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An Integrated Technique for Automated Generalization of Contour Maps

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This paper describes an integrated technique for the generalization of contour maps. The technique consists of an objective line generalization algorithm (Li-Openshaw algorithm) and an algorithm for the derivation of a new contour from two original neighbouring contours. The algorithms are implemented in such a way that they guarantee (a) no self-intersection within a line and no cross-intersection between lines; (b) very smooth resultant contours; and (c) very coherent relationship between resultant contour lines, with shape very faithful to the original contours (at a larger scale). These conclusions have been supported by experimental tests. One of such tests was carried out through comparing the generalized results with the original contour lines and the other is through a comparison with a popular algorithm.

INTRODUCTION

The use of contour lines for the representation of the variations of a 3D surface dates back to the 18th century. Contouring has been widely regarded as the most effective means for the representation of 3D variations on a 2D surface and has therefore been considered as being one of the most important inventions in cartographic history.

Contours have been used for the representation of continuous variations of 3D phenomena on topographic maps, thematic maps and other graphics. Contours are the most fundamental element of topographic maps. When the generalization of topographic maps is carried out for either derivation of maps at a smaller scale from maps at a larger scale (in the case of cartography) or for "real-time" zooming (in the case of visualization), contour lines need to be generalized together with other features.

Contour generalization is an important topic for a number of reasons. Firstly, a contour is the most fundamental type of feature on topographic maps. Secondly, the generalization of contours is an important and challenging but vexing and unsolved problem in cartography and geographic information systems (GIS). Thirdly, it can be regarded as the key step for the development of a more comprehensive procedure for map generalization, if the problem can be successfully solved.

This paper describes an integrated technique for the generalization of contour maps. It integrates an objective line generalization algorithm based on a natural principle with a triangulation-based technique for the derivation of a new line from two neighbouring lines, which will be required if the new contour interval is not a multiple of the original contours (e.g. from 2 m to 5 m).

This paper will examine existing approaches for contour generalization and discuss a technique for the generalization of contour lines. It will also discuss a triangulation-based technique for the derivation of a new line from two neighbouring lines. The integrated technique has been intensively tested and the results are reported at the end of this paper, which are followed by some concluding remarks.

A CRITICAL EXAMINATION OF CONTOUR GENERALIZATION APPROACHES

In contour representation, the quality and/or effectiveness is determined by a few parameters, mainly the spacing between contour lines, faithfulness of individual contour lines to the 3D surface and coherent relationship between contour lines.

Generalization of contours means to transform the contour representation from a larger scale to suit the representation at a smaller scale while the quality and/or effectiveness of the representation is still compatible at that level.

In general, two approaches are possible, i.e. direct generalization and indirect modelling. In the latter, a three-step procedure is used, i.e. (a) contour data are used to construct a DTM of the area; (b) the DTM is to be generalized; and (c) to new contours are to be produced from the generalized DTM. The resultant contours are supposed to be generalized. The issue now becomes how to generalize the DTM. The advantage of this approach is that there will be a guarantee of no intersection between contours if appropriate contour interpolation algorithms are employed. However, so far, no algorithm for the generalization of DTM surfaces with comprehensive theoretical basis is known to the authors. In most cases, a low-pass filter is applied to smoothed out the DTM (e.g. Weibel, 1987) and there is no theory behind the use of such filters. Another disadvantage of this approach is that a loss in accuracy and/or fidelity may be caused and noise introduced during the contour/DTM/contour conversion process.

In the direct approach, individual contour lines are simplified (generalized) to suit the representation at target (smaller) scale. The main problem with this approach is that, as pointed out by many researchers (e.g. Weibel, 1996), most of existing line simplification algorithms provides no guarantee of intersections (i.e. self-intersection and cross-intersection) except a few (Li and Openshaw, 1992; Wang and Müller, 1992; de Berg et al., 1995). This could be the main reason why this direct approach is not very popular. This is the practical part of the problem. To avoid intersections, researchers have used some constraints. One of these approaches is to employ Voronoi diagrams for points along all contour lines as an extra constraint (Wu, 1987).

The theoretical part of the problem associated with this direct approach is that most of the existing so-called line simplification algorithms employ a strategy of selective omission of points along the lines. The theoretical background of these algorithms is the discovery by Attneave (1954), i.e. some points on an object are richer in information than others and these points are sufficient to characterize the shape of the object. These algorithms can be grouped into three types (Li, 1995), i.e. corner detection, polygonal approximation and a hybrid technique (a combination of the first two). The one widely used in GIS is the Douglas-Peucker (1973) algorithm, which is also known as Rammer algorithm in computer vision and pattern recognition (see Li, 1995). Attempts have also been made to improve this algorithm (e.g. Li, 1988). However, as has been pointed out by many researchers (e.g. Li, 1993), it is misleading to use these algorithms for line generalization purposes because the original purpose of these algorithms were not for line generalization but for curve approximation (to approximate a curve line using straight line segment). Although there are also other algorithms based on spectral analysis (e.g. Boutoura, 1989) for line simplification (generalization), the experience gained by the authors reveals that these algorithms are also not working well.

