Semantic and Qualitative Spatial Reasoning Based Road Network Modeling

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Abstract. Road Network Modeling is a fundamental issue for urban computing and uses massive primitive geospatial data retrieved from Geographic Information Database. The modeling for road network is extremely complicated because of the scalable and reticular relations between the roads in the city. In this paper, we propose an approach of qualitative spatial relation and semantic web based predication for road network modeling, and define five spatial relation predicates according to the notions in point-set topology for better representing the spatial relation between roads. The roads and junctions in road network are modeled as standardized well-known text literals, and deterministic spatial realtions are calculated by spatial relation reasoning. Then, all road network elements and their relations are stored as RDF triples into LarKC, a platform for scalable semantic data processing and reasoning. In this paper, we show that the triplized road network data stored in semantic web repository is very convenient for spatial information quering and junction type calculation.

Keywords: road network, spatial relation predicates, point-set topology, LarKC.

1 Introduction

Road Network Modeling is a fundamental issue for Urban Computing which is an emerging field of study that focuses on technology applications in public environments. The road length all over the world has totally reached 102,260,304 kilometers in 2008 and are still increasing fast these years. A large number of geographic database has been used to store spatial data of the roads up to date. The relations' number between roads is exponential compared to the number of roads and has become an incredible big digit. If the deterministic spatial relation can be calculated and stored in geographic information system, it will be more efficient to query the roads which have specified spatial relation with others, or some roads which share the same junction.

Big geographic data has been provided on the Web and become available data sets for road network modeling. OpenStreetMap[1] is one of the free datasets

[1] http://www.openstreetmap.org/

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available which include worldwide geographic data. It defines element Node and Way to represent geographic point and line respectively, and can be retrieved as linked data provided on LinkedGeoData[2] which is a large spatial knowledge base derived from OpenStreetMap. The contents in OpenStreetMap and LinkedGeoData are equivalent and provide adequate two-dimensional geospatial data. A third optional dimension, altitute, just as latitude and longitude for locating a spatial point, can also be recorded.

Even these geographic dataset provide enough coordinate information for the spatial features, they don't contain explicit spatial relations between them. Region connection calculus [1] are widely used to represent qualitative sptaial relation between two regions. 9-Intersection Model was developed by Clementini and others[2][3], based on the seminal works of Egenhofer and others[4][5] ,and was used as a basis for standards of queries and assertions in geographic information systems (GIS) and spatial databases were introduced. These spatial relation information is not only useful, but also big because the underlying geographic data is large-scale. If this useful and big spatial relation information can be stored explicitly in geographic information system, it will be convenient for some applications to query according to spatial relationship.

In this paper, we propose an approach of qualitative spatial relation reasoning which comes from a major brunch of spatial-temporal study. The qualitative aspects of road network are abstracted in terms of notions in point-set topology theory. The elements of road network are modeled as standardized well-known text, which is a text markup language for representing vector geometry objects in map. Five common binary spatial relation predicates between roads are also defined here, which include Touches, Joins, JoinsedBy, Crosses and Disjoint. Each relation can be denoted by a four-tuple, according to the relation between two geometries' interior and/or bounday. These four-tuple spatial relations are later extended as 9 intersection model[6], for easier calculating spatial relation by some application interface like GeoSPARQL[7].

After getting the spatial relation between roads, we also use point-set theory to calculate the intersection between roads which have spatial relation except Disjoint. The common point set shared by roads is the junction between them and are modeled as POINT literal or MultiPoint literal of well-known text. We also give a practial algorithm to calculate the type of junction by spatial relation between junction and related roads. All road network elements and their relations are stored as RDF triples into LarKC, a platform for scalable semantic data processing and reasoning[3], at last. This explicit triplized spatial knowledge provides an efficient way for geographic information application to query later.

