ONTOLOGIES FOR NEXTGEN AVIONICS SYSTEMS

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Abstract

The Federal Aviation Administration (FAA) Next Generation Air Transportation System (NextGen) system incorporates many updates to aerospace technology including coordination of air traffic management (ATM), flight deck control, and avionics architectures. One such consideration is the need for ontologies. An ontology is a formal naming and definition of the types, properties, and interrelationships of the entities that exist (and persist) for a particular domain. In aviation, an ontology is needed to organize the variables to afford computations, instructions, and the relationships between parameters. For example Triples are used as Universal Resource Identifiers (URIs) in the case of {subject, predicate (verb), object}. The subject and object entities can be connected with the relationship predicate. Together, they are an event such as an ontology coordinating Notice to Airmen (NOTAM) flight weather information. In this paper, we explore the concepts of ontologies for applications to aerospace avionics as motivated by the NextGen and Single European Sky ATM Research (SESAR) standards.

Keywords: Ontologies, NOTAMS, avionics

1. Introduction

An *ontology* is a structured approach to categorizing concepts, entities, and relations. An ontology builds on the philosophical notion of knowledge to support decision making [1]. Within information science, an ontology serves to bring together classes of related elements in a formal way towards a specification of a concept to share knowledge [2]. One example is the class of terms, properties, and functions associated with avionics such as Air Traffic Management (ATM). With the needed interoperability for the Single European Sky ATM Research (SESAR) [3] and the US NextGen [4] avionics systems, an ontology serves as bridge for data sharing. While the use of ontological approaches are common in many domains including medical [5, 6], intelligence [7], information fusion [8], and uncertainty analysis [9]; there is a need to formalize the avionics community with a common ontology. A common ontology would support interoperability and coordination among standards and mandates.

1.1 Use of Ontologies in Avionics

There is an emergence of interest of the use of ontologies for air traffic management (ATM) [10-13]. Examples include the NextGen and the SESAR systems. In order to frame the discussion, Figure 1 highlights an example of how ontologies are included in a system analysis. Using the incoming data from weather, flight profiles, and airports; that data needs to be accessed and normalized. Structuring the data is enabled with templates and ontologies. The structured ontology organizes the information (including syntactic and semantic metadata) for analytic tools. The resulting analytics supports visualization for aviators and air traffic controllers (ATCs). Examples include mandates, current reports, and airspace information. Hence, ontologies afford a common method to organize, process, and share data.

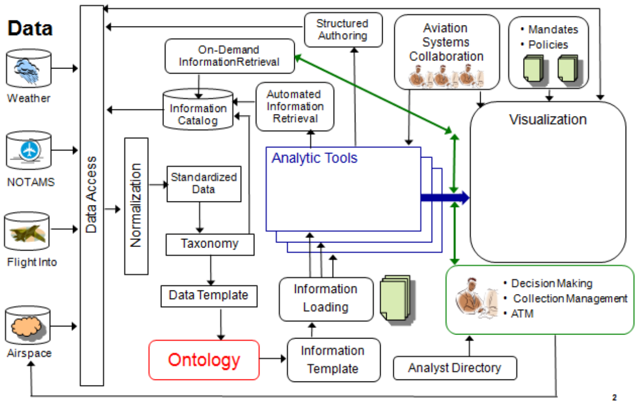

Figure 1. Use of Ontologies for Avionics Analytics

In order to determine the usefulness of ontologies for avionics systems, it is important to review that enormous work done in the field across many application domains.

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1.2 Ontology Definitions

The use of the concept of an ontology took hold in computer science with the need to bring together knowledge, information science, and computer analysis; such as the DARPA Agent Markup Language (DAML) program [10]. Since 2000, there has been an explosion of techniques using an ontology for accessing knowledge through the World Wide Web Consortium (W3C) [11]. The use of ontologies extends from philosophical analysis to information science (e.g., information fusion [12]). As shown in Figure 2, an ontology represents knowledge for application domains through concepts and relationships for scientific reasoning as related to:

- *Philosophy*: The metaphysical study of the nature of being and existence [13].
- *Information Science*: a common understanding of some domain that can be communicated between people and machines [14].