TECHNIQUE FOR THE GENERALIZATION OF INDIVIDUAL CONTOUR LINES

To generalize contour lines for the representation at the target scale, the following conditions must be fulfilled, i.e. (a) The contour lines must be simplified in structure; (b) The resultant contours must be smooth enough in appearance; and (c) The natural characteristics of contour lines (e.g. being parallel, without self- and cross-intersections, geometrically similar to the shape of the 3D surface) must be retained.

Among available algorithms, Weibel (1996) has made a critical evaluation and found that the Li-Openshaw algorithm (Li and Openshaw, 1992) (see Weibel, 1997, p. 124 for terminology) is able to guarantee no self-intersection. And later in this paper, it will be demonstrated by experimental testing that other conditions for contour generalizations can also be fulfilled by careful implementation of this algorithm.

Theoretical Basis – A Natural Principle

The so-called Li-Openshaw algorithm (see Weibel, 1997) is the line generalization algorithm developed by Li and Openshaw in 1992 and published in the *International Journal of Geographical Information Systems.* The theoretical basis of these algorithms is the so-called natural principle for objective generalization, discovered by Li and Openshaw (1993). The natural principle states:

> For a given scale of interest, all details about the spatial variations of geographic objects beyond certain limitation are unable to be represented and can thus be neglected.

From this principle, a simple corollary can be derived as follows:

> By neglecting all spatial variations within a certain limitation, natural results can be obtained for the generalization.

This limitation is called the smallest visible object (SVO) by Li and Openshaw (1992).

Implementation of Algorithm for Individual Lines

This corollary can be easily implemented. This can be demonstrated by Figure 1. It shows that, for a given target scale, all spatial variations within certain limitations can be completely neglected and a point can be used to represent this limitation (area). The appropriate size of this limitation is about 0.6–0.7 mm at map scale, as concluded by Li and Openshaw (1992) based on intensive experimental testing.

Based on this natural principle, Li and Openshaw (1992) have implemented three algorithms for line generalization and they have recommended the "vector-raster" algorithm. In this algorithm, the average of the coordinates of the first and last intersections between the line and the grid cell is taken as the position of the new point (to represent the cell) (see Figure 2). Of course, the cells can also be overlapped to produce more realistic results and to avoid the dependency of starting points, as suggested by Li and Openshaw (1992). More detailed discussion lies outside of this paper.

In the implementation of the algorithm, special attention needs to be paid to thin necks of contour lines. Figure 3(a) shows an example. If the neck is too thin (thinner than two cells), there are three solutions, i.e. to throw the small convex parts away (Figure 3b), to form a close loop for the small convex parts (Figure 3c) or to exaggerate the thin necks (Figure 3d). However, some additional constraints must be imposed while exaggerating the concave parts. In this implementation, this option is omitted. In fact, the first two options are not isolated but rather inter-related. If the convex parts are too small (i.e. occupying less than four cells), then the first option is taken, or else the second option is taken.

Implementation of Algorithm for Contour Lines as a Whole

As mentioned in the previous section, the generalization of contour lines is more complicated than that of a single line.

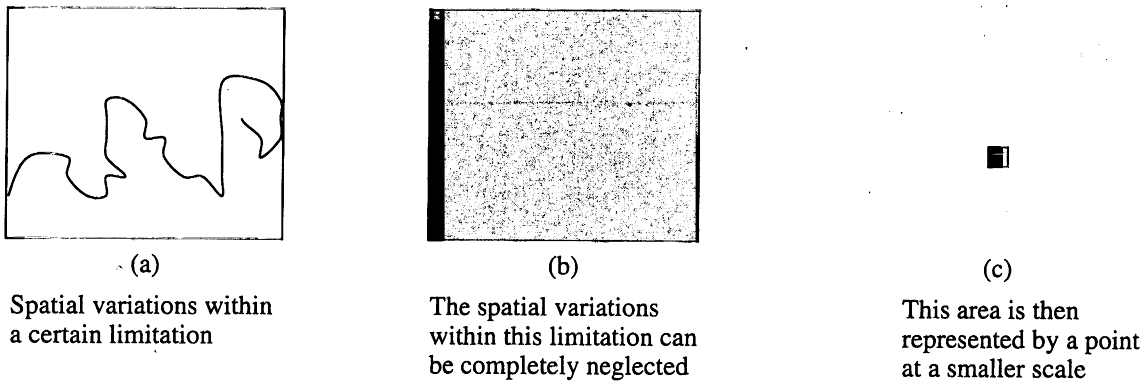


Figure 1. The natural principle by Li and Openshaw (1993): A point or a raster cell can be used to represent the spatial variations within a certain limitation

