SPATIO-TEMPORAL MODELING IN ROAD NETWORK CHANGE DETECTION AND UPDATING

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ABSTRACT:

Automatic road map updating has been one of the difficult and important research topics in the community of geomatics. An operational road map updating system should include three key components: the generation of a new version of roads, the automatic road change detection/updating and the spatio-temporal modelling of road data. Special considerations have to be given to the spatio-temporal modelling of road networks, such as the decomposition of road attributes, the maintenance of road topological relationships, the choice of state-based or event-based modelling, etc. This paper presents a new spatio-temporal data model for road networks in which both the state and event information are integrated with road geometric and topological relationships. A prototype system for road map updating is developed based on the proposed data models. The system has demonstrated that it is necessary and possible to incorporate spatio-temporal modelling in a road network updating system.

1. INTRODUCTION

It is very important to keep the road network database up-to-date for many Geographical Information System (GIS) applications (e.g. urban planning, vehicle navigation, traffic management, emergency handling, etc). As Agouris *et al.* (2001) pointed out that rapidly changing environments, and the availability of consistently increasing amounts of diverse, multi-resolution datasets, bring forward the need for frequent revisions of modern GISs. However it is well known that the topographic map updating or the GIS database updating is a very tedious and time-consuming task [Fiset *et al.*, 1998] in a traditional manual process. Automation has been considered the most effective way to remove the obstacles of labor intensive manual processes and reduce the cost and shorten the turnaround time of spatial database updating [Hu and Tao, 2003].

In an operational system for road change detection and updating, the following processes have to be taken [Zhang and Couloigner, 2004].

1. Generation of a new version of road features through either automatic road extraction from remotely-sensed imagery or field surveying.
2. Road network change detection and updating, which may include [Auclair-Fortier *et al*., 2001; Baltsavias, 2004]:
    a) Elimination of roads which do not exist anymore;
    b) Updating of roads which have changed;
    c) Improvement and refinement of existing non-changed roads.
3. Spatio-temporal data modelling, i.e. to organize the change information of the road network in an efficient way to facilitate spatio-temporal queries and spatio-temporal analysis.

Both automatic road extraction and map updating and spatio-temporal GIS have been under research for more than twenty years now. There are a lot of new ideas and new approaches promoted in both areas [Hornsby and Egenhofer, 2000; Peuquet, 2001; Mena, 2003; Baltsavias, 2004]. However, most of the research is carried out separately and very few people are working on both problems simultaneously.

Since Langran's work (1992), temporal GIS (TGIS) has been popularly studied and several spatio-temporal models were proposed, such as snapshot model, attribute-labeling temporal model, and event-based modeling. Most of the existing models were designed for a specific application (e.g. land use [Langran, 1992], cadastral management [Chen and Jiang, 1998]). There are very few papers devoted to spatio-temporal modeling for road networks.

Agouris *et al*. (2000) presented a Spatio Temporal Gazetteer (STG) as a model that makes use of multiple information resources and, in particular, incorporates components to track changes to objects over time. This Gazetteer framework manages representations of instances of geographic entities and their changes over time rather than changes to layers or scenes. It allows them to organize geospatial information in an object-oriented manner that captures essential components of the spatiotemporal behaviour of objects. The STG has been used to model the change of man-made geographical features such as buildings.

A differential Snakes model for change detection in road segments was proposed by Agouris *et al.* (2001) and Mountrakis *et al.* (2002), by which a road feature can be detected as totally or partially changed. Based on this idea, a road feature can be decomposed into different parts with different timestamps. Such decomposition could be obtained easily using a Snakes model. If a road is detected unchanged, the whole feature can be stored with a single time stamp because the whole feature has the same temporal information.

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There is no need to decompose it. If the road is identified as partially changed, it has to be decomposed into different parts. The differential Snakes model combines the road extraction and change detection processes together. However, it does not take consideration of the spatio-temporal modelling of the road network.

