A Progressive Line Simplification Algorithm

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1 Introduction

Map generalization is one of the classical cartographic problems. All maps are generalized representations of the reality. Generalization is necessary to improve the display quality of small scale maps, allow analysis with different grades of detail; and reduce data storage requirements[1]. Line simplification algorithms can be divided into five categories[2].

The result of map generalization should always retain the important geographic spatial knowledge, according to the conditions of the new small scale map[3]. Therefore, the existent spatial knowledge related to the line should be maintained in the process of line generalization. In many researches the line generalization algorithms are compared with each other[4]. Because spatial line knowledge is essential in generalization, researchers have investigated the classification and the application of cartographic knowledge for line generalization[6-9]. Furthermore, the self-intersection of a generalized line is another problem in line generalization. In order to overcome it, some algorithms have been evaluated[5,10-13].

In this paper, the geometric knowledge related to cartographic lines is discussed. By means of computational geometry algorithms, the global and local characteristics of cartographic line features can be gained. At the moment, the integration of these characteristics into the process of line generalization is one of the main research topics in digital cartography. To solve the problem of line self-intersection within the process of generalization, an identification routine for them is introduced.
2 Identification of potential conflict regions

In line simplification, self-intersections of the generalized lines often occur, because the elimination of vertices influences the adjacent vertices and the spatial relation between them. Thus the potential conflict region with generalized self-intersecting polylines should be identified and tested for self-intersection. In Fig. 1, different local situations of potential conflict regions are shown. All vertices O in Fig. 1 are points which will be tested. Adjacent vertices inside a circle are searched, and the direction of this line is determined (Fig. 1).

![Fig. 1 Identification of potential conflict regions](image)

(The radius of the circle is the influence distance)

The algorithm for identification of potential conflict regions runs as follows:

1) According to a given triangle area as a threshold, the influence distance of a vertex is computed in form of a circle. In our test, this influence distance equals to $2 \times \text{SQRT}(2 \times \text{Area})$, where Area is the given minimal triangle area. Because the influence scope of an eliminated vertex is SQRT$(2 \times \text{Area})$ (Fig. 2(a)), and the influence distance of two vertices is double influence scope of a vertex (Fig. 2(b)). The start point of an original cartographic line is the first point that will be tested, such as point O in Fig. 1. (In Fig. 2, Area is a given triangle area as a threshold; C and D will be eliminated; L is the influence distance of a vertex and $L = \text{SQRT}(2 \times \text{Area})$). Line sections A and B belong to a line.

2) The vertices inside or outside the circle are identified (Fig. 1(a)). The vertices, such as $A, B$ and $C$ in Fig. 1(a), are very important, which are used to identify influenced by the vertex O. But vertices $E$ and $F$ in Fig. 1(a) will not be detected, because vertices between vertex $E$ and vertex $F$ will be tested in the next step, which must be in the potential conflict region.

3) If a vertex $C$ exists (Fig. 1(b)) and is not the end point of the original line, then all vertices inside the circle are regarded as a potential conflict partners of vertex O (Fig. 1(b)). Hence the existing potential conflicts between vertex O and these partners are stored as basis for solving the self-intersection problem of generalized lines.

![Fig. 2 The influence distance of a vertex](image)

4) In Fig. 1(c), vertex $C$ inside this circle is the end point of this original line. If the length of the line section $BC$ in Fig. 1(c) is greater than a given threshold, then all vertices within the circle belong to the potential conflict region of vertex O. In this test, this pregiven threshold is double the circle radius. By a closed original cartographic line, the length of a line section inside this circle and the distance between the two end points of this line section are calculated. If this length is greater than double the radius, or this distance is greater than the radius, then the potential conflict region can be identified, for example, Fig. 1(e) shows a potential conflict region, but Fig. 1(f) does not.

5) If only vertex $A$ exists (Fig. 1(d)), and the length of the line section inside this circle is greater than a certain given length, such as, three times of the radius in our test, then a potential conflict region of the vertex O can be identified.

