Road Density Analysis Based on Skeleton Partitioning for Road Generalization

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Abstract  This paper proposes an algorithm for road density analysis based on skeleton partitioning. Road density provides metric and statistical information about overall road distribution at the macro level. Existing measurements of road density based on grid method, fractal geometry and mesh density are reviewed, and a new method for computing road density based on skeleton partitioning is proposed. Experiments illustrate that road density based on skeleton partitioning may reveal the overall road distribution. The proposed measurement is further tested against road maps at 1:10k scale and their generalized version at 1:50k scale. By comparing the deletion percentage within different density interval, a road density threshold can be found, which indicate the need for further operations during generalization. Proposed road density may be used to examine the quality of road generalization, to explore the variation of road network through temporal and spatial changes, and it also has future usage in urban planning, transportation and estates evaluation practice.

Keywords  multiple-representation; map generalization; road density; skeleton partitioning

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Introduction

Road network generalization needs to be performed at three spatial levels\[1\]: macro level generalization regarding the overall distribution of network, meso level generalization dealing with relationships between road elements, and micro level generalization handling the properties of individual roads. Road density may effectively convey the metric and statistical information about overall road distribution at macro level. Therefore, various techniques have been invented to compute road density, and three major methods, i.e., grid method, fractal geometry method and sub-region based mesh density, may be identified.

Grid method\[2\] is the most common method in road density analysis. However, the determination of grid size, position and orientation is rather arbitrary. It also fails to provide information within grids, and may bring obstacles to road selection process, since grid boundaries may ‘split’ the roads into several parts and ultimately give rise to the loss of information about connectivity. Fractal geometry method\[3\] is devised by introducing self-similar fractal concepts. This method splits the whole study area into self-similar grids iteratively and the algorithm stops when the features within grids are homogeneous. It has the setback that the initial grid size exerts too much influence on computed road density, and the
information lost at larger grid may not be recovered. Mesh density based on sub-region\cite{4} avoids several of the aforementioned setbacks. However, it neglects geographical characteristics of road networks and may not reflect information about the area each road is serving and its relative importance.

Planar partitioning of space among geographical objects is essential for the structural spatial analysis like road density computation. Among all partitioning methods, skeleton partitioning\cite{5}, with the property of equal-area splitting, is used most frequently. This technique has been applied in many applications: commercial sites’ serving areas grow outward and their boundaries ultimately coincide (approximately) with Voronoi diagram generated from those commercial sites. As for generalization of river systems, watershed area is determined by the spatial competition model applying the approximated Voronoi diagram partitioning\cite{6}. Skeleton is adopted to determine where minor ridges and valleys exist in analyzing digital terrain model. Infrastructural objects without postal code are divided at their skeleton and then merged into their most likely neighboring parcels with postal code for constructing postal code map\cite{7}. In the aggregation of urban building clusters, each building has a growth region which is delineated by skeletons among building polygons. This idea is also useful in analyzing road networks\cite{8}, which may also be well-illustrated by real-world phenomena: skeletons among road segments are usually coincident with roads’ designed functional areas.

This paper proposes an algorithm for road density analysis based on skeleton partitioning at the macro level. The proposed method utilizes Voronoi diagrams of road segments, and takes geographical and geometric information of the road network into consideration. The following sections are organized as follows: The next section discusses the road density analytical methods based on skeleton partitioning. The article then presents four case studies to illustrate the property of road density based on skeleton partitioning and identify road density threshold for road selection, after which the article ends with conclusions and future work.

1 Road density analytical methods based on skeleton partitioning

The algorithm involves the modeling of road networks, extraction of the skeleton, construction of growth polygon, and calculation of road density, which are summarized as follows.

1.1 Partitioning of gap space among roads

1.1.1 Constructing constrained delaunay triangulation

Constrained delaunay triangulation is first applied to the road network, and triangles generated may be classified into different categories according to the number of road segments on which their vertex locate, i.e., triangles have their vertex on one, two, or three road segments (Fig.1). Triangle type 1, 2 and 3 represents that the triangle locates in the road’s concave part, the triangle connects two road segments, and the triangle connects three road segments, respectively. The triangle with all three vertexes on the same road segment should be removed from further analysis. The classification of triangles avoids generating dangling skeleton branch in the following steps.
1.1.2 Classifying different types of triangle

For triangles connecting two or three road segments, another classification is carried out according to the number of their neighbors, i.e., those having one neighbor, two neighbors and three neighbors are labeled as type 1, type 2 and type 3, respectively (Fig.2). ‘Neighbors’ refer to triangles that share the common edges which do not necessarily coincide with road segments.

GVD’s main geometric properties is described as follows: each partitioning polygon contains one road segment; each node links with three skeleton edges; each edge of partitioning polygon boundary faces to a left segment and a right segment, separating two segments equally in space.

