GENERATION OF DEM FROM CONTOURS FOR THE ORTHORECTIFICATION OF HIGH-RESOLUTION STELLITE IMAGES

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ABSTRACT:

We present a technique for constructing a digital elevation model (DEM) from contours. The elevation of each ground point in DEM is computed by interpolating the heights of the two adjacent contours of the point. The technique decomposes each sub-domain between adjacent contours into a set of sub-regions. The decomposition is accomplished by constructing a medial axis of the sub-domain. Each sub-region in the decomposition is classified into a variety of terrain features like hillsides, valleys, ridges, etc. The elevations of points are interpolated with different methods according to terrain features they belong to. For a given point in hillside, an approximate gradient line passing through the point is determined and the elevation of the point is interpolated from the known elevations of the two adjacent contours along the approximate gradient line. The univariate monotone rational Hermite spline is used for the interpolation. The DEM constructed by the technique is to be used to orthorectify the high-resolution KOMPSAT3 imagery.

KEY WORDS: Digital Elevation Model (DEM), Contours, Medial Axis, Monotone Interpolation, KOMPSAT3

1. INTRODUCTIONT

High-resolution satellite images are now widely used for a variety of applications including general mapping, photogrammetry, GIS data acquisition and visualization. Since satellite images are distorted by the tilt of the satellite sensors and the topographical variations in the surface, it is desirable that the images are orthorectified to be used in the applications. Orthorectification of satellite images is usually carried out by utilizing resampling model using a digital elevation model (DEM), or Rational Polynomial Coefficient (RPC), or both. Since the RPC resampling method needs accurate, well-distributed ground control points (GCPs), it is not practical in forested mountain areas.

Digital elevation model (DEM) is a digital representation of ground surface topography or terrain surface over a specified area in the form of a raster grid and it consists of terrain elevation for ground positions, sampled at equally spaced intervals. In addition to the orthorectification of remote sensed images, the DEM's are utilized in support of modeling, analyzing, visualizing, and interrogating topographic features. DEM's are generated from a variety of resources. DEM can be generated by automatic DEM extraction from stereo satellite scenes or stereo digital aerial photography. However, in mountain areas, automatic extraction from stereo image is not always satisfactory. In most cases, DEM for mountain areas are provided by involving interpolation from pre-existing digital contour maps which many have been produced by direct survey of the terrain.

The general surface reconstruction of three-dimensional object from a set of contours is to determine a surface that approximates an unknown surface using geometric information in the contours. The contours are usually terrain contours or contours obtained from cross-sectional data of CT, MRI, or range sensors.

The general surface reconstruction from contours can be broken into three subproblems: correspondence problem, branching problem, and tiling problem (Meyers *et al.*, 1992). Correspondence problem is to determine which contours at a given level must be connected to which contours of adjacent levels. When a contour at a given level corresponds to a single contour of an adjacent level it is called one-to-one correspondence. When a contour corresponds to more than one contour at adjacent level, it is called one-to-many correspondence. The branching problem occurs when there is a one-to-many, or many-to-many correspondence between adjacent levels. It is to determine how to connect the corresponding contours at adjacent levels. The tiling problem is to construct a surface connecting a set of corresponding contours with a triangular mesh.

In the terrain surface reconstruction from contours, only the cases of one-to-one or one-to-many correspondences occur since one contour encloses one or more adjacent contours (Hormann *et al.*, 2003; Zhang *et al.*, 2005). The rather complicated many-to-many correspondence or branching structures do not occur in this problem. The problem of extracting DEM from contours is simpler than terrain reconstruction problem since the approximate surface does not need to be constructed and the problem can be solved with the correspondence and branching subproblems. (Gousie and Franklin, 2003) presented a technique for creating DEM from contours by constructing new intermediate contours in between existing contours.

