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分散環境下で多層に管理される道路片間の位相関係の計算

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あらまし　分散環境下で地図情報の共有性と一貫性を実現する目的に対して、分散的に多層の道路ネットワークを管理するための枠組を述べる。本枠組は継承機能とオーバレイ機能を用いて多層の空間データを統合できるために非常に強力である。しかし、道路片間の位相関係は”オン　ザ　フライ”に計算しなければならない。本稿では、 9-intersection モデルを拡張して計算する方法を提案する。
キーワード　地理情報システム (GIS), 多層地図情報モデル, 位相関係

Computation of Topological Relations among Road Segments Managed in Multi-levels under Distributed Environment

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Abstract　For the target of map information sharability and consistency under distributed environment, we address a framework for managing multi-levels road networks in distributed environment. Our framework is very powerful to integrate spatial datasets of multi-levels by using inheritance and overlay functions. However, the topological relations among road segments should be computed ”on the fly”. In this paper, we extend 9-intersection model for this computing.
Keywords　Geographic Information Systems (GIS), Multi-levels Map Information Model, Topological Relations

1 Introduction

Though there is too much map information on Internet, it cannot be said that users could get the latest map information about desired themes and regions at desired or proper scale whenever and wherever. This is because most of the maps on Internet are created for specific themes based on many source datasets. Once they have been generated, they are *static* due to the fact that keeping information in the generated map consistent with the version of those source datasets is a difficult problem to solve when the maps are not regenerated based on the updated source datasets immediately. To solve this problem, we proposed a Multi-level / Multi-theme (M^2) map information model [1][2] to instantly maintain maps in consistency with original source datasets under distributed environment. Under this model, there is no overlap among the datasets, and inheritance and overlay functions are introduced to generate maps dynamically. All these funtions are based on the coordinates of spatial objects, the topological relations among spatial objects may be also changed after these functions. In this paper, we address a method for computing topological relations among road segments by "on the fly" under our model.

Topological relations are spatial relations that are preserved under such transformations as rotation, scaling, and rubber sheeting [3], including adjacency, overlapping, disjointness and inclusion, and constitute an important class of spatial relations. A formalization of topological relations has been investigated based on the point-set topology. 9-intersection model [4] is regarded as the most comprehensive model for determining topological spatial relations between candidate pairs so far. In the model, the topological relations between two objects **A** and **B** are defined in terms of the intersections of **A**'s interior, boundary and exterior with **B**'s interior, boundary and exterior. The exterior of an object is represented by its complement. This model has been used or extended to examine the possible topological relations between areas in discrete space, for modelling conceptual neighborhoods of topological line-area relations and so on. These investigations have contributed to the development of state of the art.

However, 9-intersection model has imperfections: the exterior (defined as the complement), boundary and interior of **A** (or **B**) are linearly dependent. Therefore, there is one-degree redundancy in the model. To improve this situation, Chen, et al.[5] presented a Voronoi-based 9-intersection model which replaces the complements of spatial objects by their Voronoi regions. Additional relations can be distinguished in comparison with the old one in a 2-dimensional (2-D) space. And also there is imperfection in 9-intersection model when we compute the topological relations between objects in our M^2 model. As the map objects are not all in 2-D space, in this paper we extend 9-intersection model by replacing the complements of spatial objects with their non-2-D features.

This paper is organized as follows. The framework for managing multi-levels road networks under distributed environment is presented in Section 2. Extended 9-intersection model for computing topological relations among road segments by "on the fly" is proposed in Section 3. Section 4 shows the prototype sytem, and our conclusion is given in Section 5.

