Chapter 17

The Semantic Trajectory Pattern

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17.1. Introduction and Motivation

Trajectory data have been widely used in a variety of domains, such as transportation, geography, ecology, oceanography, and zoology, to name but a few. These trajectories can be generated by humans, animals, cars, and other moving objects, and their location information can be recorded through different approaches including GPS receivers, RFID, WiFi, mobile phone cellular towers, and so forth. With the fast development of location-based technologies, it has become technically and economically feasible to collect a vast amount of trajectory data.

A trajectory can be considered as a set of temporally-indexed positions or *fixes*. Simplified, each *fix* can be represented by $\{x_i, y_i, t_i\}$, with x_i, y_i denoting a position in a 2D (geographic) space, and t_i representing a time point. While these spatiotemporal fixes can already support an exploration of the basic mobility pattern of moving objects, many applications require additional information to interpret the trajectories. For example, a transportation analysis based on the trajectories of vehicles may not be able to derive meaningful results, if the road network information or mode of transportation is not incorporated. Similarly, studies on the migration patterns of birds may require information about the studied birds, such as their species, body sizes, food sources, and age.

Semantic trajectories fill this gap by associating the fixes and segments (a linear interpolation between two consecutive fixes) of the trajectories with geographic information, domain knowledge, data provenance, as well as other related information. Such semantically enriched trajectories enhance the discovery of knowledge which otherwise may remain hidden. For example, the trajectories generated by humans can be better understood when the fixes are associated with corresponding place types, such as *restaurant* or *movie theater* and activities performed at these fixes, such as *dining* can be inferred based on the semantically annotated trajectories.

In this chapter, we present an ontology design pattern for semantic trajectories. While trajectory ontologies have been developed before [3, 4], they were confined to specific application areas and were not designed for the purpose of querying Linked Data, e.g., via the GeoSPARQL query language. This chapter is based on a previously published article [2]. In the following sections, we will introduce the competency questions that motivate this work (section 17.2) and then develop and formalize the semantic trajectory pattern using the Web Ontology Language (OWL) (section 17.3). We will then use an example trajectory dataset generated by an individual to demonstrate the applicability of this pattern (section 17.4). Finally, section 17.5 concludes this work by summarizing the characteristics of the semantic trajectory pattern.

17.2. Competency Questions

We motivate the development of the semantic trajectory pattern using competency questions. A competency question is a typical query that a domain expert may want to submit to a knowledge base to obtain answers [1]. To identify the competency questions for the semantic trajectory pattern, we held a two-day workshop to discuss with researchers from geography, ecology, computer science, and oceanography to understand the common queries they need. Such queries have been grouped into four categories, and are listed below. To better describe these queries, we will use specific examples, such as the trajectories generated by animals, while the semantic trajectory pattern is not restricted to these application areas.

Group 1: queries that can be answered by spatiotemporal fixes and segments.

- "Show birds which have stopped at x and y"
- "Show birds which have moved at an average speed of 0.4 m/s"

Group 2: queries that need additional geographic information.

- "Show the trajectories that cross national parks"
- "Show the trajectories that have stopped by liquor stores"

Group 3: queries that need additional domain knowledge about the moving object.

- "Show the respective trajectories of sheepheads and kelp basses"
- "Show all trajectories that used multiple modes of transportation"

Group 4: queries that need additional information about the data provenance, e.g., the location-tracking device.

- "Show the trajectories captured by Gamin GPS"
- "Show the trajectories generated by iPhone users"

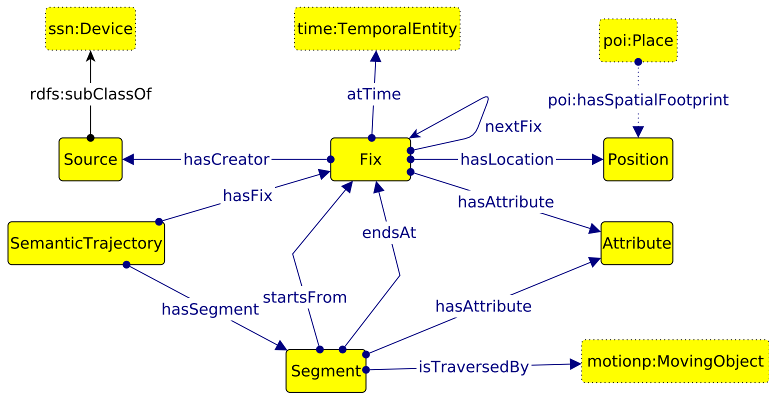

Figure 17.1. Schematical description of the pattern

17.3. Trajectory Pattern and its OWL Formalization

In this section, we present a semantic trajectory pattern that can answer the identified competency questions. Figure 17.1 shows a schematic view of the pattern. In the following paragraphs, we explain the classes and properties of the pattern respectively, and formally encode them using Web Ontology Language.