In this paper, we propose a new algorithm to construct DEM from a set of terrain contours. The elevation of each ground point is computed by interpolation from two adjacent contours of the point. The algorithm consists of two steps. First, the terrain features (hillsides, ridges, valleys, canyons, pits, and peaks) are extracted from contours. These terrain features are the most significant regional features to characterize and extract from terrain model (Mascardi, 1998). Secondly, the elevations of points are interpolated with different methods according to terrain features they belong to. For example, for a given point in hillside, we determine an approximate gradient line from a higher elevation position to a lower position that passes through the point. Gradient lines should intersect contour lines perpendicularly. The elevation of the point is interpolated from the known elevations of the two adjacent contours along the approximate gradient line. For the univariate interpolation method, the monotone rational Hermite spline (Gregory and Delbourgo, 1982; Hormann *et al.*, 2003) is used.

2. GEOMETRIC PRELIMINARIES

2.1 Terrain Model by Contours

A contour is represented by a simple polygon and any point on a contour has the same height value. Contours modeling terrain has certain restrictions on the allowed geometrical configurations. Terrain is modeled as strictly nested hierarchy of contours: Any contour encloses an arbitrary number of other contours, but is entirely contained within only one other contour at the next hierarchical level, and any contour does not intersect with other contours. Contour tree (Chen *et al.*, 2005) is a data structure to describe the hierarchical relationship among contours. The correspondence problem to determine adjacent contours to be connected together can be solved by utilizing the contour tree (Hormann *et al.*, 2003; Zhang *et al.*, 2005).

Suppose that we are given a set of n contours $\{c_1, c_2, \ldots, c_n\}$ in the plane where contour c_i has height value h_i and c_i lies inside some c_j with $j < i$ for $i \geq 2$. The outermost contour c_1 encloses all the other contours and it partitions the plane into two open sets, the unbounded domain Ω_0 and the domain bounded by c_1 which in turn partitioned by other contours into n disjoint open sets Ω_i. Each sub-domain Ω_i has c_i as an exterior boundary and k_i interior boundaries c_j with $j > i$. For simplicity, we suppose that all k_i interior boundaries have the same height and the height is different from that of c_i.

- If $k_i = 0$, then the sub-domain Ω_i has a local extremum point and the sub-domain is a *peak* or a *pit*. We differentiate them by considering the height relationship between h_i and h_j, where c_i is an interior boundary of sub-domain Ω_j. If $h_i > h_j$, then Ω_i is a peak and otherwise it is a pit.
- If $k_i = 1$, then a contour c_i corresponds to one contour c_{i+1}. In this case, the sub-domain Ω_i is a mixture of hillsides, ridges, or valleys. Just like the peak and pit case, if $h_{i+1} > h_i$, then Ω_i is a mixture of outbound hillsides and ridges; otherwise it is a mixture of inbound hillsides and valleys.
- If $k_i > 1$, then a contour c_i corresponds to k_i contours. This case is called a one-to-many branching and it forms complex terrain. The sub-domain Ω_i is a mixture of hillsides, ridges, valleys, and canyons.

2.2 Medial Axis of a Polygon

The *medial axis* of a simple polygon P is the locus of all centers of circles (called maximal circles) contained in P that are tangent to P in two or more points. The medial axis is a simple tree graph composed of vertices and edges, where edges are either parabolic arcs or straight line-segments. The medial axis is closely related to the generalized Voronoi diagram of line-segments and their end points. The generalized Voronoi diagram of edges and reflex vertices of a polygon is different to the medial axis of the polygon only near reflex vertices of the polygon. The medial axis does not have any edges leading to reflex vertices, while the generalized Voronoi diagram always have such edges. There exist optimal O($n$log$n$) algorithms to compute the generalized Voronoi diagram of n line-segments and hence the medial axis (Lee, 1982; Yap, 1987). For a simple polygon with polygonal holes, the medial axis of the polygon can be computed in O(n(log$n$+h)) time, where n is the number of edges of the polygon and holes, and h is the number of holes (Srinivasan, 1987). The medial axis of a polygon with holes is a general planar graph with parabolic arcs or straight line-segments (see Figure 1).

