Discussion on Spatio-temporal Modeling

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Abstract: The temporal GIS data modeling methods are discussed in this paper. At first, two conceptual models of spatio-temporal data are introduced, and then some typical STDMs based on these two models are summed up and compared. After that, the spatio-temporal changes are analyzed thoroughly, and then how to model spatio-temporal data from different aspects is discussed. At last, several issues that need further research are pointed out.

Keywords: spatio-temporal data model, data model, GIS.

1. Introduction

It has been identified in GIS research society that the world we live is dynamic rather than static. As a result, in the studies of the real world, temporal GIS that include temporal data becomes equally significant as the spatial information system including spatial data. In general, a time-integrative or temporal GIS (TGIS) may be defined as an attempt to store and analyze spatial objects and changes in their attributes through time [1].

The capabilities of any information system largely rely on the design of its data models. Without well-designed data model, it will be ineffectual for a temporal GIS to implement temporal queries and temporal analysis.

Two conceptual models of spatio-temporal data (STD) are introduced in this paper, and then some typical spatio- temporal data models (STDMs) based on the two concept data models are summed up and compared. After that, based on the detailed analysis of spatio-temporal changes, how to build different views of STDM is discussed.

2. Conceptual STDMs

Generally, data model can be described from three hierarchies which are conceptual model, logical model and physical model. Conceptual STDMs of TGIS can be roughly classified into two categories, i.e. space-time cube models and time-slice models [2].

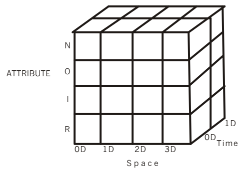

Fig.1 Multidimensional cube of space, time, and attribute [3]

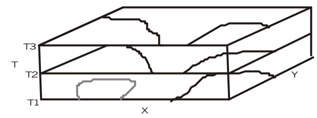

Fig.2 Time slice [4]

Space-time cube model (Fig.1) is based on object, the essential of which is to treat time axis and space axis coequally. That is to integrate time with the description of the entity rather than treat the time as an external tag. The real word object's history can be represented by tracking the 3D/4D objects. Spatial and temporal relations among spatio-temporal objects can be derived through applying set operators to their properties along different dimensions. Theoretically, space-time cube is the ideal model for integrating space and time. However, the GIS research society has developed mature methods only for modeling, analyzing and visualizing 2D spatial data.

Due to the difficulties in developing 3D/4D STDMs, time-slice model (Fig.2), which uses time slice to "flat" the 3D/4D space-time cube into 2D representation, is brought forward. Time slices in a layer oriented GIS environment is represented by a set of layers in which each layer contains spatial objects of the same category being valid at a given time interval.

3. STDM based on time-slice

1) Modeling from the view of space

The STD can be modeled from the view of space by extending either the traditional raster or vector data in time dimension.

1.1 Extension of the raster data structure

In snapshot model proposed by Armstrong [5], the time-slice is built by adding time information to each raster layer. Although this is the most direct and understandable way, but it has three disadvantages: (a) store the spatio-temporal data in a redundant way, (b) must manipulate each pixel in every time slice to get the change information, unable to give the exact time when any single change takes place.

1.2 Extension of the vector data structure

More methods have been tried to model STD using the time slices based on the vector layer. The most representative models include base-state with amendments, space-time composite, and the amendment vector method.

a) Base-state with amendments

In this model, the changes of entities and their topological information are recorded directly by special methods in which only the base-state at a particular time point and changes compared with the base-state are stored, rather than all information of each state[6]. With this method, the redundancy can be reduced and changes of an entity in its life span can be described, however, the spatial and temporal relationships of entities can not be represented directly. Moreover, it will get more difficult to maintain the topology relationships of the entities as the time goes and the changes increase.

b) Space-time composite

The space-time composite model is proposed by Christman in 1983[7], and Langran & Christman further described the model in detail in 1988[8]. Least common geometries (LCG) will be built if the consecutive overlay and intersection of all objects at all time steps when a change occurred have been done. When and which object each LCG belongs was recorded. In the space-time composite method, time-slice at each time step can be reconstructed by recombining the LCGs.

c) Amendment vector method

The amendment vector method ameliorated the space-time composite by putting time tag on smaller part, i.e. line-segments, instead of region objects used in the space-time composite model. If an existing line segment has to be altered when new border appears, only one relation should be added, which is the old line segment will be replaced by two new line segments. The advantage of this approach is that all objects used to build time slice may be retrieved from the system using relational structures [9]. The performance of such model will exceed the space-time composite method for less redundancy [10].

1.3 Summaries

When modeling STD from the space view, although information can be recorded by extending traditional spatial data structure, only simple query for location and object can be provided, and the deeper analysis in the time dimension such as analysis of temporal topology or the cause of an event can not be accomplished.