2 Framework

2.1 M^2 map information model

The guideline that one map object is stored only into one corresponding dataset is the starting point of M^2 map information model. M^2 model (the definition in UML is given in Figure 1) gives a division method for countrywide map information. The model is formalized as two kinds of hierarchies: one is a directory tree, which is obtained by recursively decomposing map regions into a sequence of increasingly finer tessellations; and another is a theme tree, which consists of multi-level theme map datasets of regions, corresponding to the directory tree. As every map object is assigned to one corresponding dataset ("Section" in Figure 1), there is no overlap among these datasets: for a particular requirement, map information can be prepared dynamically by using generation functions. For instance, city-roads inside a city are stored in a city-level dataset, prefecture-roads inside a prefecture are stored in a prefecture-level dataset and country-roads are in a country-level dataset; to generate a city-level road map, we can combine the information of country and prefecture roads inside the corresponding regions managed in conutry-level and prefecture-level datasets with the city-level datasets.

2.2 Representation of road network

For road management, the management organizations are exactly corresponding to the region divi-

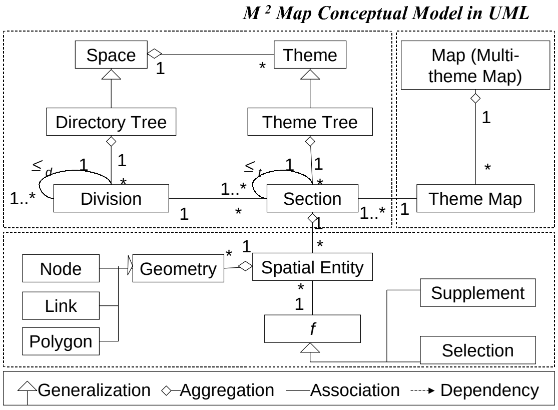

Figure 1: M^2 map information model in UML

sions in the hierarchy. The country-wide highways and country roads are managed by country-level organizations, prefecture roads are managed by organizations in every prefecture, and so on. Therefore, the levels of hierarchy can also be regarded as the important degrees of roads. Certainly, the important degrees of roads are not corresponded to kinds of roads absolutely: e.g., the highways inside a city may be managed by an organization of that city, and are regarded as city-level roads.

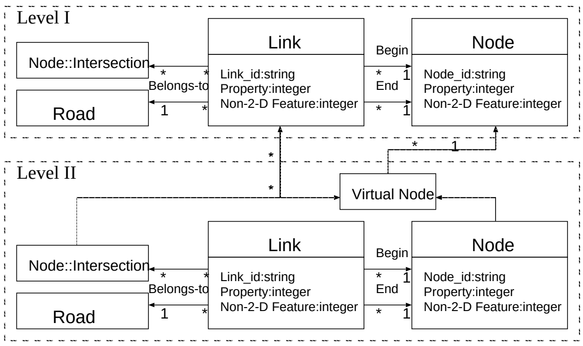

Figure 2: Schema diagram for road-datasets in multi-levels

Though the road network is managed in multiple levels, road segments are represented by nodes and links in every level. Figure 2 shows the schema diagram of road theme in two levels. There are two kinds of nodes: real node and virtual node. A real node is a spatial entity in M^2 model with point geometry and non-2-D feature and describes a point in the road network where traffic conditions change: e.g., a crossroad, a traffic circle, a toll, a dead end, an intersection with boundary line, or a point where some values of road attributes change. A node can delimit several road fragments; and each road fragment has only one begin-node and only one end-node. A virtual node is an object in the lower level without any of attribute values, but points out the corresponding real node in the upper level. To access a virtual node is actually to access a real node in the upper level. The definition of real and virtual nodes reduces the representation redundancy in the model.

The non-2-D features of node and link are used to signal the overpass, regular (on the ground) or underground feature of them by using an integer value. The feature of a regular node is 0, a node on the first level overpass is 1, on the second is 2, and on the undergrounds are minus ones. For a link, the non-2-D feature represents the road segment is overpass or underground.

3 Topological Relations

In M^2 model, to find out the topological relations between roads is corresponded to finding the logical relations between point-line and line-line. This is because all the road segments are represented by nodes (point in geometry) and links (line in geometry). At first we introduce 9-intersection method [5] for computing topological relations between point-line and line-line. However, only by 9-intersection method, we cannot compute out all the topological relations between objects with non-2-D feature directly. Therefore, we extend 9-intersection method.

