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Ontology-based Knowledge Management for Space Data

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Abstract

This paper discusses some ways ontologies help with knowledge management. The discipline of ontology engineering in relation to knowledge management is briefly explained. Summaries of projects using ontological models in their knowledge or information architectures for space data, astronautics and space science are provided. The author's space ontology development efforts are presented.

Keywords: knowledge management, knowledge representation, ontologies, ontology, ontological engineering, ontology-based modeling, space ontology, big data, space situational awareness

1. Introduction*

The data-intensive nature of space-related disciplines calls for tools to help understand, structure, share, and draw actionable conclusions from that data. Astronomy, astronautics, aerospace computing, space situational awareness, and earth science and remote sensing are some disciplines that can use ontologies as part of their knowledge management architectures.

To safety and efficiently operate in space, conduct space science, and maintain awareness of the orbital space environment, the space domain community needs to leverage not only the information contained in legacy data (and in the growing volumes of space data), but also the knowledge of subject matter professionals.

Towards this, knowledge engineer and ontological engineering may be used to: express knowledge in a computable format, foster its discovery, help with decision support; and facilitate data search, sharing and integration of space data.

This paper discusses how ontologies may help with knowledge management (section 2). Summaries of projects that use ontology-related approaches to space data/disciplines are given in section 3, including the authors on-going project. From this we glean some perceived goals and benefits of ontology engineering. Section 4 offers a discussion with ideas for partnerships, and 6 concludes the paper.

2. Ontology in Knowledge Management

Knowledge Management involves the organization and formal expression of knowledge for problem-solving. That formal expression may be in structured form for human users, as well as a computable form for machine processing. Knowledge management is thereby related to *knowledge engineering*, a branch of Artificial Intelligence (AI).

Ontology development and engineering is a research field in AI. It is used for knowledge representation and engineering, is related to informatics, is considered a semantic technology. In the historical context of the internet and semantic technologies, ontologies represent a means to capture and communicate greater meaning than previous tools.

Ontology engineering has been described as "the set of activities that concern the ontology development process, the ontology life cycle, the methods and methodologies for building ontologies, and the tool suites and languages that support them." [0]

The relationship between knowledge management and ontology engineering can, in part, be described in this way: the process of knowledge management involves knowledge organization and structuring, which "[…] is done through ontologies (ontology engineering)" [1]

The ontology development process involves the design, development and implementation of **computational ontologies**. Computational ontology can be broadly understood as a modelling tool for describing the meaning of data and the content of some area of interest (or domain). It is but one tool or approach in knowledge management.

Ontologies of a particular domain (domain ontologies) provide formal abstractions of domain knowledge [2], and a formal expression of the concepts and semantic relations in some topic [3]. Ontologies are used for different reasons, one of which is to represent some conceptualization of a universe of discourse,

* This paper (and [12-18]) was created independent of author's past and present affiliations.

knowledge domain, or aspect of the world in a way that computers can process. This particular goal is common to the related fields of AI, database management and software engineering [4].

Computational ontologies are composed of a machine-readable terminology with a formally-specified semantics. Ontologies serve as catalogues of terms or concepts used to represent knowledge of some domain.

Not only are there various approaches (methods, methodologies, etc.) to ontology development, but there are various ontology architectures (e.g., consider [16]) as well as definitions/descriptions of *ontology*. Some other descriptions are as follows.

- An ontology "defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary." [5]
- an ontology is defined as "an explicit specification of a conceptualization" [6] (This definition can be understood as implicitly expressing the preceding)
- "Ontology may be thought of as a terminology for representing a conceptualization" [7]
- Ontology is the study or analysis of the fundamental concepts and relationships in a domain [8].

The meaning of terms and data—the semantics—is specified using an implementation language (also called a *knowledge representation language*), such as Knowledge Interchange Format (KIF), Common Logic Interchange Format (CLIF), and Web Ontology Language (OWL). To paraphrase Lowell Vizenor, the ontology vocabulary is written in a technical language to be used by computers for drawing inferences and identifying inconsistencies. While this affords computability, natural language definitions afford human readability. To reach the implementation stage, subject-matter research, and conceptual development are on-going tasks.

2.1 How ontologies may help with knowledge management of space data

Some functions of ontologies have already been mentioned. This section discusses a few in more detail, which will also be seen in section 3's project summaries. For example, if knowledge management is about organizing and representing knowledge, ontologies provide one means to do precisely that.

2.1.1 Classification & Structuring Data

The set of terms in an ontology represents (or otherwise express) concepts of the target/problem area. Categories terms provide a *means of grouping*, and thus *organizing*, others. They help describe the characteristics of individuals in the domain. Relational terms among non-relational category terms help capture either the relationships in the domain, or in the intended semantics. Combined with computable definitions, this provides a structured and consistent formal representation that ideally communicates intended meaning, knowledge, and subject matter content. It offers a computable formalization of meaning that is also human-readable. Ontology terms can be used to tag or annotate data housed in databases.

2.1.2 Inference & Automated Reasoning

Reasoning engines (inference engines, or automated reasoners), when together with software package, affords making inferences, and performing quality assurance on ontologies.

User-specified queries on the ontology and ontology-annotated data can be answered. Some query languages include SPARQL, and OWL-QL. Query languages can be for specific web formats or formalisms such as RDF, OWL, Topic Maps [21].

Reasoners can perform consistency checks, and classification checks, among other quality assessments. Some reasoners include Racer, