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Road Density Analysis Algorithm and Optimization Based on Constrained D-TIN

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Abstract: As an important method of spatial analysis, road network density analysis is widely used in intelligent transportation, urban planning and automatic map generalization. Classical grid-based method for solving road network density is widely adopted in GIS. However, this method has the disadvantages of low accuracy and lack of general applicability. Through a survey of the road network density analysis method, this work proposes a novel optimized analysis method based on skeleton partitioning with constrained Delaunay Triangulated Irregular Network (D-TIN). By means of breaking up the whole into parts, the method calculates the area contributions of all associated triangulations to the road growth region and in this way the road network density was obtained finally. It simplifies the process of road network density solving. The experiment shows that the optimized D-TIN method is robust and efficient in the whole calculation process. In the real application scenarios of 1:50000-1:100000 comprehensive road network map automatic selection and generalization, our test indicates that the optimized D-TIN method can provide an efficient means of road network automatic map generalization and can be applied to the quality evaluation of the road network generalization.

Key words: Geographic information system, delaunay TIN, road density, map generalization

INTRODUCTION

Linear road is an important element of human geography and the level of road network density is one critical assessment index to reflect the total number and construction level of urban roads, which is often used to check the rationality of the road network distribution and verify whether the plan is correctly balanced. It is also one of the decisive factors for road selection in map generalization. The commonly-used process applied to road selection firstly formulate density index calculation model according to map scale and characteristics of the generalization region, then perform selection operation by density index computation. Current technologies in computer hardware and software are insufficient to meet the requirements of the same intelligent recognition capability of the human brain and can not do the similar density identification action performed well by human eyes. Therefore, how to automatically calculate the density of the road network is the key point to achieve the automation of road network generalization.

In recent years, a number of studies have addressed the problems of road density analysis:

Grid based analysis method (Jenelius and Mattsson, 2012) is widely used in road density estimation. But the rules of determining attributes on grids, such as grid size, position, etc., are rather arbitrary. Due to this method is lack of necessary information for grids, it may lead to information loss errors in road selection process.

Mesh density based calculation method (Li and Zhou, 2012) use meshes as units and represents local region density in a network and use meshes density to approximate density of roads. This method is only suitable for relatively developed urban traffic network or small-scale road networks with network loops. However, in the relatively sparse road distribution areas, the road does not form loops, this method is not applicable.

Skeleton partitioning method (Liu *et al*., 2009, 2010) utilizes Voronoi diagrams of road segments and takes geographical and geometric information of the road network into consideration. It uses road network mesh skeleton to construction road growth polygons, then calculate road density by computing polygons' area. However, in the triangular skeleton extraction process, the complexity of the data causes that it is very difficult to extract a complete skeleton. Especially in the polygon construction process using skeleton, a lot of topological errors can even take place and cause the total solving process failed.

In allusion to the disadvantages of above methods, this work analyzes the area relationship between triangles associated with the road and corresponding polygons,

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proposes a novel method to directly calculate the growth area of the road and can be used to compute the density of road network.

This approach, which absorbs the idea of breaking up the whole into parts, according to the different area contribution of associated triangles to road growth region, divide these triangles into several categories, compute the area contribution of different kind of triangles, respectively. Then, the road growth area can be obtained by directly accumulating contribution area for each associated triangle. And finally road density is computed. Our method does not need the complex process of network mesh skeleton extraction and road growth region polygon construction. It greatly simplifies the solving process for road growth region area computing problem and improves the reliability and efficiency of calculation algorithm. The experiment results show that this method meets completely the practical requirements of large-scale road network density estimation.

The following sections are organized as follows: the next section explores the road density analytical methods based on constrained D-TIN. Then an optimized method for road growth area computing is discussed in detail. This section focused on the classification rules for associated triangles and calculation strategies applied to each category. The article then presents case studies to illustrate the property of road density based on skeleton partitioning for road selection, after which the paper ends with conclusions and future work.

ROAD DENSITY ANALYTICAL METHODS BASED ON D-TIN

Road density calculation formula: According to the classical definition, density is described as “a measure of how much mass is contained in a given unit volume (density = mass/volume) ”. Refer to this definition, road density can be considered as units of length possessed by a given unit of area, it can be viewed as a linear density, which is calculated as flowing equation:

$$D = L/S \quad (1)$$

where, L represents the sum of the roads length, S is the area of region in which road is located and D refers to the local density.