OpenStreetMap currently lacks of practical sources and devices to provide the altitude of a given spatial point. It is limited for us to process spatial data assuming they are on the same plane and focus on at-grade road junction, instead of grade-separated road junction. Because of the big amount of available

[2] `http://www.linkedgeodata.org/`
[3] `http://www.larkc.eu`

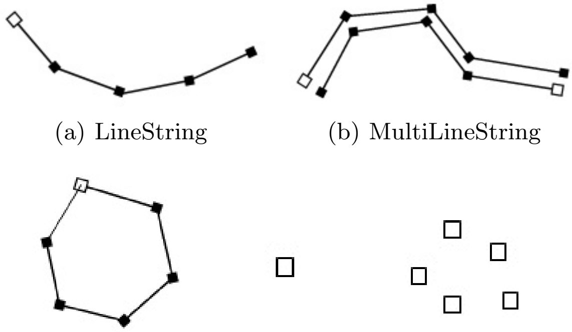
geographic data and extremely heavy spatial reasoning, some new computing architecture should be adopted for massive geographic data processing.

The remainder of this paper is organized as follows: Section 2 introduces the method about how to model road network elements, including road and junction. Section 3 gives an approach to represent spatial relation between roads and five predicates are defined based on point-theory topology. We apply it on some data from geographic database and discuss about the result. In Section 4, we design an algorithm which is still based on point-set topology to calculate the type of junction and has a contrast with the geographic landform. The conclusion is given in Section 6 and future researches are also discussed based on the previous results.

2 Road Network Spatial Structure

2.1 Road Network Elements

Road Network is the network of motorways, trunk roads and principle roads that serve the country's strategic transport needs. Road Networks, roads, and junctions are examples of natural language terms whose semantics can be described by affordances of their referents[8].



(a) LineString (b) MultiLineString

(c) LinearRing (d) Point (e) MultiPoint

Fig. 1. Typical Geometry Objects Type

The most important objects to construct road network are roads and junctions in a city. These objects will be represented as different geometry objects shown in Fig 1. The white dot represents the first node of a sequence while the dark ones do not. A road is a route or way on land between two places, which has been paved or otherwise improved to allow travel by some transport. We model the road which has one roadway as a LineString in Fig 1(a), and the road with two roadways as MulitLineString which has and only has two LineString shown in Fig 1(b). As a special case, ring road is modeled as LinearRing shown in Fig 1(c). More complicated road which has fork is not considered in this paper. A junction is a location where vehicular traffic going in different directions can proceed in a controlled manner designated to minimize accidents. We model the junction as Point, as in Fig 1(d) or MultiPoint, as in Fig 1(e) according to how many intersected points between roads.

2.2 Types of Junctions

Two different types of junction between roads exist according to whether the relative roads are at grade or not. One type is interchange and the other is intersection. Interchange are junctions where roads pass above or below one another, preventing a single point of conflict by utilizing grade separation and slip roads. The terms motorway junction and highway junction typically refer to this layout. Intersections do not use grade separation and road cross directly. Forms of these junction types include Roundabouts and traffic circles, priority junctions, and junctions controlled by traffic lights or signals.

In this paper, we focus on the secondary type of junction which may be explicit or implicit. The explicit intersection is a Node element which has a special tag indicating that the node has contributed to constructing different ways. Instead of having correspond Node element in OpenStreetMap, the implicit intersection has an implicit spatial point due to the intersected road trajectories. This problem is due to quality issues in the OpenStreetMap data set, so not all the junctions are explicitly stated.[9] These implicit junctions can be calculated by the following sptial topological reasoning approach.

(a) explicit intersection (b) implicit intersection

Fig. 2. Intersection in OpenStreetMap

3 Spatial Relations between Roads

3.1 Point-Set Topology

Point-set topology is the branch of topology which studies preperties of topological spaces and structures defined on them. A topology on X, which is a set, is a collection A of subsets of X that satisfies the following three conditions:

(1) the exmpty set and X are in A,
(2) A is closed under arbitrary unions,
(3) A is closed under finite intersections.