3.1 Spatial relations defined by 9-intersection method

[**Definition** 9-intersection method]

Suppose A and B are two sets representing two entities. Then, the spatial relations between A and B can be described by values of 9-tuples as follows:

$$R_9(a,b) = \begin{pmatrix} A^0 \cap B^0 & A^0 \cap \partial B & A^0 \cap B^- \\ \partial A \cap B^0 & \partial A \cap \partial B & \partial A \cap B^- \\ A^- \cap B^0 & A^- \cap \partial B & A^- \cap B^- \end{pmatrix}$$

Here, A^0, ∂A and A^- mean the interior, boundary and exterior of A, respectively. The annotation for B is the same. This method indicates whether the values of 9-intersections are empty or not, and a

Table 1: Spatial relations defined by 9-intersection method(a)

A B Joint(point A, line B) $A \cap \partial B = -\Phi$	A B Inside(point A, line B) $A \cap B^0 = -\Phi$	B A Disjoint(point A, line B) $A \cap B^- = -\Phi$

Table 2: Spatial relations defined by 9-intersection method(b)

A B Disjoint(line A, line B) $\begin{pmatrix} \Phi & \Phi & -\Phi \\ \Phi & \Phi & -\Phi \\ -\Phi & -\Phi & -\Phi \end{pmatrix}$	A B Joint(line A, line B) $\begin{pmatrix} \Phi & \Phi & -\Phi \\ \Phi & -\Phi & -\Phi \\ -\Phi & -\Phi & -\Phi \end{pmatrix}$	A B Meet(line A, line B) $\begin{pmatrix} \Phi & \Phi & -\Phi \\ -\Phi & \Phi & -\Phi \\ -\Phi & -\Phi & -\Phi \end{pmatrix}$	A B Cross(line A, line B) $\begin{pmatrix} -\Phi & \Phi & -\Phi \\ \Phi & \Phi & -\Phi \\ -\Phi & -\Phi & -\Phi \end{pmatrix}$
A B Overlap(line A, line B) $\begin{pmatrix} -\Phi & -\Phi & -\Phi \\ -\Phi & \Phi & -\Phi \\ -\Phi & -\Phi & -\Phi \end{pmatrix}$	A B Equal(line A, line B) $\begin{pmatrix} -\Phi & \Phi & \Phi \\ \Phi & -\Phi & \Phi \\ \Phi & \Phi & -\Phi \end{pmatrix}$	A B Contains(line A, line B) $\begin{pmatrix} -\Phi & -\Phi & -\Phi \\ -\Phi & \Phi & -\Phi \\ \Phi & \Phi & -\Phi \end{pmatrix}$	A B Interior-joint(line A, line B) $\begin{pmatrix} -\Phi & -\Phi & -\Phi \\ -\Phi & -\Phi & -\Phi \\ \Phi & \Phi & -\Phi \end{pmatrix}$

range of binary spatial relations can be identified[6]. □

The spatial relations between point-line and line-line can be identified in 2-D space by 9-intersection method as shown in Table 1 and Table 2. Here, Φ means empty and $-\Phi$ means non-empty.

There are Joint, Inside and Disjoint relations between a point and a line, and there are Disjoint, Joint, Meet, Cross, Overlap, Equal, Contains and Interjoint relations between two lines. By using 9-intersection method, we can find out these topological relations for 2-D objects.

However, in the situation of road segments managed under our model, the topological relations are different to the ones of 2-D objects. The comparison is given in Table 3 and Table 4. From Table 3, we can observe that:

1) Joint relation between a point and a line in 2-D space may result in two possibilities: *Joint* and *Disjoint*. This is because when the point and the projection of the point on the line are not on the same 2-D space, the relation between the point and the line is *Disjoint*;

2) Inside relation is changed to *Inside* and *Disjoint* relations. *Disjoint* relation is found when the point and its projection on the line are not in the same 2-D space.