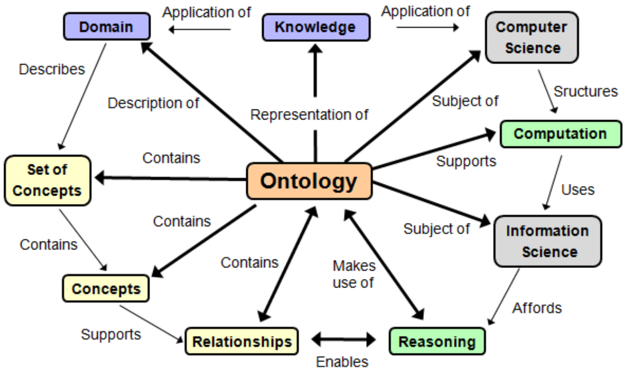

Figure 2. Ontology Concepts

An ontology, defined in computer science [15], is a *controlled vocabulary* for descriptions of entities and relationships between entities. An ontology is formal written specification of a set of concepts and relationships in a domain of interest designed as a shared conceptualization for coordinating across multiple applications and implementations. Some of the fundamental concepts in the definition are:

- *Formal*: machine readable
- *Specification*: Concepts, properties, functions, axioms are explicitly defined
- *Shared*: consensual knowledge
- *Conceptualization*: abstract model of phenomena in the world.

The benefit of the controlled language [15] supports understandability, extensibility, and discovery; such as warnings in stressing situations.

There are active forums such as the *Basic Formal Ontology (BFO)* [16]. A BFO is small, upper level ontology that is designed for use in supporting information retrieval, analysis and integration in scientific and other domains. There are over 130 BFOs for the scientific community since 2002 such as GeO (for Geographical Ontology) and DisReO (for Disaster Relief Ontology). Two subsets include a continuant BFO and an occurrent BFO. A *continuant BFO* is for enduing entities a specific instant (e.g., location), while an *occurrent BFO* include processes of entities that occur over a given interval in time (e.g., activities). Grenon and Smith [17] provide many examples over different domains. For aviation, a continuant example is an airport, while an occurent example is a takeoff activity in flight operations.

Numerous reviews, tutorials, and applications discuss the use of ontologies. For example, Meenachi *et al.* [18], provide a coarse overview that lists 23 applications of ontologies in different domains. This paper is focused on discussing the issues for the NextGen and SEASAR issues for the Digital Avionics Systems community.

The rest of the paper is as follows. Section 2 focuses on SESAR/NextGen ontology discussions. Section 3 discusses information fusion ontology analysis. Section 4 focuses on the semantic ontology with an example for ATM. Section 5 presents a notional example to demonstrate improvements using text analytics and the airspace management navigation for a combined air picture. Section 6 provides conclusions. The article will focus on ontologies as a concept of interest for future NextGen systems, a discussion of examples, and results from visualization.

2.0 SESAR/NextGen Developments

Two groups reported on the developments for NextGen and SESAR. The first includes Gringinger, Eter, and Merkl [10, 11], for the *Ontology-based Control Room Framework* (ONTOCOR). The second is Koelle, *et al.*, [12, 13] for situation management.

2.1 Ontologies Discussions for SESAR/NextGen

One of the first demonstrations of an ontology for SESAR and NextGen systems is by Eduard Gringinger, Dieter Eier, Dieter Merkl for the ONTOCOR [10]. ONTOCOR uses the open standards of the Ontology Web Language (OWL) for information management for such applications as ATM and System Wide Information Management (SWIM). These elements of avionics [19] were developed for communications, navigation and surveillance (CNS) systems. In their paper, different ontology techniques were highlighted including Frame Logic, Resource Description Framework (RDF), SPARQL, and OWL. Many software tools were reviewed as possibilities for avionics systems integration with a focus on the Control Room (CR), Control Tower (CT), and aviator. Facilitating the semantic coordination of people would increase efficiency in ATM. Likewise; ONTOCOR increases productive code reusability, reduces software development, and facilitates efficient ATM between machines.