From the perspective of spatio-temporal modelling, we would argue that the road network data have many different characteristics than that of land use data and cadastral data. Special care has to be given to modelling road network.

The main purpose of this research is to explore the key issues in updating a road database and to investigate how we can address these issues from an integral view of temporal GIS and change detection and map updating. A spatio-temporal data model for road networks is proposed and accordingly a prototype system based on the proposed data models is developed, in which both road network updating and spatio-temporal queries have been realized.

2. THE UNIQUENESS OF SPATIAO-TEMPORAL MODELING FOR ROAD NETWORK

A road network is unique in many aspects. Firstly, it has strong topological relationship, which makes the maintaining of the data consistency very difficult through the space and through the time domain.

Secondly, in cadastral management, the data is highly controlled by people. The events, such as land subdivision, are recorded timely, which is not the case for road networks. This is why an event-based data model [Chen and Jiang, 1998] is suitable for cadastral database management while it is not so attractive for road database. In addition, the updating of cadastral information can be only made on a case by case basis and batched updating is usually not desired. However, for road network, automatic road extraction has been under research for more than three decades and it is very possible and necessary to automate the map updating process.

Thirdly, a raster data model is not suitable for road network because the change of roads is discrete and the explicit representation of the topological relationship is demanded in a road database. Therefore most existing spatio-temporal data models are not useful for modelling the change information of roads. Moreover, special visualization techniques for representing change information have to be developed for road network.

Finally, it is difficult to relate the vertices in different versions of a road map, even though they may correspond to the same point in reality. This is because the different versions of a road network not only differ from each other in the temporal line, but also differ from the map production processing. Even if a specific road did not change during the time period under consideration, their geometric representation in the different versions may have discrepancy. We may have more vertices in one version and less in other, or we may have the same number of vertices but at different positions. However both versions are a valid representation from the perspective of surveying and mapping. What can be concluded is that it is not suitable to put time stamps in the vertex level.

In [Zhang and Couloigner, 2004] three modes for road database updating have been identified. They are:

1. Ground surveying, either by using a traditional method (total station, GPS) or by using a more automatic method (e.g. mobile mapping system).
2. Map comparison, i.e. use of a recent map to update the old road map.
3. Image-based road change detection and updating using new remotely-sensed imagery.

The first mode is currently most often used and it is supported by most of the commercial GIS software. The last two modes have been in practice for many years in a manual fashion. We still have a long way to go before any automated map comparison algorithm becomes operational.

As pointed out by Zhang and Couloigner (2004), all the three modes have their own strengths and weaknesses. It is desirable to have all the modes available in a road map updating system.

3. SPATIO-TEMPORAL MODELLING FOR ROAD NETWORK

Based on the above discussions, we propose the following data models to organize the spatio-temporal data of a road network.

3.1 Non-spatial attributes of the road features

Table *RoadAtt*

RoadID	Int(6)	Unique identity of the road
Name	Char(100)	Name of the road
Class	Int(4)	Class code
Width	Dbl(12.3)	Width
Pavement	Int(4)	Pavement type code
BeginTime	Date(8)	Begin time
EndTime	Date(8)	End time
EventID1	Int(6)	Pointer to the corresponding record in *RoadEvent* table describing the birth-event
EventID2	Int(6)	Pointer to the corresponding record in *RoadEvent* table describing the dead-event

3.2 Spatial attributes of the road features

Table *RoadGeo*

RoadID	Int(6)	Unique identity of the road
FromNodeID	Int(6)	The node ID of from-node
ToNodeID	Int(6)	The node ID of to-node
VertexNum	Int(4)	The number of the inner vertices
VertexIDList	Pointer(Var)	The list of the vertex ID
Length	Dbl(12.3)	Length
MinX	Dbl(12.3)	The information of MBR
MinY	Dbl(12.3)	
MaxX	Dbl(12.3)	
MaxY	Dbl(12.3)	
BeginTime	Date(8)	Begin time
EndTime	Date(8)	End time
EventID1	Int(6)	Pointer to the corresponding record in *RoadEvent* table describing the birth-event

