# A unified spatiotemporal schema for representing and querying moving features

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## Abstract

A conceptual schema is essentially required to effectively and efficiently manage and manipulate dynamically and continuously changing data and information of moving features. In the paper, spatiotemporal schema (STS) is proposed to describe characteristics of moving features and to efficiently manage moving features data, including the necessity aspects: abstract data types, dynamic attributes, spatiotemporal topological relationships and a minimum set of spatiotemporal operations. On the basis of the proposal of schema, spatiotemporal object-based class library (STOCL) is further developed for the implementation of STS, which allows development of various spatiotemporal queries and simulations. The conceptual schema and implemented object library are then applied to the development of passengers' movement simulation and pattern analysis in railway stations in Tokyo.

## 1. Introduction

Nowadays, management and manipulation of moving features (i.e. continuously time-evolving spatial objects) has become a reality and it is forecasted that applications on moving features will create an entire new class of applications and possible new massive markets thanks to the convergences of two technologies: (1) advances of powerful spatial data positioning and acquisition systems, and (2) development of fast reliable mobile computing and wireless communication networks. Along with this trend of technology push, application pull is also increasingly demanded in diverse domains that require behavior understanding, behavior forecast of moving features, such as Location-based Services (*l*-services), Intelligent Transportation Systems (ITS) and so forth. One of the core factors for this application paradigm shift is how to effectively and efficiently manage and manipulate dynamically and continuously changing data and information of moving features. Existing data models and access methods are not well equipped to satisfy with these new requirements due to their traditional management paradigm for static objects or discretely spatiotemporal objects, which always cause high computation cost to access between spatial data sets and temporal data sets.

Therefore, a conceptual schema is essentially required to describe such moving features by continuously spatiotemporal object in terms of integration of both spatial and temporal dimensions. Currently, main difficulties in moving features data modeling lie in the complexity of their components: space itself is complex, spatial attributes change values depending on specific locations, and also relationships among moving features are complicated (Pfoser and Tryfona 1998). Over the past years, the development of spatiotemporal data model has become an important research subject (Worboys 1994). Despite these efforts, research on the integration of spatial and temporal area has not yet met satisfactorily. There is currently no such integrated spatiotemporal schema for moving features. ISO/TC 211 International Standard (http://www.isotc211.org/) is preparing to standardize moving feature geometry in terms of a combination of spatial and temporal characteristics within the ISO 19141 (2004), however, new work items have not decided yet.

Our work aims at proposing a unified conceptual schema for spatiotemporal management and manipulation of moving features. Our approach supports a perspective of integration of space and time and of representation of continuous spatial changes. In the paper, spatiotemporal schema (STS) is proposed to represent characteristics of moving features and efficiently manage moving features data. Further, a spatiotemporal object-based class library (STOCL) is developed for the implementation of such schema, which allows development of various spatiotemporal queries and simulation on moving features.

The rest of the paper is organized as follows. Section 2 reviews the related work. Section 3 proposes STS. Section 4 presents STOCL object library. In section 5, the proposed approach and schema are applied to the implementation of passengers' movement simulation and pattern analysis in railway stations in Tokyo. Finally, conclusions and future work are presented in section 6.

## 2. Related works

Spatiotemporal data modeling for efficiently processing of moving features has received increased interests in the last few years. A number of papers in the recent VLDB, SIGMOD, EDBT etc. have been dedicated to the efficient management of moving objects. An overview on these works is omitted here due to space constraint. On the basis of existing research, our research work is mainly developed and improved as follows: (1) Representation of continuous changes of spatial objects over time; (2) Data abstract of dynamic characteristics; (3) Operations and their semantics of all data types, including changes in the size or shape of moving features; (4) Actual implementation on application system to support spatiotemporal reasoning.

