Fuzzy Spatiotemporal Data Modeling Based on UML Class Diagrams: Postprint

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Abstract

Fuzziness is ubiquitous in spatiotemporal application domains, yet existing spatiotemporal data models lack the capability to describe and represent the intrinsic mechanisms and semantic relationships of fuzzy spatiotemporal objects. Through investigating the semantics of fuzzy spatiotemporal data, this paper presents a formal definition of the fuzzy spatiotemporal data model. On this basis, UML class diagrams are extended to propose a fuzzy spatiotemporal UML data model, and examples are provided to demonstrate the applicability of the proposed model.

Full Text

Preamble

Fuzzy Spatiotemporal Data Modeling with UML Class Diagram

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Abstract: Fuzziness widely exists in many spatiotemporal applications. Existing spatiotemporal data models lack the ability to describe and represent the internal mechanisms and semantic relationships of fuzzy spatiotemporal objects. This paper investigates the semantics of fuzzy spatiotemporal data and provides a formal definition of a fuzzy spatiotemporal data model. Based on this foundation, we extend the UML class diagram to propose a fuzzy spatiotemporal UML data model, demonstrating its applicability through illustrative examples.

Keywords: fuzzy spatiotemporal data; UML class diagram model; modeling

0 Introduction

Human beings inhabit a spatial world that dynamically evolves over time. Nearly every object, event, or phenomenon in the real world is associated with both time and space, giving rise to vast spatiotemporal application domains. Beyond typical applications such as urban transportation, cadastral management, and ecological monitoring, spatiotemporal research has recently expanded into numerous fields including biology, medicine, hydrology and meteorology, criminal investigation, smart homes, network communications, and big data analytics. The widespread application of computer technology in these domains, particularly the extensive use of GPS, GSM, Bluetooth, and RFID technologies, has generated massive volumes of spatiotemporal data. Consequently, the effective representation and processing of spatiotemporal data has become increasingly important and has attracted significant attention from researchers worldwide.

It should be noted that although various spatiotemporal data models have been developed, their capabilities for representing and processing spatiotemporal data still cannot fully meet practical application requirements. Existing models typically assume that spatiotemporal entities have precise boundaries and exact state descriptions, and that their positions and relationships can be accurately measured and defined. However, these assumptions are often difficult to satisfy in real-world applications. Due to measurement errors and the discretization of continuous motion, spatiotemporal information and the relationships among entities inherently contain fuzziness, which is recognized as an intrinsic characteristic of spatiotemporal applications.

To represent and process fuzzy spatiotemporal data, previous research has discussed fuzzy spatial entities and fuzzy topological relationships, proposing methods for representing fuzzy spatial data in fuzzy object-oriented databases and demonstrating simple query forms and execution processes through meteorological applications. From an object modeling perspective, some researchers have proposed fuzzy spatiotemporal conceptual data models based on UML class diagrams. However, these works primarily focus on fuzzy spatial entities and fuzzy topological relationships without adequately considering fuzzy temporal information, and the proposed fuzzy spatiotemporal UML data models do not support modeling complex semantic relationships among fuzzy spatiotemporal entities. To address fuzzy spatiotemporal data processing in Web environments, other researchers have proposed fuzzy spatiotemporal XML data models for representing both fuzzy spatial and fuzzy temporal data, along with definitions for simple node operations and topological relationship operations.

UML (Unified Modeling Language) is a widely accepted and used object-oriented modeling language that has found extensive application in many domains, including spatiotemporal applications. This paper proposes a fuzzy spatiotemporal UML data model by extending traditional UML class diagram models based on a thorough analysis of fuzzy spatiotemporal data semantics, demonstrating its applicability through examples.

1.1 Spatiotemporal Entities

Entities that change in spatial domains over time are called spatiotemporal entities. A spatiotemporal entity has an identity and contains attributes describing its characteristics. These attributes can be categorized as temporal attributes, spatial attributes, and non-spatiotemporal ordinary attributes. Based on whether the entity identity changes, two types of spatiotemporal changes can be identified: entity-level changes and attribute-level changes. Entity-level changes involve alterations to the spatiotemporal entity' s identity, such as splitting or merging, while attribute-level changes do not affect the entity' s identity but may modify its temporal, spatial, or ordinary attributes. Spatial attribute changes can be further classified into three forms: location-based changes, shape changes, and combined location/shape changes. This paper focuses on attribute-level spatiotemporal changes.