In 2011, the NextGen and SEASAR were highlighted as utilizing the power of ontology-based systems for software development [11]. One example is the European *ATM Reference Model* (AIRM). Specifically, they looked at Notices to Airman (NOTAM). NOTAMS provide weather and emergency updates to aviators in the form of text messages. Using OWL, the system seeks a semantic-based Aeronautical Information Management system. With semantic reasoning and digital NOTAMS, efforts were underway to bring structure to the knowledge gained from text-based information.

Rainer Kaelle *et al*. [12], reports on ontologies as useful for avionics using concepts from situation management, net-centric operations, and ATM. Using an agent-based framework, situation management using an ontology supports federated operations for and an example is shown for SWIM.

Kaelle *et al*., [13], follow up in 2013 with a *Semantic Drive Security* application which is similar to information management [1]. For a situation in a data dictionary of avionics terms, a feature correlator was developed for the NextGen and SESAR functions to coordinate situation update reports.

2.2 SESAR/NextGen Focus

Rainer Koelle and Walter Strijland [13] outlined progress at ICNS 2013 as for semantic assurance for systems engineering in SESAR/NextGen:

Initial Capability:

- Use-case applications of Security Support
- Analysis of ontologies

Current Capability:

- ATM Security
- Emerging field
- Fragmented approaches
- Extra burden / hassle

Mid-Term Capabilities

- Consistent Rule-Base Systems Implementation
- Provides functionality for SESAR Processes
- Validated & Harmonized Rule-Base
- Support to SESAR Security Assurance Case

A key example for NextGen system includes developments in the weather ontology, implemented in three operational capability phases [20]:

- Initial (2013): Significantly enhanced weather infrastructure providing modestly improved meteorological data to all users of the Nation's Air Transportation System
- Midterm (2016): NextGen begins to implement automated decision assistance tools and algorithms for managing the air space, requiring high resolution weather forecasts and observations with a greater degree of accuracy and precision
- Farterm (2022): NextGen weather must meet all meteorological and engineering performance requirements to support the NextGen traffic management systems.

While weather as reported in NOTAMS is a good example, there are many other types of data that can be included through information fusion.

3.0 Information Fusion

Security, information management, and ontology developments are also being explored in the information fusion community. As per the developments in ontologies, software, and architectures, the Probabilistic Ontology Web

Language (PROWL) capability [21] aids in the ability to process and reason over data. Given the recent activity in ontologies, it is useful to explore these concepts for aviation.

3.1 Information Fusion Overview

Situation Awareness Management (SAM) is essentially context analysis which is termed Level 2 fusion in the *Data Fusion Information Group* (DFIG) model (see Figure 3). Information fusion concepts are divided between Low-level information fusion (LLIF) and High-level Information Fusion (HLIF) [22].

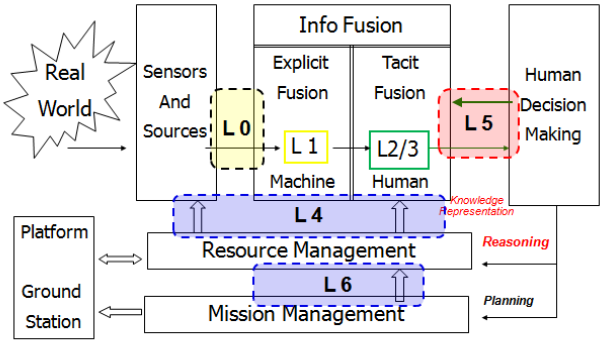

Figure 3. DFIG Information Fusion Model (L = Information Fusion Level)

LLIF (L0-1) composes data registration (Level 0 [L0]) [23] and explicit object assessment (L1) such as an aircraft location and identity [24, 25, 26]. HLIF (L2-6) composes much of the open discussions in the last decade including ontologies. The levels, to denote processing, include situation (L2) and impact (L3) assessment [27] with resource (L4) [28], user (L5) [29], and mission (L6) refinement [30]. Here we focus on fusion through effective visualization User Defined Operating Picture (UDOP) of ontology-driven semantic data.