GVDs can be deemed as the consequence of each road segment competing outward for growth space. Therefore, these partitioning polygons may be called Growth polygon (GP), and the analysis of road segment can be transformed to that of the corresponding GP.

1.2 Computation of density index

Road density based on skeleton partitioning may provide an accurate impression of local road density and involves the information about geographical properties with its basis on voronoi diagrams.

In the classical definition, density is described as “a measure of how much mass is contained in a given unit volume (density=mass/volume)”. In turn, density can be implied by the units of volume possessed by a given unit of mass (1/density=volume/ mass).

Therefore, by calculating the area of its GP, we may find out the local density for each road segment, i.e., we may find out how much area is possessed by a road segment. The calculation of local road density is as:

$$D = 1/A$$  \hspace{1cm} (1)

Where, $A$ is the area of GP, and $D$ refers to the local density.

The mass of linear object refers to its length, and Eq.(1) may be further revised as:

$$D = L/A$$  \hspace{1cm} (2)

Where $L$ represents the length of the road segment.

GP areas usually have a positive correlation with road segments’ length. By calculating the ratio between segments’ length and area of corresponding GP, measures of distances between road and its neighbors may be obtained, i.e., the value reflects how closely roads are distributed.

2 Case studies

To illustrate the soundness of the new algorithm,
four experiments are given in this section. The first three experiments aim at illustrating the properties of road density based on skeleton partitioning and use simulated datasets, while the fourth experiment utilizes the road network map of Hankou district, Wuhan City. The procedures and results of these four experiments are summarized as follows.

2.1 Experiments for properties of density based on skeleton partitioning

The first experiment aims at testing whether the computed density is a useful indication of local road density. A road density map for a simulated road network with 98 road segments is generated by mapping the density values into grayscale levels. The road density map (Fig.4) also illustrates the corresponding growth polygons. The denser and smaller room one road gets during competing outward, the more closely roads are distributed, and the larger number of road segments will be eliminated during selection.

The second experiment aims at testing whether the density based on skeleton partitioning may preserve the macro density difference among regions. Another simulated network consists of grids designed to simulate city streets and both mesh density based on sub-region and road density based on skeleton are computed. Density maps (Fig.5) based on these two methods show that both indices illustrate similar overall density distribution.

Fig.4 Road density based on skeleton partitioning (Darker color represents higher density and vice versa)

The third experiment is developed to detect the initial segmentation’s influence on density computation. Network initial segmentation has a consequence on the density computation since road density is a function of parameters like segment fraction, length and distance between segments. This may be illustrated by comparison between constructed Growth Polygon and corresponding road density for a simulated network and density calculated with several roads split into several parts. As for straight and evenly-spaced roads, densities before and after split do not change greatly. However, the values for more curved or crammed lines demonstrate the influence of segmentation (Fig.6). In Fig.6, wider line is to be split into two halves; grey-scales of growth polygon indicate relative density; density unit is 1e-4. Therefore, the initial segmentation should be carefully selected before density computation.

2.2 Density threshold for road selection

The selection of roads from road networks is usually the first step in map generalization. The threshold of road density may be detected where roads are densely distributed and selective omissions are needed. A simple method for detecting such threshold is to calculate and compare the percentage of selection within different density ranges on the manually-generalized road maps at different scales, i.e., acquire knowledge about density threshold from existing maps.
The experiment data sets are 1:10 k and 1:50 k road network map of Hankou District (Fig.7), Wuhan City. In Fig.7, ‘current scale’ in the image indicates the scale at which roads are viewed. The network consists of mainly urban roads and there are apparent distinctions between densities in different zones.

Identifiers are assigned to road segments and serve as linkages between road segments before and after generalization. Therefore, each segment may have two densities based on skeleton partitioning before and after generalization, and the density after generalization is assigned to be zero if the corresponding segment does not exist in the map at smaller scales. Then the segments are sorted in ascending order according to their densities before generalization, and the total number of segments within different density ranges and the number of ‘zeros’ (i.e., the number of deleted segments) are computed. The proportion of selection within each density range may consequently be derived by dividing the number of zeros and total number of segments. The statistics about percent of selection are given in Table 1 and Fig.8.

The road segments associated with density smaller than 0.000 7 has an average deletion proportion of 0.37, and this value for road segments associated with density larger than 0.007 increases dramatically to 0.67 (gaps between average deletion proportion of point 1~5 and point 6~10 in Fig.10). In the meantime, the deletion proportion in the density range right before (0.000 6~0.000 7) and after (0.000 7~0.000 8)
0.000 7 changes from approximately 0.37 to 0.55, i.e., 0.000 7 is the ‘turning point’ in the deletion proportion changes. Fig. 10 also reveals that the value for five data points (1,3,4-6) actually display a certain degree of clustering. Therefore, 0.000 7 may be deemed as the density threshold for selection/deletion for the generalization of similar road networks between corresponding scales.