EventID2	Int(6)	Pointer to the corresponding record in *RoadEvent* table describing the dead-event

3.3 Spatial attributes of the road node features

Table *RoadNode*

NodeID	Int(6)	Unique identity of the node
X	Dbl(12.3)	The X coordinate of the node
Y	Dbl(12.3)	The Y coordinate of the node
Z	Dbl(12.3)	The Z coordinate of the node
InArcNum	Int(4)	Number of arcs reaching the node
OutArcNum	Int(4)	Number of arcs exiting the node
TrafficCode	Int(4)	Traffic code of the node
BeginTime	Date(8)	Begin time
EndTime	Date(8)	End time
EventID1	Int(6)	Pointer to the corresponding record in *RoadNodeEvent* table describing the birth-event
EventID2	Int(6)	Pointer to the corresponding record in *RoadNodeEvent* table describing the dead-event

3.4 Spatial attributes of the road vertex features

Table *RoadVertex*

VertexID	Int(6)	Unique identity of the vertex
X	Dbl(12.3)	The X coordinate of the vertex
Y	Dbl(12.3)	The Y coordinate of the vertex
Z	Dbl(12.3)	The Z coordinate of the vertex

3.5 Road change event data

Table *RoadEvent*

EventID	Int(6)	Unique identity of the road event
RoadID	Int(6)	Unique identity of the involved road
EventTime	Date(8)	The time the event/change occurs
RecordTime	Date(8)	The record time, database time
ChangeType	Int(4)	The type code of the change 0---Add; 1---Delete; 2---Attribute change; 3---Geometric change
Description	Char(100)	The description of the event/change

3.6 Road node change event data

Table *RoadNodeEvent*

EventID	Int(6)	Unique identity of the node event
NodeID	Int(6)	Unique identity of the involved node
EventTime	Date(8)	The time the event/change occurs
RecordTime	Date(8)	The record time, database time
ChangeType	Int(4)	The type code of the change 0---Add; 1---Delete; 2---Attribute change; 3---Geometric change
Description	Char(100)	The description of the event/change

3.7 Summary of the spatio-temporal modeling for the road network

The relationships among the different tables are illustrated in Figure 1. The main features of the proposed spatio-temporal data models for the road network can be summarized as follows:

1. While the change information of a road line or/and a road node is recorded in the model, the change information of a vertex is discarded. Any change of an inner vertex, that should only be a geometric change, will be treated as a creation of a new inner vertex.
2. The time stamp is tagged at the feature level so that all the possible types of spatio-temporal changes to a road network can be tracked.
3. Although the model is generally a state-based approach, the event information is kept. This enables most of the change information of a road network, such as the change rate, change type or the most frequent change type, can be derived.
4. The topological relationship of a road network is preserved and well represented in the model.
5. Both spatial and temporal indexing approaches can be easily realized in this model.
6. Batched updating of road data is possible. This is important for a road map updating system.

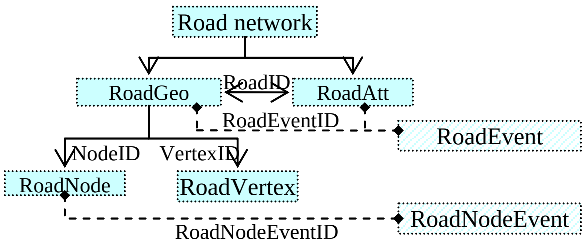

Figure 1 Spatio-temporal modelling for road network

4. STRATEGIES FOR ROAD MAP UPDATING

Each spatio-temporal data model has its own data updating strategy because the database updating operation is closely related to the data model used. In this section, we will discuss how the fundamental updating operations can be easily realized based on our spatio-temporal data models.

