An approach to data enrichment of building features using Delaunay triangulation for automatic map generalization

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1. Introduction

Automatic map generalization is a difficult task due to the contextual nature of the spatial objects represented on maps and has been the focus of much research. Understanding such contextual spatial relationships is critical to determine how map generalization is applied to spatial features on the map, considering their role, meaning and the context. Existing geographic databases lack functionality for extracting such spatial relationships in the form of auxiliary data, although researchers have explored spatial structures using various algorithms in computational geometry to enhance the spatial relations between features. The process of adding such auxiliary data to a data base is called data enrichment. This paper introduces a reliable geometrical data structure using Delaunay triangulation as a means of enriching databases of polygonal building features with the necessary auxiliary data.

2. Data enrichment with Delaunay triangulation geometrical data structure

Data enrichment has two main relations: horizontal and vertical as identified by Neun, Weibel and Burghardt (2004). Horizontal relations exist in the same level of detail (LoD) in a data set and represent common structural properties such as neighbourhood, pattern and alignment, while vertical relations can exist among homologous objects or group of objects. These vertical relations can exist on both attributes and geometric features. Vertical relations are important to leverage structural knowledge (horizontal relations) of different LoD. Identification of horizontal relations is important in deciding which generalization operatror(s) should be adopted based on the characteristics of the data. For example, buildings that are very close together can be merged to form one building when generalizing data from large scale to a smaller target scale. In vertical relations, link details such as object IDs of different data sets can be integrated and maintained either in one separate table or among the tables of the data sets themselves in an Multiple Database Management System (MDBMS; Hampe, Anders and Sester, 2003).

Identification of horizontal relations in data sets not only helps to identify structural knowledge required to deal with the contextual nature of map generalization, but also to leverage horizontal relationships among data sets at different resolutions to represent the same phenomena. The most widely used and effective geometric data structure in computational geometry to represent two horizontal relationships - topology and proximity - is the Delaunay triangulation (Delaunay, 1934). Computation of Delaunay triangulation is based on the so-called recursive edge-flipping technique (Berg *et al.*, 2008) used to satisfy Delaunay's condition applied to triangles formed from points. From the literature, several algorithms have been discussed for Delaunay triangulation from vector point data: incremental (Berg *et al.*, 2008), divide-and-conquer (Dwyer, 1987), sweep-line (Borut, 2005), circle-sweep (Biniaz and Dastghaibyfard, 2012).

Jones, Bundy and Ware (1995) used constrained Delaunay triangulation (CDT) to support generalization process of polygonal geometric features including buildings. In their approach sides of geometric features have been used as constraint edges in the triangulation. Although this approach provides rich proximity relations, its neighbourhood relations are implicit since the Delaunay property is sacrificed locally to meet all edges of triangles as sides of the geometric features.

Haowen, Weibel and Bisheng (2008) and Li *et al.* (2004) have applied Delaunay triangulation to cluster buildings using adjacency information in the context of data enrichment for generalization. In both approaches, although not stated, they have used conformal Delaunay triangulation by applying constraint breaking method (Rognant *et al.*, 1999) on the sides of buildings to make the triangulation entirely Delaunay stable. This approach adds additional redundant data to the source data set and as a result triangulation processing efficiency becomes low. Further, they have not tested their approaches on attached buildings.

Qi and Li (2008) have used constrained Delaunay triangulation on detached buildings of simple structure to cluster buildings. Although their approach is constrained based, triangles called 'building triangles' and 'false connection triangles' according to Haowen *et al.* (2008) have been formed both inside and outside each building polygon increasing the redundancy of information. In addition, the adjacency relationship of building polygons have been transformed to that of point features using centroid of each building, which is quite an unnecessary. An improved algorithm is therefore required.

