A New Approach for a Topographic Feature-Based Characterization of Digital Elevation Data

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ABSTRACT

Triangular Irregular Network (TIN) and Regular Square Grid (RSG) are widely used for representing 2.5 dimensional spatial data. However, these models are not defined from the topographic properties of the terrain (i.e., ridge lines, valley lines, saddle points, etc.). This paper introduces a three-step feature-based approach for topographic properties extraction on scattered elevation data modeled by a TIN. Firstly, a segmentation process extracts homogeneous morphological areas bounded by critical lines and points. Secondly, these lines and points are displaced using a deformable process in order to derive the terrain feature points, lines and areas. Thirdly, a classification process labels any topographic feature. This three-step approach relies on the definition of an adapted model of representation (SPIN) and data structure (DCFL2). The proposed approach is validated on a real case study (Seolak mountain in South Korea). Consistent results with the morphology of terrain are displayed.

Categories and Subject Descriptors

I.3.5 [**Computer Graphics**]: Computational Geometry and Object Modeling—*curve, surface, solid, and object representations*; E.1 [**Data Structures**]: *graphs and network*

General Terms

Algorithms

Keywords

Digital elevation data, feature extraction, SPIN model, DCFL2 data structure

1. INTRODUCTION

Thanks to the improvement of computing capabilities, 2.5D discrete surface representations are commonly used in Geographic Information Science (GIS) to model and represent digital elevation data. However, constant increase of data volume with the evolution of sampling devices (laser and synthetic aperture radar systems, photogrammetry, multi-beam echo sounders, Global Positioning System (GPS), etc.) higher leads to data processing requirements. This encompasses the need for efficient data models and algorithms for the representation, storage and analysis of 2.5D data.

Mathematical surface representations provide fundamental structures for modeling 2.5D spatial data. Those mathematical models are either global (i.e., defined through a single function interpolating or approximating all data, e.g., kriging or spline methods), or local (i.e., piecewise defined on a partition of the domain into patches). In local models, regularly distributed data generally correspond to *Regular Square Grids (RSG)*, while scattered data generally lead to *Triangulated Irregular Networks (TIN)*. The TIN model is commonly used since it can yield an adaptive description of the complexity (roughness) of digital elevation surface. This model is related to different data structures. In particular, the *implicit cell representation* enables the representation of the set of basic components (e.g., edges, faces, vertices), and their spatial relations.

The research described in this paper proposes an improvement of local models by emphasizing the shape properties of the terrain from a geomorphologic point of view. The goal is to extract the topographic features of a terrain, and to define a data model and structure which take them into account. This research is based on a three-step approach supported by a TIN representation. The first step extracts homogeneous units from a segmentation process with a new geometric attribute for the classification. This approach identifies flat, convex and concave areas, whose boundaries are defined by critical lines connecting critical points. In a second step, a deformable process displaces them to approximate real feature lines and points. Last step classifies feature points as peaks, pits or passes and feature lines as ridges, valleys or transfluent lines using a slope- and curvature-based approach. Finally, we propose a corresponding model called "Skeleton Polygonal Irregular Network" model (SPIN model) and the Doubly-Connected Feature Line List (DCFL2) data structure that describes it.

The reminder of the paper is organized as follows. Section 2 sets the terrain data model and structure used and reviews related works on feature extraction. Next sections focus

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on the representation and the method for recovering shape information from a triangulated surface. We define the SPIN model and the DCFL2 data structure in section 3. Section 4 presents the extraction strategy with a segmentation, an active contour and a classification process. Finally, section 5 concludes this paper and discusses further works.

2. DIGITAL TERRAIN MODEL

A *Digital Terrain Model* (DTM) provides information on the surface, based on a finite set of data. Terrain data are measures of elevation $Z = \{z_0, \ldots, z_{N-1}\}$ at a set of 2 dimensional points $P = \{p_0, \ldots, p_{N-1}\}$ in a space Ω (where Ω is a compact space in $\mathbb{R}^2$), plus possibly a set of non-crossing straight-line segments $L = \{l_0, \ldots, l_{M-1}\}$ having their endpoints in P. Data points p_i can either form a regular grid or be scattered.

2.1 Polyhedral terrain models

Three classes of DTMs are usually considered [27, 36]: (1) *Polyhedral terrains*, (2) *Gridded elevation models* and (3) *Contour maps*. The most commonly used polyhedral terrain and gridded elevation model are respectively the *Triangulate Irregular Network* (TIN) and the *Regular Square Grid* (RSG). Contour maps are not adapted for performing complex computer-aided terrain analysis. This is mainly due to the lack of information about terrain morphology between two contour lines.