The edges and concave vertices of a polygon that are touched by maximal circles are called active boundary elements. The number of active boundary elements touched by a maximal circle classifies the type of points on medial axis.

(1) *End points* are the points of medial axis intersecting with the boundary of a polygon.

(2) *Junction points* are the centers of maximal circles tangent to three or more active boundary elements.

(3) *Regular points* are the centers of maximal circles tangent to two boundary elements. A *transition point* is a regular point where one of the active boundary element changes.

End points, junction points, and transition points in the medial axis are called *key points*. A *segment* of the medial axis is the maximal subset of the medial axis associated with uniquely with two distinct active boundary elements. Both end points of a segment are key points.

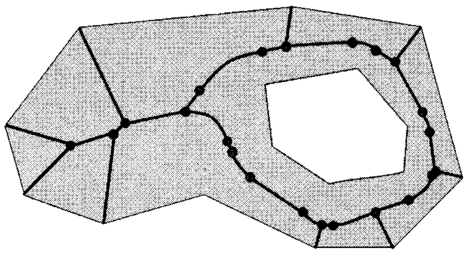

Figure 1. Medial axis of a polygon with a hole. Dots are junction and transition points on the medial axis.

3. TERRAIN FEATURE EXTRACTON FROM CONTOURS

For each sub-domain Ω_i defined in a hierarchy of terrain contours, the corresponding medial axis can be constructed. In this case, the exterior contour of Ω_i is the polygon to define the medial axis, and interior contours of Ω_i are holes in the polygon.

(Tang, 1992) proposed a method to extract linear or point terrain features (ridge lines, valley lines, saddle points, etc.) from a raster contour line image. It is based on raster operations and makes use of a medial axis derived from contours.

Similar to the method proposed by Tang, we extract regional terrain features (ridges, valleys, hillsides, canyons, pits and peaks) using a medial axis transformation. For each sub-domain Ω_i, the corresponding medial axis decomposes Ω_i into a set of regions bounded by contours and medial axis edges (see Figure 1). In sub-domain Ω_i, consider drawing line-segments connecting each junction point or transition point of medial axis to tangent points on contours of the maximal circle centered at the point. These line-segments decompose Ω_i into a set of regions and these regions are bounded by contours and the line-segments. The decomposition of the sub-domain is called the *quasi-dual medial axis decomposition*. Each region in the quasi-dual decomposition contains and matches exactly one segment of medial axis and the region is called the corresponding *zone* of the segment (see Figure 2a).

In our approach, the identification of terrain feature is derived from the quasi-dual decomposition. This can be achieved by examining the structure of the medial axis. The medial axis of a sub-domain Ω_i is a general planar graph with cycles. A maximally connected subset of edges not belonging to any cycles of the medial axis is called a *dangling subtree* (see Figure 2b). The sum of corresponding zones of all segments in a dangling subtree corresponds to a ridge or a valley. The feature to be identified depends on the relative heights of the bounding contours. The zone of a segment in a cycle of medial axis may create a ridge, a valley, or a canyon depending on the relative heights of the bounding contours.

The zone of a segment of medial axis is classified according to types of active boundary elements that define the segment.

(1) Zone bounded by two boundary elements, one on interior contour and one on exterior contour. The zone corresponds to a hillside.

(2) Zone bounded by two boundary elements on the same exterior contour. The zone corresponds to a ridge.

(3) Zone bounded by two boundary elements on the same interior contours. The zone corresponds to a valley.

(4) Zone bounded by two boundary elements on different interior contours. The zone corresponds to a canyon.

