A SPATIAL-TEMPORAL DATA MODEL FOR MOVING AREA PHENOMENA*

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ABSTRACT
The spatial-temporal data model of moving object is a critical problem for spatial-temporal database, geographical information system, and multi-media information system. In this paper we give a spatial-temporal data model for moving area phenomena, named OPH model. In this model the feature of moving area object described by three sub-geometries, which are observation geometry of the moving area object, named O; currently present geometry of the moving area object, named P; and history geometry of the moving area object, named H. We give the definition of OPH, and than using the union, intersection, and difference of set theory to populate and update the value of OPH. We define the spatial-temporal topological relation between moving area object, then we give the spatial temporal operators and define trigger on OPH.

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1. Introduction
The researches of spatial-temporal data model include spatial geometry representation of variational spatial objects over time, spatial-temporal topological relation, and operation on them. In geographical information system (GIS), spatial phenomena (or object) usually be represented as vector graphics, such as point, line and polygon. The vector model can describe spatial distribution of spatial object, but could not represent evolution for spatial object over time. The information of spatial distribution and temporal evolvement of spatial object is useful for many fields, such as moving point object of vehicle, ship, and aero-plane, moving area object of land use, weather, urban growth, and area pollution. Currently the observation of remote sensing provides huge different temporal location data of spatial object. In order to apply different spatial and temporal data to resolve the problem of interaction between spatial processes, to reply the spatial-temporal query, we need to research and develop spatial-temporal data model for spatial database. This paper contributes to the research of spatial-temporal data model of moving area object.

There are many separate researches about spatial database and temporal database, these researches did not effectively combine spatial aspect and temporal aspect [Andrew Frank, 1999]. The literatures for dynamic spatial object include David J.Wilcox's Modeling Dynamic Polygon Objects [David J.Wilcox, 2000] which models dynamic polygon object, gives Spatial Temporal Graph Model (STGM) and its data structure. In the graph the node represents polygon, direction edge represents relation of polygon evolvement. In temporal aspect, this model only represents the change of whole polygon; does not represent the growth, surviving, and disappearance of polygon object, can not reply spatial-temporal query.

Donna J. Peugeot gave an event-based spatio-temporal data model (ESTDM) [Donna J. Peugeot 1995]. In this model the changed section of area object at an instant is regarded as an event, a series of changed sections of the object at different instants regarded as a list of events which recorded the changed value of object. The changed value is recorded by run-length-encoding. This model is based on raster model.

Kathleen Hornsby and Max J. Egenhofer gave the concept of identity-based change [ Kathleen Hornsby 2000]. They introduced existence object, non-existing object without history and non-existing object with history, and brought forward continue existence object, new created object, recalled object, destroyed object, etc. but they do not give the data model and data structure.

In this paper we consider area moving object (MO) in 2-dimension plan Euclid space, discuss dynamic change and history of the object, and give spatial-temporal data representation, spatial-temporal topological relation, and several operators.

2. The OPH model of area moving object
Area objects in 2-dimension space are represented as geometry polygon or geometry function in spatial database. We usually use polygon representing spatial irregular area object, and use geometry function (such as rectangle, circle, etc.) representing regular area object. We name all of them as spatial geometry.

We give the OPH model for area moving object. Where geometry O represents the observation geometry snapshot of area object at an instant, geometry P represents the sections of object which generated at past instant and continue existing at current instant, and geometry H represent the sections of object which existed during past period but did not existing at current instant.

2.1 Spatial and temporal representation of area object
We use Geometry representing spatial distribution of object.

A 2-dimension area object can be represented as:

\[ 2\text{Object}(\text{Geometry}); \]

Geometry = \( A_{\text{object}} \cup \text{Geometry}_\text{graphics} \).

We define interior point set of Geometry A as \( A^- \), boundary point set of Geometry A as \( A^\partial \).