Automated terrain analysis is rather performed on RSGs or TINs. RSGs are easy to manage and to process (using image processing algorithms) but are too constrained by the choice of the level of abstraction: the grid spacing can lead to either a redundancy or a lack of information. This can't take into account the variation of terrain roughness [22] and the potential heterogeneous complexity of topographic features. TINs are better adapted to model terrain since the sampling density is correlated to the roughness or the surface (multi-scaling). Moreover, TINs are linked with topological graphs which can represent the topographic features and their relations. More advantages and disadvantages of the RSG and TIN models are illustrated in [8, 1]. The triangulation used in our approach is the commonly used Delaunay triangulation which maximizes the minimum angle of its triangles.

In order to represent the polygonal regions and their spatial relations, different data structures are proposed: the *Doubly-Connected Edge List (DCEL)* by Preparata and Shamos [28], the *winged-edge structure* by Baumgart [4], the *half-edge structure* by Mäntylä [23], the *vertex-edge* and *face-edge structures* by Weiler [38], the *cell-tuple structure* by Brisson [6], and the *generalized maps* by Lienhardt [20]. The two last ones are generic extension in d-dimensions. In the following, we use the DCEL data structure for TIN representation. This is a good compromise between the memory needed to store the TIN and the access time to its components (vertex, edge or facet).

Some computational geometry libraries provide standard implementations of certain data structures. For instance, the LEDA, the CGAL [26] or the GeomLib libraries offer algorithms for computational geometry. Our implementations on TIN are based on the usual CGAL library [5].

2.2 Feature extraction

Many research domains point out the interest of identifying the features in a model (e.g., surface, image). In computer vision where an image is defined as a regular grid of color values, the feature extraction problem is often solved with segmentation techniques [16]. In computational geometry, the aim is to structure a polyhedron into a collection of convex pieces [2]. The geometric feature extraction in the domain of discrete geographic elevation data processing is close to this last research domain.

2.2.1 *Geometric feature extraction*

Surface processing is part of several research areas such as computer aided geometric design in mechanical applications, image processing for face recognition, and geomatics in terrain analysis. According to the application and the aim of work, two extraction strategies are proposed:

- detection of critical points (saddle points, maxima and minima) and identification of critical lines by connecting critical points.
  The extraction of critical points is generally based on a mathematical approach using either vertex neighbor methods or local surface fitting methods. In the first case, critical points are detected from a watershed and drainage network detection [41] or from their location (height difference with their neighbors) in a scalar field with Morse Theory or an extension of it [35, 9]. In the other case, critical points are detected from their local slope (local slope near zero), and their local curvature values [39] (see section 4.3.1). Critical points are either pits, peaks, or passes (correspond to minima, maxima and saddle points) [35, 39, 3, 12, 10]. Critical lines can be perpendicular to isocontours [3] (Figure 1-a) or deduced from a local curvature analysis [40]. These critical elements may be used to define a topological graph (e.g., Reeb graph [30]): the vertices of the graph are the critical points, and the arcs represent the relationships between its endpoints [35].

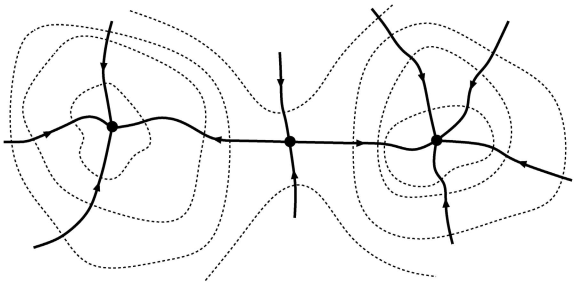
- detection of critical lines with a mesh segmentation as a preprocessing step.
  The surface is segmented into homogeneous areas having a relatively consistent curvature throughout (i.e., regions with concave convex or planar shape). Critical lines are either identified as the boundaries of the different areas [14, 22] or derived from a skeletonisation algorithm [31] (Figure 1-b).

2.2.2 *Terrain data constraints*

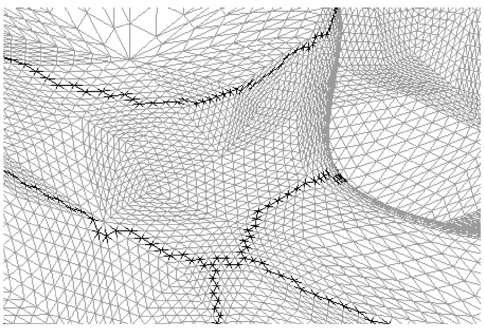
The terms used to characterize the shape of a terrain vary according to the domain of application and the author point of view. For instance, the terms critical features, structural features, morphological features, and topographic features are commonly used. Figure 1 illustrates this ambiguity and shows that "critical features" may differ from "structural features".