From Table 4, we observe the situations between two lines:

1) Joint and Interior-joint relations result in *Joint* or *Disjoint* relation and Equal relation results in *Equal*, *Joint* or *Disjoint* based on the nodes with the same projection on 2-D space are in the same 2-D space or not;

2) Meet, Cross, Contains and Overlap relations become *Disjoint* in the road situation based on the property of road segments under M^2 model;

3.2 Extension of 9-intersection Method

From the analysis of situations between objects in M^2 model, we can find out that all the topological relations between nodes and links under the model are not only determined by the interior and boundary of their geometries, but also based on the non-2-D features of them. Thus, we extend 9-intersection method to R_E(relations defined by the extended intersection method) by replacing the tuples conferring to exteriors with the tuples referring to non-2-D features:

1) Relation between point A and line B

$$R_E^1 = [\, A \cap B^0 \quad A \cap \partial B \quad A_p \cap S(\partial B)_p \,]$$

Here, A means a point A, and B means a line B. The first two intersections are computed based on the coordinates of the point and the

Table 3: Situations between point A and line B with non-2-D features

Relations Defined by 9-intersection Method	Situations in M^2 Model
Joint(point A, line B)	Place A is just one of two end-nodes of link B: *Joint*
	A and B are not in the same 2-D space: *Disjoint*.
Inside(point A, line B)	Place A is just on link B: *Inside*.
	A and B are not in the same 2-D space: *Disjoint*.
Disjoint(point A, line B)	Place A is not on link B: *Disjoint*.

Table 4: Situations between line A and line B with non-2-D features

Relations Defined by 9-intersection Method	Situations in M^2 Model
Joint(line A, line B)	Shared end(s) is(are) in the same 2-D space; really *Joint* or *Equal*.
or Equal(line A, line B)	It is *Disjoint*.
Interior-joint(line A, line B)	Shared end is in the same 2-D space: *Joint*.
	It is *Disjoint*
Meet(line A, line B) or Cross(line A, line B) or Contain(line A, line B) or Overlap(line A, line B)	To be changed into *Disjoint* in M^2 model, means A and B are not in the same 2-D space.
Disjoint(line A, line B)	There is no intersection between A and B: *Disjoint*.

line, just as 9-intersection model. As the coordinate value of a point (or end-points of a line) in M^2 model is the longitude and latitude of that point, so the coordinate value can be regarded as the projection of the point on the ground. $A \cap B^0$ means computing the intersection between the projections on the ground of point A and the interior (line B excepts its two end-points) of line B; $A \cap \partial B$ means computing the intersection between the projections on the ground of point A and the two end-points of line B. The third intersection is based on the non-2-D features of the point and the line. A_p is a set of non-2-D features of A: in the situation of point A, there is only one value in the set which represents the non-2-D feature of point A; $S(\partial B)_p$ is a set of non-2-D features of the projection of point A on line B. $A_p \cap S(\partial B)_p$ is used to decide whether A and its projection point on B are on the same 2-D space or not.

The relations between a point and a line with non-2-D features are given in Figure 3. The graphs in the first row illustrate the situations of *Joint*, *Inside* and *Disjoint* when the two objects are on the same 2-D space just as the situations in 9-intersection model. The second and third rows for *Joint* or *Inside* relation means that the two objects are not necessarily in the same 2-D space, but the projection of the point on the line and the point should be in the same 2-D space. Otherwise, the relations between them are *Disjoint*. For example, a point on the ground is not *Joint* to a line which is up or under the ground (represents overpass or underground road) except their intersection is on the ground. The *Disjoint* relation in Figure 3 illustrates that: there is an intersection point between point A and the projection line of line B on the ground, as the projection point of A on the line B is not on the same 2-D space; so, the relation between A and B is *Disjoint*.