A topological space is a set X with a topological A on X. The sets in a topology on X are called open sets, and their complements in X are called closed sets. The collection of closed sets satisfies the following conditions:

(1) contains the empty set and X,
(2) is closed under arbitrary intersections,
(3) is closed under finite unions.

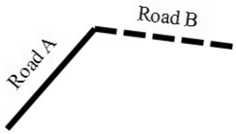
The notion of interior, boundary, and closure used in point-set theory are defined as follows[4]:
Interior: Given $Y \subset X$, the interior of Y, denoted by Y°, is defined to be the union of all open sets that are contained in Y.
Boundary: The boundary of Y, denoted by ∂Y, is the intersection of the closure of Y and the closure of the complement of Y.
Closure: The closure of Y, denoted by $\overline{Y}$, is defined to be the intersection of all closed sets that contain Y.

3.2 Approach for Describing Topological Spatial Relations

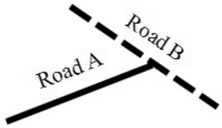
Binary topological relationships may be defined in terms of the boundaries and interiors of the two objects to be compared. A formalism is developed which identifies 16 potential relationships[10]. Our approach describes the topological spatial relations between two subsets, road A and road B, of a topological space X is based on a consideration of the four intersections of the boundaries and interior of the two sets A and B, i.e., $\partial A \cap \partial B$, $A^{\circ} \cap B^{\circ}$, $\partial A \cap B^{\circ}$, and $A^{\circ} \cap \partial B$. The topological spatial relation between two sets is preserved under homeomorphism of the underlying space X.

Some comlete and orthogonal predicates should be defined to describe the spatial relation knowledge between roads. In point-set topology theory, 57relations between two lines, 33 of them can be realized between simple lines[6]. And 8 spatial popularly used spatial relations derived from DE-9IM[11] are widely used and have been adopted in OGC GeoSPARQL specification[7] as the Simple Features Topological Relations. The explicitly stated predicates in GeoSPARQL can not provide complete and orthogonal topological relations between roads. This problem will be solved by defining five dedicated topological predicates as depicted in Fig 3.

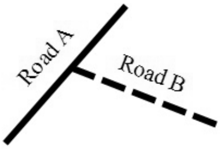
We use tuple with four elements to describe a topological spatial relation. Each element of the tuple correspond to different set intersection combination between two geometries. The four elements are interior-interior intersection, interior-interior intersection, boundary-interior intersection, and interior-boundary intersection respectively. The sixteen possibilities from those combinations are summarized in Table 1:



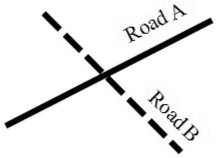
(a) Touches



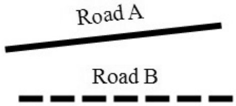
(b) Joins



(c) JoinsedBy



(d) Crosses



(e) Disjoint

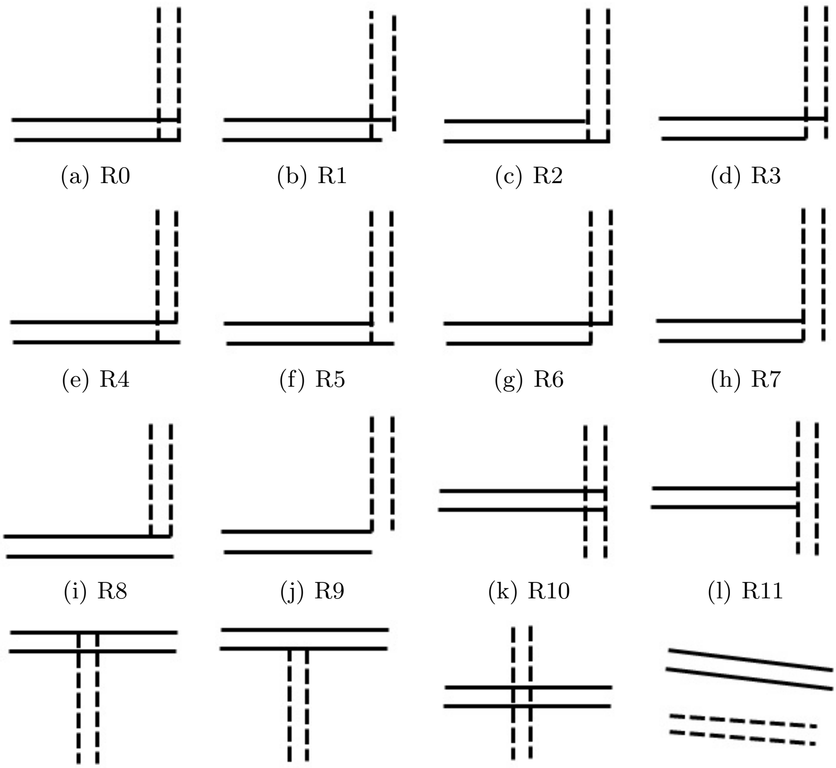
Fig. 3. Five Spatial Relation between Rods