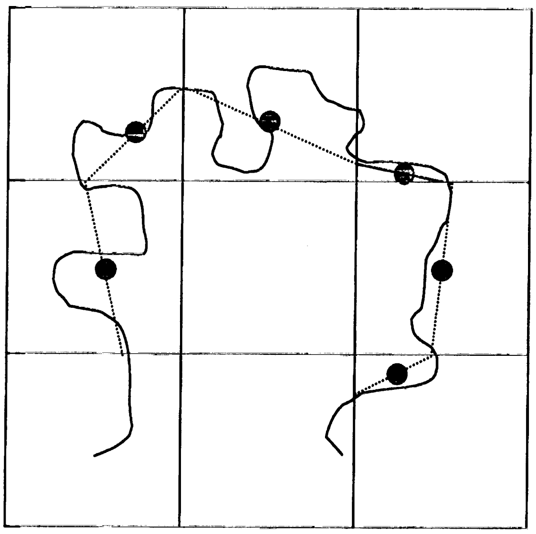


Figure 2. The working principle of Li-Openshaw algorithm

The most difficult part is to make sure that no contours will intersect each other. This implies three requirements. One is that the results of generalization should be independent of starting position. The second is that space must be the primary concern so then it will guarantee no self-intersection. The third is that the same set of conditions should be used for the generalization of all contour lines. The first two are related to the line generalization algorithm itself. The first requirement is fulfilled by an introduction of overlaps between SVOs (Li and Openshaw, 1992). The second has been fulfilled by the virtue of raster (see Weibel, 1996). Therefore, only the third requirement will be tackled in this section.

The third requirement seems a little bit ambiguous. It really means that for the generalization of all lines (a) the size of SVO used in the algorithm should be kept the same; (b) the percentage of overlap, if any, should kept the same; and (c) the mechanism to take a point to represent the SVO should be consistent. For this purpose, the simplest implementation of this natural principle of objective generalization of contour lines is to lay down a raster grid. The cell size of the grid is the SVO. The mechanism to take a point as the representative of the spatial variations within this cell is the same as that used in the "vector-raster" algorithm (Li and Openshaw, 1992).

In the generalization of the contour map, some technical issues also need to be solved. The first one is the smallest loop (closed contour) to be retained. It is quite obvious that if the looped line is within a cell, it should be deleted. However, depending on the position of the starting point of the grid, the same line may appear on four neighbouring cells. Therefore, it is still safe to delete closed contour lines occupying fewer than four cells after generalization. The second one is the change of contour interval when the map scale is changed significantly and this topic will be discussed in the next section.

TECHNIQUE FOR THE GENERALIZATION OF CONTOUR MAPS

In the previous section, an algorithm used for the generalization of individual contour lines is presented. This section discusses how extra care should be taken in the generalization contouring of a map as a whole.

A Need to Reduce the Number of Contours through a Change of Contour Interval

When a large-scale map is generalized to a small-scale map, small variations of contour lines would be removed while the most important characteristics of contour lines should be kept. When the scale change is dramatic, then the spacing between two contour lines (i.e. planimetric contour interval) will be reduced to such a level that they will touch each other. As a result, there is a need to remove some of the contour lines in order to retain the clarity of the maps. In other words, the vertical interval of contour lines needs to be changed. A rough guideline for contour intervals at different scales is summarized in Table 1.

In the change of contour interval, there are two possible cases. The first case is to use a multiple of the original contour interval as a new contour interval. For example, the original contour interval is 1 m and the new contour interval becomes 5 m. In this case, the contour lines at the multiple of 5 metres, i.e. 5 m, 10 m, 15 m, 20 m etc. will be selected from the original set of contour lines and all