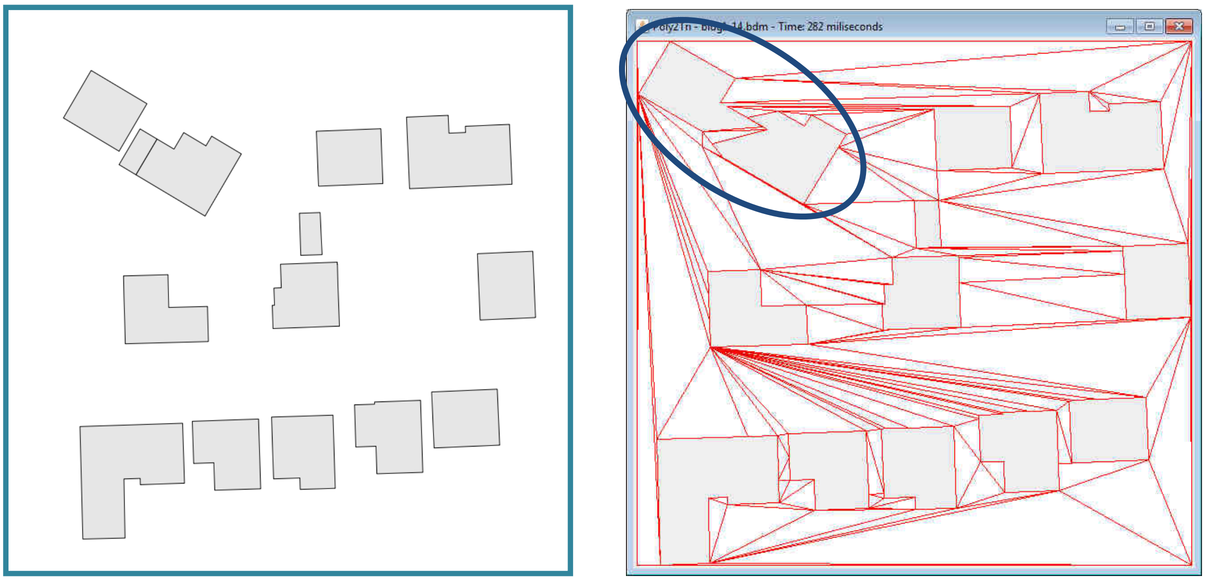
3. Efficient retrieval of topological and proximity relations of complex polygonal building features using Delaunay triangulation

When triangulation is performed on polygon features to get adjacency relationships for subsequent generalization, if attached buildings are merged before triangulation to form a single entity, identity of some important buildings that are required as landmarks especially in the application of way-finding in LBS get lost. Therefore, what is required is to process triangulation and retrieve adjacency relationships of all buildings in the source data set without any post processing for subsequent generalization needing to be performed in.

Tested here are three approaches in the application of Delaunay triangulation to building polygons to derive topological and proximity relations: treating edges of building polygons as constraints, called constrained Delaunay triangulation; triangulating the convex hull polygon of all the buildings with holes formed by each building using polygon triangulator and; using Delaunay triangulation on incremental algorithm with considering building sides as constraints preserving Delaunay property.