1.2 Fuzzy Spatiotemporal Entities and Attributes

Spatiotemporal entities contain temporal attributes, spatial attributes, and ordinary attributes. In practical applications, these attributes may contain fuzziness due to data acquisition or processing methods. Spatiotemporal entities with fuzzy attributes are called fuzzy spatiotemporal entities. For example, "high-speed moving tropical cyclone" is a fuzzy spatiotemporal entity because it contains the fuzzy attribute "high-speed moving." Depending on which attributes contain fuzziness, fuzzy spatiotemporal entities may include fuzzy spatial attributes, fuzzy temporal attributes, and fuzzy ordinary attributes.

1.2.1 Fuzzy Spatial Attributes

Fuzzy spatial attributes primarily involve fuzzy spatial data and fuzzy spatial relationships. Fuzzy spatial data can be further divided into fuzzy points, fuzzy lines, and fuzzy regions.

a) **Fuzzy Point:** A fuzzy point is a point with coordinate fuzziness in three-dimensional space, representing a location uncertainty. Formally, a fuzzy point is represented as Ãsp(x, y, z,), where x, y, z are the coordinates in three-dimensional space and represents the membership degree (0 1) of the point being located at (x, y, z). For example, the fuzzy point Ãsp(4, 6, 3, 0.4) indicates a possibility of 0.4 that the point is located at coordinates (4, 6, 3).

b) **Fuzzy Line:** A fuzzy line represents a collection of points between two possible endpoints. Formally, it is represented as Ãsl(x1, y1, z1, 1, x2, y2, z2, 2), where (x1, y1, z1) and (x2, y2, z2) are the coordinates of the two endpoints in three-dimensional space, and 1 and 2 represent the membership degrees (0 1 1, 0 2 1) of the endpoints being located at their respective coordinates.

c) **Fuzzy Region:** A fuzzy region refers to an area with fuzzy boundaries. This paper uses Minimum Bounding Rectangle (MBR) to represent regions with uncertain boundaries. Formally, a fuzzy region is represented as Ãsr(xmin, ymin, min, xmax, ymax, max), where (xmin, ymin) and (xmax, ymax) represent the minimum and maximum coordinates when projected onto the x and y axes, and min and max represent the membership degrees (0 min 1, 0 max 1) of points being located at (xmin, ymin) and (xmax, ymax).

[Figure 1: see original paper] provides a graphical illustration of these three types of fuzzy spatial data. The fuzziness of spatial data directly leads to fuzziness in spatial relationships. Let O1 and O2 be two fuzzy spatiotemporal entities; the fuzzy spatial topological relationship between O1 and O2 is represented as Ãs_topology(O1, O2,), where (f-disjoint, f-meet, f-overlap, f-equal, f-contain), representing fuzzy disjoint, fuzzy meet, fuzzy overlap, fuzzy equal, and fuzzy contain relationships, respectively. [Figure 2: see original paper] graphically illustrates the semantics of these five fuzzy spatial relationships, with black and gray ellipses representing two fuzzy spatiotemporal entities.

1.2.2 Fuzzy Temporal Attributes

Fuzzy temporal attributes include fuzzy temporal data and fuzzy temporal relationships. Fuzzy temporal data is further divided into fuzzy time points (e.g., "around 3:10") and fuzzy time intervals (e.g., "early morning").

a) **Fuzzy Time Point:** A fuzzy time point represents temporal fuzziness when a spatiotemporal entity occurs. Ãtp(t,) represents a fuzzy time point, where t denotes the time point and represents the possibility (0 1) that the time point is t.

b) **Fuzzy Time Interval:** A fuzzy time interval consists of two time points representing start and end times, where at least one is a fuzzy time point. Formally, Ãti(ts, s, te, e) represents a fuzzy time interval, where ts and te denote the start and end times, and s and e represent the fuzziness degrees (0 s 1, 0 e 1) of the start and end times being ts and te, respectively.

The fuzziness of time intervals leads to fuzziness in temporal topological relationships. Let t1 and t2 be two fuzzy time intervals; the fuzzy temporal topological relationship between them is represented as Ãt_topology(t1, t2,), where (f-before, f-after, f-equal, f-meet, f-overlap), representing fuzzy before, fuzzy after, fuzzy equal, fuzzy meet, and fuzzy overlap relationships. [Figure 3: see original paper] graphically illustrates the semantics of these five fuzzy temporal relationships.

1.2.3 Fuzzy Ordinary Attributes

Ordinary attributes are non-spatiotemporal attributes other than spatial and temporal attributes, such as the moving speed of a spatiotemporal entity. Taking the fuzzy spatiotemporal class “high-speed moving tropical cyclone” as an example, its “speed” is a fuzzy characteristic attribute. Ordinary attributes in spatiotemporal entities that can take fuzzy values are called fuzzy ordinary attributes, formally represented as $\tilde{A}c$.

