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A Spatio-Temporal Resource Description Framework Schema Model for Aeronautical Dynamic Information Based on Semantic Analysis

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ABSTRACT

Aeronautical information service (AIS) involves manifold correlations among aeronautical events. The data mining technology has been used to extract the characteristics of aeronautical information. With the aeronautical dynamic information of the notice to airmen (NOTAM) as the study case, this paper carries out semantic analysis on NOTAMs and establishes a spatio-temporal resource description framework (RDF) schema model by combining a three-tuple RDF model and semantic analysis to extract features of aeronautical information. The new model is constructed by Protégé, and NOTAM texts are employed to verify the model. Experiments showed that the proposed model could effectively match the samples of NOTAM information and extract the characteristic data from the NOTAM information. The study is expected to provide a basis for further aeronautical information mining based on knowledge graph.

KEYWORDS

Aeronautical Dynamic Information, Knowledge Graph, NOTAM, RDF, Semantic Analysis, Spatio-Temporal RDF Schema

INTRODUCTION

Aeronautical information service (AIS) provides aeronautical data and information for civil air transportation and accounts for a central service module air traffic management. According to requirements proposed by International Civil Aviation Organization for the development of AIS, the aeronautical information will complete the transition from AIS to aeronautical information management (AIM) in the next decade. During the transition phase, large amounts of data on aviation operations will be accumulated, and the correlation between these dynamic data will be mined to extract data features and lay a foundation for subsequent event pattern recognition and event prediction. Due

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to the massive scale of aeronautical dynamic data, advanced technologies must be relied to fulfill data mining and feature extraction. Knowledge graph (KG), a technique that describes concepts, entities and associations in a structured form, can be employed to organize and manage massive information and represent information in a more cognitive form for humans. KG has already been widely adopted in finance, medicine, and e-commerce and other industries, such as the semantic search function of Ali, Baidu, British Museum, etc. Theories and applications of KG have revealed that it is a useful tool to build high-quality and integrated information databases and mine data relevance. The key is to use a canonical model framework to integrate and cluster aeronautical dynamic information. The commonly used description method for semantic representation is the resource description framework, the first step of KG.

In this work, we performed semantic analysis on the aeronautical dynamic information of NOTAMs in AIS. By combining semantic analysis and a triple RDF model, a spatio-temporal RDF model was established to extract features of aeronautical information. A new model was constructed using Protégé, and the sample NOTAMs texts were employed to verify the constructed model. The model can effectively match the sample NOTAM information and extract features from within. The constructed model can lay a foundation for subsequent mining of aeronautical information based on KG.

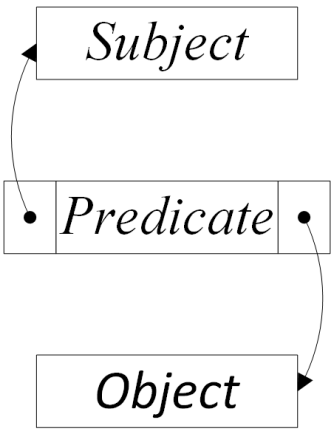
RELATED THEORIE AND DEFINITIONS

Resource Description Framework

The temporal data model provides a useful tool for temporal data management. Various forms of temporal database models have been proposed, including historical relational database models (Guo and Yan, 2018; Zhang, 2018; Bernstein and Kiefer, 2006; Kiefer et al., 2007), TemSQL models (Kiefer et al., 2007; Kiefer, 2007; Calvanese et al., 2005), bitemporal database models (Kottmann and Studer, 2007) and object historical models (Acciarri et al., 2005; Chen, 2014; Zhao, 2018; Pang, 2018).

The resource description framework (RDF) model was first proposed by W3C to provide a basic structure that enables applications to exchange metadata on the web (Pang, 2018). RDF is a labeled directed graph and an object-oriented data model. It is a three-tuple <*s, p, o*> representation pattern consisting of edges and nodes, namely "*Subject-Predicate-Object*", as shown in Figure 1.