The geometry of area object in spatial database is always closed, that is to say the geometry of an object includes its interior and its boundary. So we need to base on point set geometry of such union, intersection, and difference of two geometries, the result geometry must be closed. We can define the point based operation of two geometries. Give geometries A, B \( \in \text{2DObject} \) (Geometry), the difference, union, and intersection of A, B:

\[ \text{Difference: } A - B = \{ p | \text{p} \in A \text{ and } \text{p} \notin B \} \]
\[ \text{Union: } A + B = \{ p | \text{p} \in A \text{ or } \text{p} \in B \} \]
\[ \text{Intersection: } A \cap B = \{ p | \text{p} \in A \text{ and } \text{p} \in B \} \]

These operations will degenerate lower dimension geometry, such as swing point or swing edge, these degenerated geometries will be neglected in spatial database.

We use instant and period represent the temporal of area object. The instant is a point in time reference system. In life time of an object, the observation instant of the object can be represented as \( t_0, t_1, \ldots, t_n \). The period is closed section between two instant. Period = \( \{ t_i, t_{i+1} | t_i, t_{i+1} \in (t_0, t_1, \ldots, t_n) \text{ and } t_i < t_{i+1} \} \).

There are two kinds of change for area moving phenomena, one is continuous change which occurs during period, the other is discrete change which occurs at instant. We assume that the time interval of observation sampling on continuous change phenomena satisfies the rules which accord with dynamic change law of the phenomena.

The observation instant of moving area phenomena or object (MO) is represented as \( t_0, t_1, t_2, \ldots, t_n \), here \( t_0 \) is the first observation instant and \( t_n \) is the latest observation instant. The arbitrary instant between two neighboring observation instant \( t_i \) and \( t_{i+1} \) can be represented as \( t + \delta \), here \( \delta \) is an increment of time granularity in time reference system. The current instant \( c \) of area moving object is represent as latest observation instant \( t_n \) plus time increment \( \delta \), that is \( c = t_n + \delta \). In the next observation instant \( t_{n+1} \), the current instant \( c \) of phenomena will be updated. Before updating, the current instant \( c \) is replaced by \( c^* \), that is \( c^* = c = t_n + \delta \), then the current instant \( c \) is updated by \( c = t_n + 2\delta \).

For the spatial-temporal data representation of MO, we consider the area geometry status in different time, and use two types of geometry object to describe the MO:

- object1 (Geometry, instant) an observation snapshot of MO distribution in space at an instant.
- object2 (Geometry, period) the fact of MO existing on a period.

We use a series of geometry object with spatial geometry and time reference to represent moving object, that is using O, P, H to represent MO:

\[ \text{MO} = \{ (O, P, H) | O \in \text{object1} \wedge P \in \text{object2} \wedge H \in \text{object2} \} \]

2.2 The definition of OPH model

In order to represent the spatial and temporal geometry of MO, we define three kinds of geometry object, named OPH model. First is observation geometry snapshot of MO at an instant, represented as O. Second is geometry object part of MO which is formed at past instant and continues existing at current instant, represented as P. Third is the geometry object part of MO which is formatted at past instant and disappeared at latter instant, represented as H, that is the history of MO during a period. Using the observation geometries O at different observation instant, we can calculate and update P and H. Using the records of OPH, we can reappear spatial-temporal evolving of MO, reflect the developing process of MO, and execute spatial-temporal query, analysis of interaction and relationship between moving objects. Following we give the formal definition:

Definition 1: At observation instant \( t_i \), spatial observation geometry of moving object represented as \( O_{t_i} \), which is the snapshot of spatial distribution of MO. We named it observation geometry:

\[ O_{t_i} (\text{Geometry}, t_i) \in \text{object1} \]

Example 1: At instant \( t_0, t_1, t_2 \), observation geometry distributions of MO are \( O_{t_0}(\text{Geometry}, t_0) \)and \( O_{t_1}(\text{Geometry}, t_1) \), showed in Figure 1(a) and (b).

Definition 2: The geometry part of MO which appeared at instant \( t_i \) and continuously existing at current instant \( c \), defined as P. We named it present geometry:

\[ P_{t_i} (\text{Geometry}, t_i) \in \text{object2} \]

Example 2: The geometries which formed at instant \( t_0, t_1, t_2 \) and continue existing at current instant \( c \) are \( P_{t_0}(\text{Geometry}, t_0, c) \) and \( P_{t_1}(\text{Geometry}, t_1, c) \), showed in Figure 1(c).
Definition 3: The geometry part of MO which formed at \( t_0 \) and continues existing until \( t_1 \) disappeared after \( t_1 \), that is to say the part existed during period \([t_0, t_1]\) defined as \( H_{t_0} \), we named it history geometry:

\[ H_{t_0} (\text{Geometry}, t_0, t_1) \in \text{object2} \]

Example 3: the geometry which existed during period \([t_0, t_1]\) and became history after instant \( t_1 \) is \( H_{t_0}(\text{Geometry}, t_0, t_1) \), as showed in Figure 1(d).