## 3. Spatiotemporal schema

In the section, we propose an integrated framework of conceptual model for moving features, called spatiotemporal schema (STS), which provides a foundational abstraction for modeling moving features in space and time, attributes, their relationships, and their operations. The STS captures spatial and temporal aspects simultaneously, in particular, it provides the necessity aspects: (1) specification of abstract data types to support spatial data changing over time; (2) specification of dynamic attribute of moving features; (3) specification of topological relationship among moving features, and (4) a minimal set of spatiotemporal operations for query processing.

### *3.1 Abstract data type*

Different from static objects or discretely spatiotemporal objects, moving features (pedestrian, satellite, hurricane etc.) are referred to as continuous spatiotemporal objects, changing their positions, sizes or shapes over time continuously. Abstract data types are introduced to describe these features. The concept of spatial information and temporal information is combined by recording the spatial objects in time to get a new spatiotemporal concept. The types of moving features are viewed as mapping from time objects *t* into space objects *s*. In general, a type constructor $\tau$ is introduced which transforms the given data type *s* into type $\tau(s)$ with semantics:

$$\tau(s) = f : t \to s \qquad (1)$$

Spatial object models geometric data in spatial database system. Basic conceptual entities of spatial objects identified in spatial schema (ISO 19107 2000) are *GM_Primitive*, consisting in *GM_Point*, *GM_Curve*, G*M_Surface* and *GM_Solid*. On the other hand, temporal object describes the valid time dimension in temporal schema (ISO 19108 2000) which includes two types: *TM_Instant* and *TM_Period*.

According to (1), basic 9 abstract data types of moving feature are identified and defined in Table 1.

### *3.2 Dynamic attribute*

*Dynamic attribute* is referred as a kind of motion information whose value changes continuously as time evolves, without being explicitly updated. A higher data abstraction on dynamic attribute is represented as a nature attribute of moving feature, which is derived from the combination of spatial and temporal information, such as *speed*, *turn*, *acceleration*, *range* and *distance* as shown in Table 2.

**Table 1**. Abstract data types of moving feature

| Object type | Signature | Description |
|---|---|---|
| *ST_PointInstant* | *TM_Instant*→*GM_Point* | a moving point whose position is given at given time |
| *ST_CurveInstant* | *TM_Instant*→*GM_Curve* | a moving curve whose position is given at given time |
| *ST_SurfaceInstant* | *TM_Instant*→*GM_Surface* | a moving surface whose position is given at given time |
| *ST_SolidInstant* | *TM_Instant*→*GM_Solid* | a moving solid whose position is given at given time |
| *ST_PointPeriod* | *TM_Period*→*GM_Point* | a moving point whose positions change over time |
| *ST_CurvePeriod* | *TM_Period*→*GM_Curve* | a moving curve whose positions change over time |
| *ST_SurfacePeriod* | *TM_Period*→*GM_Surface* | a moving surface whose positions change over time |
| *ST_SolidPeriod* | *TM_Period*→*GM_Solid* | a moving solid whose positions change over time |
| *ST_ShapePeriod* | *TM_Period* → {*GM_Primitive*} | a moving shape whose positions change over time as well as size or shape |

**Table 2**. Dynamic attributes of moving feature

| Dynamic attribute | Signature | Description |
|---|---|---|
| *speed* | $\varsigma'(t) = \lim_{\Delta t \to 0} f_{distance}(\varsigma(t+\Delta t) - \varsigma(t)) / \Delta t$ | the fraction of traveled distance over time |
| *turn* | $\tau'(t) = \lim_{\Delta t \to 0} f_{direction}(\tau(t+\Delta t) - \tau(t)) / \Delta t$ | a vector difference between two positions |
| *acceleration* | $\alpha'(t) = \lim_{\Delta t \to 0}(\alpha(t+\Delta t) - \alpha(t)) / \Delta t$ | the acceleration of a moving point |
| *range* | $r(t_0, t_n) = \cup_{i \in \{0,1,\ldots n\}} p_i$ | the convex hull of trajectory |
| *distance* | $\delta(t) = \min\{\| p_1(t) - p_2(t) \|\}$ | the shortest distance between two points |