We assume the definition of topographic features proposed by De Floriani *et al.* [11] : "Topographic features are special points, lines and regions that have a specific meaning for describing the shape of the terrain: they correspond to local differential of the terrain surface".

A *feature point* is identified as being a local or global extremum on a surface: a *peak* is a maximum point, a *pit* is a minimum point and a *pass* is a saddle point (i.e., a point which is a local minimum in one direction and a local maximum in another one).



(a)



(b)

Figure 1: (a) Criticial curves connecting critical points (isocontours are in dotted lines), extracted from [3]. (b) Structural feature lines extracted from [31].

A *feature line* is a ridge or a valley line. A line (or polyline) is a ridge if it sends flows to two adjacent faces (Figure 2-a). A line (or polyline) is a valley if it receives flows from two adjacent faces (Figure 2-b).

A *feature area* is an area having its surface flat, convex or concave.

In geomorphologic applications, the shape of the terrain is not restricted to ridge and valley lines but one needs to extract specific feature lines that define the breaks of slope. The previous feature line definition is extended by introducing "transfluent lines", assuming that a line is transfluent if it receives a flow from one adjacent face and sends it to the other (Figure 2-c-d).

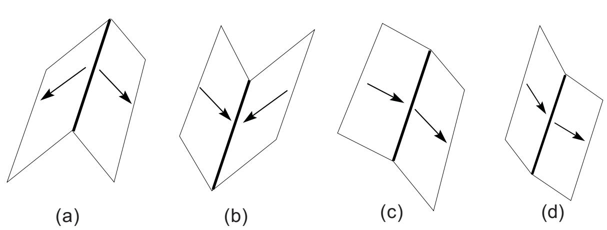


Figure 2: Feature line definition: (a) ridge line, (b) valley line, (c-d) transfluent lines.

The use of critical points to define critical lines, as mentioned previously (see Figure 1-a), enables the definition of topological graph based on flow direction constraints (i.e., direction of maximum decreasing slope). This approach is particulary well adapted to characterize hydrogeological features such as watershed or drainage networks. In other context (volcano tectonic features, karst relief), this approach does not extract all pertinent features such as transfluent lines.

Several works pointed out that a segmentation-based approach with a partition of the surface into a set of homogeneous morphometric areas (e.g., homogeneous slope, curvature) is a better way to improve the extraction of morphological structures of a terrain [15, 22]. However, curvature-based segmentation methods are better adapted to smooth surfaces (Figure 3) because they are very sensitive to the noise and even small fluctuations in surface shape [22]. This provides non significative information because every local extrema in curvature is detected. For terrain data, the noise corresponds to the surface roughness and is an intrinsic property of this kind of data. This problem increases with the density of data. In that case, a segmentation technique often implies an over-segmentation. Applying a threshold level on the segmentation geometric attribute often reduces this problem, but the choice of the accurate threshold level depends on the mesh and it is thus empirical.

This motivates the choice for a different approach for feature extraction on terrain data. This approach relies on the definition of an adapted model of representation and data structure.

3. TOPOGRAPHIC FEATURE REPRESENTATION

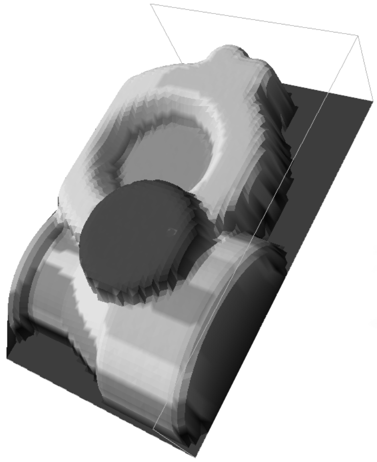
3.1 SPIN model

We introduce an alternative concept, based on the extraction of homogeneous polygons, where initial space Ω is partitioned into several disjoint polygons (see Figure 4). Each polygon is bounded by feature lines whose points are in the original set P. Two or more feature lines are connected by feature points. According, to the terminology used for describing polyhedral terrain models (see section 2.2.2) these polygons are called *feature polygons* and form a basic set of closed units for Ω. Thus, there is no overlapping area between feature polygons and the union of all feature polygons describes the whole space (i.e., $\bigcap s_i = \phi$ and $\bigcup s_i = \Omega$). The elevation of a feature polygon is a *feature patch.* This feature patch corresponds to the feature area previously defined. A feature area is not necessarily a plane surface since it may be defined by more than three non-coplanar points. This model is called *SPIN (Skeleton Polygonal Irregular Network)* and it belongs to the class of polyhedral models.