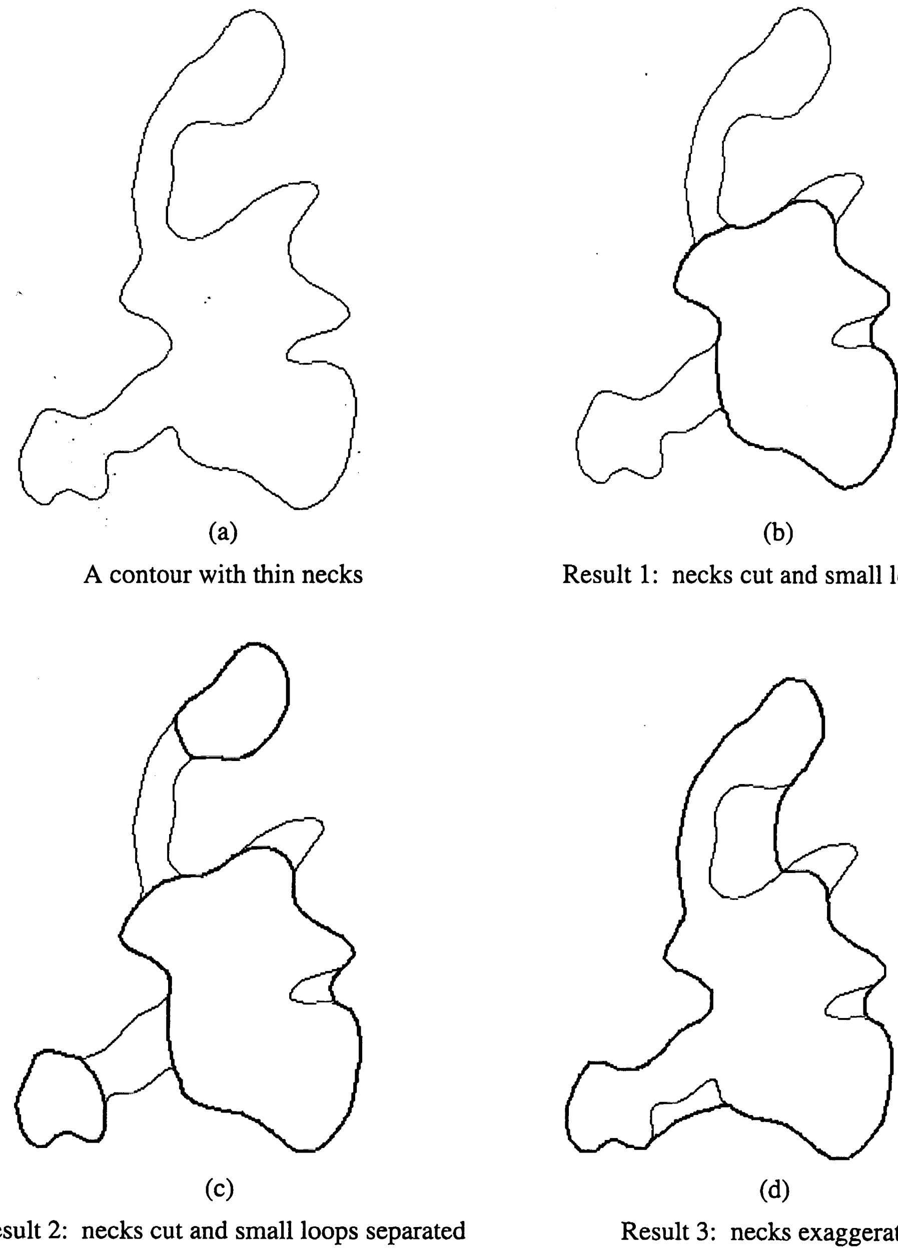


Figure 3. Various possible results for a contour line with thin necks

SCALE	CONTOUR INTERVAL
1: 200 000	25 to 100 m
1: 100 000	10 to 40 m
1: 50 000	10 to 20 m
1: 25 000	5 to 20 m
1: 10 000	1 to 10 m

Table 1. Contour Intervals at Different Map Scales

other contour lines will be discarded. However, sometimes, there is a need to change from 2 m to 5 m (or from 20 m to 50 m). In this case, a new contour line needs to be derived from two neighbouring contour lines in the original set; e.g. a new 5 m contour from original 4 m and 6 m contours (Figure 4).

Derivation of a New Contour from Two Neighbouring Contours

One way to derive a new contour line from the original two lines is to derive the skeleton (e.g. Bookstein, 1979; Shapiro et al., 1980; Su et al., 1998) of the areas formed by the two original lines. Experience gained from experimental testing shows that many small (unwanted) branches may be produced by skeleton algorithms (Su et al., 1998) and therefore, alternative methods have been sought. The method used in this project is the triangulation-based algorithm.

The idea behind this algorithm is

(a) to construct a triangular network using the points on the contour lines;
(b) to interpolate points with the height of new contour; and
(c) to join these points to form a new contour line.

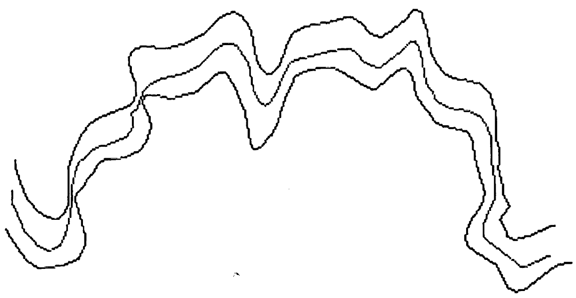


Figure 4. A new contour to be derived from two original neighbouring contours

In this implementation, the Delaunay triangulation algorithm is employed. Figure 5b shows an example of such a triangular network constructed from the contour map shown in Figure 5a. The resultant new contour would be something as shown in Figure 5c. As can be clearly seen, there is a problem with this network, i.e. there is an artificially flat area formed by a set of "flat" triangles on the left side of map. This will be a common problem if there are spike-like lines. To avoid this problem, one possible solution is to add some points along the ridgeline. The result is shown in Figure 5d. The quality of the resultant contour will be dependent on the accuracy of those feature points added. Another solution is to set a constraint for the