1.3 Fuzzy Spatiotemporal Entity Semantic Relationships

Spatiotemporal entities in the real world do not exist in isolation. Beyond temporal and spatial topological relationships, complex semantic associations typically exist among them, such as generalization, aggregation, and association relationships. For fuzzy spatiotemporal entities, their inherent fuzziness leads to the existence of fuzzy generalization, fuzzy aggregation, and fuzzy association relationships.

1) **Fuzzy Spatiotemporal Generalization Relationship:** Spatiotemporal generalization represents classification relationships among spatiotemporal entities (i.e., superclass/subclass relationships). For example, tropical cyclones are superclasses of super typhoons, severe typhoons, and typhoons. When participating spatiotemporal entities are fuzzy, the relationship becomes a fuzzy spatiotemporal generalization relationship, representing fuzzy superclass/subclass relationships (e.g., the relationship between “high-speed moving tropical cyclone” and “super typhoon”).
2) **Fuzzy Spatiotemporal Aggregation Relationship:** Spatiotemporal aggregation represents whole-part relationships where component entities can exist independently of the whole. For example, a tropical cyclone consists of an eye, eyewall, and spiral rain bands. When component entities are fuzzy spatiotemporal entities, the relationship becomes a fuzzy spatiotemporal aggregation relationship, representing fuzzy whole-part relationships (e.g., “super typhoon” composed of eye, eyewall, and spiral rain bands).
3) **Fuzzy Spatiotemporal Association Relationship:** Association relationships link two spatiotemporal entities, connecting instances of one entity with instances of another. For example, the association between subtropical high pressure and tropical cyclones. When fuzzy spatiotemporal entities are associated, they form fuzzy spatiotemporal association relationships representing uncertain connections among fuzzy spatiotemporal classes.

1.4 Fuzzy Spatiotemporal Data Model

The representation and processing of fuzzy spatiotemporal entities require support from a fuzzy spatiotemporal data model. To represent the various forms of fuzzy data (both spatiotemporal and ordinary) discussed above, we present an abstract fuzzy spatiotemporal data model.

Definition 1. An abstract fuzzy spatiotemporal data model can be represented as a triple ˜ = (Ã, ˜, ˜), where:

a) Ã = (Ãsp, Ãsl, Ãsr, Ãs_topology, Ãtp, Ãti, Ãt_topology, Ãc) is a set of fuzzy attributes, where:

  - Ãsp = (x, y, z,) represents a fuzzy point
  - Ãsl = (x1, y1, z1, 1, x2, y2, z2, 2) represents a fuzzy line
  - Ãsr = (xmin, ymin, min, xmax, ymax, max) represents a fuzzy region
  - Ãs_topology = (O1, O2,) represents fuzzy spatial topological relationships ((f-disjoint, f-meet, f-overlap, f-equal, f-contain))
  - Ãtp = (t,) represents a fuzzy time point
  - Ãti = (ts, s, te, e) represents a fuzzy time interval
  - Ãt_topology = (t1, t2,) represents fuzzy temporal topological relationships ((f-before, f-after, f-equal, f-meet, f-overlap))
  - Ãc represents fuzzy ordinary attributes

b) ˜ = (˜ ,˜ , ···,˜) is a set of fuzzy spatiotemporal entity classes. Additionally, Õ(˜) denotes the set of fuzzy spatiotemporal entity instances in class ˜ , and Ã(˜) denotes the set of fuzzy attributes (including spatiotemporal and ordinary) constituting class ˜ .

c) ˜ = (˜ ,˜ ,˜) is a set of fuzzy spatiotemporal semantic relationships, where ˜ represents fuzzy spatiotemporal association relationships, ˜ represents fuzzy spatiotemporal generalization relationships, and ˜ represents fuzzy spatiotemporal aggregation relationships.

2 Fuzzy Spatiotemporal UML Class Diagram Model

For the abstract fuzzy spatiotemporal data model described above, we implement fuzzy spatiotemporal entity data modeling by extending the UML class diagram model. In this approach, (fuzzy) spatiotemporal entities are represented by classes in UML class diagrams, their spatial, temporal, and ordinary attributes are represented as class attributes, and semantic relationships among (fuzzy) spatiotemporal entities are represented by semantic relationships between classes.

2.1 Representation of Fuzzy Spatiotemporal Classes

In the UML class diagram model, fuzzy spatiotemporal entities are modeled as fuzzy spatiotemporal classes, with their attributes (including fuzzy spatial, fuzzy temporal, and fuzzy ordinary attributes) called fuzzy spatiotemporal class attributes.