Table 1. 16 Possible Combinations and Their Semantic

Relations	$A^\circ \cap B^\circ$	$A^\circ \cap \partial B$	$\partial A \cap B^\circ$	$\partial A \cap \partial B$	Semantic
R0	$\neg\emptyset$	$\neg\emptyset$	$\neg\emptyset$	$\neg\emptyset$	
R1	$\emptyset$	$\neg\emptyset$	$\neg\emptyset$	$\neg\emptyset$	
R2	$\neg\emptyset$	$\emptyset$	$\neg\emptyset$	$\neg\emptyset$	
R3	$\neg\emptyset$	$\neg\emptyset$	$\emptyset$	$\neg\emptyset$	
R4	$\neg\emptyset$	$\neg\emptyset$	$\neg\emptyset$	$\emptyset$	Touches
R5	$\emptyset$	$\emptyset$	$\neg\emptyset$	$\neg\emptyset$	
R6	$\emptyset$	$\neg\emptyset$	$\emptyset$	$\neg\emptyset$	
R7	$\emptyset$	$\neg\emptyset$	$\neg\emptyset$	$\emptyset$	
R8	$\neg\emptyset$	$\emptyset$	$\emptyset$	$\neg\emptyset$	
R9	$\emptyset$	$\emptyset$	$\emptyset$	$\neg\emptyset$	
R10	$\neg\emptyset$	$\emptyset$	$\neg\emptyset$	$\emptyset$	Joins
R11	$\emptyset$	$\emptyset$	$\neg\emptyset$	$\emptyset$	
R12	$\neg\emptyset$	$\neg\emptyset$	$\emptyset$	$\emptyset$	JoinsedBy
R13	$\emptyset$	$\neg\emptyset$	$\emptyset$	$\emptyset$	
R14	$\neg\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$	Crosses
R15	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$	Disjoint

As depicted in Table 1, the first 10 combinations has a spatal semantic Touches in terms of practical connection between roads' geometry trajectory. R10 and R11 hava a semantic of Joins which means one road's boundary is conneted to other's interior. R12 and R13 are symmetrical to R10 and R11 respectively, named JoinsedBy, which means one road's interior is connected by other's boundary. R14's spatial semantic is typical Crosses, which indicates two roads intersect in both interior. The last relation combination, R15, which holds great majority in practical scenes, means two roads have no intersection.

The examples in Fig 4 are not complete and considering more complecated roads which are strictly modeled as a MultiLineString containing two, and only



(a) R0 (b) R1 (c) R2 (d) R3
(e) R4 (f) R5 (g) R6 (h) R7
(i) R8 (j) R9 (k) R10 (l) R11
(m) R12 (n) R13 (o) R14 (p) R15

Fig. 4. Example of Each Spatial Relation Combination

two LineString. Each example intuitively exhibits the spatial relation between roads and its spatial semantic. If the spatial relaiton is considered as a predicate in Semantic Web, then the real line and dotted line represent subject and object respectively. Some extreme occasion may happen, as an example, spatial relation combination R14 donot really mean Crosses because of poor geographic data quality. This problem is not the key component considered in this paper.