Figure 1. Three-tuple representation of RDF



Symbols in Figure 1 are interpreted as follows:

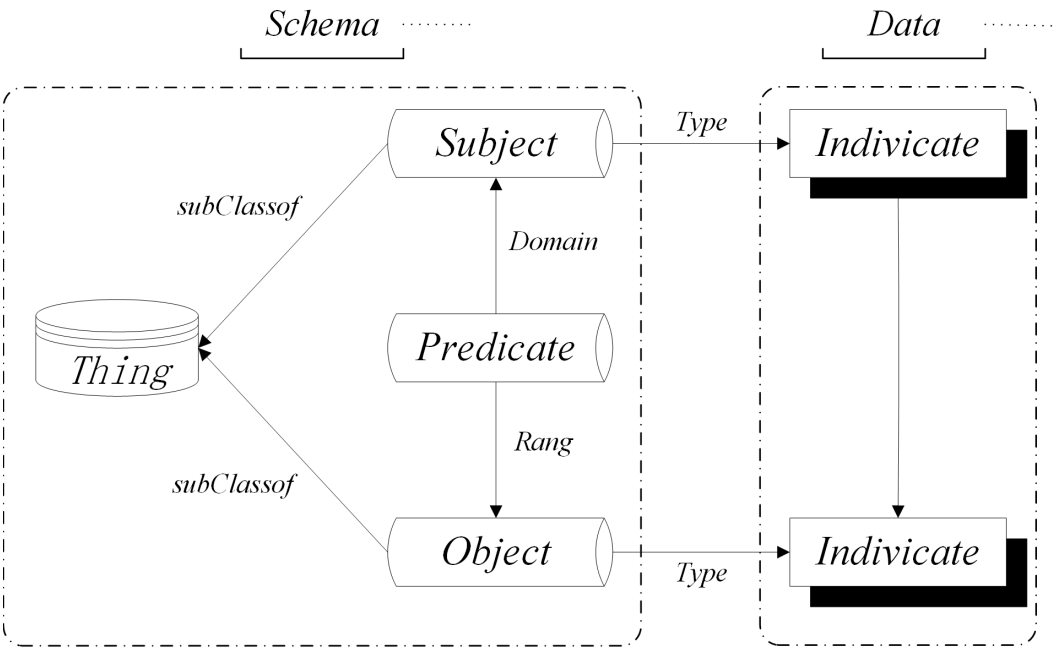
- **Subject:** Resources: the object represented by the RDF, identified by the uniform resource identifier (URI).
- **Predicate:** Relation/Attribute: the representation attribute of the resource object.
- **Object:** Attribute Value: the value of the attribute corresponding to the identification object, which can be used as the subject of the next three-tuple.

The three tuples of RDF can be used as a whole to construct new three-tuple into a new subject. The RDF model itself is an unconstrained resource description framework, which can neither distinguish between categories and objects, nor can it describe or define class relationships/attributes. In order to ensure the correctness and extensibility of resources, the RDF Schema mathematical model is proposed. The model is an extension of the RDF model to describe RDF data. As per the needs of users, RDF provides definitions such as terms and concepts to describe the relationship between different metadata. Four definitions as shown in Figure 2.

Symbols in Figure 2 are interpreted as follows:

- **subClassof:** A subclass representing the inheritance relationship; *Subject* and *Object* are both subclasses of Thing;
- **Domain:** The domain of an attribute. It is the bridge connecting the *Predicate* and the *Subject*, and its directivity is from the attribute to the resource;
- **Rang:** The value range of the attribute, which contains all attribute values, and the directivity is from the attribute to the attribute value;
- **Type:** The definition of a class, and its directivity is that the ontology of the conceptual layer points to the entity of the data layer.

Figure 2. Structure of the RDF Schema model



With the development of the Semantic Web, RDF models begin to show limitations and the needs for data storage run beyond static data, leading researchers to explore dynamic RDF models. Therefore, by introducing temporal dimension to the RDF model, the model is extended and the temporal RDF model is proposed. Currently, the major way to build a temporal RDF model is to add time tags or versions, but the temporal RDF model is only a descriptive framework, which does not define constraints based on user intentions and has no constraints on the spatial dimension. Therefore, to meet the needs of NOTAM data mining, this paper proposes a new spatio-temporal RDF schema model, and constructs a set of aeronautical dynamic information that is in line with the development of aeronautical information and reflects both temporal and spatial elements.

AERONAUTICAL DYNAMIC INFORMATION

Aeronautical dynamic information currently refers specifically to NOTAMs, which are messages about the establishment, status, or changes of any aeronautical facilities, services, procedures, or dangers released in the form of telecommunications (Chen, 2017). Due to its suddenness and temporary nature, NOTAM information plays a vital role in the safety of daily aviation operations. As defined by International Civil Aviation Organization, NOTAM can be regarded as a semi-structured text, and its structure is neatly structured and the resource description of the spatiotemporal RDF schema model is more maneuverable. A complete NOTAM consists of eight items, and the structure is explained by a specific NOTAM as follows:

(U1888/19 NOTAMN
Q) ZPKM/QMPAW/IV/M/A/000/999/3035N10357E005
A) ZUUU B) 1907031559 C) 1911061559
E) PARKING STAND NR.508, NR.508L, NR.508R COMPLETELY WITHDRAWN)

The main message conveyed by this NOTAM is that at Chengdu ZUUU Airport from 15:59 on July 3, 2019 to 15:59 on November 06, 2019, aircraft stands 508, 508L, and 508R are completely canceled.