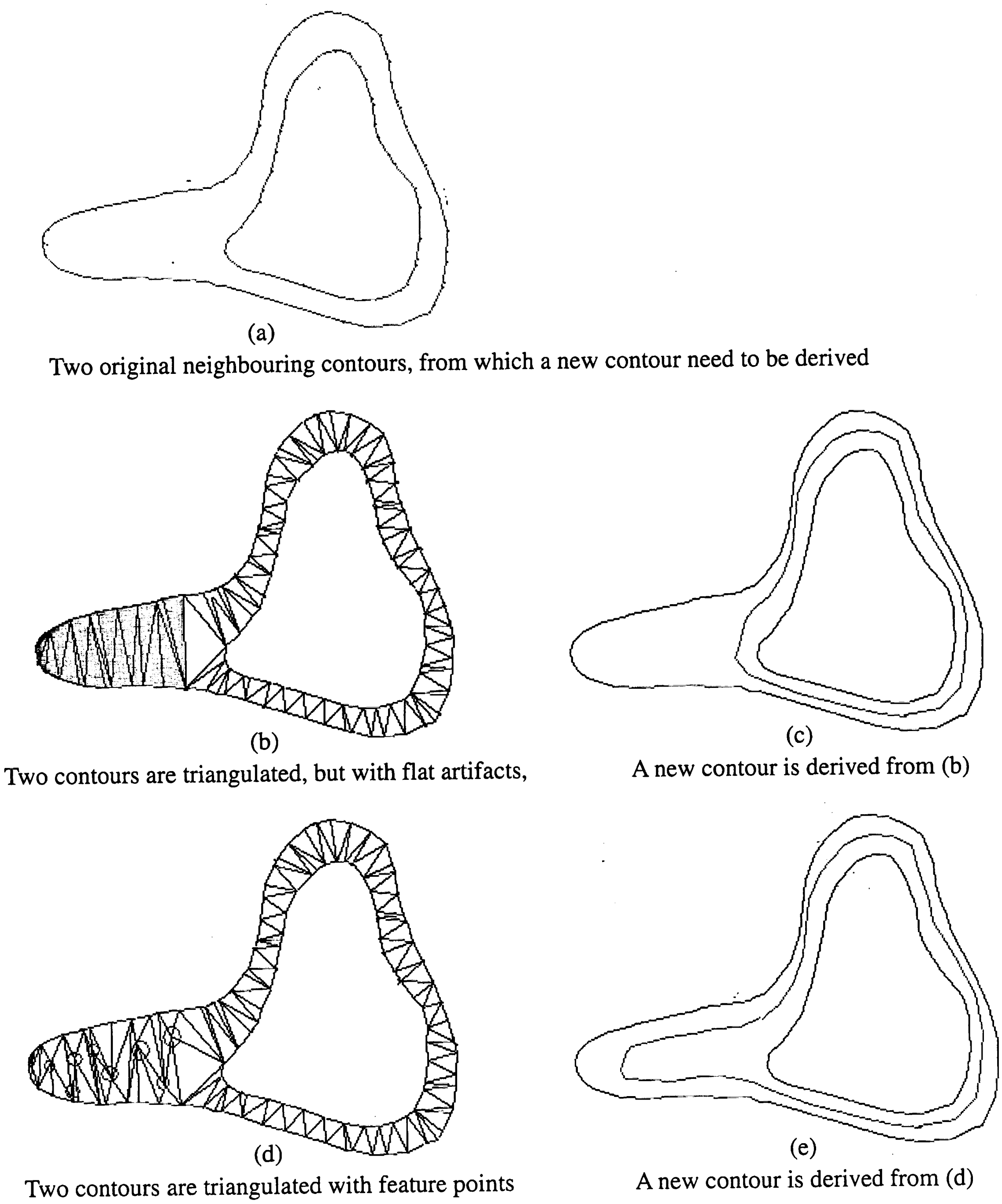


Figure 5. A triangulation-based technique for derivation of a new contour from two original neighbouring contours

triangulation – no more than two points should be selected from a contour line in forming a triangle.

EXPERIMENTAL TESTING

In the previous sections, the theoretical background and algorithmic implementation of the new technique for contour generalization have been discussed. In this section, some experimental testing results will be reported.

Experimental testing was carried out in both a relative and absolute sense. In the former, the generalized results at smaller scales will be compared with the original lines at a larger scale. In the latter, a comparison with other techniques will be made.