A set is either empty or non-empty, therefore, it is clear that these sixteen topological spatial relations provide complete coverage, that is, given any pair of sets of A and B in X, there is always a topological spatial relation associated with A and B, exactly one of the sixteen spatial relations can occur between two sets. Depending on various restrictions on the sets and underlying topological space, the actual set of existing topological spatial relations may be a subset of the sixteen in the table. For general poin-sets in the plane $\mathbb{R}^2$, all sixteen topological spatial relations can be realized(figure1).

3.3 Spatial Relation between Roads

Our object of road network modeling is to reason topological spatial relations that occur between lines. The complete and orthogonal spatial relation between roads are defined as follows:

Definition 1. *A Joins B if and only if* $A^\circ \cap \partial B = \emptyset$ *and* $\partial A \cap B^\circ \neq \emptyset$ *and* $\partial A \cap \partial B = \emptyset$

Definition 2. *A is JoinsedBy B if and only if* $A^\circ \cap \partial B \neq \emptyset$*,* $\partial A \cap B^\circ = \emptyset$ *and* $\partial A \cap \ partialB = \emptyset$

Definition 3. *A and B Crosses with each other if only if* $A^\circ \cap B^\circ \neq \emptyset$*,* $A^\circ \cap \partial B = \emptyset$*,* $\partial A \cap B^\circ = \emptyset$ *and* $\partial A \cap \partial B = \emptyset$

Definition 4. *A and B Disjoint with each other if only if* $A^\circ \cap B^\circ = \emptyset$*,* $A^\circ \cap \partial B = \emptyset$*,* $\partial A \cap B^\circ = \emptyset$ *and* $\partial A \cap \partial B = \emptyset$

Definition 5. *If the relation between A and B is neither Joins, JoinsedBy, Crosses, nor Disjoint, then A and B Touches with each other.*

In this paper, for better calculating the qualitative relation between roads for more general spatial reasoning purpose. We extend the tuple with four elements to DE-9IM matrices in Tab 2.

Table 2. Five Predicates and Their DE-9IM Matrice's Pattern

Predicate	Corresponding DE-9IM Matrice's Pattern
Touches	$\begin{bmatrix} 0 & 0 & \ast \\ 0 & 0 & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} 0 & 0 & \ast \\ 0 & \emptyset & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} \emptyset & 0 & \ast \\ 0 & 0 & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} 0 & \emptyset & \ast \\ 0 & 0 & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} 0 & 0 & \ast \\ \emptyset & 0 & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} \emptyset & 0 & \ast \\ 0 & \emptyset & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} 0 & \emptyset & \ast \\ \emptyset & 0 & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} \emptyset & \emptyset & \ast \\ 0 & 0 & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} \emptyset & 0 & \ast \\ \emptyset & 0 & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} \emptyset & \emptyset & \ast \\ \emptyset & 0 & \ast \\ \ast & \ast & \ast \end{bmatrix}$
Joins	$\begin{bmatrix} 0 & \emptyset & \ast \\ 0 & \emptyset & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} \emptyset & \emptyset & \ast \\ 0 & \emptyset & \ast \\ \ast & \ast & \ast \end{bmatrix}$
JoinsedBy	$\begin{bmatrix} 0 & 0 & \ast \\ \emptyset & \emptyset & \ast \\ \ast & \ast & \ast \end{bmatrix}$ or $\begin{bmatrix} \emptyset & 0 & \ast \\ \emptyset & \emptyset & \ast \\ \ast & \ast & \ast \end{bmatrix}$
Crosses	$\begin{bmatrix} 0 & \emptyset & \ast \\ \emptyset & \emptyset & \ast \\ \ast & \ast & \ast \end{bmatrix}$
Disjoint	$\begin{bmatrix} \emptyset & \emptyset & \ast \\ \emptyset & \emptyset & \ast \\ \ast & \ast & \ast \end{bmatrix}$