In order to provide SAM, there is a need to leverage developments in big data processing such as machine, visual, and text analytics [31] with a controlled ontology. These developments would enable air traffic controllers or pilots to better understand the plethora of information available in the environment (e.g. weather [32]), airspace/airports (e.g., other aircraft), and things on the ground (e.g., aircraft takeoff and landings) [33]. The visualization of information has to be pragmatically displayed to a user for safety, timeliness, accuracy, and confidence of emerging events. Together, these attributes constitute the need for developments between SAM and user refinement for cognitive readiness [34] through an ontology.

Three emerging situation management topics are information management, visualization, and ontologies. Aviation awareness supports effective pilot and ATC understanding of their surroundings for such applications as take-offs and landings [35]. Likewise, efforts include airport management [36] and communications evaluation [37]. SAM *ontologies* are also developed in connection with threat prediction [38] and uncertainty reduction [39].

Information management methods and architectures are needed for future avionics enterprise systems (with UAVs [40]) for information fusion [41]. Information fusion includes many avionics concepts such as aircraft tracking, data monitoring, and an integrated picture for interactive user analysis. Future displays will seek methods for text, audio, and visual analytics of the information unfolding in a scene [42]. Human-derived text and sensor visual information analytics need to be matched with machine analytics for effective visualization.

Visualization of information is important for user interaction with the ontology data which is a HLIF decision support challenge [43]. For example, icons representing data analysis are important [44]. A recent example focuses on cockpit icon degradation [45]. Ontology-derived icons for displaying uncertainty which could improve safety in air traffic collision avoidance systems, mark traffic of impending hazards, and provide warnings of critical situations. Visualization efforts need to be tested with operators for usability, attention, and trust.

For many aerospace systems there has been a need for communication through ontologies in the air and on the ground. In this paper, we use the developments in UDOP visualization for situation management for ground operators that includes a controlled ontology to update semantic content. An example is the NASA ACES.

3.2 Airspace Concept Evaluation System

As an example of a complex avionics system, the National Aeronautics and Space Administration (NASA) has an effort called the *Airspace Concept Evaluation System* (ACES) [46] to explore air traffic management (ATM). ACES seeks to reduce flight delays, increase capacity, and mitigate risks in air transportation within the National Airspace System (NAS).

ACES focused on simulation [47], modeling, data integration, and user actions within a modeling framework for community understanding. Some of the developments and efforts include uncertainty analysis [48], complexity measurement [49], and trajectory analysis [50], which are all consistent with ontology developments. Similarly, information fusion ontology definitions are needed for safety and cost in routing and scheduling aircraft [51, 52], conflict scenarios [53], and user preferences [54]. Finally, a key aspect of ACES is the use of weather assessment for ATM [55].

Previous ACES efforts include visualization [56] and integration of flight physics, airspace configurations, airport layouts, weather modeling, and scheduling in the ACES system [57]. As related, the *IEEE Aerospace and Electronics Systems Society* deemed air traffic control (ATC) as a key next decade system engineering need [58].

3.3 Fusion with Ontologies

Three concepts for human interaction with digital avionics systems include situation awareness (SAW) [59], information fusion [60], and visualization [61]. Future aerospace applications need effective visualizations of ontology data for interactive human-in-the loop (HIL), or human-on-the-loop (HOL) developments, information management, and systems-level performance. HIL includes pilots with local SAW [62], whereas HOL includes ground operators such as air traffic controllers with global SAW [63]. Auxiliary supporting information can come from textual reports and mandates providing social and cultural persistent SAW [64]. Advances in visualization support SAW which could benefit from use of ontologies. For example, using ontologies can support Dynamic Data-Driven Application Systems (DDDAS) [65, 66, 67] reporting.

Some developments and applications of ontologies for information fusion include geospatial data alignment [68], semantic analysis [69], motion imagery [70, 71], and knowledge management [72]. Using discussions from civil aviation [73] and airport security operations [74], we seek ways to integrate the information from mandates, regulations, and real time operations. We will demonstrate the use of the ontology for ATM combined with visualization extending our 2013 paper [75].

4.0 Ontology Implementation

Ontologies have evolved as an emerging development starting from the W3C ontology. We are interested in ontologies with subjects, objects, and relations which are best discussed from the Semantic Web Stack.