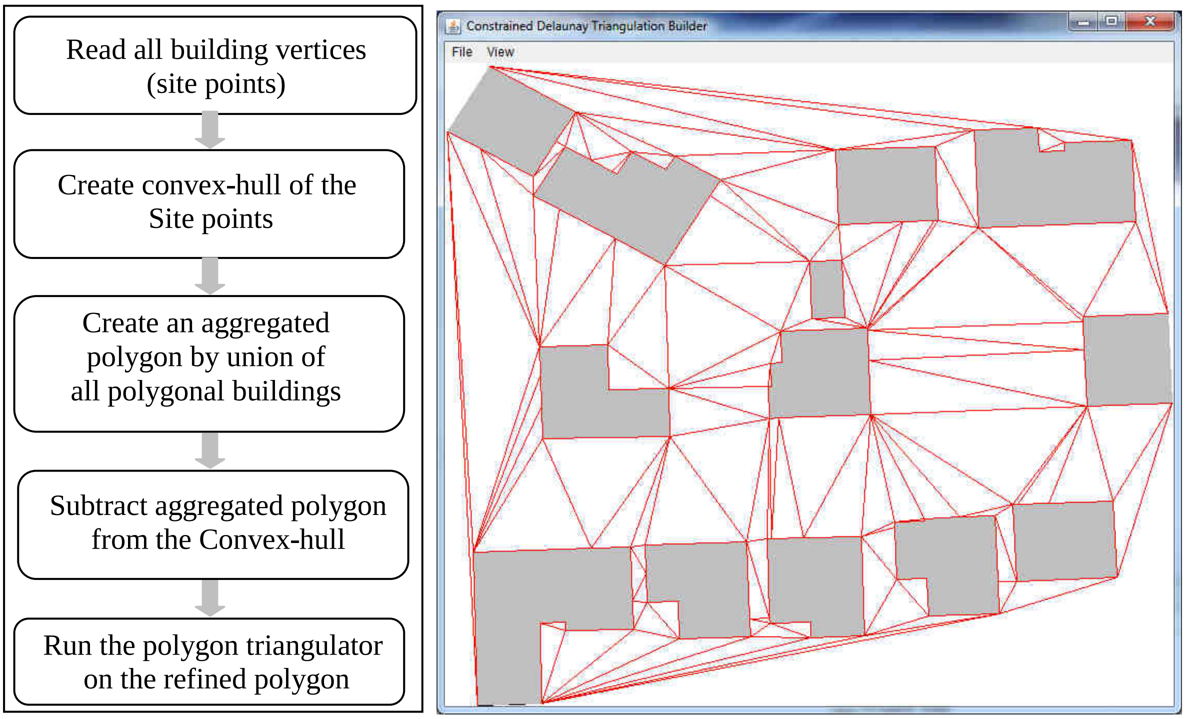
The first approach was developed and implemented using Poly2Tri open source java library (http://code.google.com/p/poly2tri/) based on the sweep-line constrained Delaunay triangulation algorithm developed by (Domiter and Žalik, 2008). In constrained Delaunay triangulation, in addition to the site points normally used in Delaunay triangulation, edges are considered as constraints which must become edges of triangles finally generated in the triangulation. This constraint weakens the Delaunay property in generating triangles thereby adversely affecting the representation of topology. On testing, two drawbacks of the constrained Delaunay triangulation were identified for the application of deriving horizontal relations in terms of topology and proximity. The first drawback is that it produces skinny triangles losing important topological relationships among the building features. The second drawback is that the algorithm does not work properly for building polygons that share a side (Figure 1).

The second approach was developed and implemented using the Java Topological Suite (JTS) open source java library (http://www.vividsolutions.com/jts/) using ear-clipping polygon triangulation algorithm developed by ElGindy, Everett and Toussaint (1993). First a convex-hull of all the buildings is created and then the polygon formed by the union of all buildings is subtracted from the convex-hull polygon to end up with a refined multi-polygon with holes. Then the ear-clipping algorithm is run to form triangles (Figure 2). One of the advantages of this approach is that the triangles thus formed preserve the Delaunay property. Also, this approach can process triangulation buildings that share a side. However, this approach does not provide stable result in terms of topological relations, when testing for different numbers of buildings from the same data set.



(a) (b)

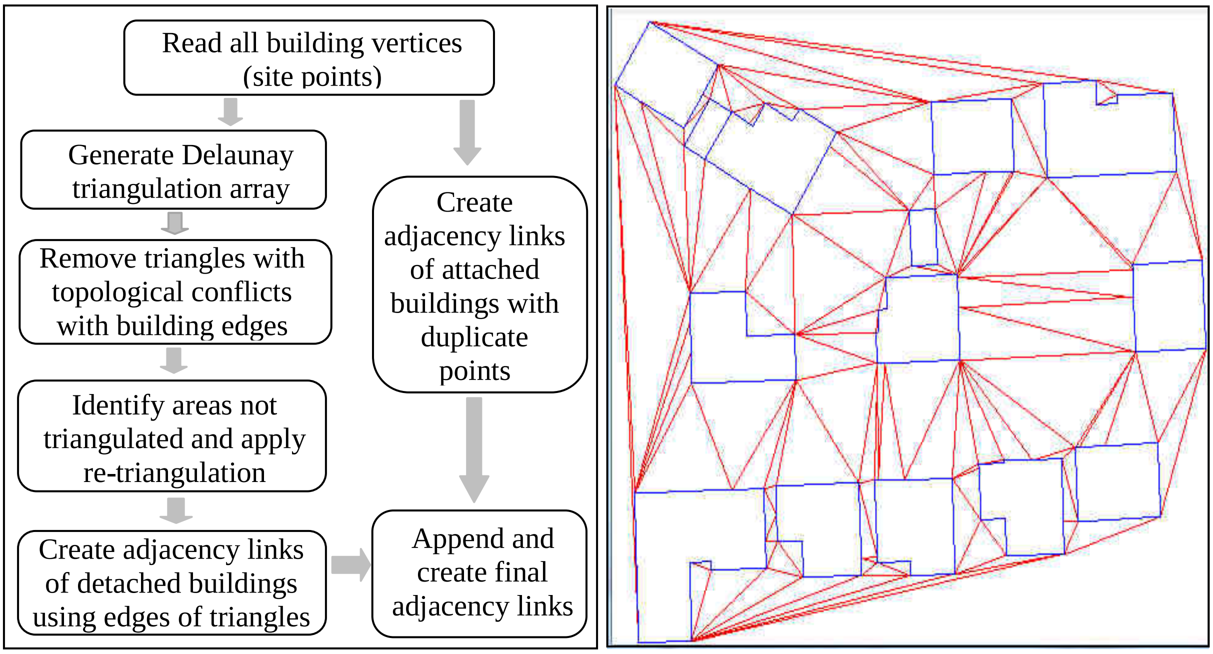
Figure 1: (a) Example set of building features; (b) constrained Delaunay triangulation on polygonal building features depicting erroneous formation of triangles (encircled) for a pair of buildings that share one side (data source: OSMasterMap, Crown copyright).