The first line is the telegram header, including: telegram level, receiving address, issuing date and time group, and issuing address. Its meaning is: U series 2019 No. 1888 new NOTAM.

Item *Q)* is a restricted line, which mainly includes: *FIR*, NOTAMs selection standard code (*Q code*), flight type, purpose of issuing air notice, sphere of influence, upper and lower limits, coordinates and radius.

Example: In ZPKM, all aircraft stands have been canceled, which will affect the flight of instrument flight rules and visual flight rules. It belongs to other NOTAMs. The affected area is the airport area. The altitude limit is not clear. The coordinates are 30 degrees 35 north latitude. Minutes, 103 degrees 57 minutes east longitude, radius 5NM.

Item *A)* is the place of occurrence, Chengdu ZUUU Airport.
Item *B)* is the effective time, at 15:59 on July 3, 2019.
Item *C)* is the expiration time, at 15:59 on November 06, 2019.
Item *E)* is the main text of the NOTAM, which is composed of texts and is a specific description of the entire event.

Example: Stands 508, 508L, and 508R are completely canceled.

Except for *E)*, which is free text, all other items have strict requirements for the content and format of the input information.

CONSTRUCTION OF A SPATIO-TEMPORAL RDF SCHEMA MODEL OF AERONAUTICAL DYNAMIC INFORMATION

Comparison With Existing Data Representation Models

It is important to process heterogeneous data, integrate new data and analyze data when performing semantic analysis of unstructured texts and mining data. The graph data structure provides an ideal solution.

The current graph data structure mainly uses RDF and attribute graphs. These two structures share similarities in the composition of nodes and edges, but are different in the following aspects:

- **Terminology and expression capacity:** The RDF can use labels to identify the value of the display name of any resource, but the attribute graph cannot capture any information. RDF is a resource that can be used to define the intended purpose and semantics of a node, while the attribute graph is used to query relationship matching.
- **The difference in additional information on the side:** Two different edges of the attribute graph can have the same type but different characteristics. The RDF uses the same edges for the same type, and the edges can be reused, and its method of adding edges is more convenient and powerful than that used in the attribute graph.

In general, RDF can express semantic information through a uniform identifier, and can describe resources and define them according to user needs, so as to build a framework model that meets user needs. The attribute graph can only carry out the surface information of nodes and edges, but cannot give specific semantic information. Therefore, compared with attribute graphs, RDF has more powerful functions, richer semantic information that can be represented, and can better meet the needs of users.

SEMANTIC ANALYSIS OF NOTAMS

Statistical analysis of the structure and content of NOTAMs shows that the timeliness and spatiality of NOTAMs are extremely important, and the Q code is more representative for the highly general expression of the entire message. Item *E)* is the content of the text, which can be displayed as a supplement to the Q code. The example NOTAM above shows that aeronautical information is time-sensitive and spatial. Therefore, based on the characteristics of NOTAMs, the semantics of NOTAMs is defined:

Definition 1: NOTAM is an unstructured text, consisting of three parts: *Time*, *Event*, and *Location*, according to its timeliness and spatiality:

$$Time = T_i = \left\{T_1, T_2, \ldots, T_n\right\}, \left(1 \le i \le n\right)$$

The equation above indicates the time, including the start time and end time. It describes the *Effective Time* and *Expiration Time* of *NOTAM*, and extract data from items *B)* and *C)*. For example, in the example shown in the previous item *B)* 1907031559 is the *Effective Time* and item *C)* 1911061559 is the *Expiration Time*:

$$Event = E_i = \left\{\left(Q_{2,3}, Q_{4,5}\right)_1, \left(Q_{2,3}, Q_{4,5}\right)_2, \ldots, \left(Q_{2,3}, Q_{4,5}\right)_n\right\}, \left(1 \le i \le n\right)$$

This equation indicates the content of the event, where $Q_{2,3}$ are the 2nd and 3rd words in the Q code, and $Q_{4,5}$ are the 4th and 5th words in the Q code. It describes the main content of the NOTAM, and extracts data from the *Q)* item. For example, in the item Q) shown in the previous, MP is the 2nd, 3rd words of the Q code, indicating the aircraft stands; AW is the 4th and 5th words of the Q code, indicating the cancellation:

$$Location = L_i = \left\{L_1, L_2, \ldots, L_n\right\}, \left(1 \le i \le n\right)$$

This equation indicates the location, which refers to the place where the incident takes place. It is divided into *FIR* and *Airpo*rt, and information is extracted from the four-character code of item *A)*. For example, the ZUUU in item *A)* in the example shown in the previous indicates that the incident occurred at Chengdu Shuangliu International Airport.