Fix. A *Fix* is a spatiotemporal point $\{x_i, y_i, t_i\}$ indicating the position of a moving object at an instant of time. Fixes are the atoms that constitute a trajectory. In Axiom 17.1, we require a fix to have a timestamp and a position and to belong to a trajectory.

$$\begin{aligned} \mathit{Fix} \sqsubseteq\ & \exists \mathit{atTime}.\mathit{time{:}TemporalEntity} \sqcap \exists \mathit{hasLocation}.\mathit{Position} \\ & \sqcap \exists \mathit{hasFix}^{-}.\mathit{SemanticTrajectory} \end{aligned} \tag{17.1}$$

Segment. A *Segment* is a line connecting a starting fix $\{x_i, y_i, t_i\}$ and an ending fix $\{x_j, y_j, t_j\}$, with $t_i < t_j$. Since the moving subject can stay at the same position for a time period, $\{x_i, y_i\}$ may not necessarily be different from $\{x_j, y_j\}$. In Axiom 17.2, we enforce that every segment is connected to some fixes through the properties *startsFrom* and *endsAt*. Axioms 17.3 and 17.4 enforce that every segment is connected to at most two fixes. Axiom 17.5 enforces that every segment belongs to a trajectory.

$$\mathit{Segment} \sqsubseteq \exists \mathit{startsFrom}.\mathit{Fix} \sqcap \exists \mathit{endsAt}.\mathit{Fix} \tag{17.2}$$

$$\top \sqsubseteq \leq 1 \mathit{startsFrom}.\top \tag{17.3}$$

$$\top \sqsubseteq \leq 1 \mathit{endsAt}.\top \tag{17.4}$$

$$\mathit{Segment} \sqsubseteq \exists \mathit{hasSegment}^{-}.\mathit{SemanticTrajectory} \tag{17.5}$$

time:TemporalEntity. This class expresses the temporal information associated with a fix. It serves as an interface which allows this ontology design pattern to be aligned with other ontologies. This class can be implemented using *OWL-Time*.

Position. A *Position* is defined as a coordinate tuple $\{x_i, y_i\}$ which indicates the location of the fix. Similar to *time:TemporalEntity*, the class of *Position* acts as for interface to integrate the ontology design pattern with other ontologies on geographic information (e.g., the Point-of-Interest (POI) ontology).

Ordering Fixes within a Trajectory. We define the properties *hasNext*, *hasSuccessor*, *hasPrevious*, and *hasPredecessor* which can be automatically created using Axioms 17.6–17.10. These properties allow us to enforce an order among the fixes within a trajectory and such an order enables the verification of the temporal consistence of a set of fixes.

$$\mathit{startsFrom}^{-} \circ \mathit{endsAt} \sqsubseteq \mathit{hasNext} \tag{17.6}$$

$$\mathit{hasNext} \sqsubseteq \mathit{hasSuccessor} \tag{17.7}$$

$$\mathit{hasSuccessor} \circ \mathit{hasSuccessor} \sqsubseteq \mathit{hasSuccessor} \tag{17.8}$$

$$\mathit{hasNext}^{-} \sqsubseteq \mathit{hasPrevious} \tag{17.9}$$

$$\mathit{hasSuccessor}^{-} \sqsubseteq \mathit{hasPredecesor} \tag{17.10}$$

StartingFix, EndingFix, and Stop. *StartingFix*, *EndingFix*, and *Stop* are important classes which are necessary for executing some queries on trajectory data [3, 4]. While we do not explicitly define these classes in the ontology design pattern, Axioms 17.11 - 17.14 are proposed to automatically detect *StartingFix* and *EndingFix* as well as *StartingSegment* and *EndingSegment*. A *Stop* is a segment whose length is shorter than a distance threshold and whose duration is larger than a temporal threshold (both thresholds can be defined by the ontology user).

$$\mathit{Fix} \sqcap \neg\exists \mathit{endsAt}^{-}.\mathit{Segment} \sqsubseteq \mathit{StartingFix} \tag{17.11}$$

$$\mathit{Fix} \sqcap \neg\exists \mathit{startsFrom}^{-}.\mathit{Segment} \sqsubseteq \mathit{EndingFix} \tag{17.12}$$

$$\mathit{Segment} \sqcap \exists \mathit{startsFrom}.\mathit{StartingFix} \sqsubseteq \mathit{StartingSegment} \tag{17.13}$$

$$\mathit{Segment} \sqcap \exists \mathit{endsAt}.\mathit{EndingFix} \sqsubseteq \mathit{EndingSegment} \tag{17.14}$$

Attribute and hasAttribute. The class *Attribute* and the corresponding relation *hasAttribute* have been defined as the generic class and relation to connect fixes and segments to their attribute values, such as the speed at a particular fix or the bearing of a segment. Users of the pattern can either remain on this level or define their own subclasses and subroles, e.g., hasSpeed.Speed, based on the requirements of the particular applications.

Source. The *Source* class captures information about the device that has collected the trajectory data. Potential device information may include the manufacturer, produced year, spatial and temporal accuracies, product model, and so forth. Here, we recommend using the W3C SSN-XG ontology to provide sensor-related information.

isTraversedBy. This relation links a *Segment* with the corresponding moving subject. The *motionp:MovingObject* class is from the *Motion Pattern* developed in a previous GeoVoCamp and can be used as an interface for integrating domain knowledge with the trajectory data.