4.1 Semantic Web Stack

The Semantic Web Stack, shown in Figure 4, captures the current state of the art of intelligent agents to process semantically structured knowledge.

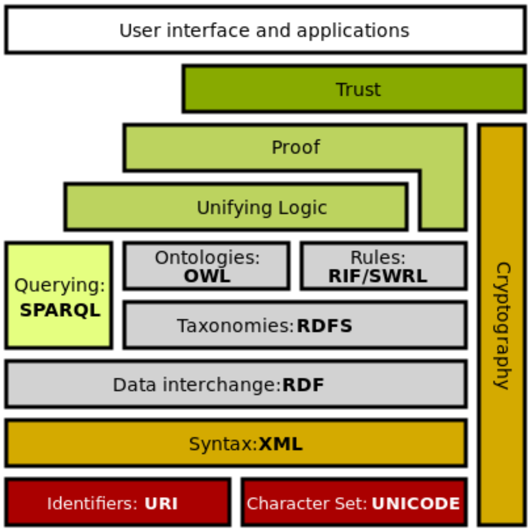

Figure 4. Semantic Web Stack [76]

(from: https://en.wikipedia.org/wiki/Semantic_Web_Stack)

There are four layers of importance:

- ***Logical layer***: Formal semantic and reasoning support (OWL), or ontology inference layer
- ***Schema layer***: Vocabulary Definitions (RDFS)
- ***Data Layer***: Simple data model for Metadata
- ***Syntax layer***: Markup Languages (XML)

Using these concepts, the syntax supports data aggregation (e.g., Flight profiles, Nav) and logical processing (e.g., NOTAMS). Methods exist for syntax analysis such as The Keyhole Markup

Language (KML), which is an XML file format that is used by Google® to represent geometry, points, and other geo-referenced information. Also, using these developments in an understandable method, builds trust [77]. A key enabler is the resource description framework (RDF), popularized by the W3C.

4.2 Resource Description Framework (RDF)

The semantic web represents data using the RDF framework about resources in a graph form [78]. RDF focuses on WWW resource data and capturing the metadata (e.g., Web page changes) using formal semantics. The paramount concept is triples *subject-predicate-object* that form a data graph. The normative syntax for popularizing RDF is XML.

A RDF Schema (RDFS) brings together description taxonomies, ontological constructs, and data models for triple-based graphs. With the RDF formal semantics, taxonomies of classes and properties are included in the resulting domain ontology, as shown in Figure 5.

Subject: Aircraft (thing)

Predicate: flies "close to" (activity)

Object: Airport (place)

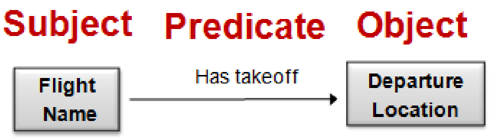

Figure 5. RDF for Avionics

4.3 Ontology Web Language

Building on RDF, the Ontology Web Language (OWL) enables more detailed ontologies [79] through formal semantics. OWL is derived from description logics, offers more constructs over RDFS, and is syntactically embedded into RDF. The results are a standardized vocabulary like RDFS. OWL options are:

- OWL Lite - for taxonomies and simple constrains,
- OWL DL - for full description logic support, and
- OWL Full - for maximum expressiveness and syntactic freedom of RDF.

Using the RDFS/OWL semantics, reasoning within ontologies and knowledge bases are possible with query languages. Using standardized query-based rules, emerging standards support RDF data queries, RDFS ontologies, and OWL languages. An example is Simple Protocol and RDF Query Language (SPARQL) [80]. SPARQL is SQL-like language, but uses RDF triples and resources for matching query requests for returning results. Since both RDFS and OWL are built on RDF, SPARQL can be used for directly querying ontologies and knowledge bases as well as a protocol for accessing RDF data.

It is expected that all the semantics and rules will be executed at the layers with logic over class constructs (see Tables 1 and 2) and the results will be used to prove deductions. Formal logic (e.g., proofs) together with reliable inputs for the proof will mean that the results can be trusted. For reliable inputs, cryptography means are to be used, such as digital signatures for verification of the origin of the sources. On top of these layers, application with user interface can be built.