SPATIO-TEMPORAL RDF SCHEMA MODEL FOR AERONAUTICAL DYNAMIC INFORMATION

As the semantic analysis of the NOTAM in the preceding section shows, the content is expressed by three-tuples in a RDF model to extract dynamic aeronautical information features; then a new spatio-temporal RDF schema model is defined under the framework of the original RDF model, and combined with semantic analysis of the NOTAM, the aeronautical dynamic information of the spatio-temporal RDF schema model is defined:

Definition 2: A spatio-temporal RDF schema model is a model built by adding the temporal information element *t* and the spatial element *l* to the original three-tuple structured RDF model, <*s,p,o*|*t.l*>, where *s, p, o* stand for Subject, Predicate, and Object in the RDF model, and *t* represents the required temporal information, and *l* represents the required spatial information. In a spatio-temporal RDF schema model, a <*s,p,o*|*t,l*> triple is used as a resource to constrain the spatiotemporal information, and $\left(T_1, T_2\right) \in t$ is the time information:

- When the temporal and spatial information is embodied, the spatio-temporal RDF model needs to add a blank node to link resources and temporal and spatial information.
- When the temporal and spatial information is added to a classic RDF model as a resource, there is no need to use blank node links, combine it with the predicate, and constrain it in the form of edge labels.

The specific structure of a spatio-temporal RDF schema model is shown in Figure 3.

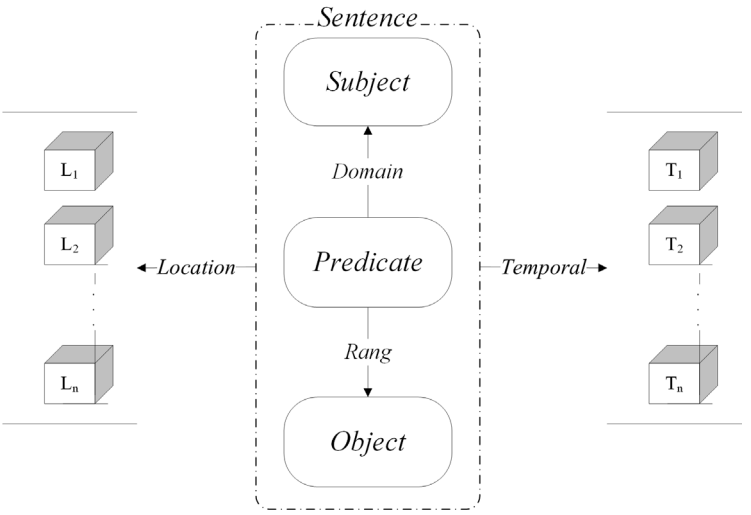
In Figure 3, *Temporal* is the time label, and the user performs the structure of the time label as needed:

$$T_i = \left\{T_1, T_2, \ldots, T_n\right\} \in t, \left(1 \le i \le n\right)$$

where *t* is a time set, and T_i is the effective or invalid time of the NOTAM, which is added to the time constraint of the event in the form of a timestamp.

The spatio-temporal RDF schema model of aeronautical dynamic information combines the NOTAM with the spatio-temporal RDFs after semantic analysis to represent the NOTAMs in triples. The model is composed of two modules: *Schema* and *Individuals*. *Schema* is composed of

Figure 3. Structure of a spatio-temporal RDF schema model



two functional modules, *Classes* and *Object properties*; *Individuals* is the entity data layer, which contains specific data of the NOTAM:

- *Classes* represents categories, which are the ontology construction of the *Schema* layer. It is divided into three levels: the first-level ontology is *NOTAM*; the second-level ontology is *Time, Event,* and *Location*; the third-level ontology is *Effective time, Expiration time, Airport*, and *FIR*.
- *Object properties (r, d)* represents the property relationship, where *r* is the domain of definition and *d* is the domain of value. It describes the relationship between each ontology or attribute. Information inference can be carried out through the relationship between attributes, and a NOTAM spatio-temporal RDFs triplet can be obtained from multiple data sources. The attribute relationship constraints and the reasoning of the domain and value range are as follows:

$$N_{rdf} = \left\langle T_i, E_i, L_i \right\rangle \tag{1}$$

$$\left(s0 \cup e0\right) \in \left(T_i, E_i\right), h0 \in \left(L_i, E_i\right), inI = L_i \in \left(F, A\right) \tag{2}$$