### *3.3 Spatiotemporal topological relationship*

Topological relationship among moving features is recognized to be valuable information about integration among the real-life entities in the real world. In accordance with their evolvement over time, changes of topology between any two moving features can be defined on pairs of their spatial relationship and temporal relationship. 8 spatial topological relationships are valid such as {*meet*, *disjoint*, *overlap*, *contains*, *inside*, *equal*, *covers*, *covered-by*}. Allen (1983) suggests 13 binary operators $\Theta t$ that define mutually exclusive relationships between time intervals {*equals*, *before*, *after*, *meets*, *met-by*, *during*, *contains*, *starts*, *started-by*, *finishes*, *finished-by*, *overlaps*, *overlapped-by*}. Spatiotemporal topological relationship can be defined as,

$$f : \Theta st \to \Theta s \times \Theta t = \{(s,t),\, s \in \Theta s,\, t \in \Theta t\} \qquad (2)$$

As far as temporal relationship $\Theta t$ is concerned, however, in the cases of *before*, *after*, *meets* and *met-by*, temporal overlap among moving features never occurs. Therefore, in the procedure of evolution of moving features, only definitions of topology upon the overlapped time period make sense. We define the spatiotemporal topological relationships in Table 3.

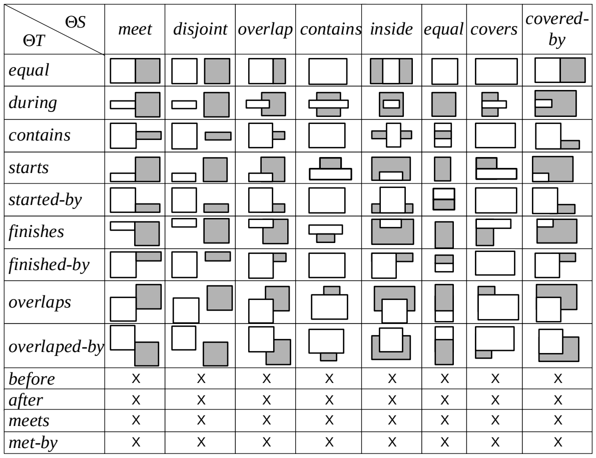
### *3.4 Spatiotemporal operation*

The spatiotemporal operations extend the spatial operations by adding a temporal dimension. We support a minimal set of spatiotemporal operations, including geometric-temporal operation, topological-temporal operation and dynamic attribute operation.

(1) The geometric-temporal operation

The geometric-temporal operation obtains the spatial representation of a moving feature $x$ at the specific time $t$ or projection onto the plane of a moving feature $x$ during time period $t_1$ to $t_2$. Also, it obtains the temporal representation of a moving feature $x$ at the specific position $p$ or during the trajectory $tr(p_1, p_2, \dots, p_n)$.

**Table 3.** The spatiotemporal topological relationships



| ΘS / ΘT | *meet* | *disjoint* | *overlap* | *contains* | *inside* | *equal* | *covers* | *covered-by* |
|---|---|---|---|---|---|---|---|---|
| *equal* | | | | | | | | |
| *during* | | | | | | | | |
| *contains* | | | | | | | | |
| *starts* | | | | | | | | |
| *started-by* | | | | | | | | |
| *finishes* | | | | | | | | |
| *finished-by* | | | | | | | | |
| *overlaps* | | | | | | | | |
| *overlaped-by* | | | | | | | | |
| *before* | x | x | x | x | x | x | x | x |
| *after* | x | x | x | x | x | x | x | x |
| *meets* | x | x | x | x | x | x | x | x |
| *met-by* | x | x | x | x | x | x | x | x |