Experimental Testing in an Absolute Sense

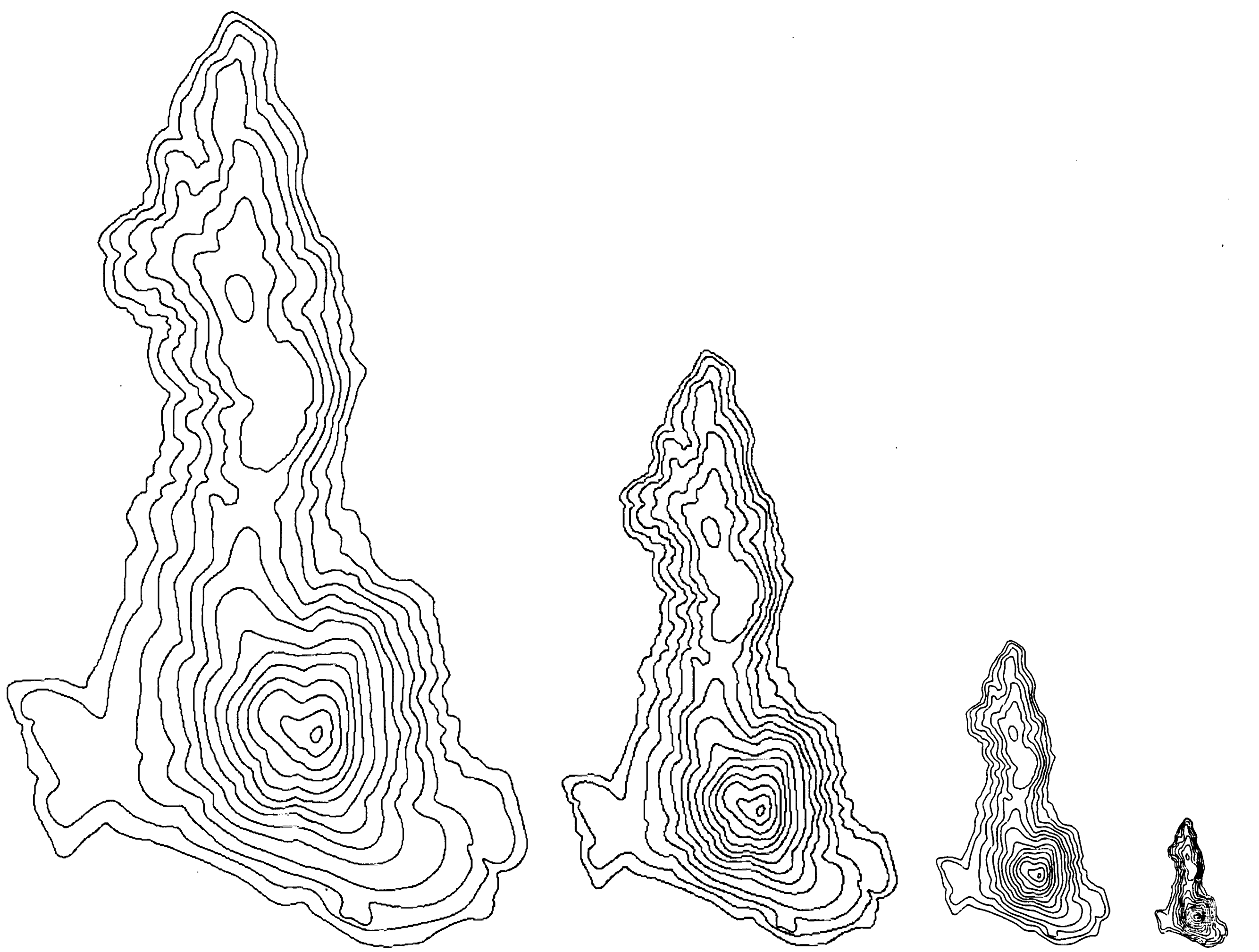
In this test, a contour map of an island in Hong Kong has been digitized. The map scale is 1:10 000, as shown in Figure 6a. This map is generalized to 1:20 000, 1:50 000 and 1:100 000 scales and the results are shown in Figure 6b, 6c and 6d. As one can see clearly, the resulting contour lines are very pleasing.

In this test, the contour interval is not changed for all the generalized maps in order to show the capability of the line generalization algorithm implemented by the authors, although scale reduction has been as large as ten times.

To illustrate the robust performance of the algorithm, the generalized contour maps are enlarged to the original scale (i.e. 1:10 000) and then superimposed onto the original contour maps. Figure 7a and 7b show the superimposition of the generalized maps at 1:100 000 and 1:200 000 onto the original contour map at 1:10 000. It is very clear that the main characteristics of the contour lines are well kept but small details are removed. More importantly, there is not self-intersection of contour lines and cross intersection between contour lines.