So, a moving object comprises three parts:

\[ \text{MO}(O \cup \{ \text{Geometry}, t \, \cup \text{P}(\text{Geometry}, t_0, t_1, c) \cup H_{t_0}(\text{Geometry}, t_0, t_1) \}) \]

Here \( O \) \((\text{Geometry}, t_0)\) is the union of geometry observation snapshot at a series of instants \( \cup \text{P}(\text{Geometry}, t_0, t_1, c) \) is the union of geometry formed at previous instants and continue existing at current instant. \( \cup H_{t_0}(\text{Geometry}, t_0, t_1) \) is the union of geometry history during periods. The three parts of MO are represented as MO, \( O \), \( \text{P}(\text{Geometry}, t_0, t_1, c) \) and \( H_{t_0}(\text{Geometry}, t_0, t_1) \).

In the following calculation, we simplify replaced as \( O \), \( \text{P}(\text{Geometry}, t_0, t_1, c) \) and \( H_{t_0}(\text{Geometry}, t_0, t_1) \).

2.3 Calculating and updating OPH.

(a) At first observation instant \( t_0 \), the observation geometry of MO served as original condition, that is to say current instant \( c = t_0 \) we have \( P_{t_0} = O_{t_0} \) because there is only one observation instant, there is no new formed geometry and no disappeared, as history geometry. At instant \( t_0 \), MO represented as:

\[ \text{MO}(O_{t_0}(\text{Geometry}, t_0), P_{t_0}(\text{Geometry}, t_0, c) \cup O_{t_0}(\text{Geometry}, t_0)) \]

Here: \( P_{t_0}(\text{Geometry}, t_0, c) \) = \( O_{t_0}(\text{Geometry}, t_0) \).

(b) Next observation occurred at instant \( t_0 \), current instant \( c = t_0 \) is updated with \( t_1 + 5 \), and \( c = t_2 + 10 \), using the observation geometry \( O_{t_2} \) at instant \( t_2 \) to calculate \( P \) and \( H \).

(a) The geometry \( P_{t_1}(\text{Geometry}, t_1, c) \) that did not appear at instant \( t_0 \) but appeared at instant \( t_1 \) and continuously existing at current instant. That is to say \( P_{t_1} \) is the part of observation \( O_{t_0} \) which did not exist at instant \( t_0 \), calculating of \( P_{t_1} \) is the geometry point set difference of \( O_{t_0}(\text{Geometry}, t_0, c) \) and \( O_{t_0}(\text{Geometry}, t_0) \):

\[ P_{t_1}(\text{Geometry}, t_1, c) = O_{t_0}(\text{Geometry}, t_0, c) \cup P_{t_0}(\text{Geometry}, t_0, c) \]

(b) The history geometry that appeared at instant \( t_0 \) and disappeared at instant \( t_1 \) according to definition 3, which represented as \( H_{t_0}(\text{Geometry}, t_0, t_1) \). Calculating of \( H \) is the geometry point set difference of \( P_{t_1}(\text{Geometry}, t_1, c) \) and \( O_{t_0}(\text{Geometry}, t_0) \):

\[ H_{t_0}(\text{Geometry}, t_0, t_1) = P_{t_1}(\text{Geometry}, t_1, c) \cup O_{t_0}(\text{Geometry}, t_1, t_1) \]

(c) The part of geometry that appeared at instant \( t_0 \) and continuously existing at observation instant \( t_1 \), which actually is to update \( P_{t_0} \). Calculating is the geometry point set intersection of \( P_{t_1}(\text{Geometry}, t_1, c) \) and \( O_{t_0}(\text{Geometry}, t_1) \):

\[ P_{t_0}(\text{Geometry}, t_0, c) = P_{t_1}(\text{Geometry}, t_1, c) \cap O_{t_0}(\text{Geometry}, t_1) \]

Then at instant \( t_1 \), the moving object MO is represented as:

\[ \text{MO}(O_{t_1}(\text{Geometry}, t_1), P_{t_1}(\text{Geometry}, t_1, c) \cup H_{t_0}(\text{Geometry}, t_0, t_1)) \]

(3) Observation occurred at instant \( t_0 \), current instant is \( c = t_0 + 10 \), and \( c = t_0 + 15 \), the observation geometry of area object is \( O_{t_0}(\text{Geometry}, t_0) \), to calculate \( P \) and \( H \).