**Table 4**. The geometric-temporal operations

| Operation | Signature | Description |
|---|---|---|
| *getPosition* | *TM_Instant→GM_Point* | Get spatial position at given time instant. |
| *getTrajectory* | *TM_Period→{GM_Point}* | Get trajectory at given time period. |
| *getTimeInstant* | *GM_Point→TM_Instant* | Get time value when position is given. |
| *getTimePeriod* | *{GM_Point}→TM_Period* | Get time period when trajectory is given. |
| *getShape* | *TM_Instant→GM_Primitive* | Get shape characteristics at given time instant. |
| *getShapeChange* | *TM_Period→{GM_Primitive}* | Get time period when process of shape changes is given. |

(2) The topological-temporal operation

The topological-temporal operation returns type of topological relationship or boolean value, which indicates whether there is a specific topological relationship between two features in the considered time. It also returns time value when a specific topological relationship between two features is given.

**Table 5**. The topological-temporal operations

| Operation | Signature | Description |
|---|---|---|
| *getRelationship* | *TM_Instant,GM_Primitive1, GM_Primitive2→ TP_Primitive* | Get types of topological relationship of two moving features at given time instant. |
| *getTimeInstant* | *TP_Primitive,GM_Primitive1, GM_Primitive2→TM_Instant* | Get time instant when topological relationship of two moving features is given. |

(3) The dynamic attribute operation

The dynamic attribute operation obtains motion information of a moving feature, including *speed*, *turn*, *velocity*, *range* and *distance* as defined in section 3.2.

**Table 6**. The dynamic attribute operations

| Operation | Signature | Description |
|---|---|---|
| *getSpeed* | *GM_Point,TM_Instant→real* | Get moving speed. |
| *getTurn* | *GM_Point,TM_Instant→real* | Get movement direction. |
| *getAcceleration* | *GM_Point,TM_Instant→real* | Get acceleration. |
| *getRange* | *{GM_Point}→ GM_Surface* | Get convex hull of trajectory. |
| *getDistance* | *GM_Point1, GM_Point2, TM_Instant→real* | Get distance between two moving features. |

## 4. Implementation of spatiotemporal schema

A three-level architecture is proposed in Figure 1 to implement STS, which consists of user interface, spatiotemporal database, spatiotemporal data processing, and visualization. They have their own features as follows respectively. (1) *Database level*. Spatiotemporal database stores and manages geometries data changing over time, which including spatial data, temporal data, spatiotemporal data and attribute. (2) *Model level*. It provides capabilities for storing, querying spatiotemporal data and performs spatiotemporal operations required to various spatiotemporal queries. For the purpose of visualization of query, trajectory construction and simulation is developed to simulate the trajectory movement and the whole process continuously. (3) *Application level*. Users can request their general queries using spatiotemporal database through user interface, and users can also obtain their results by user interface.

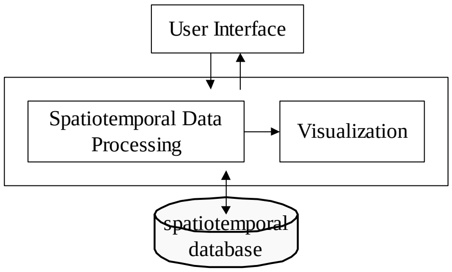


**Figure 1.** System architecture.

The implementation of the above framework is based on providing users with a kernel of class hierarchies. We implement a spatiotemporal object-based class library (STOCL), which packages all the capabilities we have discussed in the STS. Appendix shows UML representation of implementation of these functions.

## 5. Case study

We develop a prototype system about passengers' movement and pattern analysis in railway stations in Tokyo to evaluate the effectiveness of spatiotemporal data model of moving features we propose.