6) The adjacent sequent vertices of vertex O will be tested. If all vertices to be tested are inside this circle, then this process ends. Fig. 3 (b) shows the points in a potential conflict region of a line. Fig. 3 (a) shows samples of circles without potential conflict regions.
3 Spatial knowledge and spatial cognition in line simplification

In a generalized map, the geographic spatial knowledge should be correctly communicated. Therefore, the geographic spatial knowledge of the map must be retained in the process of map generalization. In the test, characteristic points of a line and their spatial cognition are investigated.

3.1 The spatial knowledge in line simplification

There are two kinds of characteristic line points. One kind consists of local maximal points, and the other contains points having a local inverse direction change in X or Y direction. A point with a local inverse direction change in X or Y direction can be identified by comparing X (or Y) coordinates of a vertex with the coordinates of its adjacent vertices. Fig. 4 shows the basic principle for identifying vertices with a local inverse direction change. In Fig. 4(a), the X coordinate of the considered vertex is less or equal than the X coordinates of all adjacent vertices, or is greater or equal than the Y coordinates of all adjacent vertices. In Fig. 4(b), the Y coordinates are applied for this comparision.

The points on a convex hull of a line and monotone lines on a line are considered in this test.

3.2 Spatial cognition of characteristic points

The spatial characteristic line points have different degrees of importance for the process of line simplification. Some points express local line features, e.g., local maximal points and others express global line features, e.g., points on a convex hull. Therefore, the spatial characteristic line points build a hierarchical structure. In this test, four different kinds of characteristic line points are considered, which are: the local maximal points, the points with direction change, the points between two monotone polylines and the points of the convex hull. The importance of vertices is assigned to three categories. The classification for all points algorithm runs as follows:

1) Firstly, the degree of vertices' importance is set to zero.

2) If a vertex is a local maximal point or a point with a direction change, then the vertex degree is altered to one.

3) But if a vertex is a local maximal point and also a point with a direction change, then the degree of the vertex is changed to two.

4) If a vertex is a point between two adjacent monotone polylines and its degree is equal to zero, then the vertex degree is also set to two. If its degree is not equal to zero, then the vertex degree is set to three.

5) For points of the convex hull, the degree is three. The degree of end points and other fixed points of the line is four.

4 The basic principle of progressive line simplification

In this section, a progressive line generalization algorithm will be discussed, which is similar to those of Visvalingam and Whyatt [14]. This algorithm should be explained by a very simple test data set (Fig. 5 (a)), and only one important vertex is fixed, e.g., vertex 8 in Fig. 5(b). This algorithm runs as follows:

1) Every vertex beginning with the fixed vertex 2 to vertex 13 and its two adjacent vertices form a triangle (Fig. 5(a)). For example, vertices 4, 5 and 6 in Fig. 5(a) build a triangle. The size of this triangle corresponds to the degree of the vertex 5. The area of this triangle can be determined. For simpli-
fying the algorithm explanation, only vertex 8 in Fig. 5(b) is selected as a significant vertex.

2) When vertices are inside this triangle, e.g., vertex 12 in Fig. 5(a), or for a vertex which belongs to the categories of important vertices, the area of the triangle cannot be compared with those of other triangles. In this case, this vertex cannot be deleted.

3) The triangle areas are compared with each other until the smallest is found. Thus, the corresponding vertex can be deleted, and a new line is formed. For example, after deleting vertex 9 in Fig. 5(a), the new line in Fig. 5(c) is defined.

4) The new areas of the triangles, which belong to two adjacent vertices of the deleted vertex, e.g., the two adjacent vertices 8 and 10 of the vertex 9 in Fig. 5(c), must be recomputed.

5) This process returns to Step 2) until the smallest triangle area is greater than the given threshold. Its workflow is shown in Fig. 5(c) to Fig. 5(h).