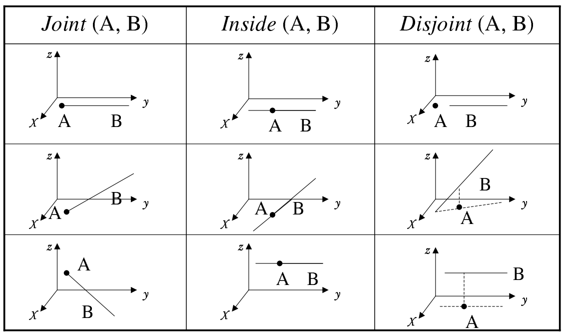

Figure 3: Spatial relations between point A and line B defined by extended 9-intersection method (a)

Relations between node A and link B with non-2-D features can be judged by the following equations (X means any value):

$$Joint(A,B) = [\Phi \quad -\Phi \quad -\Phi]$$

$$Inside(A,B) = [-\Phi \quad \Phi \quad -\Phi]$$

$$Disjoint(A,B) = [\Phi \quad \Phi \quad X] \cup [\Phi \quad -\Phi \quad \Phi] \cup [-\Phi \quad \Phi \quad \Phi]$$

2) Relation between line A and line B

$$R_E^2 = \begin{bmatrix} A^0 \cap B^0 & A^0 \cap \partial B & A_p^0 \cap B_p^0 \\ \partial A \cap B^0 & \partial A \cap \partial B & S(\partial A)_p \cap S(\partial B)_p \end{bmatrix}$$

Here, A means a line A, and B means a line B. The first two columns are the same as those in 9-intersection model. The third column is based on the non-2-D features of objects. A_p^0 is a set of non-2-D features of A; B_p^0 is that of B; and $A_p^0 \cap B_p^0$ is used to decide whether A and B are on the same 2-D space or not. If there is an intersection point between the two lines in 2-D space, $S(\partial A)_p$ means the non-2-D features of the projection point for the intersection in A, and $S(\partial B)_p$ is that in B. $S(\partial A)_p \cap S(\partial B)_p$ is used to decide whether the two projection points in A and B are on the same 2-D space or not.

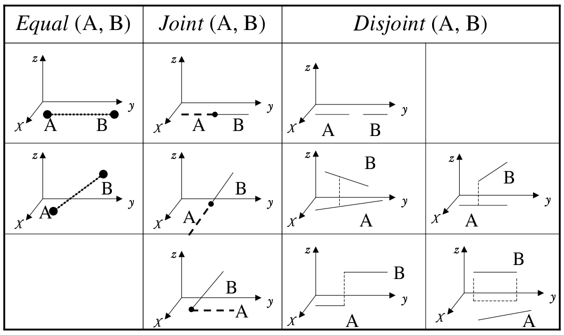

Figure 4: Spatial relations between line A and line B defined by extended 9-intersection method (b)

The relations between two lines with non-2-D features are given in Figure 4. The first row represents the situation that the two lines are on the same 2-D space; so the relations between them is the same as that in 9-intersection model. The second and third rows mean that the relations between two lines may be *Disjoint* even if the projections of them are Equal or Joint when the projection of the intersection point of the two lines are not in the same 2-D space. All these relations can be computed out by using the extended 9-intersection model directly.

Relations between line A and line B can be judged by the following equations:

$$Equal(A,B) = \begin{bmatrix} -\Phi & \Phi & -\Phi \\ \Phi & -\Phi & -\Phi \end{bmatrix}$$

$$Joint(A,B) = \begin{bmatrix} \Phi & \Phi & X \\ \Phi & -\Phi & -\Phi \end{bmatrix} \cup \begin{bmatrix} -\Phi & -\Phi & X \\ -\Phi & -\Phi & -\Phi \end{bmatrix}$$

$$Disjoint(A,B) = \begin{bmatrix} \Phi & \Phi & X \\ \Phi & \Phi & X \end{bmatrix} \cup \begin{bmatrix} -\Phi & \Phi & \Phi \\ \Phi & -\Phi & \Phi \end{bmatrix} \cup$$