Semantic Trajectory. This class connects fixes, segments, and related knowledge into a meaningful path linking the origin and the destination. Using Axiom 17.15, we enforce that every trajectory is linked to at least one segment through the *hasSegment* property. Axioms 17.15 and 17.17 automatize the *hasFix* relationship linking every trajectory to the fixes within this trajectory.

$$SemanticTrajectory \sqsubseteq \exists hasSegment.Segment \tag{17.15}$$

$$hasSegment \circ startsFrom \sqsubseteq hasFix \tag{17.16}$$

$$hasSegment \circ endsAt \sqsubseteq hasFix \tag{17.17}$$

Domain and Ranges and Class Disjointness. We declare all classes defined for the pattern to be disjoint. We also recommend the definition of domains and ranges for existing classes. Axioms 17.18–17.21 show how to enforce some of these restrictions.

$$\exists hasSegment.Segment \sqsubseteq SemanticTrajectory \tag{17.18}$$

$$\exists hasSegment^{-}.SemanticTrajectory \sqsubseteq Segment \tag{17.19}$$

$$\exists hasFix.Fix \sqsubseteq SemanticTrajectory \tag{17.20}$$

$$\exists hasFix^{-}.SemanticTrajectory \sqsubseteq Fix \tag{17.21}$$

To sum up, the proposed semantic trajectory pattern uses *fixes* and *segments* to capture the trajectory data and defines a number of interfaces to incorporate additional geographic information, domain knowledge, and device data. The owl file of this pattern can be accessed at: `http://descartes-core.org/ontologies/trajectory/1.0/trajectory.owl`.

17.4. Application

In this section, we demonstrate the applicability of the proposed semantic trajectory pattern by using it to formally annotate an example trajectory dataset. This dataset was collected using a handhold GPS receiver, and it captured the trajectory of an individual who traveled to the 2012 GeoVoCamp held in Wright State University, Dayton, Ohio. During the trip, he also switched the transportation mode from driving to walking. Fragments of the formally annotated data are shown in Table 17.1. It can be seen from the table, a fix (e.g., *fix1*) is associated with the location (*:pos1*), time (*:2012-09-15T11:26:22Z*), and device (*:mikesGPS*). A segment (e.g., *:segment1*) is associated with the fixes (*:fix1* and *:fix2*) and the moving subject (*:mikesCar*). Such integration allows us to answer competency questions, such as 'show the trajectory segments that were traversed by Mike (walking) and Mike's car (driving) respectively' or 'show the trajectory segments that were in Wright State University'. More details are given in [2].

Table 17.1. Part of the annotated data for the individual trajectory using N3

:mikesTrajectory	a	:SemanticTrajectory;
	:hasSegment	:segment1, :segment2, ...;
	:hasFix	:fix1, :fix2, :fix3, :fix4, ...;
:mikesCar	a	motionp:MovingObject;
:mikesGPS	a	:Source;
:segment1	a	:Segment;
	:startsFrom	:fix1;
	:endsAt	:fix2;
	:isTraversedBy	:mikesCar;
:fix1	a	:Fix;
	:hasCreator	:mikesGPS;
	:inXSDDataTime	:2012-09-15T11:26:22Z;
	:hasLocation	:pos1;
:pos1	a	:Position;
	geo:asWKT	Point(x_0,y_0);

17.5. Conclusions

In this paper we presented an ontology design pattern for semantic trajectories and highlighted its applicability. The pattern can be used to semantically annotate trajectory data from a range of domains. This pattern has the following characteristics: 1) **Expressiveness**: the design pattern can express a trajectory's spatiotemporal properties, geographic knowledge, domain knowledge, as well as relations among them. 2) **Simplicity**: only a minimal number of classes and relations are defined, which makes the design pattern easy to understand, reuse, and extend. 3) **Flexibility**: the provided interfaces (such as *Source*) allow the ODP user to integrate additional knowledge according to the specific needs of the application. 4) **Scalability**: depending on the required granularity of the applications, the ontology design pattern can model trajectories at different scales. While we have demonstrated this pattern using the trajectory data from an individual, this ODP can also be applied to annotating the trajectory data from other moving subjects, such as vehicles and animals.

Bibliography

[1] M. Grüninger and M. S. Fox. The role of competency questions in enterprise engineering. In *Proceedings of the IFIP WG5*, volume 7, pages 212–221, 1994.

[2] Y. Hu, K. Janowicz, D. Carral, S. Scheider, W. Kuhn, G. Berg-Cross, P. Hitzler, M. Dean, and D. Kolas. A geo-ontology design pattern for semantic trajectories. In *Spatial Information Theory*, pages 438–456. Springer, 2013.

[3] S. Spaccapietra, C. Parent, M. Damiani, J. De Macedo, F. Porto, and

C. Vangenot. A conceptual view on trajectories. *Data and Knowledge Engineering*, 65(1):126–146, 2008.

[4] Z. Yan, J. Macedo, C. Parent, and S. Spaccapietra. Trajectory ontologies and queries. *Transactions in GIS*, 12:75–91, 2008.