Using (2) to constrain (1), we obtain:

$$N_{rdf} = \left\langle T_1, E_1, L_1 \right\rangle \tag{3}$$

where:

$$T_i = \left\{T_1, T_2, \ldots, T_n\right\}, \left(1 \le i \le n\right) \tag{4}$$

$$E_i = \left\{\left(Q_{2,3}, Q_{4,5}\right)_1, \left(Q_{2,3}, Q_{4,5}\right)_2, \ldots, \left(Q_{2,3}, Q_{4,5}\right)_n\right\}, \left(1 \le i \le n\right) \tag{5}$$

$$L_i = \left\{L_1, L_2, \ldots, L_n\right\}, \left(1 \le i \le n\right) \tag{6}$$

where *sO* is short for *startOn*, which means the multi-mapping relationship between *NOTAM's Event* and *Effective Time*. Each event can occur in multiple time periods.

eO is short for *endOn*, which means the multiple mapping relationship between *NOTAM's Event* and *Expiration Time*. Each event can expire in multiple time periods.

hO stands for *happendOn*, which means the single mapping and multiple mapping relationship between *NOTAM's Location* and *Event*. Multiple events can occur in each location.

inI is short for *includeIn*, which means the single mapping relationship between *Airport* and *FIR*. Each airport belongs to a FIR.

Data properties are obtained by analyzing the *E)* item, and then 6 aspects are obtained: *Event Content, Event Status, Event Category, Latitude and Longitude, Range (purpose, type), Height (upper and lower limits)*. This type of information is implicit information contained in the Q code.

The construction steps are as follows:

Step 1: Analyze the semantic structure of the NOTAM.
Step 2: Define the *Schema* of *NOTAMs*.
Step 3: Set the attribute/relationship *Object properties*, which mainly maps the ontology in *Classes* with the entities in *Individual*.
Step 4: Set the relationship between entities in the *Data properties* of the data layer.
Step 5: Set the specific data information of *Individuals* and enter the entity data of *NOTAM* to form a complete NOTAM spatiotemporal RDF schema model.

The flow chart is shown in Figure 4:

Figure 5 shows the structural relationship of the newly constructed NOTAM spatio-temporal RDF schema model.

Through the connection of *Object property* and *Schema*, the specific time, location, *Q code* and other information in the NOTAM are entered, and finally a set of new and unique NOTAM spatio-temporal RDF schema models conforming to the development of aeronautical information are formed. The difference between the newly constructed NOTAM spatio-temporal RDF model and the original RDF model is that the original event constraints are carried out by adding time and place constraints, and knowledge matching and effective extraction of NOTAM features are achieved within multiple data sources based on the constraints of spatio-temporal information.

VERIFICATION OF CONSTRUCTED SPATIO-TEMPORAL RDF SCHEMA MODEL

In order to verify the spatio-temporal RDF schema model of aeronautical dynamic information, the Protégé software was employed to construct the spatio-temporal RDF model of aeronautical dynamic information. Protégé provides the definition of ontology, the construction of attributes/relationships and entities. It can display RDF/XML, OWL/XML, Turtle, JSON-LD and other models on a graphical interface and can realize SPARQL query. Aeronautical dynamic information implements spatio-temporal RDF schema modeling of multiple NOTAMs through Protégé. The specific steps are as follows:

Figure 4. Model-building flowchart

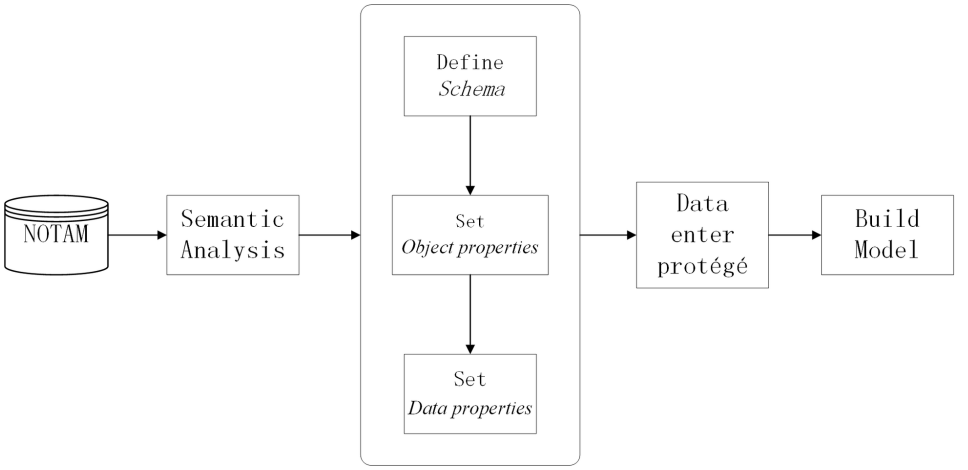
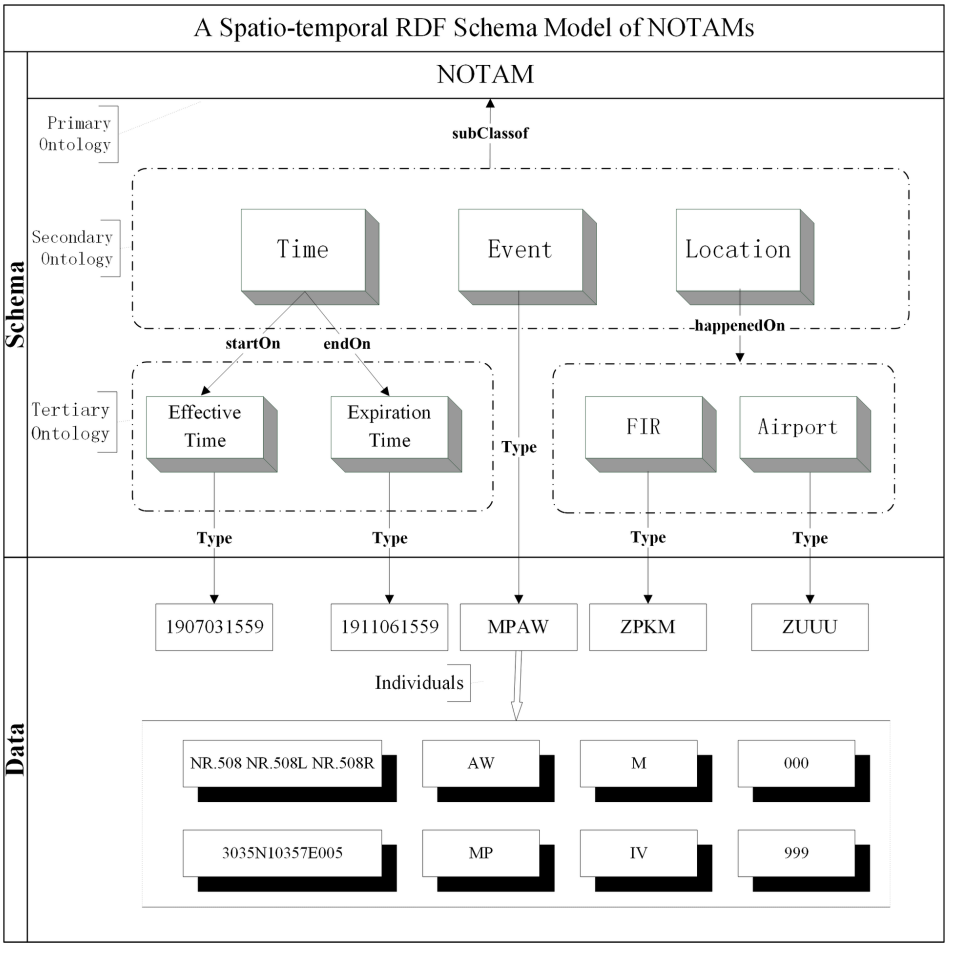


Figure 5. A spatio-temporal RDF schema model of NOTAMs



Step 1: Define the concept layer *Classes* of NOTAMs and construct the ontology. Part of the core codes and ontology construction results are shown in Tables 1-3.

Step 2: Set the properties/relationship *Object properties*, mainly to connect each ontology in *Classes* with entities in *Individual*. Part of the core codes (*startOn*) and the attribute relationships built as shown in Table 4.

Step 3: Set the relationship between the entities in *the Data properties* of the data layer, mainly the *E)* item connects the Q code supplementary information with the Q code entity. The relationship between part of the core code and the entities set by Table 5.

Step 4: Set the specific information in *Data*, that is, enter the entity data of NOTAM to form a complete NOTAM spatio-temporal RDF schema model.

In this paper, we sample multiple text instances of NOTAMs to convert spatio-temporal RDFs triples and then enter the entities into Protégé. According to the constructed new spatiotemporal model, the spatiotemporal properties of NOTAMs can be visualized, as shown in Figure 9.

The sampled physical time is "1906031200-2004212335", which can be *Effective time* or *Expiration time*; The *Q code* is "MPAW, NVAK and XXXX", indicating the main event that occurred; "RPHI, RPLP, ZPKM and ZUUU" indicate the location of occurrence, which is *FIR* or Airport.

Figure 9 is a diagram of the spatio-temporal RDF model of NOTAM after data visualization. In the figure, the yellow mark is the Schema layer, the purple mark is the Data layer, and the linear marks between entities indicate the knowledge association between each other.