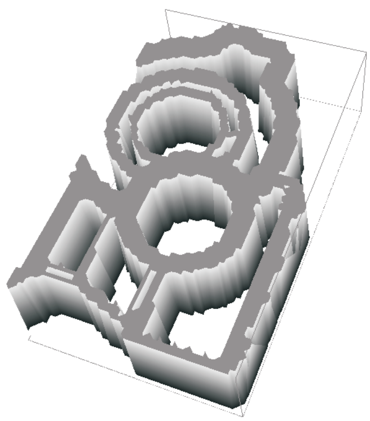
The addition of polygon adjacency information as a graph improves the topology and decreases the processing time of several terrain analysis processes. In such a graph, each node and edge may represent a polygon (resp. a feature point) and the adjacency between two polygons (resp. two feature points).

3.2 DCFL2 data structure

The proposed data structure for SPIN representation is based on the DCEL data structure. It is called *DCFL2 (Doubly-Connected Feature Line List)* data structure. As for the DCEL data structure, it is a comprise between the memory needed to store the SPIN and the access time to



(a)



(b)

Figure 3: (a) A mechanical part (4100 scattered data from http://www.cs.technion.ac.il/~vitus/mingle /data_sets.html). (b) Highly curved region extraction.

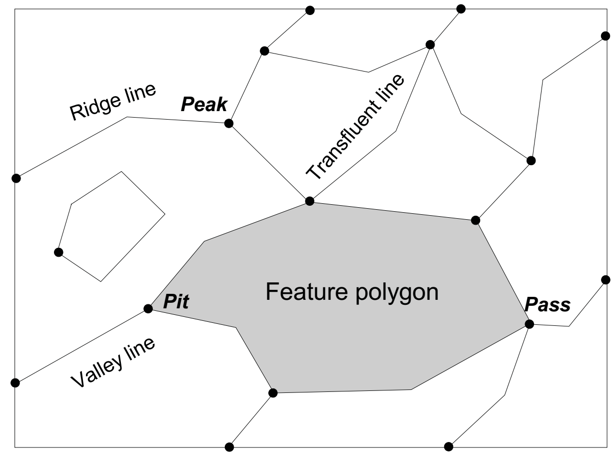


Figure 4: An example of representation using the SPIN model.

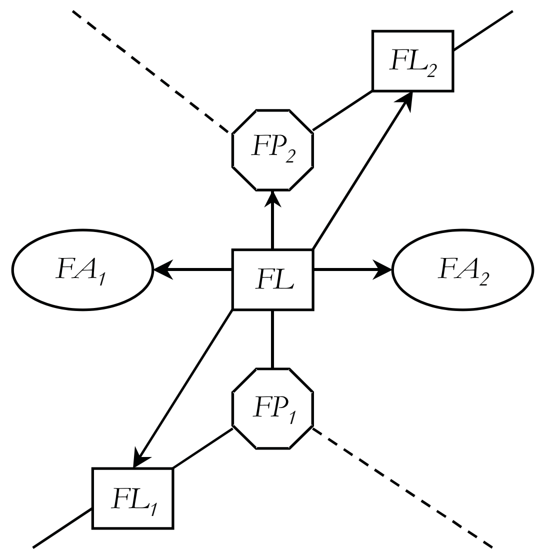


Figure 5: DCFL2 data structure.

its components (i.e., feature points, feature lines and feature areas). The DCFL2 data structure is composed by a list of oriented feature lines. For each feature line (FL), the DCFL2 stores two links FP_1 and FP_2 to its feature endpoints, two links FL_1 and FL_2 to the first neighboring feature line that will be found turning around FP_1 and FP_2 counterclockwise, two links FA_1 and FA_2 to the left and right faces sharing this line, and a list of points forming this feature line (Figure 5).

In order to perform the accessibility to the different components, a list of feature points and feature areas can be added in the structure. These lists are linked by the feature line attribute. In the feature point list, each point is defined by its subscript in the structure, its co-ordinates (x y z), and a related feature line subscript where the feature point is an endpoint. In the feature area list, each area is defined by its subscript, a related boundary feature line subscript and a list of points or facets included in this area. Each area includes a list of feature areas inside and is possibly included in a feature area.

4. TOPOGRAPHIC FEATURE EXTRACTION PROCESS

The topographic feature extraction process is composed of three steps. Firstly, a segmentation protocol leads to extract homogeneous units where the boundaries yield critical lines and points. Secondly, the topographic features are obtained from a deformable process. Finally, these topographic features are classified.