### *5.1 Experimental data*

In the case study, investigation data of 10,000 passengers' movement from JR East Japan Railway Company (2003) are used for the experimental data. The whole project was organized and conducted during September to November in 1998 to know personal movement characteristics and pattern everyday. The study area is located inside the range of approximately 70 square km in Tokyo. With the help of questionnaire surveys, information about personal travel behavior by railway is recorded. The whole samples are comprised 10,000 passengers with age ranging from 12 to 69 years. Table 7 gives some sample data of passengers' travel attributes.

**Table 7**. Samples of passengers' travel attributes

| Passenger id | Day | Line in | Station in | Time in | Line out | Station out | Time out |
|---|---|---|---|---|---|---|---|
| 4 | 7 | 55 | 25 | 12:30 | 55 | 780 | 12:35 |
| 4 | 7 | 55 | 780 | 16:50 | 55 | 25 | 16:55 |
| 8 | 3 | 56 | 1164 | 18:10 | 56 | 780 | 18:27 |
| 8 | 3 | 55 | 780 | 18:31 | 55 | 25 | 18:40 |
| 8 | 4 | 45 | 1611 | 13:50 | 45 | 780 | 13:55 |
| 8 | 4 | 45 | 780 | 14:58 | 45 | 1611 | 15:03 |
| 17 | 2 | 1 | 780 | 07:45 | 1 | 685 | 08:10 |
| 17 | 2 | 1 | 685 | 18:00 | 1 | 780 | 18:25 |
| 17 | 3 | 1 | 780 | 07:45 | 1 | 685 | 08:10 |
| 17 | 3 | 1 | 685 | 18:00 | 1 | 780 | 18:25 |
| 17 | 4 | 1 | 780 | 07:45 | 1 | 685 | 08:10 |
| 17 | 4 | 1 | 685 | 18:00 | 1 | 780 | 18:25 |
| 17 | 5 | 1 | 780 | 06:45 | 1 | 685 | 07:12 |
| 17 | 5 | 1 | 685 | 21:30 | 1 | 780 | 22:00 |
| 17 | 6 | 1 | 780 | 12:15 | 1 | 1225 | 12:20 |
| 17 | 6 | 1 | 1225 | 16:00 | 1 | 780 | 16:15 |
| ... | ... | ... | ... | ... | ... | ... | ... |

The object types, such as spatial, temporal and spatiotemporal object can be applied into DBMS data model as attribute data types. According to the original data and application requirements, some relations are organized as follows in which data types are integrated into the models.

- *station*(*s_id*: *integer*, *s_name*: *string*, *coordinate_x*: *GM_point*, *coordinate_y*: *GM_point*);
- *line* (*l_id*: *integer*, *l_name*: *string*);
- *line_to_station*(*l_id*: *integer*, *s_id*: *integer*);
- *passenger*(*p_id*: *integer*, *gender*: *integer*, *generation*: *integer*, *marriage*: *integer*, …);
- *route*(*p_id*: *integer*, *day*: *integer*, *line_in*: *ST_CurveInstant*, *station_in*: *ST_PointInstant*, *line_out*: *ST_CurveInstant*, *station_out*: *ST_PointInstant*)

### *5.2 Movement pattern query*

The proposed operations defined in 3.4 can be applied to the following queries and analysis on passengers' movement patterns (Xie 2003): (1) Personal trajectory simulation in one day; (2) Passengers' movement in specific station in one day; (3) Comparison of passengers' movement among stations; (4) Passengers' movement simulation on specific railway line; (5) Topological relationship among passengers.

### *5.3 Simulation result*

On the basis of the above various queries on movement pattern, visualization can be further implemented for the analysis of spatial behavioral pattern, such as distribution density of passengers, trajectory simulation of passengers' movement etc. Here, some examples are given. Figure 2 shows passengers' movement at various time series in Shinjuku station. Comparison results are given to show the flow density in Shinjuku station in the morning, afternoon and evening on Monday. Figure 3 represents snapshot of crowd situation and passenger density on Yamanote line at 8:30 am in the morning.