The Eq. 1 is calculated from the abstract level but from the practical perspective, it is very hard to calculate the density for one segment of roads network, because the area for one segment of roads is difficult to identify in the locating region. There is an effective model to solve this problem-Delaunay triangulation model.

Delaunay triangulation model: In the planar partitioning of space among geographical objects, Delaunay triangulation is an essential tool. It has the circumcircle principle and closest to equilateral properties (Dolbilin *et al*., 2012) and plays an important role in the spatial adjacent relationship analysis. Its successful application resulted in series of achievements related to spatial neighbor assessment. Delaunay triangulation model can be applied to detect neighbor objects to analyze the conflict between them. For polygon categorical map generalization, some studies are based on an approach of polygon combination by dividing the small polygon equally along the skeleton and blending two parts into neighbor polygons, respectively (Fink *et al*., 2012). Some studies construct a binary tree on the basis of Delaunay triangulation to represent the curve bend hierarchical structure. For the river network analysis, Delaunay triangulation is successfully used in the derivation of watershed area of each channel and further to select important river branches (Kraus *et al*., 2013). The most common practical road selection method in this road network scenario is to build cluster distribution to contain much information associated with the adjacent relationship under context environment.

Road reachable region representation: Region in which the road network is located can be expressed as below: Assuming put the road network at the center of reachable region, each road grows outward at the same rate and their boundaries ultimately intersect with each other. According to this pattern, it will finally form the target region on the road network plane. This result is similar with Ordinary Voronoi Diagram (OVD). Nonetheless, according to the strict definition of OVD, it is not an OVD: OVD cell is convex, while this geometric construction may be concave. Moreover, OVD is originally generated from point cluster and needs to be modified for linear objects. Nevertheless, these partitioned polygons for road segments can be called General Voronoi diagram (GVD), which indicates its differences between OVD and equal-partitioning property. GVD’s main geometric properties are described as follows:

- Each partitioned polygon contains only one road segment
- Each node links with three skeleton edges
- Each edge of partitioned polygon boundary faces a left segment and a right segment and it separated these two segments equally in space

GVD can be deemed as the consequence of each road segment competing outward against each other for growth space. Therefore, these partitioned polygons may

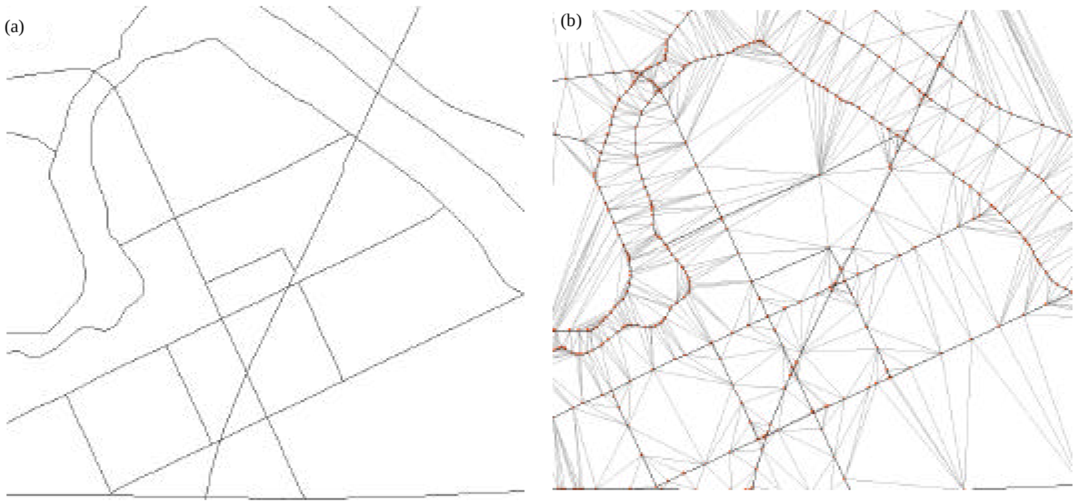

Fig. 1 (a-b): Test on constrained D-TIN, (a) The road network for test, (b) The result of triangulation

be called Growth Polygon (GP), so the analysis of road segment can be transformed to area calculation problem of the corresponding GP. Next we will use Delaunay triangulation to construct a special geometric construct to extract this kind of distribution structured information.

