A Fuzzy Spatiotemporal Data Model and Dynamic Query Operations

Vu Thi Hong Nhan, Sang Ho Kim, Keun Ho Ryu
Database Laboratory, Computer Science of ChungBuk National University
Cheongju, Chungbuk, 361-763, Korea
E-mail: {nhanvth, shkim, khryu}dblab.cbu.ac.kr

Abstract: There are no immutable phenomena in reality. A lot of applications are dealing with data characterized by spatial and temporal and/or uncertain features. Currently, there has no any data model accommodating enough those three elements of spatial objects to directly use in application systems. For such reasons, we introduce a fuzzy spatio-temporal data model (FSTDM) and a method of integrating temporal and fuzzy spatial operators in a unified manner to create fuzzy spatio-temporal (FST) operators. With these operators, complex query expression will become concise. Our research is feasible to apply to the management systems and query processor of natural resource data, weather information, graphic information, and so on.

Keywords: fuzzy regions, fuzzy set theory, spatio-temporal data modeling, fuzzy spatio-temporal query.

1. Introduction

Nowadays a lot of applications are dealing with non-standard data characterizing by spatial and temporal and/or uncertain features. Those types of data have an inner complex structure requiring sophisticated data representation and their operations necessitate sophisticated and efficient algorithms. In addition, spatio-temporal application need to model objects varying over. For such issues, it is necessary to model real-world phenomena not simply by crisply determined objects but rather through vague concepts that accommodating indeterminate boundaries and change over time.

Up until now, spatial modeling implicitly assumes that the extent. In practice, vagueness is ubiquitous in spatial and geographic concepts. In the GIS community, a number of models [2,3,5,7] have been proposed for spatial objects with indeterminate boundaries. But these models have not accommodated the time dimension of geographic data.

In this paper, we aim at spatial fuzziness that captures the property of spatial objects that do not have crisp boundaries. The goal is to introduce a fuzzy spatio-temporal data model for simple fuzzy regions based on fuzzy set theory. We apply existing models, the 9-intersection model [4] to approximately analyze the fuzzy spatial topological relations among them. We then provide a mechanism to integrate temporal and fuzzy spatial predicates into a unified manner such that support users with dynamic query operations.

The discussion of this paper is organized as follows. Some related works are showed in section 2. Section 3 presents the fuzzy spatio-temporal database model. The algorithm for FST operators is described in section 4. In section 5, an experimental result of query is displayed. Section 6 concludes the paper and gives future works.

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2. Related Work

This section describes some models for vague regions, a definition for simple fuzzy regions and fuzzy spatial topological predicates.

1) Models for Objects with Vague Boundaries

There exist a number of approaches to represent vague objects. Exact models [2,3,5] transfer type system for spatial objects with sharp boundaries to spatial objects with indeterminate boundaries. The approaches in [2,3] treat the indeterminate boundary as a thick boundary, thus finer distinctions between points lying within the thick boundary cannot be made [10]. The view of vague regions in [5] differentiates only between three parts. Therefore the original gradation in the membership values of the points of the boundary gets lost [7]. Recently, there has been an effort to incorporate uncertainty related with spatio-temporal data by using fuzzy logic [8].

2) Definition of Fuzzy Regions and Fuzzy Spatial Topological Predicates

A fuzzy region defined based on fuzzy set theory [6,9] is a collection of nested crisp α-cut regions. Let F be a fuzzy region, which is defined in two-dimensional space. The membership function of F is determined as $\mu_F: X\times Y \rightarrow [0,1]$.

An α-cut region F_α for an $\alpha\in[0,1]$ is represented as $F_\alpha=\{(x,y)\in IR^2 |\ \mu_F(x,y)\geq\alpha\}$. The fuzzy region F is defined as $F=\{F_{\alpha i}|1\leq i\leq\Lambda_F\}$ with $\alpha_i>\alpha_{i+1} \Rightarrow F_{\alpha i} \subseteq F_{\alpha i+1}$ for $1\leq i\leq|\Lambda_F|-1$ in which Λ_F is the level set $\alpha\in[0,1]$. A fuzzy region is a simple fuzzy region if and only if it is fully connected and convex. The core of a fuzzy region is the area in which each point has the membership function value of 1