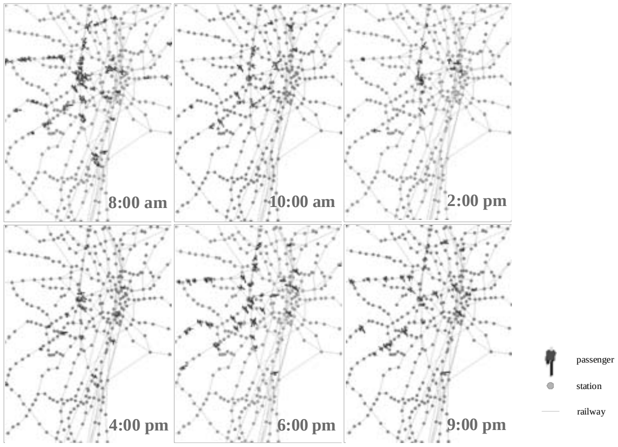
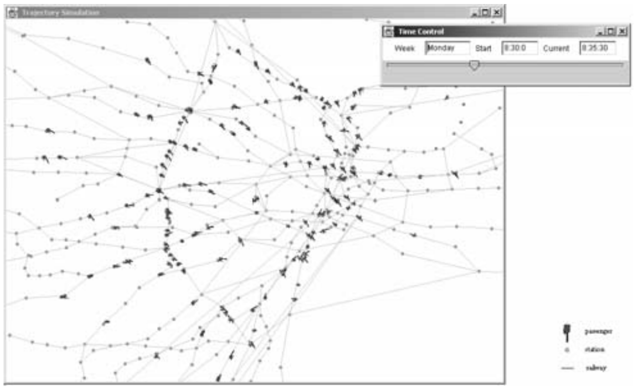


**Figure 2.** Passengers' movement simulation in JR Shinjuku station in one day.



Week Monday Start 8:30:0 Current 8:35:30

**Figure 3.** Snapshot of passengers' movement on JR Yamanote line.

## 6. Conclusions and further works

In our research, we support a unified perspective of integration of space and time and of representation of continuous spatial changes over time for spatiotemporal applications related to moving features. The main contributions of this paper can be concluded as follows. (1) We propose an integrated schema – spatiotemporal schema (STS) for representing characteristics and data modeling of moving features. STS provides a conceptual schema for describing and manipulating both spatial characteristics and temporal characteristics of moving features in the necessity aspects, including abstract data type, dynamic attribute, spatiotemporal topological relationship and a minimum set of spatiotemporal operations. (2) We develop and implement a spatiotemporal object-based class library (STOCL) for the implementation of STS to bridge the gap between conceptual schema and applications. (3) We develop a prototype system of passengers' movement simulation and pattern analysis in railway stations in Tokyo to evaluate the performance of STS.

In the paper, the research focuses on high-level abstraction of various GIS application related to data modeling of moving features. The example of moving features we discuss in the case study is "passenger movement", as a profile of spatiotemporal schema, however it is not the only example, which can be also applied to various other application domains, or easy to expand to such kinds of application domains such as management of materials handling and delivery, monitoring of special vehicles, battlefield simulation, monitoring of wildlife etc. We firstly consider to model moving feature as a point object, since in many applications, size and shape of moving features is minor important. Next, we would handle our work on the other spatial geometric types of moving features with changes in size and shape, to focus on solutions to the representation and analysis of dynamic changes and phenomena in some case studies, such as hurricane storm tracking, earthquake monitoring, river monitoring etc.

## Acknowledge

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## Reference

[1] Allen J.F. Maintaining knowledge about temporal intervals. *Communications of the ACM*, 26, 11, pp.832-843, 1983.

[2] Armstrong M.P. Temporality in spatial databases. In *Proceedings of GIS/LIS'88*, San Antonio, TX, pp.880-889, 1988.

[3] Claramunt C. and Jiang B. An integrated representation of spatial and temporal relationships between evolving regions. *Journal of Geographical System*, 3, pp.411-428, 2001.