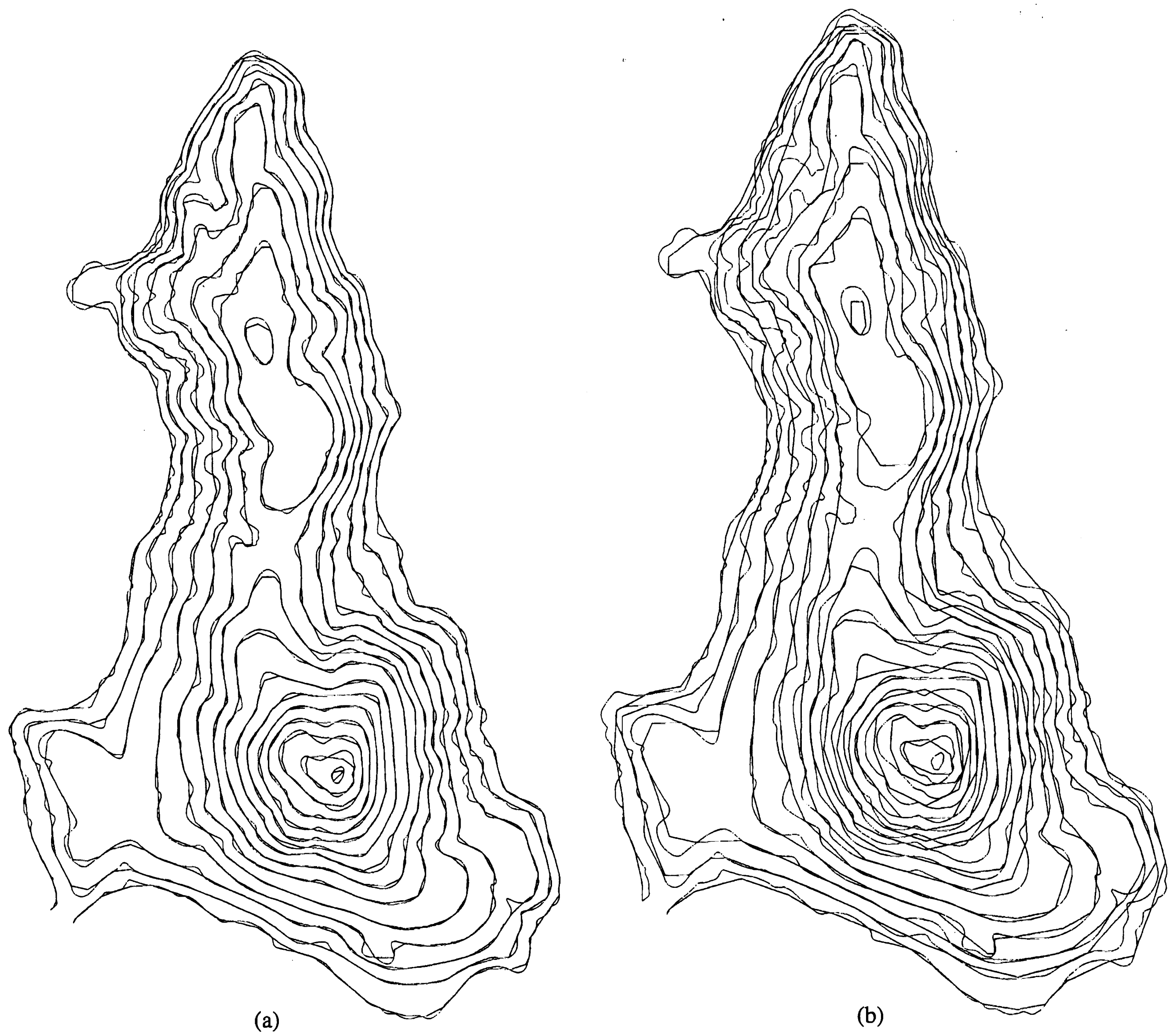
Experimental Testing in a Relative Sense

In the previous section, contour intervals are not changed although map scale has been reduced by a factor as much as ten times in order to illustrate the performance of the algorithm. In this test, the contour interval will be changed



(a) Original contour map at 1:10 000 scale; (b) to 1:20 000; (c) to 1:50 000; (d) to 1:100 000

Figure 6. Generalization of contour map to various scales by the new technique



(a) Generalised to 1:100 000 scale (i.e. 10x reduction) superimposed onto the original (1:10 000)

(b) Generalised to 1:200 000 scale (i.e. 20x reduction) superimposed onto the original (1:10 000)