Fuzzy topological predicates between two fuzzy regions is determined by computing the topological relations between two collections of α-cut regions. Let $\pi_f(P,S)$ be the value representing the topological relations between two fuzzy regions. It is determined by the following formula:

$$p_f(P,S)=\sum_{i=1}^{N}\sum_{j=1}^{N}(a_i-a_{i+1})(a_j-a_{j+1})p_{cr}(P_{a\,i},S_{aj})$$

in which N is the number of α-cut regions and $\pi_{cr}(P_{\alpha i},S_{\alpha j})$ is the topological predicates between two α-cut regions. It is calculated by using the 9-intersection model of topological relations between two simple regions with no holes. Values of the aggregated topological relations between P and S should fall into range [0,1]. By doing that, the set of eight fuzzy spatial topological predicates T_f={$disjoint_f$, $meet_f$, $overlap_f$, $covers_f$, coveredBy, $contains_f$, $inside_f$, $equal_f$} between two fuzzy regions is obtained.

3. The Data Model

This part describes the data model based on fuzzy set theory and a definition of fuzzy spatio-temporal database scheme based on the relational data model.

Geographic entities are represented as a set of locations in space-time with a set of properties characterizing locations. Entities are referred to real-world spatial objects. We examine objects in two-dimensional space. Space-time is represented in three-dimensional geographic space.

The thematic data is associated with geographic entities and characterizing them depends on the application domain. The application domain defines a set of l lexical values characterizing a phenomenon. Each individual entity, related to that phenomenon, is attached with l degrees of membership in the rage [0,1], one for each lexical value.

The data model can be as the following description. Map is a set of space-time cubes called thematic layers. Each thematic layer refers to a theme characterizing geographic entities. Each thematic layer consists of a set of space-time cubes called lexical layers. Each lexical layer accommodates the degree of membership (d.o.m) value of each space-time location in the lexical layer characterizing a theme.

Objects are identified from field observation data to tract the uncertainty propagation. Data are converted from field sampling to distinct objects through classification. The uncertainty transformation is discussed from the thematic data to geometric aspect of objects. Due to the vagueness of object class definition, each individual location P_{ij} will generate a membership value vector $[L(P_{ij},C_1), .., L(P_{ij},C_n)]^T$, $0\le L(P_{ij},C_k)\le 1$ after classification. Here $L(P_{ij},C_k)$ represents the membership function value of each individual location P_{ij} belonging class C_k, n is the total number of classes.

The extent of an object, all individual locations with: a d.o.m value within a specified range [a,b], geographic location within geographic space, and temporal location within temporal space constitute a space-time region. We then provide a varying number of α-cuts for each space-time regions called fuzzy spatio-temporal regions. Fuzzy spatial overlaps among objects are permitted, i.e. fuzzy regions may overlap. In the transition zones the individual locations might belong to multiple objects.

Definition: fuzzy spatio-temporal database scheme

The feature relation FRi' and the feature history relation FRi" for i^{th} layer, l^{th} lexical layer, describe a vector of spatial relation <fid,Density,f_1, ..,f_n,Geo_i> in which fid is used to distinguish objects; Density indicates the number of α-cuts of objects; f_1, ..,f_n are geometric elements describing the spatial extent of the objects; Geo_i identifies the actual shape and size of the object in a metric sense.

The attribute history relation ARi" for i^{th} layer presents an attribute vector of non-spatial data <fid,A_i,VT,prev>, where A_i is an attribute vector for the spatial object fid of the i^{th} layer <fid,a_1,a_2, ..,a_n>, a valid time vector VT=<VTs,VTe> denotes the beginning and the ending time of valid time and prev is an historical pointer of a feature in a relation. The attribute relation AR' for i^{th} relation is described by an attribute vector of non-spatial data <A_i,VTs,prev>. A merge relation MRi describes an historical pointer vector of merged objects, <hid,fid,VT> in which hid denotes the historical pointer of the spatial object determined by fid in the feature history relation. The merge relation MR_i stores only historical information of fuzzy spatial objects where merge relation occurs.

4. Algorithm of Fuzzy Spatitemporal Operators

FST operators are defined by combining temporal predicate and fuzzy spatial predicates into a unified manner.

Integrating temporal predicates into query language is to determine the temporal relationship between objects. The set of temporal predicates for time interval {before, equal,meets,overlaps,during,starts,finishes} are proposed and have proved to be complete. Their semantics expression is described in [1].

Fuzzy spatial predicates are employed in query language by embedding their linguistic description called quantified fuzzy spatial predicates. Each fuzzy quantifier is represented by an appropriate fuzzy set with a membership function μ_τ:[0,t]→[0,1]. Firstly, we define a classification for fuzzy quantifier: **Create** classification **ClassFQ**(*not,somewhat,quite,completely*); Then activate it: **Set** classification **ClassFQ**;.