2) Modeling from the view of time

In computer communities, modeling temporal data is based on the concept of time sequence and time object. Using such concepts in GIS, spatio-temporal date model can be built from the view of time such as event-based STDMs proposed by Peuquet and Duan [11~12], in which the timestamps for any changes were recorded and associated details of each specific change was described in temporal order. The sequence of timestamps can thus be regarded as a timeline, and the new events that occur as time progresses are added to its end. The time line is compacted because the time points when no change occurs are not recorded. A similar model, with associated query operators, was described by Claramunt and Theriault [13~14].

Although ESTDM can support the query of space and time, but it mainly suit to describe the changes relating to a single thematic domain, the gradual change process of the object will be broken if a change occurs to a spatio-objects or topology relations.

4. STDM based on object

1) Spatio-temporal object model

The earliest STDM based on object is the spatio-temporal object model proposed by Worboy in 1992[15~16]. The spatio-temporal object model (STOM) represents the world as a set of discrete objects consisting of spatio-temporal atoms which are the largest homogeneous units with certain properties in both space and time, so STOM is able to record changes in attributes of an object in both spatial and temporal dimensions by projecting its atoms to the spatial and temporal space. However, gradual changes in space through time are unable to represent in STOM since the spatio-temporal atoms are discrete.

Raza and Kainz proposed a data model in 1999[17], which is an extension to Worboy's model using the OO methodology to separate out space, time and attributes conceptually, and consolidate them in a modular fashion as distinct elements.

2) Abstract data type (ADT)

In 1999, Erwig proposed a new line of research where moving points and moving regions are viewed as three- or higher-dimensional entities whose structure and behavior is captured by modeling them as ADT [18]. In contrast to Worboy's discrete STOM, Erwig focused upon the representation of spatial objects and their interrelations. Thus, in the representation discussed by Erwig, movement is explicitly stored as trajectory vectors in 3-D space for coherent objects. In the subsequent researches, models building upon ADT given in Erwig et al, Florizzi et al. described an implementation level representation for continuously moving objects, which are more specific and can be implemented in a temporal DBMS [19].

3) Others

Other than these abstract models, many researchers proposed modeling methods for specific applications. For example, Tryfona and Jensen propose an extension of the E-R technique, which they call STER (spatio-temporal ER)[20~21]. Yi et al. defined OPH model to represent the moving area object's spatiotemporal change series and its shape at various time [22].

5. Conclusion and future work

According to the above classification of the existing STDMs, a clear idea can be gotten on the modeling technologies of STD. From two aspects including world view and the types of spatiotemporal changes, the following conclusions can be given.

a) The world can be viewed in two ways that are field-based and feature-based view. According to the field-based view, individual entity are represented as attributes attached to a given field in space-time, while in feature-based view, every entity is an unit for representation, their spatial and temporal extents are denoted as attributes attached to these features. The STDM based on time slice has advantages at representation of the changes of the field for the reason that it can capture the status of field at a time point by snapshot, while space-time cube is based on object, so it satisfied the feature-based view.

b) According to their characters, the spatio-temporal changes can be classified as continuous changes and discrete changes. Most of the geographic changes are continuous, such as moving car, while there are still some discrete changes, such as cadastral change. Because the time slice is based on the concept of layers and time is just an external tag, it can not get the continuous changes without interpolation between statuses from two consecutive layers. Although the attribute data are obtained at discrete time point, a continuous track can be calculated according to the discrete points of an entity in the space-time cube when the STD was modeled based on object. Both the ADT defined by Erwig and OPH proposed by Yi give the methods to represent the continuous change of entities.

c) According to their contents, the changes can be classified as changes of shape and changes of location. The entities with positional change, such as moving cars, can be modeled based on discrete space-time cubes, while the entities with changes of shapes, such as rivers in flood and the land parcels, can be represented either in field-based view or in feature-based view. An appropriate way can be found in both of them. The STDMs become much more complex for the objects with motion as well as changes of shape, such as storm and wildfire. Yuan has done some researches for this kind of changes by defining a conceptual framework of three domain models including semantic domain, temporal domain and spatial domain [23~25].

The models summarized above can be very helpful for the future research; however, none of them can thoroughly resolve all spatio-temporal problems, there still are several problems need to study.

a) The advantage of STDMs based on object is obvious, however, we should pay attention to the fact that object-oriented database technologies are still in the status of research, and it will take a long period of time to apply OODBMS in GIS.

b) The second problem is that the geo-spatial uncertainties lead to the increasing complexity of STDMs. At present, rather little research has been done on uncertainties of STD, so we should resolve how to integrate the fuzzy and uncertainty concept in the spatio-temporal model and develop space-time query languages that can appropriately handle inexactness.

c) At last, when dealing with STD, large quantities of historic data will probably be faced. How to organize and store the large volume of data effectively is also a problem need to be resolved.

The solutions to these three problems may lead to essential revolution of GI science and technology and emergence of next generation of GIS.

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