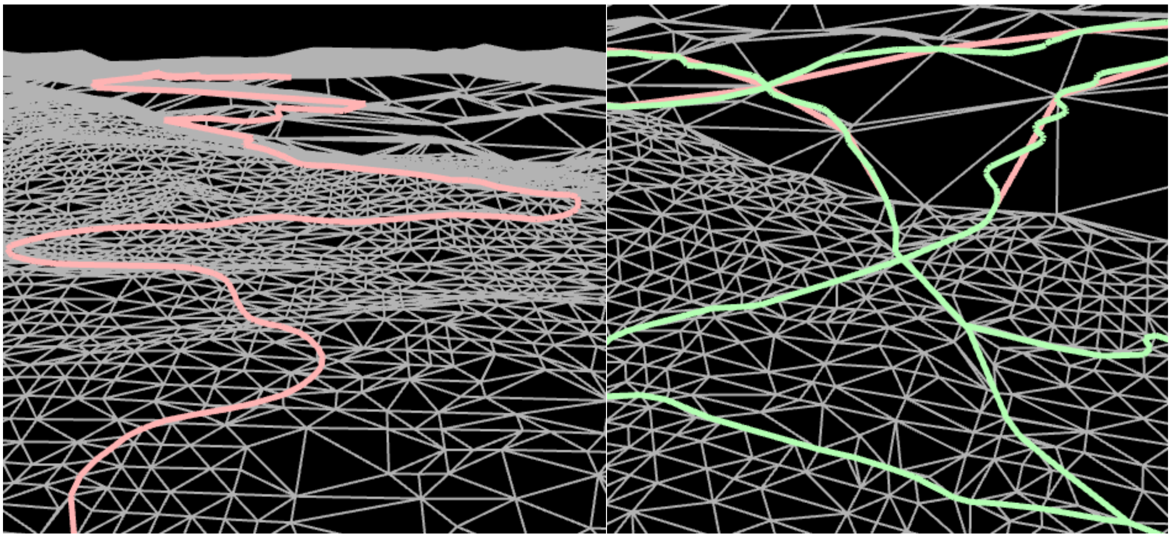

Figure 4. (Left) SRTM elevation data associated with OSM railroads data layer (red poly-line) on multiple LOD, both simplified in distant areas. (Right) Closer view on the threshold between two LOD with the OSM road network visualized also by the green color to illustrate the original course of the road centerline footprints in comparison to the simplified ones (red color).

To manifest the enhancement of topographic surface model with complex 3D feature, the sandstone arch Pravčická brána was modeled as 3D mesh, like in Figure 1. Processing workflow of the project consists of following stages.

I. Initial data processing

During preprocessing, the heights of OSM points were inferred from the terrain model with respect to the character of data (given resolutions, constant height of building's footprint). Weights of vertices were assigned to individual points based on Douglas-Peucker algorithm. From airborne and terrestrial laser scanner data 3D model of the sandstone arch was built. The levels of resolution of the 3D model were hardcoded during the preprocessing with respect to chosen GIG LOD. The co-registration of 3D model with the topographic surface model provided the feature's footprint.

The initial data processing also handled identical points, intersecting and overlapping edges, provided unified boundaries between neighboring features and lists of unique edges and vertices with weights adjusted. In the experiment the threshold epsilon value was set to 0.1 m to determine points to be considered identical or in edge.

II. Database building

The output provided by the topology analysis of the European region data was mapped on cells of GIG levels 100, 500 and 1500. For this data input and determined GIG cells multiple LOD database of footprints' records was built. The threshold for point removal from the LOD1 was set as $\varepsilon_1 = 50$ m limiting the error introduced on the LOD2, and $\varepsilon_2 = 120$ m limiting the error for the LOD3.

The database of records can be regarded as the result of the experiment that validates the entire approach for representing features' footprints globally using the GIG method.

III. Feature-enhanced topographic surface reconstruction

At-runtime, the *4NN* GIG query retrieves for all desired LODs the four nearest cells to camera position, which define the extent of Earth surface to be visualized, and retrieves stored representations of footprints and clusters of elevation points only for concerned GIG cells. The constraint Delaunay triangulation was applied on elevation points from concerned clusters and on footprints that served as constraints to the triangulation.

Resulting scene is depicted on Figure 5 with coarser resolution in distant areas of the scene. For observer position 49.395N, 13.293E tested data covered a domain of approximately 40 km x 40 km. The full-resolution road network, railways, buildings, pipeline, stations and sandstone arch footprints in this spatial extent consisted of 245508 points before simplification. For declared position the rate of position-dependent simplification of footprints reached 59 % on LOD2 partition, 73 % on LOD3 (0 % on the finest LOD1), with the overall simplification rate of 64 \% producing approximation of 88435 points.