4.1 Segmentation

The mesh segmentation method leads to a partition of the surface into a set of connected regions. Two ways are proposed to lead to this goal: find morphological heterogeneities that locate the contours lines of these areas, or find homogeneity criteria to aggregate similar facets. In the case of natural terrain, two connected reliefs are limited by a transition area rather than by an accurate boundary [22, 29, 33]. Therefore, the second way is more efficient [25, 22, 29]. This approach assumes to classify each facet and to define a merging process that aggregates similar adjacent ones.

4.1.1 Geomorphometric attributes for classification

In the context of terrain data, Weibel and DeLotto [37] define the principle of classification as a succession of three steps: selection of attributes, extraction and classification. The first step selects the most representative morphological parameters. The second computes the parameter values for each basic unit (point or facet). The last step distributes each of these basic units in a class adapted to the objective of the segmentation. Geomorphometry gives a set of mathematical measurements which characterize morphological features (geometric landform information) or processes (hydrologic phenomena). There is not a universal set of attributes, but many combinations adapted to a given terrain. A great number of attributes does not generally improve the result because some parameters often bring more noises than information [13, 24]. Nevertheless, some of these parameters appear as fundamental in all contexts. The normal vector parameters of a facet are the most important ones. A normal vector is characterized by its deviation $\theta \in [0, \frac{\Pi}{2}]$ from the horizontal (slope) and its deviation $\varphi \in [0, 2\Pi[$ in the horizontal plane (Figure 6).

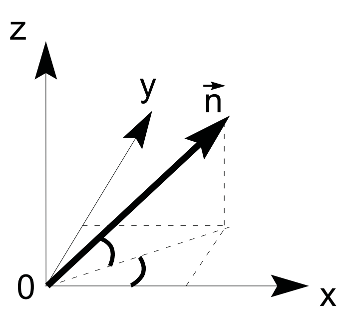


Figure 6: Slope θ and deviation φ of a normal vector.

For the classification, we propose a *Global Attribute* At_g as a combination of the slope θ and the deviation φ. At_g is computed on each facet of the TIN. Let NCs be the number of slope classes, and NCd be the number of deviation classes, then:

$$At_g = E\left[\frac{At_s + At_d}{NC_s}(NC_s \times NC_d)\right] \quad (1)$$

where $At_s = \begin{cases} E\left[\frac{2\theta \times NC_s}{\Pi}\right] & \text{if } \theta \in [0, \frac{\Pi}{2}[\\ NC_s - 1 & \text{otherwise} \end{cases}$, $At_d = \frac{\varphi}{2\Pi}$ and E being the floor function.

Equation 1 classifies the facets in $NC_s * NC_d$ classes that describe the variability of the terrain in slope and in deviation at once.

4.1.2 Merging process

The merging protocol takes into account the neighborhood relationships between the basic units (i.e., the triangular facets for a TIN). This protocol starts from a basic unit and merges gradually the similar adjacent units (facets with the same Global Attribute At_g). In order to avoid the extraction of a great number of non-representative microareas, an absorbtion operator removes the smallest areas by aggregation with an adjacent and almost similar area [32, 19].

4.1.3 Segmentation results

Figure 7 presents segmentation results with different number of classes in slope and deviation. Scattered data are extracted from a South Korea relief digitization (Seolak mountain). The higher the number of classes, the higher the number of areas: 343 areas for 80 classes (Figure 7-a) and 110 areas for 10 classes (Figure 7-b). Results appear to be consistent with the actual terrain morphology. A high number of classes NC_s and NC_d increases the roughness detection, respectively on horizontal and vertical flanks. This approach is well adapted to extract flat areas. As regards convex and concave area segmentation, they are subdivided in NC_d sectors and NC_s tracks (Figure 8-a).

As the Global Atribute At_g is an integer value, small variations of θ et φ related to the intrinsic local roughness of terrain data, are integrated in the merging process. Similarly, the results do not depend on the choice of the starting basic units.

The variation of At_s puts forward the convexity and transfluent lines. For morphological shapes not characterized by these lines (i.e., not affected by a hydrological process), a "smooth" regular conic hill or doline for instance, the φ-based segmentation is not necessary (Figures 8-b and 9 where $NC_d = 1$). As regards the variation of At_d, this puts forward φ-deviation changes, and thus focuses on ridge and valley line extraction (Figure 10 where $NC_s = 1$).

As the location of critical points and lines depends on a the class numbers NC_s and NC_d, critical points and lines may be close to the relief feature points and lines. Moreover, local artifacts on the boundaries (not removed by the absorption operator) still remain (see Figures 7 and 11). Consequently, an additional accurate location of feature lines and points is needed using a curvature approach.