Table 1. First-leve ontology (core code)

First-level ontology (core code)
<!-- http://www.KGNOTAM.com#NOTAM --> <owl:Class rdf:about="http://www.KGNOTAM.com#NOTAM"> <rdfs:subClassOf rdf:resource="http://www.w3.org/2002/07/owl#Thing"/> </owl:Class> …

Table 2. Secondary ontology (core code)

Secondary ontology (core code)
<!-- http://www.KGNOTAM.com#Event --> <owl:Class rdf:about="http://www.KGNOTAM.com#Event"> <rdfs:subClassOf rdf:resource="http://www.KGNOTAM.com#NOTAM"/> </owl:Class> …

Table 3. Third-level ontology (core code)

Third-level ontology (core code)
<!-- http://www.KGNOTAM.com#Effective Time--> <owl:Class rdf:about="http://www.KGNOTAM.com#Effective Time"> <rdfs:subClassOf rdf:resource="http://www.KGNOTAM.com#Time"/> </owl:Class> …

Figure 6. Constructing the ontology of Classes

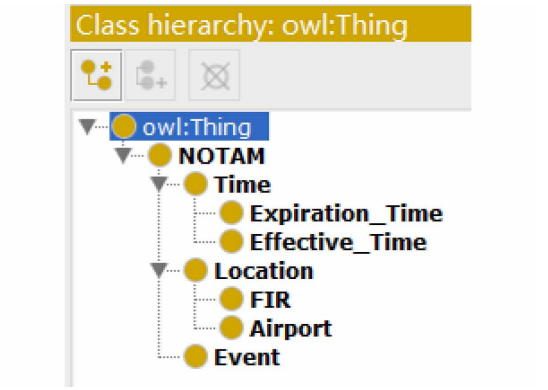


Table 4. startOn code

startOn
<!-- http://www.KGNOTAM.com#startOn --> <owl:ObjectProperty rdf:about="http://www.KGNOTAM.com#startOn"> <rdfs:subPropertyOf rdf:resource="http://www.w3.org/2002/07/owl#topObjectProperty"/> <rdfs:domain rdf:resource="http://www.KGNOTAM.com#Event"/> <rdfs:range rdf:resource="http://www.KGNOTAM.com#Time"/> </owl:ObjectProperty> …

Figure 7. Setting properties/relationship Object properties

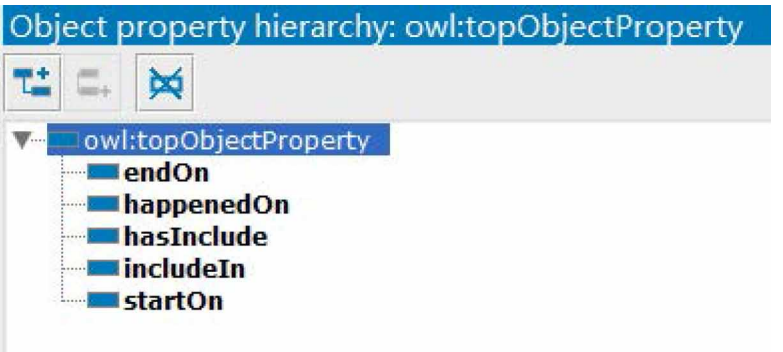


Figure 10 shows that during the time period of 1907031559-1911061559, an MPAW (Stands Cancellation) event occurs at ZUUU Airport.

Figure 11 shows that MPAW (Stands Cancellation) and XXXX (unknown) events occurs at ZUUU Airport, and ZUUU belongs to ZPKM FIR.

Based on the verification of the above data examples, the knowledge visualization can display the correlations between knowledge in a intuitive and clear manner, which shows that the newly introduced spatiotemporal information model is feasible for the visualization of the correlations between aeronautical dynamic information knowledge and knowledge extraction.

Table 5. Setting the relationship between entities (core code)

Setting the relationship between entities (core code)
<!-- http://www.KGNOTAM.com#Event --> <owl:DatatypeProperty rdf:about="http://www.KGNOTAM.com#Event_Content"> <rdfs:subPropertyOf rdf:resource="http://www.w3.org/2002/07/owl#topDataProperty"/> <rdfs:domain rdf:resource="http://www.KGNOTAM.com#Event"/> <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/> </owl:DatatypeProperty> …