Constrained D-TIN: When performing Delaunay triangulation constructing operation, all roads in the network must be forced to serve as triangle edges, which are not intersected with any other triangles. This kind of triangulation is called the constrained Delaunay Triangulated Irregular Network, i.e. D-TIN.

The triangles in Delaunay triangulation (not constrained) network have the properties of "as equilateral as possible" to avoid the appearance of very narrow triangles or very sharp angles. It is just this nature that makes the Delaunay triangulation a powerful model in spatial adjacency analysis. In the case of building cluster, some of the boundary segments may be long and leads to the long-edges triangles inherited from these long lines. However, the constrained triangulation will not correctly detect the adjacent relationship between objects. One of the methods to resolve this contradiction is to apply a method of point-interpolation on long boundary edges. Below we will use the constrained D-TIN model to analyze the road density.

Road density computation based on D-TIN: From the analysis of GP's space construction, the road's GP can be considered as the road network's survival range, it is the competition result of a road growth outward with its adjacent road. This space partition is similar with the expression of skeleton splitting in the plane based on D-TIN and it is suitable for using D-TIN to construct the GP of the road network. When the road's GP is determined, its area size can be easily calculated, then use Eq. (1) to calculate the density of each road. According to this idea, the method of computing the road density based on D-TIN model is described as following steps:

- Construct D-TIN with the roads set $\{L_i\}$. Each member of set $\{L_i\}$ is considered as a constrained edge for constrained triangles of the road network.
- Extract skeleton for road network's D-TIN
- Build the road's growth polygons with the extracted skeleton lines for all roads and get the GP set $\{P_i\}$
- Match the road set $\{L_i\}$ with the GP set $\{P_i\}$ and calculate each road's length and its corresponding GP's area sequentially, then compute the density of the road by the Eq. 1

The part B of Fig. 1 shows the constrained D-TIN construction result for the road network data in part A of Fig. 1. Through this experiment, we find that, in step 2), it is hard to extract all skeleton lines for the road network. Moreover, the extracted skeleton lines may have many dangling skeleton branch lines, which can not be used to build a closed polygon for road's GP in step 3). In this case, many roads can't complete their density calculation. To avoid this situation, we present an optimized method to solve this problem.

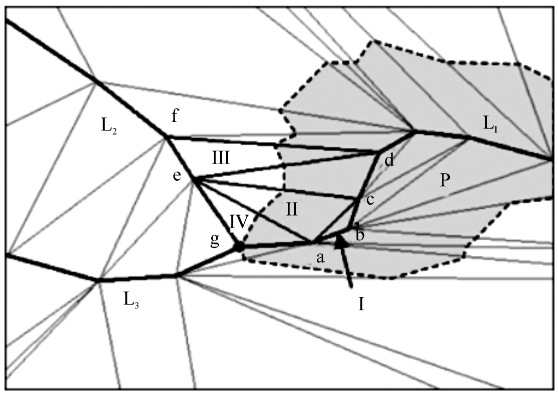

Fig. 2: Four types of triangle associated with the road

OPTIMIZE METHOD

Since the road density calculation is only related to the road's length and its GP's area, by analyzing the area attribution of triangles associated with the road to the growth polygons, we find a method to quickly calculate the GP's area size without building the road's GP region in advance. The main idea is: Take the road's GP as the set of split triangles and break up the whole into parts, classify the triangles into four types according to the area contribution for the GP, next calculate the contribution area for each type triangle, then, accumulate all the contribution area of each triangles associated with road and finally get the GP's area value.

Firstly, we will discuss how to classify the associated triangles into four different types and explore how to calculate the contribution area for each type.

Classification of associated triangles: Figure 2 is one part taken from the result region by road network constrained D-TIN splitting operation. P represents the growth zone for road L_1, which is obtained by connecting the boundaries' midpoints of the triangles associated with L_1. According to the difference in the size contribution of each associated triangle to the growth zone, they can be divided into the following four categories:

Type 1: Three vertices of the triangle all lay on the same segment, e.g. the three vertices of triangle Δ_{abc} lie on the road L_1 in Fig. 2. (where Δ_{abc} represents a triangle with three vertices a, b and c. Hereafter this representation will be used.)

Type 2: Two vertices of the triangle lay on the same segment, e.g. vertex c, d of the triangle Δ_{cde} and vertex a, c of the triangle Δ_{ace} all lies on L_1 in Fig. 2.