(a) The new part that appears at instant \( t_0 \) but did not appear at instant \( t_1 \) and \( t_1 \), and continuously exist at current instant, represented as \( P_{t_0}(\text{Geometry}, t_0, c) \) which is the geometry point set difference of \( O_{t_0}(\text{Geometry}, t_0) \) and \( P_{t_1}(\text{Geometry}, t_1, c) \):

\[ P_{t_0}(\text{Geometry}, t_0, c) = O_{t_0}(\text{Geometry}, t_0) \cup P_{t_1}(\text{Geometry}, t_1, c) \]

(b) The history geometries that appeared at instant \( t_0 \), \( t_1 \) but disappeared at instant \( t_1 \) represented as \( H_{t_0} \), \( H_{t_1} \), \( H_{t_2} \), \( H_{t_3} \) the calculation of them as:

\[ H_{t_0}(\text{Geometry}, t_0, t_1) = P_{t_0}(\text{Geometry}, t_0, c) \cup P_{t_1}(\text{Geometry}, t_1, c) \]

\[ H_{t_1}(\text{Geometry}, t_1, t_1) = P_{t_1}(\text{Geometry}, t_1, c) \cup P_{t_2}(\text{Geometry}, t_2, c) \]

\[ H_{t_2}(\text{Geometry}, t_2, t_2) = P_{t_2}(\text{Geometry}, t_2, c) \cup P_{t_3}(\text{Geometry}, t_3, c) \]

\[ H_{t_3}(\text{Geometry}, t_3, t_3) = P_{t_3}(\text{Geometry}, t_3, c) \cup O_{t_0}(\text{Geometry}, t_0) \]

(c) The geometry part that appears at instant \( t_0 \), \( t_1 \), \( t_2 \), \( t_3 \) but continuously exist at current instant, which is actually to update \( P_{t_0} \) to \( P_{t_1} \) to \( P_{t_2} \) to \( P_{t_3} \). The calculation of them:

\[ P_{t_0}(\text{Geometry}, t_0, c) = O_{t_0}(\text{Geometry}, t_0) \cup P_{t_1}(\text{Geometry}, t_1, c) \]

\[ P_{t_1}(\text{Geometry}, t_1, c) = O_{t_1}(\text{Geometry}, t_1) \cup P_{t_2}(\text{Geometry}, t_2, c) \]

\[ P_{t_2}(\text{Geometry}, t_2, c) = O_{t_2}(\text{Geometry}, t_2) \cup P_{t_3}(\text{Geometry}, t_3, c) \]

\[ P_{t_3}(\text{Geometry}, t_3, c) = O_{t_3}(\text{Geometry}, t_3) \cup O_{t_0}(\text{Geometry}, t_0) \]

At instant \( t_0 \), after calculating and updating OPH, MO is represented as:

\[ \text{MO}(\cup O_{t_0}(0, 1, \ldots, k) \cup H_{t_0}(\text{Geometry}, t_0, t_1), \cup P_{t_0}(\text{Geometry}, t_1, c)) \]

The steps of calculating and updating \( P \) and \( H \) at each instant are showed as in table 1.

At instant \( t_0 \), the number of geometry set operation is 2K-1.

2.4 Anti-calculation of O with P and H

The present geometry \( P \) and history geometry \( H \) of MO are calculated by observation geometry \( O \) of MO, so \( P \) and \( H \) have composite relationship with \( O \).

If current instant is \( t_0 \), the observation geometry \( O_{t_0} \) can be anti-calculation with \( P \).