4.2 Active contours

Active contours are a special case of deformable models. They were proposed by Kass *et al.* [17] in the field of computer vision and pattern recognition in order to detect object contours. The principle is to define an initial curve on an image (also called the "snake") and to deform it by minimizing its energy[1]. Let $u(t)$ be the snake where $t \in [0, 1]$, then:

$$E_{tot}(u(t)) = \int_0^1 E_{int}(u(t)) + E_{ext}(u(t))dt \quad (2)$$

where E_{int} and E_{ext} are the internal and external energies.

This approach is adapted to deform the critical lines defined in the previous section. Thus, the critical lines or polylines are the snakes $u(t)$, and are displaced towards the relief feature lines. We assume that their endpoints are feature points and have been previously displaced to neighboring points having a higher absolute curvature (see Figure 11). They are fixed during the deformation process

[1]Burghardt and Meier [7] adapted the approach to line displacement in cartographic generalization. In this case, the snake does not represent the curve to be deformed but the displacement itself.

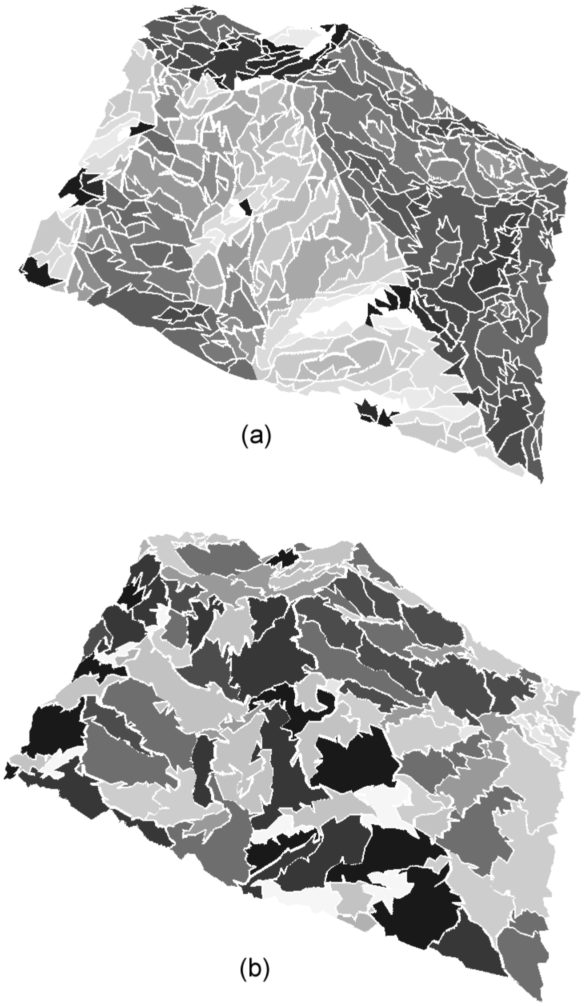


Figure 7: Segmentation results of Seolak mountain (South Korea). The TIN has 8860 scattered data points, 17686 triangular facets. (a) $NC_s = 5$ **and** $NC_d = 16$**, (b)** $NC_s = 2$ **and** $NC_d = 5$**.**

to ensure the continuity between lines.

External energy: A deformation towards highly curved places is enforced. The external energy is defined as:

$$E_{ext}(u(t)) = \left|\frac{1}{K_{abs}}\right|^2 \quad (3)$$

where K_{abs} is the continuous absolute curvature (Eq. 6) computed on a mesh point $\begin{pmatrix} p_i \\ f(p_i) \end{pmatrix} \in \mathbb{R}^3$ and f is the thin plate spline interpolating the whole data.

Internal energy: The internal energy is set to zero to avoid internal and external energy compensation, where the total energy of the snake may decrease while having an increasing external energy.

Thus, the problem of snake energy minimization (Eq. 2) is reduced to an external energy minimization.

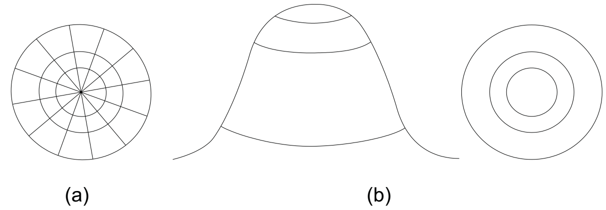


Figure 8: Segmentation of a convex shape: (a) $NC_s = 3$ **and** $NC_d = 12$**, (b)** $NC_s = 3$ **and** $NC_d = 1$**.**