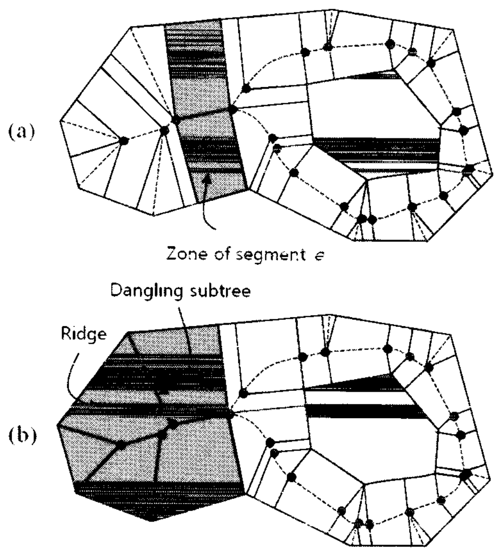

Figure 2. (a) Quasi-dual medial axis decomposition (b) Dangling subtree of medial axis and its corresponding ridge

4. INTERPOLATION METHOD

To interpolate the height of a point in a sub-domain of a set of contours, the terrain feature they belong to has to be determined beforehand. For a point in a terrain feature of ridge, valley, or canyon, we can adopt the method by (Dakowicz and Gold, 2003) to interpolate the heights of the point. In this paper, we propose a new method to interpolate for a point in hillsides.

(Chai *et al.*) proposed a method to obtain smooth terrain surface by solving partial differential equations with contour heights and gradient conditions. They assumed that a terrain surface height function defined by contours is smooth so that the height function can be governed by PDEs. The method they proposed is based on the observation that terrain contour is very similar to the potential contour in the 2D electric field generated by some electrodes. Similar to the flux lines to describe the electric field distribution, they modeled the *gradient lines* which describe the paths of slopes on the surface from high elevation points to low elevation points. The gradient lines are assumed to obey similar properties of flux lines in electric field;

(1) (Orthogonality) The gradient lines and the contours are orthogonal each other everywhere.

(2) (Non-intersection) Gradient lines do not meet nor branch out each other.

(3) (Monotonicity) The height varies monotonously along a gradient line between two neighboring contours with different heights.

The usual interpolation method to compute the height of point between contours is based on the ratio of shortest distances from the point to both contours (see Figure 3a). The new method we propose to interpolate the height of a point between contours is done by computing an approximation of gradient line that passes through the point. For a point p between two consecutive contours, the nearest point p_i on one of the contours defines a maximal circle centered on medial axis and the circle touches on the other contour at p_{i+1}. The approximate gradient line, called *medial gradient line*, passing through p is defined by the two line segment $[p_i, c]$ and $[c, p_{i+1}]$, where c is the center of the circle on the medial axis (see Figure 3b). Therefore any medial gradient line touches contours orthogonally at everywhere. We can prove that medial gradient lines between two contours of different heights do not intersect by showing that the trajectories of two tangent points on contours of maximal circles moving one direction along medial axis segments move along the same and one direction along contours. To preserve the monotonicity of gradient lines, we use monotone Hermite interpolation method to compute the heights of points on the gradient line.

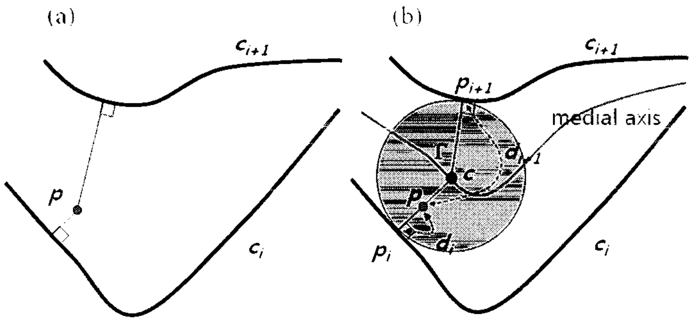

Figure 3. (a) Shortest distances to contours from a point p (b) Medial gradient line Γ passing through a point p