The fuzziness of fuzzy spatiotemporal classes manifests in two aspects: a) The class contains fuzzy attributes (spatial, temporal, and/or characteristic attributes), where instances—spatiotemporal objects—may have fuzzy values for these attributes. b) There exists uncertain membership relationships between spatiotemporal objects (precise or fuzzy) and fuzzy spatiotemporal classes.

Following approaches similar to existing literature, we use dashed rectangular boxes to represent fuzzy spatiotemporal classes and add a special attribute with domain [0,1] to indicate the second aspect of fuzziness. For the first aspect, the method of prefixing fuzzy attributes with the keyword "Fuzzy" cannot be directly applied because fuzzy attributes may be spatial or temporal and should be treated differently. Based on the different forms of spatial attributes, we present representation methods for fuzzy spatiotemporal attributes in fuzzy spatiotemporal classes.

1) **Representation of Fuzzy Spatial Attributes:** As described in Section 1.2, fuzzy spatial attributes mainly include fuzzy points, fuzzy lines, and fuzzy regions, plus an additional form where the specific type (point, line, or region) is currently unknown. To explicitly represent these four categories, we use dashed circles with specific letters as markers in fuzzy spatiotemporal classes, as shown in Figure 4: see original paper. The letter "s" denotes unknown spatial attributes; "P" denotes point-type fuzzy spatial attributes; "L" denotes line-type fuzzy spatial attributes; and "R" denotes region-type fuzzy spatial attributes. These markers are placed after the corresponding spatial attributes to differentiate categories.

Figure 4: see original paper shows a fuzzy cadastral spatiotemporal class Cadastral, where the river shape attribute uses the "L"marker for fuzzy lines, cultivated land shape can use either "P" (fuzzy point) or "R" (fuzzy region), and unused land uses the unknown "s" marker.

2) **Representation of Fuzzy Temporal Attributes:** Fuzzy temporal attributes include fuzzy time points and fuzzy time intervals, plus a third form where the temporal attribute is currently unknown whether it represents a point or interval. To explicitly represent these three types, we use dashed circles with specific letters as markers, as shown in Figure 5: see original paper. The letter "t" denotes unknown temporal attributes; "P" denotes fuzzy point-time attributes; and "I" denotes fuzzy interval-time attributes. These markers are placed after the corresponding temporal attributes.

Figure 5: see original paper shows a fuzzy spatiotemporal class Typhoon, where start time uses the "P" marker for fuzzy time points, running time uses the "I" marker for fuzzy time intervals, and failure time uses the uncertain "t" marker when the specific dissolution time is unknown.

3) **Representation of Fuzzy Ordinary Attributes:** Fuzzy ordinary attributes are general attributes other than temporal and spatial attributes. Following existing approaches, fuzzy ordinary attributes in fuzzy spa-

tiotemporal classes can be marked by prefixing with the keyword “Fuzzy” .

[Figure 6: see original paper] shows a fuzzy spatiotemporal class Subtropical High describing subtropical high pressure, where the West-extending point attribute (a general attribute representing the ridge point index) can take fuzzy values and is prefixed with “Fuzzy” . Additionally, the class contains the special attribute to represent the membership degree of spatiotemporal objects belonging to the fuzzy spatiotemporal class.

2.2 Representation of Fuzzy Spatiotemporal Class Semantic Relationships

Semantic relationships among fuzzy spatiotemporal entities can be represented through semantic relationships between fuzzy spatiotemporal classes in UML class diagrams. The representations for fuzzy spatiotemporal association, generalization, and aggregation relationships are described below.

1) **Representation of Fuzzy Spatiotemporal Generalization Relationships:** A generalization relationship between two spatiotemporal classes indicates that one class provides a more general description of another, with the former called the superclass and the latter the subclass. If either the subclass or superclass is a fuzzy spatiotemporal class, the relationship becomes a fuzzy spatiotemporal generalization relationship, representing fuzzy superclass/subclass relationships. In UML class diagrams, we use dashed triangles to represent fuzzy spatiotemporal generalization relationships.

[Figure 7: see original paper] illustrates a fuzzy spatiotemporal generalization relationship where Super typhoon (a fuzzy spatiotemporal class with fuzzy temporal and ordinary attributes), Severe typhoon (a precise spatiotemporal class with fuzziness), and The typhoon (a fuzzy spatiotemporal class with fuzzy spatial and ordinary attributes) all have fuzzy generalization relationships with the Tropical Cyclone class.