4 Experiment and Evaluation

We take Zhenjiang city as an example, there are 66 roads in OpenStreetMap. So the relation number between roads is the combination C_2^n and totally 2145. By using DE-9IM matrices defined in Table 2, we find there are 26 pairs of Crosses relations, 50 pairs of Touches relations, and 86 pairs of Joins/JoinsedBy relations in Fig 5. It is reasonable that disjoint relations hold absolutely large proportion in that most roads have no intersection with each other.

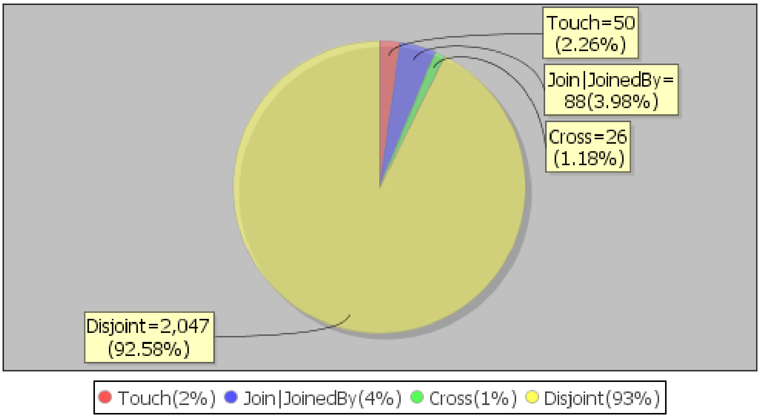


Fig. 5. Statistics of Roads' Relation in Zhenjiang

By calculating the binary spatial relations between roads, we also can get the geometry points of the junctions. If the binary spatial relation between A and B is not Disjoint, then the set C, where $C = A \cap B$, is the points belonging to the junction between the two roads. At last, we get many points belonging to different junction. Some junction point is the same or quite near according to some threshold value, so these junction should be merged and it implies that some roads, more than three, share the same junction.

(a) intersects in boundary (b) intersects in interior

Fig. 6. Spatial Relation between Junction and Road

After merging the junctions which share the same points, we use the points to judge the junction type. If a junction has an intersection with the boundary of a road, the road must join to other roads at this junction. Otherwise, if a junction has an intersection with the interior of a road, the road must be divided by the junction. As an example, a junction, represented as P, is shared by road A_0, A_1, $\cdots$, A_n. The branches number of P, represented as variable T, can be calculated by the following prodecure:

function RETURNJUNCTIONTYPE(P, A)
  $T \leftarrow 0$
  for $i = 0 \rightarrow n$ **do**
    if $P \cap \partial A_i \neq \emptyset$ **then**
      $T += 1$
    else if $P \cap A_i^\circ \neq \emptyset$ **then**
      $T += 2$
    else
      continue
    end if
  end for
  return T
end function