FST operators are used in the 'where' clause of query statement. The below function FST_Opertors() defining FST operators firstly verify if the two fuzzy regions satisfy the temporal predicate Top. If the answer is yes, then continue to check if they satisfy quantified fuzzy spatial predicate Fq.Sop. This function returns a Boolean value *true* if both conditions are satisfied and *false* otherwise.

Function Boolean FST_Opertators(P, S, Fq, Sop, Top)

Input: Primary Fuzzy Relation (P), Secondary Fuzzy Relation (S), Fuzzy quantifier (Fq), Spatial opoperator (Sop), Temporal operator (Top)
Output: a Boolean value fst_predicate
Begin
fst_predidcate=false; //default
Step1: Check temporal condition
- Get time periods of the first region and the second (VTs,VTe) and (begin,end) respectively;
- Verify the temporal relation between the two fuzzy regions whether it satisfies the time condition Top by using the semantic expression in [1]

Step 2: Check quantified fuzzy spatial condition
If (the temporal condition is satisfied){
- Calculate the aggregated relation between two fuzzy regions P & S
- Let *result* be the calculated value of the aggregated relation between P& S

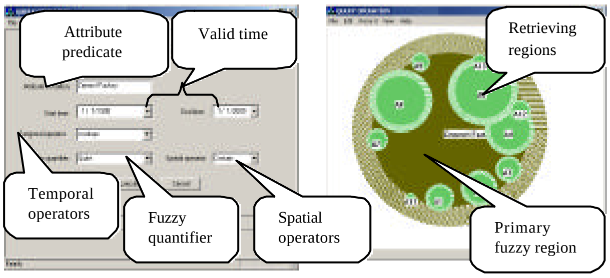
Repeat
Compute the spatial predicate Sop between two crisp α-cut regions $P_{\alpha i}$ $S_{\alpha j}$ respectively
Until (spatial relations between all α-cut regions are determined)} //endif
If (*result* satisfies the predefined value for Fq in the class **ClassFQ**) {fst_predicate=true;}
Return fst_predicate;
End

Assume that we have two relations. The first relation Pollution stores information about the factors causing pollution, the blurred geometry of polluted area as fuzzy regions. The other one Landuse which keeps information about the use of land areas whose vague spatial extent as fuzzy regions and valid time VT=(VTs,VTe). A query can be to find all land-used regions quite inside the polluted area caused by Cement Factory during years 1999-2000. To answer this query we apply the function FST_Operator().The land-used regions returned must be temporally *overlap* and spatially *quite contain*.

5. Experiment

We now carry out an experiment to demonstrate the methods presented in this paper. The methods are built to use in GIS. It is possible for the GIS to respond to various types of query, temporal query, fuzzy spatial query or FST query. In the experiment, we use only simple fuzzy regions with circular boundaries, the computational procedure can be extended easily to regions whose alpha-cut boundaries are arbitrarily shaped. Fuzzy quantifiers are defined as **ClassFQ**{not(0.0,0.05),somewhat(0.05,0.5),quite(0.5,0.8), completely(0.8,1.0)}.

Users enter conditions for searching features via a dialog window shown in fig.1(a). The conditions for fuzzy spatio-temporal query are as follows. Primary feature: a fuzzy region, the temporal relationship operator: overlap, time period '1/1/1990,1/1/2000', quantified fuzzy spatial predicate: Quite.Contain, and secondary feature: a set of fuzzy spatial regions. As a result, fuzzy spatial regions that satisfy temporally overlap the above time period and spatially quite overlap the primary feature are displayed in fig.1(b).



(a) An identify operation with fuzzy spatial and temporal topological conditions

(b) Result of query operation with fuzzy spatial and temporal topological conditions

Fig 1. Fuzzy spatiotemporal query

6. Conclusions

We have just proposed the fuzzy spatio-temporal data model accompanied with a definition of fuzzy spatio-temporal database scheme. It is based on fuzzy set theory. The algorithm for FST operators has also been described. We implemented a prototype. From the results of implementation we believe that our work useful and have practical significance. With the application of newly proposed operators, complex query expression will become concise. Our proposal is feasible to use in the management systems and query processor of natural resource data, weather information, geographic information and so on.

We are looking forward to creating a richer set of operations for geographic reasoning. We are also investigating fuzzy spatio-temporal join processing and query optimization.

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