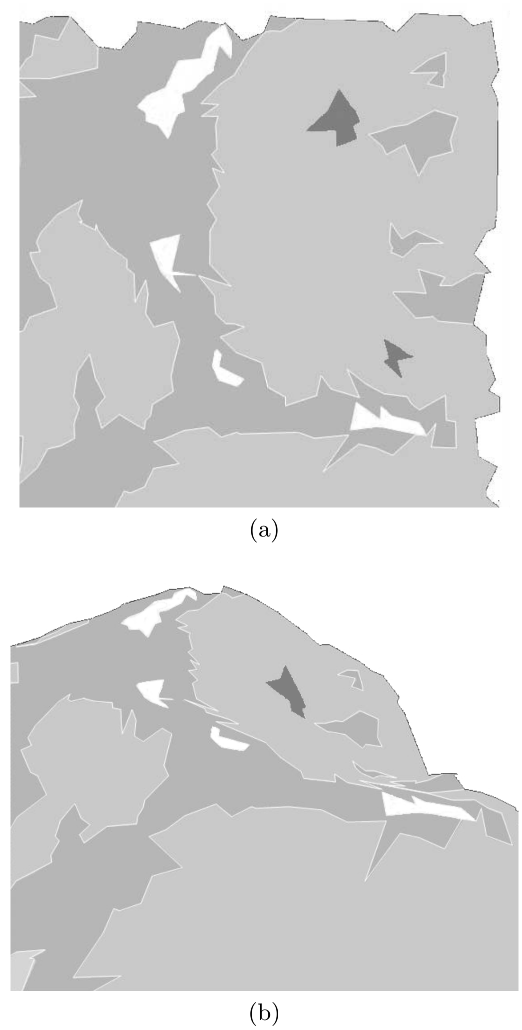


Figure 9: Convex shape segmentation of Seolak mountain ($NC_s = 5$ **and** $NC_d = 1$**): (a) Projection in space** Ω**, (b) 3D relief.**

The method is iterative. Let $u^{(0)}$ be the initial critical line. $u(t)$ can be modeled by a parametric curve[2] of degree 1. The step n consists of the definition of $u^{(n)}$ by deforming

[2]For instance, $u(t)$ can be a B-spline curve of degree 1. In this case, the control points of the B-spline curve are equal to the points of the polyline and the parameter t is the curvilinear co-ordinate.

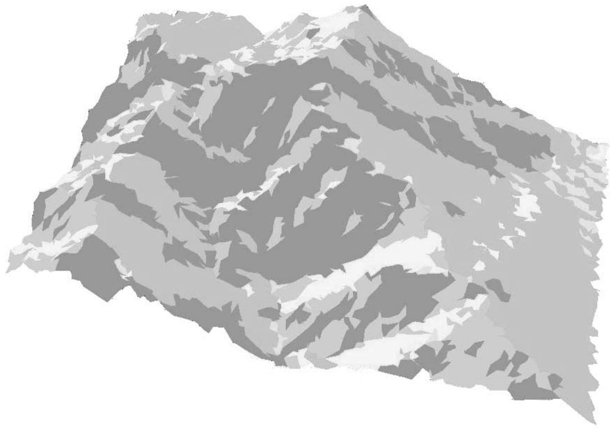


Figure 10: φ-deviation segmentation of Seolak mountain ($NC_s = 1$ and $NC_d = 5$).

the snake $u^{(n-1)}$ such as $E_{tot}(u^{(n)}(t)) < E_{tot}(u^{(n-1)}(t))$. This is obtained by:

1. displacing each point of $u^{(n-1)}$ towards a neighboring point having a higher absolute curvature K_{abs};
2. computing geodesic lines connecting these new points;
3. removing artifacts such as loops.

The second step is realized in order to constraint the displacement on the initial mesh. An example of snake deformation is displayed in Figure 11, where initial critical points have been previously displaced to neighboring points having a higher absolute curvature. This approach removes the boundary artifacts induced by the segmentation process.

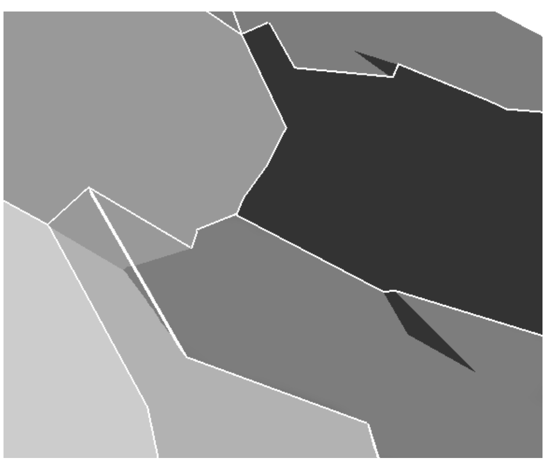


Figure 11: Example of boundary deformation (white lines) using active contours. Endpoints may be displaced to neighboring points.

4.3 Classification

Curvature measurements combined with slope measurements, enable to classify the points and lines according to the definition of section 2.2.2.