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For arbitrary instant $t_k$, the observation geometry $O_{tk}$ can be anti-calculated with $P$ and $H$:

$$O_{tk} = \left( \bigcup_{i \in \{0,1,\ldots,n-k\}} P_i \right) \cap \left( \bigcup_{j \in \{0,1,\ldots,n-k\}} H_j \right)$$

3. Spatial-temporal topological model of MO based on consistent topological relation

According to the spatial topological model of Max J. Egenhofer (Max J. Egenhofer, 1991), we can define spatial topological relationship $\theta_x$ between two MOs. Given the boundary of area object geometry $A$ (such as observation geometry $O$, present geometry $P$, and history geometry $H$) as $\Delta A$, interior as $A^*$, the four intersection model which describe the spatial topological relationship of the two area objects $A$ and $B$ is:

$$\forall I = \begin{pmatrix}
\Delta A \cap \Delta B & \Delta A \cap B^* \\
A^* \cap \Delta B & A^* \cap B^*
\end{pmatrix}$$

If the element is true in the above matrix, the value of it is 1, otherwise is 0. The model describes eight kinds of spatial topological relationship $\theta_x$:

<table>
<thead>
<tr>
<th>$\theta_{s1}$</th>
<th>$\theta_{s2}$</th>
<th>$\theta_{s3}$</th>
<th>$\theta_{s4}$</th>
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<tr>
<td>0 0 0 0</td>
<td>1 0 1 1</td>
<td>1 1 1 0</td>
<td>0 1 0 1</td>
</tr>
</tbody>
</table>

- disjoint
- meet
- overlap
- equal

<table>
<thead>
<tr>
<th>$\theta_{s5}$</th>
<th>$\theta_{s6}$</th>
<th>$\theta_{s7}$</th>
<th>$\theta_{s8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 1 1</td>
<td>0 0 1 0</td>
<td>0 1 0 1</td>
<td>1 1 1 1</td>
</tr>
</tbody>
</table>

- inside
- contains
- covers
- covered-by

The temporal relations of two area objects have thirteen cases according to Allen’s event based time relation (Allen J.F., 1983, ISO/TC211 1998).

The survival temporal period of area object is represented as $[t_L, t_U]$. Given the appearing or start instant $t_L$ of $A$ as $A_L$, the disappeared or end instant $t_U$ of $A$ as $A_E$, the temporal relation $\theta_x$ of area object $A$ and $B$ is shown as Table 2.

During their evolving process, the spatial topological relation of the two moving object is diverse. The change of the spatial topological relation between two moving object at different instant or in different period reflects the interaction of two moving objects. But only the regular change of the spatial topological relation reflects significant interaction of two moving objects. We define the spatial topological relation that maintains consistent during their evolving as the significant relation; that is to say during the overlap period $[t_L, t_U]$ of evolving of two moving objects, the spatial topological relation of two moving objects maintains invariant. In temporal relation $\theta_x$, there are four relations, before, after, meets and meet-by, which have no overlap time period, other nine relations have overlap time period.

We define spatial-temporal topological relation $\theta(x) = \theta_x \times \theta_t$ of two moving object based on consistent topological relation during their overlap time period as showed in Table 3.

Given two arbitrary instant $t_1$ which belong to the overlap time period, the spatial topological relation $\theta_{t_1}$ of observation geometry $O_{t_1}$ of $A$ and observation geometry $O_{t_1}$ of $B$ maintains invariant.

In this model, the query of spatial temporal topological relation of moving objects can be represented as: $A \theta_{t_1} B$ and $A \theta_{t_1} B$. For example:

- select A from MO where A during B and A inside B
In Table 2, the expression is \( t(A) > r(B) \) & \( t(A) = r(B) \) & \( D_{O_1} \cap D_{O_2} = 0 \) & \( D_{O_1} \cap D_{O_2} = 1 \) & \( D_{O_1} \cap D_{O_2} = 0 \) & \( D_{O_1} \cap D_{O_2} = 1 \). For the non-consistent topological relation of two objects, such as at instant \( t_1 \), the spatial topological relation of two objects is \( \theta_n \), and at instant \( t_5 \), the spatial topological relation of two objects is \( \theta_s \), but \( \theta_n \neq \theta_s \). In this case, the spatial temporal topological relation is diverse, we can build query express according to real cases.