The class constructs follow formal definitions using: C is a concept (class); P is a role (property); and x is an individual name for description logic (DL).

Table 1. Class Constructs

Constructor	DL Syntax	Example
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	Location $\sqcap$ Airport
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	Pilot $\sqcup$ ATC
complementOf	$\neg C_1$	$\neg$ Pilot
oneOf	$\{x_1\} \sqcup \ldots \sqcup \{x_n\}$	{PRG} $\sqcup$ {SAC}
allValuesFrom	$\forall$ P.C	$\forall$hasChild.Pilot
someValuesFrom	$\exists$ P.C	$\exists$ hasChild.ATC
minCardinality	$\leq$ nP	$\leq$1hasChild
maxCardinality	$\geq$ nP	$\geq$2hasChild

Table 2. First Order Logic (FOL) Rules

Constructor	DL Syntax	FOL Syntax
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	$C_1(x) \wedge \ldots \wedge C_n(x)$
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	$C_1(x) \vee \ldots \vee C_n(x)$
complementOf	$\neg C_1$	$\neg C_1(x)$
oneOf	$\{x_1\} \sqcup \ldots \sqcup \{x_n\}$	$x = x_1 \ = \vee \ \ldots \vee = x = x_n$
allValuesFrom	$\forall$ P.C	$\forall y.P(x, y) \rightarrow C(y)$
someValuesFrom	$\exists$ P.C	$\exists y.P(x, y) \wedge C(y)$
minCardinality	$\leq$ nP	$\exists^{\leq n} y.P(x, y)$
maxCardinality	$\geq$ nP	$\exists^{\geq n} y.P(x, y)$

Common components of ontologies include [18]:

- *Individuals:* basic instances or objects
- *Classes:* sets, collections, concepts for programming
- *Attributes:* aspects, characteristics, properties, features, or parameters of objects and classes
- *Relations:* correspondence between individuals, classes and attributes
- *Function terms:* complex relational structures used in place of an individual term in a statement
- *Restrictions:* formally stated input descriptions of what must be true in order for accepted assertions
- *Rules:* if-then (antecedent-consequent) sentence statements that describe the logical inferences
- *Axioms:* logical form assertions (including rules) in a logical form (generative, formal, or derived) describing the domain ontology (Table 1 and 2)
- *Events:* attributes or relations dynamic changes

4.2 RDF Avionics Graph Example

With communications between ATM/ATC, there is needed a common semantic text ontology. For example, ***'Flight takes off from Departure and arrives at Destination'*** can be in a database, from audio communication or a message. The annotation connects an aircraft with its departure and arrival points. The following HTML-fragment shows, how a small graph is described, in RDF-syntax using a designated schema.org vocabulary:

There are there elements such as the *subject*:

http://schema.org/name

http://schema.org/nameType

http://schema.org/**Aircraft**

the object:

http://schema.org/itemType

http://schema.org/**Depature**

http://schema.org/**Destination**

and predicate:

http://schema.org/**takeoff**

http://schema.org/**landing**

The RDF graph resulting from the example is shown in Figure 6.

```
<div vocab="http://schema.org/"typeof="Aircraft">
   <span property="name">Activity</span> took off from
      <span property="takeoff" typeof="Place" href="Flightprofile">
   <span property="name">Departure</span>.
  </span>
</div>
```

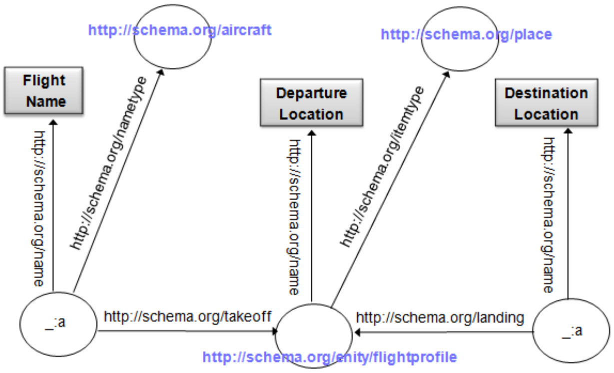

Figure 6. Avionics RDF graph

The example defines the following seven triples (shown in Turtle Syntax). Each triple represents one edge in the resulting graph: the first triple element (the *subject*) is the name of the node where the edge starts, the second element (the *predicate*) the type of the edge, and the third element (the *object*) either the name of the node where the edge ends or a literal value (e.g., a text, a number, etc.). The graph resulting from the RDF example, is enriched with further data from the airspace systems in Figure 7 such as:

green edge: http://schema.org/Aircraft

blue edge: http://www.schema/entity/flightprofile

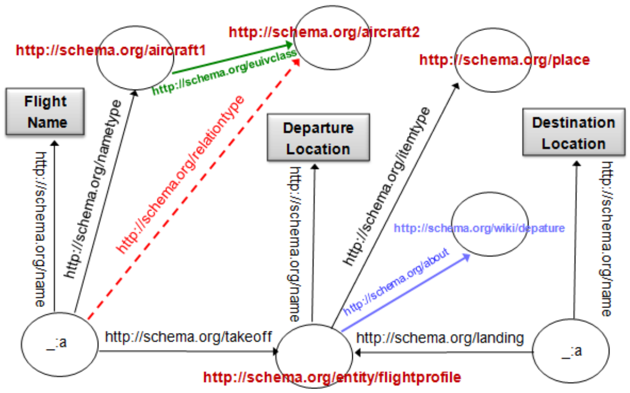

Figure 7. Enhanced RDF graph

Additionally to the edges can be automatically inferred from explicit document data: the triple

_:a <http://schema.org/rdf-syntax-ns#type>
<http://schema.org/Aircraft1>

from the original RDFa fragment and the triple

<http://schema.org/
Aircraft1><http://schema.org/Aircraft1/owl#equivalentClass><http://schema.org/ Aircraft12>.

from the document at http://schema.org/Aircraft (green edge in the Figure) infers the following triple, given OWL semantics (red dashed line in Figure 7). With the data, there is a need for visualization.

5.0 Examples

In these examples, we extend our user-defined operating picture (UDOP) visualization techniques to highlight the use of ontology which adds textual context to the airspace picture.

5.1 Visualizations

Figures 8, 9, and 10 show examples of semantic updates, on top of geophysical data, including NOTAMS, density, and flight profiles; respectively. Note that the flight profile can be related to the RDF graph example. The ontology data can be further developed for future cockpit designs [81, 82, 83].