(a) (b)

Figure 2: (a) Delaunay triangulation process using polygon triangulator; (b) Delaunay triangulation with constraint building edges. (data source: OSMasterMap, Crown copyright).

The third and final approach was developed and implemented using Open source Java Delaunay Triangulation library (http://code.google.com/p/jdt/), which is based on the incremental algorithm for constructing Delaunay triangulation (Berg *et al.*, 2008). In this approach, first Delaunay triangles are generated irrespective of the constraints from all the vertices of the building data set and then the triangles that come across topological conflicts with building edges are removed from the triangle array. Then the areas which do not have triangles after removal of conflicting triangles are re-triangulated to construct the final Delaunay triangles, which is entirely Delaunay stable and therefore, can be known as Delaunay constrained triangulation.



(a) (b)

Figure 3: (a) The process of retrieving adjacency relationships, (b) Delaunay constrained triangulation on a data set with simple geometry (data source: OSMasterMap, Crown copyright)

The triangles so generated provide rich proximity and correct neighbourhood relations and ignore duplicate points and therefore, it does not generate topological relations and proximity among buildings that share a side. However, relations of such attached buildings are calculated from the duplication point array and appended to the adjacency links generated from the detached buildings (Figure 3). The advantage of this approach is that it can handle buildings of very complex geometry including attached buildings, buildings with holes whilst preserving the Delaunay property (Figure 4).

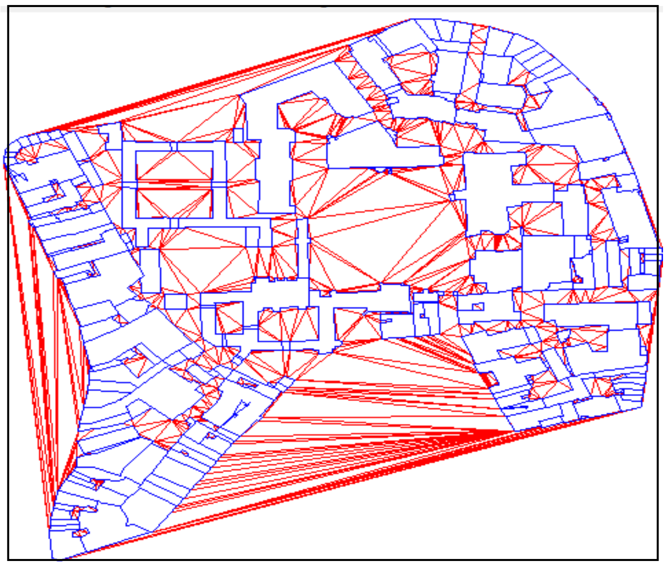


Figure 4. Delaunay constrained triangulation on a sample data having complex building geometry in part of the City of London (data source: OSMasterMap, Crown copyright)

4. Conclusion

Three approaches have been implemented and compared based on three different algorithms related to Delaunay triangulation to enrich polygonal building data of a complex geometrical nature in order to get topological and proximity relations to support map generalization, with the goal of providing better map design useful for various applications such as way-finding in LBS. Of these three approaches, the incremental algorithm coupled with topological conflict-search algorithm is Delaunay stable and hence provides explicit topological relationships between polygonal building features for the effective derivation and application of different generalization operations in automatic map generalization.

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