Fig. 5  The basic principle of progressive line simplification

Fig. 6 shows the complete process of the progressive line simplification. For the line vertices, the degrees of importance as mentioned above are evaluated. Fig. 6(e) shows the line sections between two characteristic points, with a degree of importance of one, after generalization, and the new generated line (Fig. 6(a)). In Fig. 6(b) and Fig. 6(c), the line generalized sections between two characteristic points, with a degree of importance of two or three (in Fig. 6(f) and Fig. 6(g)),

are also generalized. Fig. 6(d) shows the result of the entire line generalization.

5  A test of progressive line simplification

The above-mentioned progressive line simplification algorithm has been applied to a complex test dataset. In Fig. 7, the original lines are visualized,
which are downloaded from html. In Fig. 8, the results produced by a progressive line simplification algorithm with different generalization degrees are displayed. This line generalization process is equal to the process in Fig. 6. In Fig. 8, the results possess the main line features, according to the requirement of the different generalization degrees, without any line self-intersection.

6 The self-intersection of generalized lines

The self-intersection of lines frequently occurs in line generalization. In Fig. 9, the result of a line generalization by means of a Douglas-Peucker line simplification is represented. In Fig. 7 the original test data is given. For a better program performance, most progressive line simplification algorithms do not take into account the self-intersection problem in data processing. If self-intersections occur in the result, then the original corresponding line sections should be processed again with the progressive algorithm proposed in this paper.

To identify line segments which intersect each other is easy. In Fig. 10, \( P_1, P_2, P_3, P_4 \) and \( P_5 \) are enumerated codes of vertices on an original line, and parts of an entire generalized lines with self-intersections are shown. In Fig. 10 (a), the line segment \( P_1P_2 \) intersects the line segment \( P_3P_4 \). Therefore, the original line section from point \( P_1 \) to point \( P_4 \) must be handled once more, with \( P_1, P_2, P_3 \) and \( P_4 \) as original line vertices, and \( P_2 > P_1, P_4 > P_3 \). In case a line segment intersects more than two other line segments, then the original line section is the polyline from the vertex with lowest number to the vertex with the highest number in the related vertices, e.g. an original line section from vertex \( P_1 \) to vertex \( P_5 (P_1 < P_2 < P_3 < P_4 < P_5) \) in Fig. 10(b).

7 Conclusion and discussion

From the presented results in this test, it can be concluded that by considering the spatial knowledge the quality of line simplification can be essentially improved. And the spatial characteristics of a line can be retained in the generalization result according to the generalization requirement. The self-intersections of a generalized line do not occur.

But there exist further spatial knowledge for lines which should be also considered. How to apply these to the process of line generalization should be investigated in further researches.

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teacher and hand out the assistantship of class hour and work out the examination schedule of the end of the semester.

Ⅶ. RCX14 From the beginning of June 11, the Dean’s office elects the prize of excellent teaching.

Ⅶ. RCX15 Every college (department) and teaching and research section organizes teachers to assign a topic for examination.

Ⅶ. RCX16 Four weeks before of examination at the end of the semester, every college (department), teaching and research section organizes the teachers to print examination papers.

Ⅶ. RCX17 The Dean’s office organizes all students to exam and select lessons.

Ⅶ. RCX18 Every teaching and research section organizes to read and appraise the examination papers.

Ⅶ. RCX19 The teachers send the students’ marks to the college(department) and the Dean’s office.

Ⅶ. RCX20 The Dean’s office make a record of performances of the students.

Ⅶ. RCX21 The presidents checks out the condition of teaching equipments (teaching aid) and their operation.

Ⅶ. RCX22 Before the holidays, we have a presidents’ meeting to discuss the teaching problems of the whole university and sum up the teaching work of this semester.

Ⅶ. RCX23 Before the holidays, The leaders listen to a report of every department and check out the condition of placing a file for documents.

Ⅶ. JDX01 From the beginning of April 1, the Dean’s office appraise the achievements of teaching research.

Temporary jobs

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