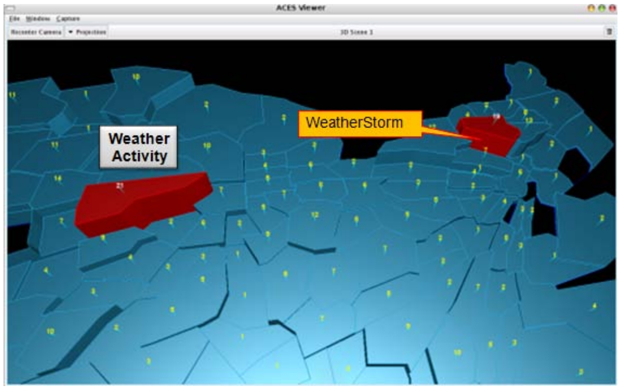

Figure 8. Semantic-Based Weather Map Update

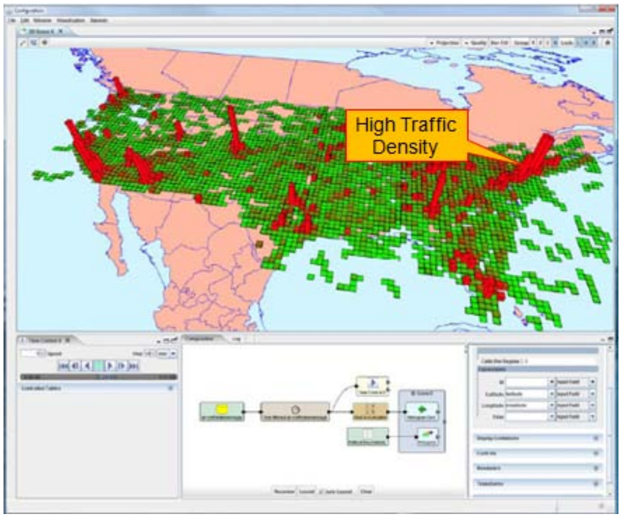

Figure 9. Semantic-Based Airport Map Update

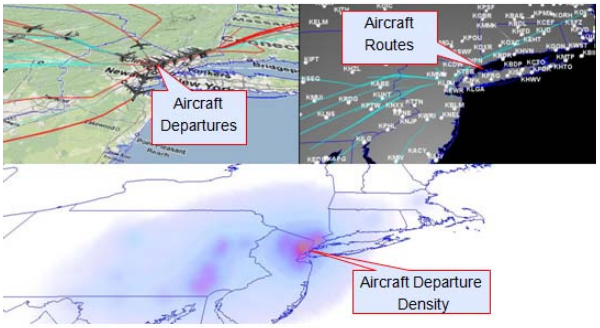

Figure 10. Semantic-Based Route Map Update

5.2 Performance Analysis (Risk)

In many flight situations, responding to emergencies is a key desire. In this scenario, we are looking at identify risk with new technologies. Risk can come from pilots [84, 85], power [86, 87], and/or life-cycle development [88] errors.

NextGen will increasingly rely on integrating multiple systems and information sources together to enable improved performance/responsiveness, generate safety/reliability, and reduce uncertainty/error. In this case, we simulate the a constant coordination between interactions spanning ground automation systems, Automatic Dependent Surveillance-Broadcast (ADS-B) surveillance, cockpit flight management systems and displays, precision navigation, data communication, new operating procedures, and collaboration tools between cockpit, facilities, and airlines.

During Trajectory Based Operations (TBO), the ontology departure to landing includes warnings that are updated to a fused system. When the fused result is overlapped in semantic analysis, a warning is sent to the airspace system to identify to all the possible safety challenges. Figure 11 shows the fusion of NAV and ontology-based semantic event identification updates while Figure 12 is a combined probabilistic (e.g., PROWL) risk update. The use of controlled semantic data through the ontology assists in identifying a risk, which can be reported as a warning to the pilot or ATC.

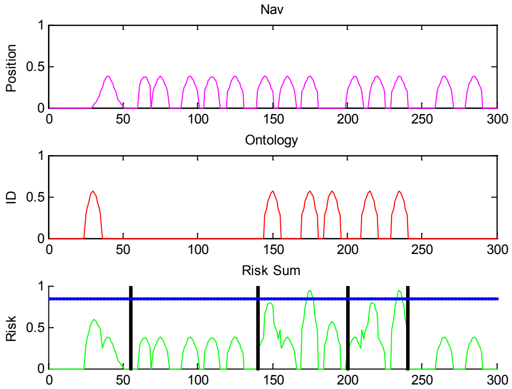

Figure 11. Fusion of Nav (CNS) Position Data with That of Ontology-Based Semantic ID Text Data

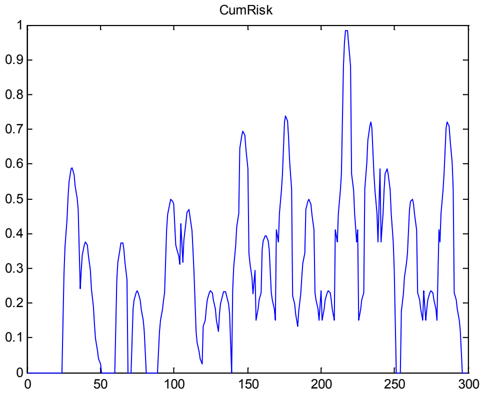

Figure 12. Combined Risk Analysis

6. Conclusions

In this paper, we focused on the use of ontologies for analysis of both mandates and real-time messages that support future avionics systems. Recent developments in the NextGen/SEASAR were presented, along with a use case avionics example using a resource description framework (RDF). By abstracting an ontology, we provided an analysis to show how the inclusion of ontologic analytics of semantic information can be combined with that of communications, navigation and surveillance (CNS) position information to help assess risk for safe air traffic management.

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