4.3.1 *Feature point classification*

Curvature measurements yield a feature point classification. Both continuous or discrete curvatures can be computed. Continuous curvature computed on an approximating or interpolating continuous surface is less sensitive to noise and small perturbations than discrete curvature [21, 34]. As regards the continuous surface, it can be computed either on the whole data or on a neighborhood of a point of interest. A curvature computed in the neighborhood-based environment defined by the TIN introduces a non-representative local classification. Thus, the curvature values are computed in the neighborhood-based environment defined by the DCFL2 structure. The values are computed on a thin plate spline interpolating the feature point of interest and its adjacent feature points (in the DCFL2 structure).

Gaussian and mean curvatures are the most widely used indicators for analyzing the local shape of a surface [18]. They are defined for surfaces which are derivable twice.

The two principal curvatures k_1 and k_2 enable us to estimate the local shape of the surface, through different curvature formulae:

- *Gaussian curvature*:
$$K = k_1 k_2. \tag{4}$$
- *Mean curvature*:
$$H = \frac{1}{2}(k_1 + k_2). \tag{5}$$

The gaussian curvature sign indicates the local shape of the surface at point p_i. From a theoretical point of view:

- $K > 0$: Point p_i is a convex point ($k_1 > 0$ and $k_2 > 0$), or a concave point ($k_1 < 0$ and $k_2 < 0$);
- $K < 0$: Point p_i is a saddle point (k_1 and k_2 have opposite signs);
- $K = 0$: Point p_i is a flat point ($k_1 = 0$ and $k_2 = 0$), or the local shape can be a convex cylindrical shape (the non-null principal curvature is positive) or a concave cylindrical shape (the non-null principal curvature is negative).

The mean curvature differentiates the convex case ($H > 0$) and the concave case ($H < 0$) (Table 1).

Table 1: Local shape of a surface based on the sign of the gaussian and mean curvatures.

	$K < 0$	$K = 0$	$K > 0$
$H < 0$	Saddle valley (Sv)	Concave cylinder (-Cy)	Concave ellipsoid (-El)
$H = 0$	Minimal (M)	Plane (Pl)	Impossible
$H > 0$	Saddle ridge (Sr)	Convex cylinder (+Cy)	Convex ellipsoid (+El)

The *absolute curvature* (Eq. 6) determines the local flatness of the surface. Planar points have an absolute curvature of zero while highly curved regions have large absolute curvature.

$$K_{Abs} = k_1^2 + k_2^2. \tag{6}$$

4.3.2 Feature line classification

The analysis of the normal and gradient vectors of adjacent areas yields a classification of feature lines (see Figure 2). Transfluent lines are identified by a positive normal vector dot product in the horizontal plane. A negative or null dot product identifies either a ridge or a valley line. The gradient vector analysis differentiates them. A divergent gradient field defines a ridge line whereas a convergent one defines a valley line.

Table 2 concludes this section by presenting the different possible connections between feature points and lines.

Table 2: Relations between feature points and feature lines ((0) impossible, (1) ridge line, (2) valley line, (3) transfluent line).

	Peak	Pit	Pass
Peak	1-3	0	1-3
Pit	0	2-3	2-3
Pass	1-3	2-3	1-2-3

5. CONCLUSION AND FUTURE RESEARCH

Usual Digital Terrain Models are not defined from the topographic properties of the terrain. This paper introduces a data model and structure based on topographic features to represent digital elevation data and their spatial relationships. This is performed by a segmentation and active contour processes on a TIN. A given surface is decomposed into homogeneous morphological areas (flat, concave, convex) using a global attribute combining slope and deviation properties of normal vectors. The resulting area boundaries define critical lines connecting critical points. The active contour process is then applied to displace these critical lines and points to real feature lines and points. Finally, a slope and curvature-based approach classifies feature points as peaks, pits or passes, and feature lines as ridge, valley or transfluent lines. The proposed results show the interest of this approach with consistent extraction of terrain features. The choice of the slope and deviation class numbers emphasizes the local roughness, the convexity ($NC_d = 1$) or the φ-deviation changes ($NC_s = 1$).

Further work consists in applying our SPIN model in order to improve current applications like height estimation, terrain analysis, contour line modeling, levels of details processing, compression or simplification, etc. One can also consider many extensions and future researches on the extraction process. An interesting way concerns the extension of the global attribute either with the integration of statistical methods (to emphasize the most discriminant attribute) or the integration of a distance attribute taking into account the error between an initial area and its approximating plan [13, 24, 37, 39]. Another extension is the integration of internal energies in the active contour process in order to impose “smooth” or “fair” deformation and thus to avoid curve loops.

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