4.1 Monotone Hermite Interpolation

Suppose a medial gradient line Γ starts from a point p_{i+1} on contour c_{i+1} and ends at a point p_i on contour c_i. The height h of any point p on Γ can be computed by univariate interpolation along the line Γ. Let d_i, d_{i+1} be distances from p to p_i, p_{i+1} along the line Γ, respectively (see Figure 3b). The simplest kind of univariate interpolation is linear interpolation defined as follows:

$$h = \frac{h_{i+1}d_i + h_i d_{i+1}}{d_i + d_{i+1}}$$

This linear interpolation results in undesirable artifacts caused by first derivative discontinuities at contours. To circumvent this problem and to produce a smoother behavior, cubic interpolation scheme can be used since it offers continuity at contours. But this interpolates heights outside the valid range $[h_i, h_{i+1}]$ of heights on the gradient line Γ. To preserve the monotonicity of height values, monotone interpolation methods exploiting cubic Hermite spline (Fritsch and Carlson, 1980), or rational two-point Hermite spline (Gregory and Delbourgo, 1982; Hormann *et al.*, 2003), can be used. The spline proposed by Gregory and Delbourgo on the gradient line Γ is as follow:

$$h = \frac{\Delta_i h_{i+1} t^2 + (h_i g_{i+1} + h_{i+1} g_i) t(1-t) + \Delta_i h_i (1-t)^2}{\Delta_i t^2 + (g_{i+1} + g_i) t(1-t) + \Delta_i (1-t)^2}$$

where $\Delta_i = (h_{i+1} - h_i)/(d_i + d_{i+1})$, and t is the local coordinate given by $t = d_i / (d_i + d_{i+1})$. The g_j are derivatives at p_j where the gradient line Γ intersects c_j (see Figure 4). If c_j is not the outermost nor the innermost contour, Γ can extend to sub-domains Ω_j^+, Ω_j^-, where c_j is the exterior (interior) boundary of Ω_j^+ (Ω_j^-), respectively. Let h_j^+ (h_j^-) be the height of the interior (exterior) contour of Ω_j^+ (Ω_j^-), and let h_j^+ (h_j^-) be the length of the extended gradient line Γ in the sub-domain Ω_j^+ (Ω_j^-), respectively. A suitable method for estimating the derivative is

$$g_j = \frac{h_j^+ - h_j^-}{\ell_j^+ + \ell_j^-}$$

which is a central difference around p_j when $j > 1$. At the boundary points on contours c_1 or c_n, the derivatives can be estimated by

$$g_1 = \frac{h_1^+ - h_1}{\ell_1^+}, \quad g_n = \frac{h_n - h_n^-}{\ell_n^-}.$$

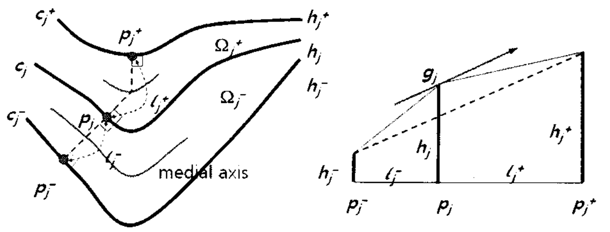

Figure 4. Derivative at a point on an interior contour

5. CONCLUSION

In this paper a new technique for computing the elevation of a ground point to construct a digital elevation model (DEM) from contours is proposed. The elevation is computed by interpolating the heights of the two adjacent contours of the point. The main contribution exists in the decomposition of each sub-domain between adjacent contours into a set of sub-regions and classifying each sub-region into a variety of terrain features. The elevations of points are interpolated with different methods according to terrain features they belong to. For instance, in the case of hillside sub-region, a gradient line is approximated with two line segments touching each adjacent contour orthogonally and joining at medial axis of the sub-domain. This type of approximate gradient line satisfies similar properties of flux lines to describe electric field distribution. The univariate monotone rational Hermite spline is used to compute an approximate height of a point on the gradient line. To improve the technique, it is need to refine approximation method to interpolate for a point in other type of terrain features.

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