2) **Representation of Fuzzy Spatiotemporal Aggregation Relationships:** Spatiotemporal aggregation represents whole-part relationships where component classes can exist independently of the whole. When component classes contain fuzzy spatiotemporal classes, the relationship becomes a fuzzy spatiotemporal aggregation relationship, representing fuzzy whole-part relationships. In UML class diagrams, we use dashed diamonds to represent fuzzy spatiotemporal aggregation relationships.

[Figure 8: see original paper] shows a fuzzy spatiotemporal aggregation relationship where the Tropical Cyclone class has a fuzzy whole-part relationship with the fuzzy spatiotemporal class TC eye, the precise spatiotemporal class TC eyewall, and the fuzzy spatiotemporal class Spiral rain band.

3) **Representation of Fuzzy Spatiotemporal Association Relationships:** Spatiotemporal classes can have association relationships. When associated classes contain fuzzy spatiotemporal classes, the association becomes a fuzzy spatiotemporal association. In UML class diagrams, we use dashed lines to represent fuzzy spatiotemporal associations.

[Figure 9: see original paper] shows a fuzzy spatiotemporal association relationship between the fuzzy spatiotemporal classes Subtropical High and Tropical Cyclone, representing the uncertain influence relationship where one subtropical high may affect multiple tropical cyclones (a 1-to-n association).

From the above description, it is evident that the fuzzy spatiotemporal UML class diagram model shares the same abstract structure as the classical UML class diagram model, with its modeling constructs representing an extension of the classical model' s expressive capabilities. A fuzzy spatiotemporal UML class diagram model can be transformed into a classical UML class diagram model when no uncertain or spatiotemporal information is present.

3 Application of the Fuzzy Spatiotemporal UML Class Diagram Model

This section demonstrates the applicability of the fuzzy spatiotemporal UML class diagram model through an example from meteorology. In meteorology, subtropical high pressure influences tropical cyclones, which primarily consist of three forms: super typhoons, severe typhoons, and typhoons. Super typhoons are further composed of three components: the eye, eyewall, and spiral rain bands. These meteorological phenomena undergo state changes (including spatial states) over time, making them spatiotemporal entities. Moreover, these entities may contain fuzziness in their internal spatiotemporal or ordinary attributes, and fuzzy relationships may exist among external spatiotemporal entities.

Based on the previously proposed fuzzy spatiotemporal classes, attributes, and relationships, we construct the fuzzy spatiotemporal UML data model shown in [Figure 10: see original paper]. This model contains eight spatiotemporal classes. The Area attribute in Subtropical High, Location attribute in The typhoon, and Location attribute in TC eye are fuzzy spatial attributes representing fuzzy spatiotemporal data. The Morning attribute in Super typhoon, Time attribute in TC eye, and Time attribute in Spiral rain band are fuzzy temporal attributes representing fuzzy spatiotemporal data. Additionally, the west-extending point attribute in Subtropical High, speed attribute in Super typhoon, speed attribute in The typhoon, and RMW attribute in Spiral rain band are fuzzy ordinary attributes.

The semantic relationships among these eight classes are also shown in [Figure 10: see original paper]. Subtropical High and Tropical Cyclone have a fuzzy spatiotemporal association relationship (influence). Tropical Cyclone has fuzzy generalization relationships with Super typhoon, Severe typhoon, and The typhoon. Super typhoon has a fuzzy aggregation relationship with TC eye, TC eyewall, and Spiral rain band. This fuzzy spatiotemporal UML data model effectively reflects the composition of fuzzy spatiotemporal data for tropical cyclone entities under the influence of subtropical high pressure.

4 Conclusion

This paper has focused on spatiotemporal data, discussing the semantics of fuzzy spatiotemporal data including fuzzy spatiotemporal entities, attributes, and semantic relationships. Building upon this foundation, we extended the UML class diagram model to propose a fuzzy spatiotemporal data model. This model accounts for information fuzziness while enhancing the description of fuzzy spatiotemporal semantic relationships, thereby providing model support for fuzzy spatiotemporal data operations and processing.

Spatiotemporal data exhibits high complexity, and UML class diagrams can clearly express relationships among spatiotemporal objects. The proposed fuzzy spatiotemporal UML class diagram model can intuitively describe the fuzzy spatiotemporal states of entities and complex semantic relationships among them at the conceptual abstraction level. However, the strength of the fuzzy spatiotemporal UML class diagram model does not lie in fuzzy spatiotemporal computation. Therefore, future research will focus on mapping the fuzzy spatiotemporal UML data model to fuzzy spatiotemporal databases to enable corresponding fuzzy spatiotemporal computation and storage (such as query processing), better meeting the needs of intelligent spatiotemporal analysis in application domains. Additionally, future work will conduct comparative analyses of the proposed model' s rationality and effectiveness through more application examples and experimental evaluation.

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