Figure 7. Generalized contour maps superimposed onto the original contour map

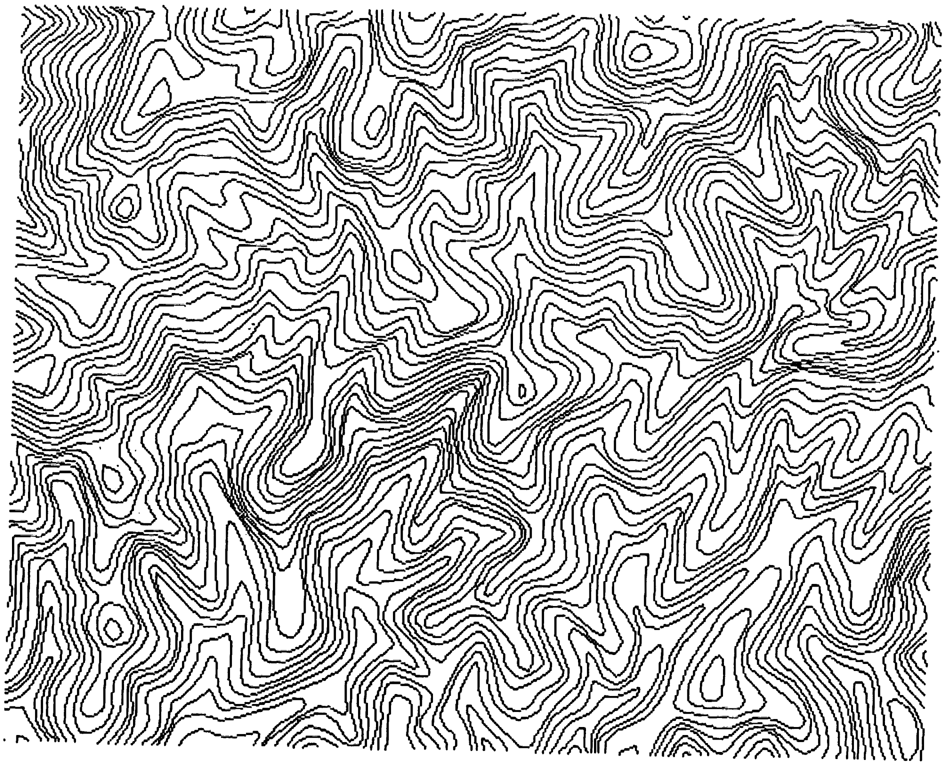
and only those contour lines with a height of the multiples of the new contour interval will be selected. Since there are only very few contours in the previous testing area, a new set of contour data is used for this test.

In this test, the popular Douglas-algorithm (Douglas-Peucker, 1973) is used for a comparative analysis. Figure 8a is a 1:10 000 scale topographic map, located in Guangzhou City of Southern China. The map is generalized to produce a resultant map as shown in Figure 8b. It is clear that the result is again very pleasing. However, on the other hand, if the same criterion is used for the popular algorithm (Douglas-Peucker algorithm), then the result is shown in Figure 8c. As one can see clearly, there are plenty of intersections of lines here and the main characteristics of the original contour set are destroyed. Indeed, such a result is clearly not acceptable.

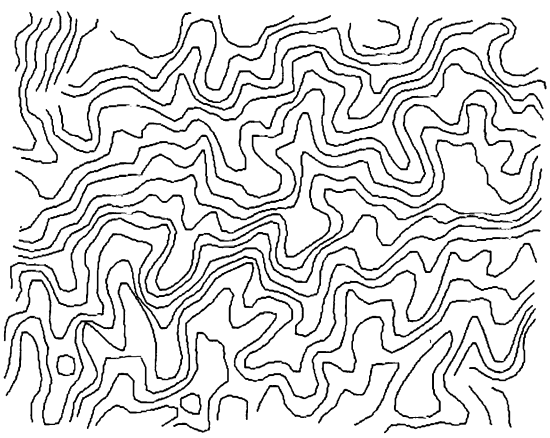
CONCLUSIONS

In this paper, existing techniques for contour generalization have been examined and an integrated technique for the generalization of contour maps is described. Experimental tests on the performance of the new technique are also reported.

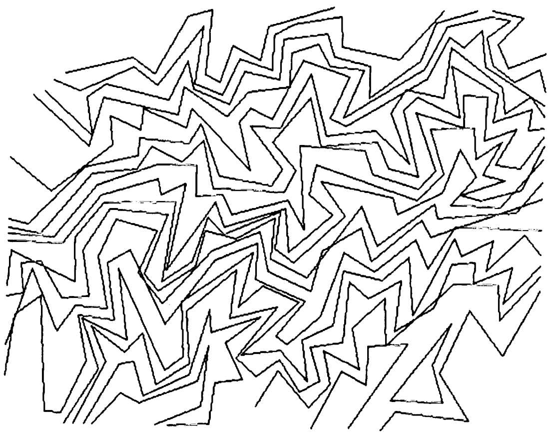
This integrated technique consists of an objective line generalization algorithm (Li-Openshaw algorithm) and an algorithm for the derivation of a new contour from two original neighbouring contours. The two are so integrated that the system will automatically employ either algorithm



(a)
A contour map at 1:10 000 for experimental evaluation



(b)
Result obtained from the integrated technique developed by the authors



(c)
Result by Douglas-Peuker algorithm

Figure 8. Experimental evaluation of the new technique through a comparison

when a contour line at a particular height is to be generalized, provided the old and new contour intervals are given.

From a theoretical point of view, the technique described in this paper guarantees

(a) no self-intersection and cross-intersection, because it is a space-primary technique;
(b) very smooth resultant contours, because it considers a SVO; and
(c) very coherent relationship between contour lines, with shape very faithful to the original contours (at a larger scale), because it follows a natural principle.

To prove these theoretical conclusions, real contour maps have been used for testing. One test is carried out to prove these conclusions in an absolute sense through a comparison with the original contour lines and the other in a relative sense through a comparison with a popular algorithm. Experimental results clearly show that the quality of the generalized contour maps is extremely good by visual inspection in an absolute sense and the new technique is superior over the popular algorithm. Indeed, the testing results strongly support the theoretical conclusions.

ACKNOWLEDGEMENT

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