[4] Egenhofer M.J. and Franzosa R.D. Point-set topological spatial relations. *International Journal for Geographical Information Systems*, 5, 2, pp.161-194, 1991.

[5] Erwig M., Güting R.H., Schneider M. and Vazirgiannis M. Abstract and discrete modeling of spatio-temporal data types. In *6th Proceedings of the 6th International Symposium on Advances in Geographic Information Systems,* Washington DC, USA, pp.131-136, 1998.

[6] Erwig M., Güting R.H., Schneider M. and Vazirgiannis M. Spatio-temporal data types: an approach to modeling and querying moving objects in databases. *GeoInformatica*, 3, 3, pp.269-296, 1999.

[7] Faria G., Medeiros C.B. and Nascimento M.A. An extensible framework for spatio-temporal database applications. *A TimeCenter Technical Report TR- 27*, Aalborg University, Denmark, 1998.

[8] Güttman A. R-Tree - A dynamic index structure for spatial searching. ACM, pp.47-57, 1984.

[9] Güting R.H., Böhlen M.H., Erwig M. and Jensen C.S. et. al. A foundation for representing and querying moving objects. *ACM Transactions on Database Systems*, 25, 1, pp.1-42, 2000.

[10] ISO 19107. ISO/TC 211 Geographical information – spatial schema, (179 pp.), 2000.

[11] ISO 19108. ISO/TC 211 Geographical information – temporal schema, (56 pp.), 2000.

[12] JR East Japan Railway Company, Marketing Information, http://www.jeki.co.jp/marketing/.

[13] Moreira J., Ribeiro C.M. and Saglio J.M. Representation and manipulation of moving points: an extended data model for location estimation. *Cartography and Geographic Information Science*, 26, pp.109-123, 1999.

[14] Peuquet D.J. and Duan N. An event-based spatiotemporal data model (ESTDM) for temporal analysis of geographical data. *International Journal of Geographical Information Systems*, 9, 1, pp.7-24, 1995.

[15] Pfoser D. and Tryfona N. Requirements, definitions, and notations for spatiotemporal application environments. *Proceedings of the 6th International Symposium on Advances in Geographic Information Systems*, Washington, DC, USA, pp.124-130, 1998.

[16] Šaltenis S., Jensen C.S., Leutenegger, S.T. and Lopez, M.A. Indexing the positions of continuously moving objects. *Proceedings of the 2000 ACM-SIGMOD International Conference on Management of Data*, Dallas, Texas, USA, pp.331-342, 2000.

[17] Sistla A.P., Wolfson O., Chamberlain S. and Dao S. Modeling and querying moving objects, *Proceedings of the 13th International Conference on Data Engineering (ICDE),* Birmingham U.K. pp.422-432, 1997.

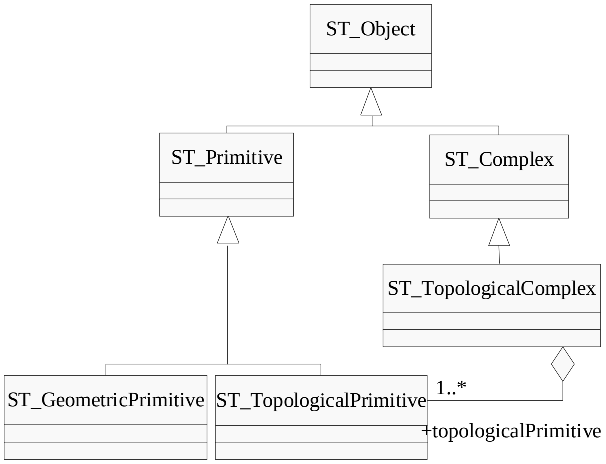
[18] Ryu K.H. and Ahn Y.A. Application of moving objects and spatiotemporal reasoning. *A TimeCenter Technical Report TR-58,* Aalborg University, Denmark, 2001.