<table>
<thead>
<tr>
<th>( \theta_{11} )</th>
<th>( \theta_{12} )</th>
<th>( \theta_{13} )</th>
<th>( \theta_{14} )</th>
<th>( \theta_{15} )</th>
<th>( \theta_{16} )</th>
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<tr>
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<td>after</td>
<td>meets</td>
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<td>during</td>
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</tr>
<tr>
<td>As=Bs &amp; Ae=Be</td>
<td>As&lt;Be</td>
<td>As&gt;Be</td>
<td>As=Bs</td>
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<thead>
<tr>
<th>( \theta_{18} ) starts</th>
<th>( \theta_{19} ) started-by</th>
<th>( \theta_{10} ) finishes</th>
<th>( \theta_{11} ) finished-by</th>
<th>( \theta_{12} ) overlaps</th>
<th>( \theta_{13} ) overlapped-by</th>
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<tr>
<td>As=Bs &amp; Ae&lt;Be</td>
<td>As=Bs &amp; Ae&gt;Be</td>
<td>As=Bs &amp; Ae=Be</td>
<td>As&lt;Bs &amp; Ae=Be</td>
<td>As&lt;Bs &amp; Ae&lt;Be</td>
<td>As&lt;Bs &amp; Ae&gt;Be</td>
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</tbody>
</table>

In Table 3, the spatial-temporal topological relation model based on consistent topological relation

4. Operation and query based on OPH model

We can query present and history of moving object using OPH model, calculate the moving speed, moving direction, affected range, and define the interaction (trigger) relation of two moving object.

4.1 Operation of MO

We define three operations of area moving object: moving speed, moving direction, and affected range.

The speed of moving object in period \( t_{i-1} \) \( t_i \) is defined as the distance of observation geometries of moving object at two instant divided by the length of time period.

\[ \text{Speed}(t_{i-1} \to t_i) = \frac{\text{Distance}(O_{i-1} \to O_{i})}{t_i - t_{i-1}} \]
The speed of moving object in period \( [t_{i-1}, t_i] \) is defined as the distance of observation geometries of moving object at two instant divided by the length of time period.

\[
\text{Speed}(t_{i-1}, t_i) = \text{Distance}(O_{t_i}, O_{t_{i-1}}) / (t_i - t_{i-1})
\]

The direction of moving object at two instant is defined as the difference of two center vectors of observation geometries.

\[
\text{Direction}(t_{i-1}, t_i) = \text{Center}(O_{t_i}) - \text{Center}(O_{t_{i-1}})
\]

Affected range of moving object is defined as the total coverage of the moving object in it's lifetime. That is the union of observation geometries at all instants.

\[
\text{Range}(t_{i-1}, t_i) = \bigcup \{O_t | t \in [0,1,..,n] \}
\]

4.2 Query

We can build spatial temporal query of area moving object using OPH model.

Example 4: find an area object A which continuously settle over area B and the length of settled time great timelength: select A from MO where (A inside B or A and B overlap or A, B equal B and c-t > timelength) or (A, B, inside or overlap or equal B and t-c > timelength)

4.3 Trigger

We can identify the moving area objects which satisfy an given condition using spatial temporal topological relation and operations. We define the interaction relation of area objects as trigger.

Example 5: define an trigger report on moving object A to illustrate that all object B occurred during period of A, occurred in area A, and their speed and direction are equal to A.

Define trigger event report

ON A

where B during A and inside A and B.speed = A.speed and B.direction = A. direction

DO report B is triggered by A.

Example 6: a moving rainfall strip A, define a trigger on A to report the area which has time of rainfall exceeding timelength

Define trigger action

On A

From A,P,Geometry, L,c

Where c,t,>timelength

Do Report area of A,P

5. Conclusion

The OPH model of area moving object has defined the observation geometry based spatial distribution of moving object with change over time, used intersection, union, and difference of geometry point set to calculate P and H. The model includes spatial distribution and time evolution of moving object, reflects the spatial temporal information about the generation, evolving, and disappearing of moving object. We defined the significative spatial temporal topological relation, and the spatial temporal operation, query, trigger.

Reference

Andrew Frank, Etc.1999. CHOROCHRONOS: A research Network for Spatiotemporal Database systems, SIGMOD Record, Vol.28, No.3, September 1999