Type 3: Only one vertex of the triangle lies on the segment, e.g. only one vertex d of triangle Δ_{def} lies on the segment L_1 in Fig. 2

Type 4: Triangle has two vertices lie on the same segment but one is shared by other segments, which is one node of road network. E.g. vertex a, g of triangle Δ_{aeg} are both on the segment L_1 in Fig. 2, where g is the junction point of road network

Above classification includes all four types of associated triangles taken from the results after processing operations using road network type constrained D-TIN splitting method. Based on the calculation of area contribution amount for each kind of triangle, the corresponding area contribution degree for each type to growth region can be obtained. Obviously, the total growth area contribution degree of triangles associated with one road, i.e., the road growth area size, can be calculated by accumulating each ones' contribution of all the triangles associated with this road. In next section, we will focus on the optimized calculation method in details.

Area calculation for growth polygon: Let S represents area, then the road's growth polygon area P can be expressed as:

$$Sp = \Sigma S_I + \Sigma S_{II} + \Sigma S_{III} + \Sigma S_{IV} \quad (2)$$

where, S_p denotes the area of road growth areas, $S_{øñ}$, $S_{øò}$, $S_{øó}$ and $S_{øô}$ represent triangle area contribution to the growth area of P for type 1-4, respectively.

As we can see from Fig. 3, Grey shading parts denote each type of triangle's contribution to the growth polygon area, where vertex *e* and *f* represents the midpoint of the edge of corresponding triangle. Based on comprehensive consideration of the median line feature and the method of cut and complement for solving triangular shaded area, the four type triangle's shade area are calculated as following:

$$S_I = S_{\Delta abc} \quad (3)$$

$$S_{II} = S_{\Delta abc} - S_{\Delta aef} = \frac{3}{4} S_{\Delta abc} \quad (4)$$

$$S_{III} = S_{\Delta aef} = \frac{1}{4} S_{\Delta abc} \quad (5)$$

$$S_{IV} = \frac{1}{2} S_{\Delta abc} \quad (6)$$

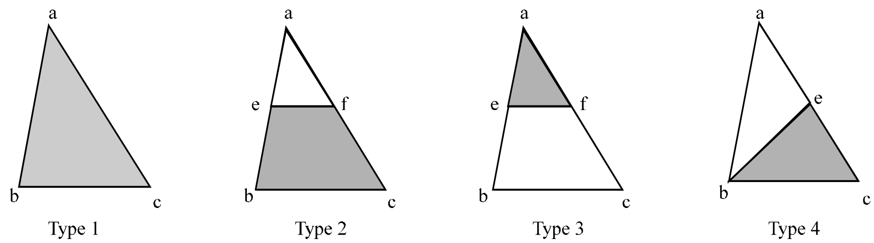

Fig. 3: Different area contribution degree of four kinds of associated triangle to GP

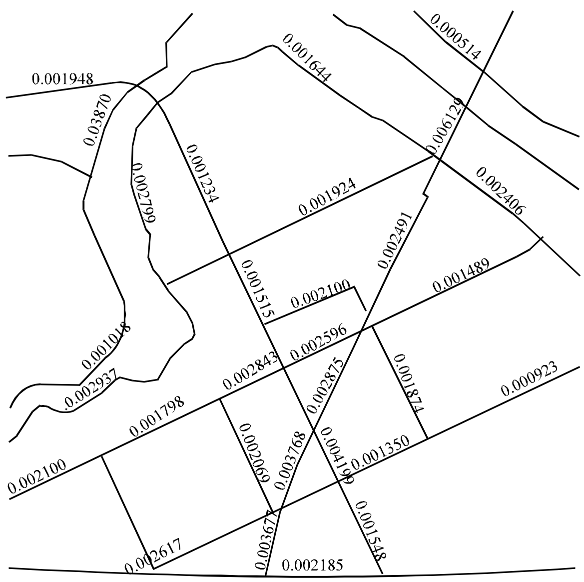

Fig. 4: Result of road density calculation

Firstly, all associated triangles can be captured by coordinate points searching on road L_i. After classification, the area contribution calculating of four types of triangle will be performed accordingly. The P-growth region area, finally will obtained by using Eq. 2.