4.1 Non-spatial attribute change

If a non-spatial attribute change only occurs, the *EndTime* attribute of the specified record will be modified to the current time. A new record with the same *RoadID* but with some new attribute values needs then to be created, with the *BeginTime* set to the current time. All these operations are performed in the same table (Table *RoadAtt*). The last thing to do is to add an event record in the Table *RoadEvent* to record the change information.

4.2 Spatial Change

If some geometric attributes change, we have to analyse the change in more details. Usually, changes in either the nodes or the vertices will change some geometric-related attributes at the same time, which are stored in Table *RoadGeo*. Some updating operations in Table *RoadGeo* should be performed when geometric changes occur.

4.2.1 Add a road

If a new road is detected, we should add the information to all the tables through *RoadAtt* to *RoadNodeEvent*. It is trivial if the from-node and to-node are existing road nodes or if they have nothing to do with any existing road features. Complication may occur, however, when either the from-node or to-node is located at the same position of an existing vertex. In this case, a topologic change has to be recognized. For example, in Figure 2, the new road creates two new nodes, which split each of the two existing roads into two parts.

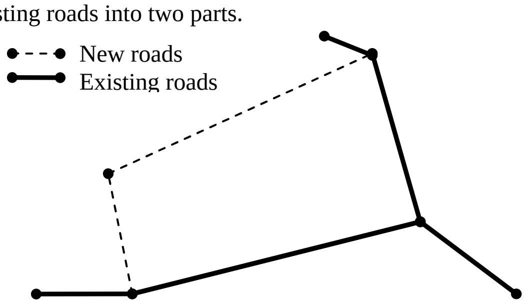

Figure 2 Adding a new road causes topologic change

The procedures to add a new road are listed in the following:

1. Select the new road feature to add.
2. For the from-node, and then for the to-node, of the new road:
   a) Check whether it is an existing node. If yes, go to step 3.
   b) Check whether it is an existing vertex. If no, add the new node record to Table *RoadNode*.
   c) Get the *RoadID* and *VertexIndex* of which the new node locates.
   d) Tag the corresponding road record in Table *RoadAtt* and Table *RoadGeo* into a dead state, i.e. the *EndTime* set to current working time.
   e) Split the road into two parts and create two new records in both Table *RoadAtt* and Table *RoadGeo*. Some of the attributes can be propagated from the old road (e.g. *Name*, *Class*). Others must be recalculated (e.g. *Length*).
   f) Record the change information in Table *RoadEvent*.
3. Add a new road record in both Table *RoadAtt* and Table *RoadGeo* with the corresponding attribute values.
4. Add a road event record in the Table *RoadEvent* with the proper attribute values, such as *ChangeType* =CHANGE_ADD, Description="A new road was added".

In the above procedures, the lineage information of the involved road has not been taken into account, which makes a question like "which road is the precedent of the new sub-roads created in the splitting operation?" difficult to be answered. This problem can be addressed either by adding some additional attributes in the Table *RoadEvent* or by overlaying the current road network with the preceding road network to find which road(s) occupies the same spatial region.

4.2.2 Delete a road

The procedures listed below are used for deleting an existing road.

1. Select the road feature to be deleted;
2. Find the corresponding records in both Table *RoadAtt* and Table *RoadGeo*, change the *EndTime* to the current working time.
3. Add a road event record in the Table *RoadEvent* with the proper attribute values.
4. Check whether the from-node or the to-node of the deleted road becomes an isolated node. If this is the case, change the *EndTime* value of the corresponding node record in the Table *RoadNode* to the current working time. Add a node event record in the Table *RoadNodeEvent* to record the change information.

4.2.3 Reshape a road

There are several cases in reshaping a road.