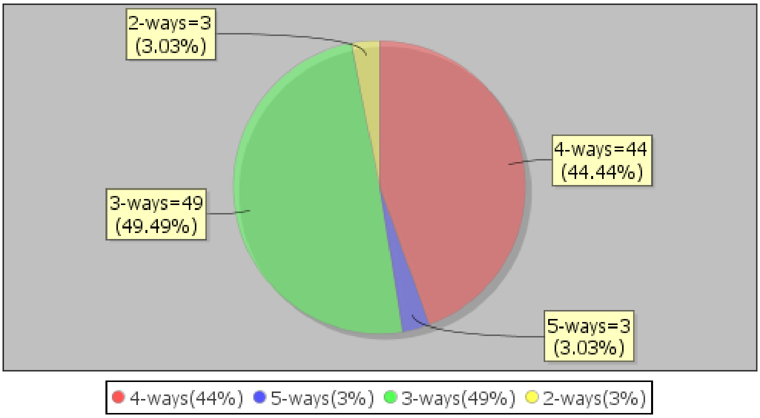


Fig. 7. Statistics of Junctions' Type in Zhenjiang

We use this algorithm to calculate the junctions of Zhenjiang city, which has 101 junctions after merging. The numbers of 2-ways, 3-ways, 4-ways, and 5-ways junctions are 3, 49, 44, and 3 respectively in Fig 7. The number of 3-ways junctions is even more than the one of 4-ways junctions. This result reflects the fact that too many hills in Zhenjiang city, and relative roads can not be easily extended.

5 Conclusions

A formal definition of spatial relation between roads has been given and it is more suitable than RCC-8 and 9-Intersection Model. RCC-8 does not have eqivalent predicate as Joins or JoinsedBy defined in this paper. While 9-Intersection Model covers all topological relation, it still does not provide explicit predicates for some useful relation combination. By asserting these spatial relations between roads, it is more efficient to query big geographic information.

The geographic data of Zhenjiang used in the experiment is about 33,000 triples, and the spatial reasoning time is acceptable. While facing some big data of giant city, like Shanghai whose geographic data in OpenSteetMap is approximately 1,000,000 triples, the spatial reasoning time is extremely consuming and unlikely estimated. We do need some new computing architecture to overcome the spatial reasoning problems on big geographic data. Some new computing technology like distributed reasoning approach is promising and we will adopt it for big geographic data reasoning in the future work.

Junctions and their relative roads can be calculated by the procedure presented in this paper and stored as semantic data in LarKC. This knowledge is very useful for road's relation querying, and can also be used to calculate the roadsigns by quantitative reasoning on road's boundary and the junction. The quantitative reasoning approach will be discussed in later paper.

References

1. Randell, D.A., Cui, Z., Cohn, A.G.: A spatial logic based on regions and connection. In: KR 1992, pp. 165–176 (1992)
2. Clementini, E., Di Felice, P., van Oosterom, P.: A small set of formal topological relationships suitable for end-user interaction. In: Abel, D., Ooi, B.C. (eds.) Advances in Spatial Databases, pp. 277–295. Springer, Heidelberg (1993)
3. Clementini, E., Sharma, J., Egenhofer, M.J.: Modelling topological spatial relations: Strategies for query processing. Computers & Graphics 18(6), 815–822 (1994)
4. Egenhofer, M.J., Franzosa, R.D.: Point-set topological spatial relations. International Journal of Geographical Information System 5(2), 161–174 (1991)
5. Egenhofer, M.J., Herring, J.: A mathematical framework for the definition of topological relationships. In: Fourth International Symposium on Spatial Data Handling, Zurich, Switzerland, pp. 803–813 (1990)
6. Egenhofer, M.J., Herring, J.: Categorizing binary topological relations between regions, lines, and points in geographic databases. The 9, 94–1 (1990)
7. Consortium, O.G., et al.: Ogc geosparql-a geographic query language for rdf data. OGC Candidate Implementation Standard (2012)
8. Scheider, S., Kuhn, W.: Road networks and their incomplete representation by network data models. In: Cova, T.J., Miller, H.J., Beard, K., Frank, A.U., Goodchild, M.F. (eds.) GIScience 2008. LNCS, vol. 5266, pp. 290–307. Springer, Heidelberg (2008)
9. Lee, T.K.I., Park, S., Huang, Z., Della Valle, E.: Toward seoul road sign management on larkc platform. In: ISWC Posters&Demos (2010)
10. Egenhofer, M.J.: A formal definition of binary topological relationships. In: Litwin, W., Schek, H.-J. (eds.) Foundations of data organization and algorithms. LNCS, vol. 367, pp. 457–472. Springer, Heidelberg (1989)
11. Strobl, C.: Dimensionally extended nine-intersection model, de-9im (2008)