CONCLUSION

The solution for a global representation of a multi-resolution topographic surface that supports a topological connectivity to other geographic features has been presented. The proposed solution can deal with features of various characteristics and data sources as long as it is possible to provide a correct footprint for the features. Footprints in the presented method act as a logical and geometrical interface between modelled features and the topographic surface.

The footprint-enhanced topographic surface with multiple LOD can be synthesized for a neighborhood of given query position. This is achieved by employment of efficient paging mechanism and building the database of records of geometry relevant only for given LOD. The pieces of geometry are associated with indexing mechanism, which ensures the refinement of geometric detail only where needed. The footprints decimation method guarantees for any observer position the preservation of topological relations between footprints in the position-dependent visualization of the Earth surface.

The reconstruction of the surface topology at run-time and only for the requested points provides high flexibility for editing of the surface geometry.

REFERENCES

De Berg, M., Van Kreveld, M., Schirra, S.,1998. Topologically Correct Subdivision Simplification Using the Bandwidth Criterion. Cartography and Geographic Information Science, 25, 243-257.

Cignoni, P., Ganovelli, F., Gobbetti, E., Marton, F., Ponchio, F., Scopigno, R., 2003. Planet- Sized batched dynamic adaptive meshes (P-BDAM). In: Proceedings IEEE Visualization,147-155, Seattle, WA, USA, 2003, IEEE Computer Society Press.

Crawford, C., Bayarri, S., Petrovic, D., 2003. Fast 3-d visualization of large image datasets in a GIS. In: ASPRS 2003 Annual Conference Proceedings, Anchorage, Alaska, USA.

Douglas, D. H., Peucker, T. K., 1973. Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. Cartographica:The International Journal for Geographic Information and Geovisualization,10(2),112-122.

Dyken, C., Daehlen, M., Sevaldrud, T., 2009. Simultaneous curve simplification. Journal of Geographical Systems, 11 (3), 273-289.

Gröger, G., Plümer, L., 2005. How to get 3-D for the price of 2-D|topology and consistency of 3-D urban GIS.

GeoInformatica, 9(2),139-158.

Kolar, J., 2006. Global indexing of topographic surface for 3D visualization and analysis. Thesis (PhD). Aalborg University, DK.

Kolar, J, Kjems, E., Bodum, L., Sorensen, E., M., 2007. Global surface model using Spaceshuttle radar topographic mission dataset and Global Indexing Grid. In: Strategic Integration of Surveying: Services FIG Working Week 2007. Hong Kong.

Kulik, L., Duckhamm, M., Egenhofer, M., 2005. Ontology-driven map generalization. Journal of visual languages and computing, 16, 245-267.

Ledoux, H., Meijers, M., 2011. Topologically consistent 3D city models obtained by extrusion. International Journal of Geographical Information Science, 25(4), 554-557.

Meijers, M., 2011. Simultaneous & topologically-safe line simplification for a variable-scale planar partition. In: S.C.M. Geertman et. al.(eds) LNGC: Advancing Geoinformation Science for a Changing World, Springer Verlag, 337-358.

Penninga, F., 2005. Towards 3D topography using a feature-based integrated TIN/TEN model. In: AGILE 2005, 8th Conference on Geographic Information Science. Conference Proceedings. Estoril, Portugal, May 26-28, F. Toppen and M. Painho, Eds., 25, 243-257.

Visvalingam, M., Whyatt, J. D., 1993. Line generalisation by repeated elimination of points. The Cartographic Journal, 30 (1), 46-51.

BIOGRAPHY

Mgr. Lukáš Brůha is a research assistant and Ph.D. candidate at the Charles University in Prague, Department of Applied Geoinformatics and Cartography. In 2010 he got an opportunity to spent 10 month at the Centre for 3DGI at Aalborg University. Since then, his research focuses on global representations of topographic surface.

Ing. Jan Kolář, Ph.D. is a geospatial researcher. Jan received his Ph.D. at Aalborg University, Denmark, where he developed a method called Global Indexing Grid, suitable for a multi-resolution modeling of global geographic features including the topographic surface, and the gravitational field of the Earth. Jan then started an academic carrier at Aalborg University. Since 2010 Jan is an independent consultant for geospatial software solutions. Jan also started Grifinor.NET - an effort regarding a distributed solution for geospatial information using an object database. He promotes the concept of computable geospatial model.