1. Node repositioning
   If a node was repositioned to a new place, the *EndTime* value is first changed to the current working time in the Table *RoadNode*. Then, in the same table, a new node record is created with new position information, i.e. the x, y and z coordinates. Some extra modifications need to be done because moving a node will cause value changes in the geometric-related attributes (e.g. *Length*) of the connected roads. So the Table *RoadGeo* need to be searched to find all the roads connected to the node and to update the affected attributes.

2. Inner vertex deletion/insertion/repositioning
   As stated in the previous section, the change information of an inner vertex is discarded in our proposed spatio-temporal data models. So any repositioning in inner vertices will result in a creation of new vertices and a deletion of the old vertices. In all cases, some changes in the Table *RoadVertex* will occur to record the change information for the related vertices. At the same time, the geometric attributes of the corresponding road should be also updated. This is easy because this will not result in a topologic change.

5. STRATEGIES FOR ROAD SPATIO-TEMPORAL QUERY

The key element of a Temporal GIS is that it possesses the capability to answer both spatial and spatio-temporal queries.

5.1 Snapshot-based query

A snapshot-based query is also called a state-based query. It is simple for the system to answer questions such as "*what did the road network look like in 1996?*" based on the proposed data models. The procedures to answer can be described as follow:

1. Input the query time (T_w).
2. From Table *RoadGeo*, find all the road records that were active at the time T_w.
3. For each of the resulting roads,
   a) Create a polyline with the corresponding nodes and vertices;

b) Get the corresponding non-spatial attributes in the Table *RoadAtt*;

c) Create a feature with the proper attribute values.

d) Add the feature to a layer.

4. Display the snapshot of the road network.

5.2 Change-based query

Obtaining an answer from the system for a question such as "*what change happened to the road network or to a specified road in 1996?*" is more complicated. Because the differences information between any different states is not stored explicitly in the proposed data models, the change that occurred need to be determined in order to respond to this kind of queries. First of all the related records that have a *BeginTime* or an *EndTime* fallen within the time duration are retrieved in Table *RoadEvent*. Then the changes are determined for each of the events.

6. A PROTOTYPE SYSTEM FOR ROAD MAP UPDATING

6.1 Platform for implementation

There are several choices for the implementation of a road map updating system. These include 1) to use an Object-Oriented (OO) system (e.g. C++, Java); 2) to use the programming language of an existing commercial GIS (e.g. VBA in ARCGIS, Avenue in ARCVIEW, MapBasic in Mapinfo).

In this work, we choose the second method to implement a road map updating system based on the proposed spatio-temporal data model. ARCGIS VBA was chosen as the programming tool, in which we have defined the corresponding feature classes and implemented the basic operations of the data.

6.2 Main System functions

In the current implementation, the following three categories of functions have been realized: 1) data processing; 2) data updating; 3) spatio-temporal enquiry. Figure 3 shows the basic interface of the prototype system.

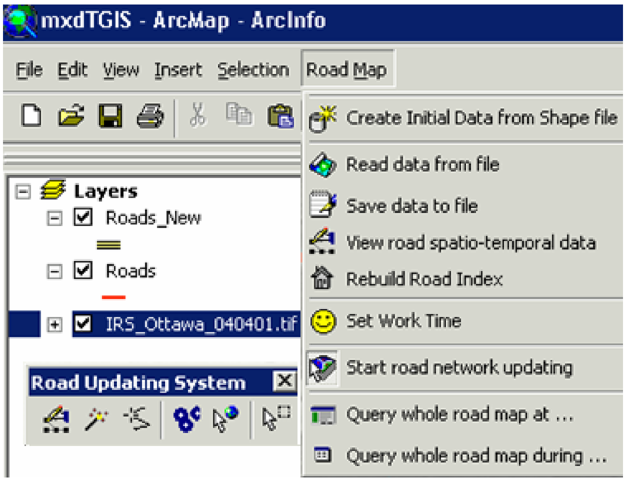

Figure 3 Main interface of the prototype system for road map updating

6.2.1 Data processing

Data processing functions have been designed for data preparation, system initialization, and data file manipulation. These include 1) Data set-up; 2) Saving data to files; 3) Reading data from files; and 4) Exploring data.