The segments with density above threshold indicate the need of further operation. However, the selection or deletion of roads should not be done only based on densities; other parameters and rules need to be taken into consideration.

| Density range | Deleted segments | Total segments | Deletion proportion | Selection proportion | Increment between deletion proportions |
|---------------|------------------|----------------|---------------------|----------------------|----------------------------------------|
| [0,1)         | 12               | 29             | 0.413 793 103       | 0.586 207            |                                        |
| [1,2)         | 29               | 70             | 0.414 285 714       | 0.585 714            | 0.000 493                             |
| [2,3)         | 16               | 65             | 0.246 153 846       | 0.753 846            | - 0.16 813                            |
| [3,4)         | 39               | 96             | 0.406 25            | 0.593 75             | 0.160 096                             |
| [4,5)         | 44               | 116            | 0.379 310 345       | 0.620 69             | - 0.02 694                            |
| [5,6)         | 49               | 123            | 0.398 373 984       | 0.601 626            | 0.019 064                             |
| [6,7)         | 36               | 95             | 0.378 947 368       | 0.621 053            | - 0.01 943                            |
| [7,8)         | 53               | 95             | 0.557 894 737       | 0.442 105            | 0.178 947                             |
| [8,9)         | 53               | 112            | 0.473 214 286       | 0.526 786            | - 0.08 468                            |
| [9,10)        | 50               | 94             | 0.531 914 894       | 0.468 085            | 0.058 701                             |
| [10,20)       | 239              | 373            | 0.640 750 67        | 0.359 249            | 0.108 836                             |
| [20,30)       | 50               | 77             | 0.649 350 649       | 0.350 649            | 0.008 6                              |
| [30,40)       | 20               | 26             | 0.769 230 769       | 0.230 769            | 0.119 88                              |
| [40,50)       | 9                | 11             | 0.818 181 818       | 0.181 818            | 0.048 951                             |
| [50,∞)        | 42               | 50             | 0.84               | 0.16                | 0.021 818                             |
| Total         | 741              | 1 432          |                     |                     |                                        |

Average 0.527 843 479 0.472 157

Increment between deletion proportions = deletion proportion(N+1) – deletion proportion(N).

2.3 Procedure of selection

Road density exceed threshold indicates the place i.e., corresponding road segment and its neighbors where selective omission should take place. However, the decision of deleting or selecting is a complex procedure that requires other parameters and rules.

Because of the limitation of the paper, we just give a simple procedure to select a road. Road selection should be based on strokes following ‘good continuation’ principle[9]. Parameters regarding road type, hierarchy, free flow speed, length, width and connectivity should be taken into consideration[10]. Road density based on GP is calculated before selection to serve as benchmark for further assessment and indicating where conflicts exist. 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 where operations have applied may be re-calculated after each iteration, 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.

3 Conclusion and future work

From the experiments above, we may conclude that road density based on skeleton partitioning is a useful indication of local road density, and it may preserve macro density difference among regions. The density computation requires careful initial segmentation of the road network. Moreover, the density threshold (0.000 7) for selective omission of road networks in the generalization between 1 to 10 k scale and 1 to 50 scale may be found.
Understanding the road network’s overall distribution is critical for road selection in generalization. This study presents a method for selecting roads based on its distribution density, and the main contribution exists in the extraction of the skeleton and GP of the road network to indicate road distribution pattern and support later selection and other operation of the road network.

For the extraction of distribution density from the road network, this paper presents a whole process, including triangulation of road segments, the generation of the skeleton of the road network through two steps of classifying triangle type and connecting neighboring triangles, the construction of Growth Polygon and the calculation of road densities. In the decision of selection of roads, much knowledge needs to be integrated to consider the context impacts.

Road density analysis may be a useful tool not only for map generalization, but also for other planning and decision-making processes:

1) Comparison between road density before and after generalization may provide indication in the quality of generalization, e.g., evolution curve of road density before and after generalization may be generated to serve as benchmark in evaluation.

2) The macro impression of road density distribution provided by road density indices based on Growth Polygon may be integrated with other data like population and industry to have an overall judgment on regional development level for planning.

3) Growth Polygons illustrate the functional areas and ultimate importance of road segments, which provide useful information in designing road level, length, and width.

4) Road density and distribution analysis is also an important procedure of real estate evaluation.

To improve the method, further works need to be done:

1) Enhancing the decision analysis of road selection based on the road density calculated from Growth Polygon.

2) Improving the skeleton construction according to not only the geometric measures but also semantic context of roads, i.e., road properties and its surroundings. Road properties including road class, type, lane, and traffic rules should be considered, while the space among road networks should not be deemed as homogeneous, i.e., circumstances include buildings, points of interest; barriers will exert influence on skeleton partitioning.

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