$$\begin{bmatrix} \Phi & \Phi & X \\ \Phi & -\Phi & \Phi \end{bmatrix} \cup \begin{bmatrix} -\Phi & -\Phi & X \\ -\Phi & -\Phi & -\Phi \end{bmatrix} \cup \begin{bmatrix} \Phi & \Phi & X \\ \Phi & -\Phi & X \end{bmatrix} \cup$$

$$\begin{bmatrix} \Phi & \Phi & X \\ -\Phi & \Phi & X \end{bmatrix} \cup \begin{bmatrix} -\Phi & \Phi & X \\ \Phi & \Phi & X \end{bmatrix} \cup \begin{bmatrix} -\Phi & -\Phi & X \\ -\Phi & \Phi & X \end{bmatrix}$$

There are many kinds of *Disjoint* relations: e.g., a road segment of highway is "on the up" of a road segment of local routes. In a simple path query algorithm, there is no need to identify these, but it is helpful in heuristic path query algorithm.

4 Example

We have implemented our prototype system in Java for ensuring its portability over different platforms. The system manages road and architecture themes of nation, state and city levels, based on the maps of National, Aichi State and Ichinomiya City of Japan.

We stored highway and country road in the country-level (the first upper level), prefecture road and main local road in the prefecture-level (the second level), and city street in the city-level (the third level). The node stored in the upper level may be referred by the lower level through the pointer of a virtual node in the lower level. The system manages 32964, 2769 and 351 road segments at city-level, prefecture-level and country-level respectively.

The key role of query functions is to find out the topological relations between point-link and link-link. By using extended 9-intersection method, the algorithms for deciding the topological relations between point-link and link-link can be simplified to:

[**Algorithm 1** Find out topological relations between point A and link B]

Case

$[A \cap B^0 \quad A \cap \partial B \quad A_p \cap S(\partial B)_p]$

of

$[\Phi \quad -\Phi \quad -\Phi]$: $R_E^1(A,B) = Joint;$

$[-\Phi \quad \Phi \quad -\Phi]$: $R^1_E(A,B) = Inside$;

Otherwise: $R^1_E(A,B) = Disjoint$;

EndCase

[**Algorithm 2** Find out topological relations between link A and link B]

Case

$$\begin{bmatrix} A^0 \cap B^0 & A^0 \cap \partial B & A^0_p \cap B^0_p \\ \partial A \cap B^0 & \partial A \cap \partial B & S(\partial A)_p \cap S(\partial B)_p \end{bmatrix}$$

of

$$\begin{bmatrix} X & X & -\Phi \\ X & -\Phi & -\Phi \end{bmatrix} : R^2_E(A,B) = Equal;$$

$$\begin{bmatrix} X & X & \Phi \\ X & -\Phi & -\Phi \end{bmatrix} : R^2_E(A,B) = Joint;$$

Otherwise: $R^2_E(A,B) = Disjoint$;

EndCase

5 Conclusion

In order to represent map information of GIS smartly, we proposed M^2 map information model, in which map elements are composed as a hierarchical structure with multi-levels. The model is powerful to integrate various scales of maps uniformly in comparison with those in the traditional GIS. Because the map elements are uniquely assigned to a special level on a particular scale, the topological relations among them should be computed by " on the fly"; moreover, the map objects are not all on the same 2-D space. So, we extend 9-intersection method for the computation by adding intersections of non-2-D features, such as $A^0_p \cap B^0_p$ and $S(\partial A)_p \cap S(\partial B)_p$, and deleting intersections with exterior of entities. With the extended intersection method, we can find out the topological relations in our road network directly and easily. Furthermore, if the extended parts A^0_p and B^0_p are used to represent the class property of road segments, $S(\partial A)_p$ and $S(\partial B)_p$ are used to represent the class properties of shared nodes of them, respectively. The mothod helps to solve the path query problem referring to different road classes.

For our future work, the change of topological relations of objects among levels before and after map generation will be considered.

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