The *Data set-up* is an initial step of the Road Map Updating System. It is used to create the initial spatio-temporal data, usually from a base database or a base map. The initial road map is assumed to be stored in an ARCGIS recognizable spatial database (e.g. shape file or geodatabase). The user is required to select the database of the road base map and determine an initial time for the map. *Saving data to files* and *Reading data from files* allow a user to import/export the data to/from the system. *Exploring data* is used to view all the data in the current system for data checking.

6.2.2 Data updating

In this category of functions, both non-spatial attribute changes and spatial changes have been realized. For the spatial changes, we have provided operations for 1) adding a new road; 2) deleting a non-existing data; and 3) reshaping a road. Figure 4 illustrates the operation of adding a new road.

To perform a new road addition, we assume that the new road is stored in a specific layer after a manual or an automatic detection. The user selects the new road feature by a simple mouse-click. The system will automatically update the whole road network according to the algorithm described in Section 4. To delete an existing road, the user can use the date manipulation tools to display the current state of the road map first (Figure 5) and select the road feature to be deleted.

Figure 4 Adding a new road: the old road map (top) and the new road map (bottom)

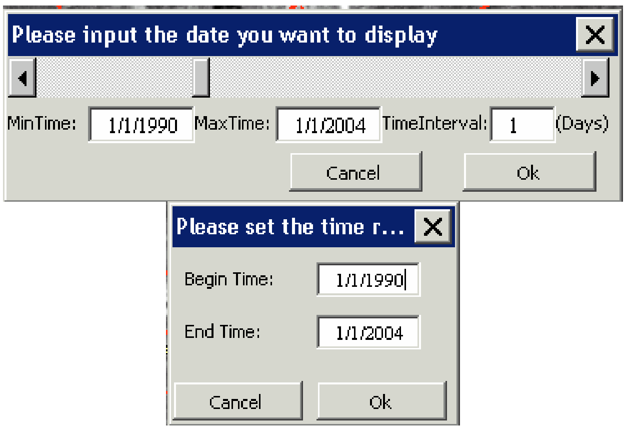

Figure 5 Time setting tools

Reshaping a road requires both the former road map and the new road map resulting usually from an automatic road extraction from imagery, to be displayed in the screen. The user selects the road to be reshaped on the old map and then select the road of the new version on the new road map.

6.2.3 Spatio-temporal query

In this category of functions, we have realized two types of queries: 1) Snapshot-based query; 2) Change-based query.

For snapshot-based query, the only required input is to specify the query time using the time setting tools shown in Figure 4. The system will display the resulting road map according to the query time. The change-based query is more complicated. In the current system, the following sample questions are the only ones accepted:

1. In which region the road network has the most frequent change during T_1 to T_2?
2. Which road has changed geometrically during T_1 to T_2 in a specified region?
3. Which type of change occurs most often during T_1 to T_2?

Figure 6 is a screen shot of the output of the spatio-temporal query "Which road was added during the time interval within the specified region?"

Figure 6 Output from a spatio-temporal query

7. CONCLUSIONS

Three key issues, namely road network generation, road change detection and updating, and road spatio-temporal modeling, have to be addressed before a road map updating system becomes operational. In this paper, a spatio-temporal model for road networks has been proposed. Accordingly a prototype system for road map updating has been implemented. The prototype system has demonstrated that it is necessary and possible to include spatio-temporal modeling in a road map updating system.

Many issues were still unsolved, e.g. the indexing methods based on both the spatial and temporal information; the visualization of the road network change over a certain period. Furthermore a road updating system should have the capability to determine the road change automatically through for example feature matching, not just by user interaction. This can be achieved by integrating map conflation techniques and will be our future work.

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