[19] Xie R. A study on data modeling for mobile object management and distributed simulation. Doctoral dissertation. *The University of Tokyo*. (163 pp.), 2003.

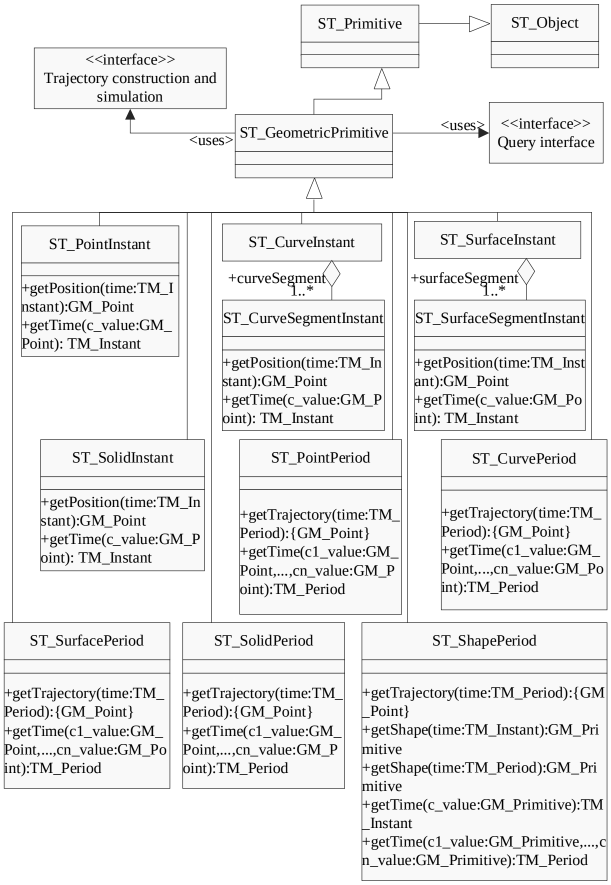
[20] Worboys M.F. A unified model for spatial and temporal information. *The Computer Journal*, 37, 1, pp.25-34, 1994.

# Appendix

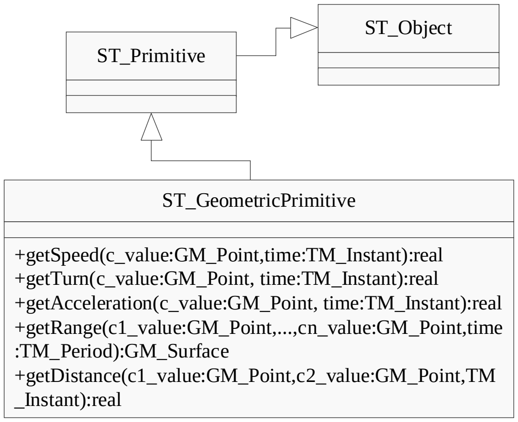
## 1. Moving feature



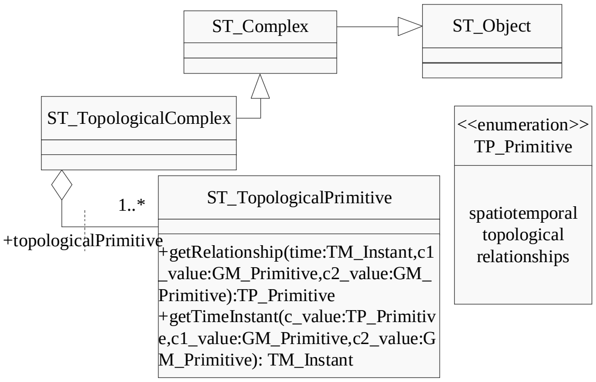
## 2. Spatiotemporal geometric object



## 3. Dynamic attribute



## 4. Spatiotemporal topological relationship



## 5. Trajectory construction and simulation