Figure 8. Setting the relationship between entities

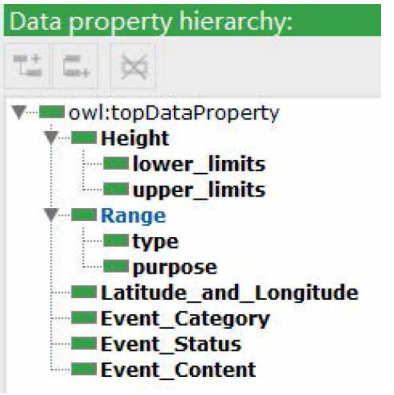


Figure 9. A Spatio-temporal RDF schema model of NOTAM

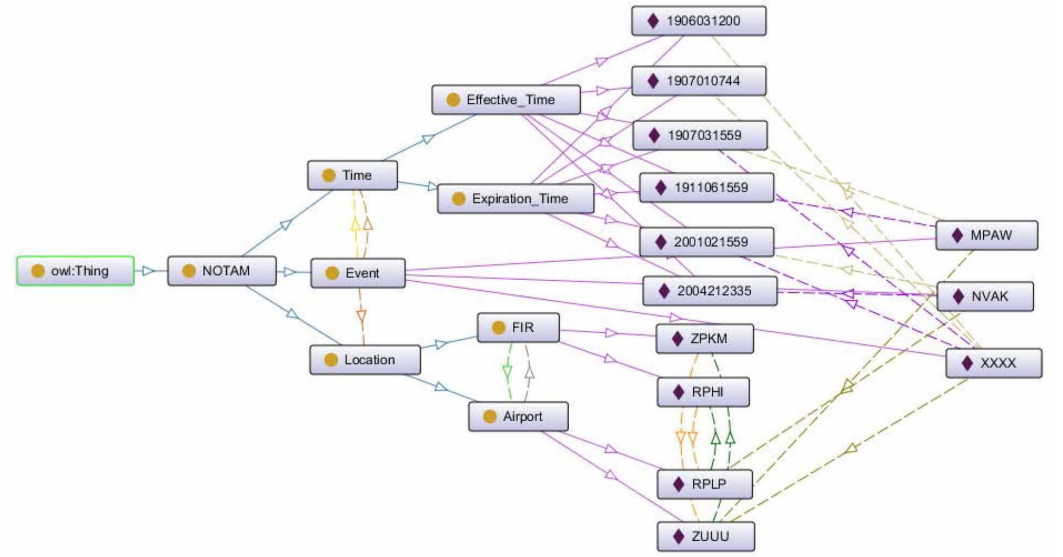


Figure 10. MPAW knowledge association

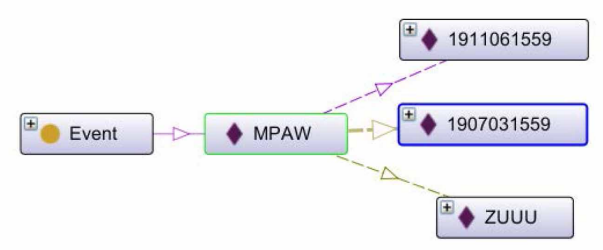
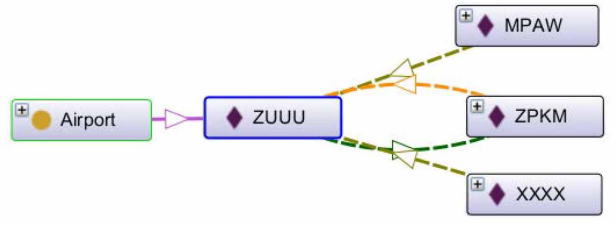


Figure 11. ZUUU knowledge association



CONCLUSION AND FUTURE WORK

The application of the RDF has gradually matured, while the temporal and spatial information in the aeronautical dynamic information has not been effectively mined. In this paper, the spatio-temporal RDF schema model of aeronautical dynamic information can be used to extract information features in aeronautical dynamic data and demonstrate the associations between knowledge through data mining, and the feasibility of extracting aeronautical dynamic information through knowledge association by means of a spatio-temporal RDF schema model of aeronautical dynamic information is verified by the example validation of Protégé. For example, MPAW and ZUUU can show the knowledge connection with other elements according to the retrieval Q code. Namely, by retrieving MPAW, we can see the knowledge association between the Effective/Expiration time of Schema's Event and Data and the airport (Location). This paper paves the way for the establishment of subsequent aeronautical dynamic data sets, provides a new research direction for data representation by spatio-temporal RDF schema models in other fields, and lays the foundation for subsequent research on natural language processing of the E) item in NOTAMs.

In the future, we will continue to carry out the text mining of aeronautical dynamic information, and expand the data mining of unstructured text entity recognition and relation extraction for item E), and then construct the knowledge graph for aeronautical dynamic data of the aeronautical intelligence field.

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