In summary, the optimization method for density estimation of road network is described as follow steps:

- Let the roads in road network be interrupted automatically by intersection, then clear overlapping coordinate and overlapping arcs from the results, construct a road network arc segment set $\{L_i\}$
- Build constrained D-TIN under the constraint of boundaries from the $\{L_i\}$ segment set. This step is time consuming
- For each arc segment L_i in $\{L_i\}$, obtain all triangles associated with the arc segment L_i by coordinate points searching and then construct the associated triangle set $\{T_i\}$
- Perform classification operation for each element of $\{T_i\}$ according to the classification rules and calculate the area contribution of each triangle to the growth zone, respectively. The computing algorithm is based on our four equations mentioned above. And then use the Eq. 2 to calculate S_i-the growth area value of segment L_i
- Calculate the arc length of segment L_i and finally get the density of the arc according to Eq. 1

Each road's density calculation can be performed by iterating over arc set $\{L_i\}$. Among above density computing steps, step 1) is preprocessing for the road network data in order to prevent the disturbance brought by overlapping arcs and overlapping coordinate during constrained D-TIN constructing process. If the data quality can meet the requirements of practice, we can skip this step and so advances to the next step 2).

Figure 4 shows a part of result of road network density calculation by this method. From the overall density distribution of the road network, we can see that, the more that the region accommodate the roads, the bigger that the road density degree is. It is proved that the result of road density analysis is consistent with the road distribution.

CASE STUDIES

To prove the practicality of our new method, we devise an experiment to perform map automatic selection generalization by adopting our road density analysis algorithms in this section.

The experiment dataset contains the road network maps of Changsha City, Hunan Province, China. The map data mainly consists of two maps, one is at the scale of 1:50, 000 and another of 1:100, 000 (shown as part A and part B of Fig. 5, respectively). The road network mainly consists of urban roads and there are apparent distinctions between densities in different zones as we can see from Fig. 5. Roads are distributed more densely in the mid-part of the map representing central business district while sparse part represents suburban.

Fig. 5 (a-b): Comparison between data sets at different scales, (a) 1:50, 000 scale data used, (b) Generalization result of 1:100, 000 scale

Procedure of selection: Road selection is a prerequisite for effective road network generalization. Selecting road segments from a road network is also the goal of road network density calculation. The determination process of road segment selection is a complex procedure in which we should consider many principles: The road distribution density is one of these important rules and others like geometric, topological, thematic rules for road selection should be also considered. And the strokes following "good continuation" principle (Liu *et al*., 2010), parameters regarding road type, hierarchy, free flow speed, length, width and connectivity of road network must be taken into consideration in practice. Because of the limitation of the study, we just consider a simple procedure to select road segments without complex constraint.

Road selection method: Before selecting the road segments, we calculate the road density based on GP first, which is used to serve as benchmark for further assessment and indicating where conflicts exist. And in order to keep the roads' stroke characteristics of a road, we build and order the road's strokes. When processing the road selections, our method is based on the information extraction in the first step, with strokes as the selection unit. Here strokes are clustered by classic ISODATA algorithm according to their weighted topological, thematic, metric properties. The resulting clusters are then ranked in descending order according to the cluster centers' values. After that, road segments contained in the first M (M = 1, 2, 3...) clusters of strokes are selected when the total number of strokes in the first M clusters is around the predefined number of segments to be selected. Finally, the selection result is assessed based on the local road density and its threshold. The road density threshold indicates the density distribution difference between source and generalized maps and can be derived from comparison between the source map and the manually generalized map (Liu *et al*., 2010).

The selection process itself is an iterative and multi-objective process which integrates parameters mentioned above and uses strokes as basic selection unit. Road density for the segments to which operations have applied may be re-calculated after each iteration process and the comparison between newly-computed density and benchmarks may reveal whether the conflicts are resolved and how well the overall distribution pattern has been preserved. The part B of Fig. 5 is just the result of road network selection at 1:100, 000 from the 1:50, 000 road network map.

CONCLUSION

Road network density analysis is an important method of spatial analysis and it is frequently used in intelligent transportation, urban planning and automatic map generalization scenarios.

This study presents an optimized method for calculating the road growth polygon area quickly based on constrained D-TIN model and it avoids the complex process of building the road's growth polygon region, by following the idea of breaking up the whole into parts and to transform the road's growth polygon area calculation into contribution area computing of triangles which are associated with the road. It effectively simplifies the calculating process and enhances the reliability of the algorithm in the whole solving process. In the end, we give a case study to illustrate how to use this road analysis in map generalization practice, it focuses on the road density principle. In addition, how to apply our optimized method used in the road density analysis to other similar fields is our next research task in the future.

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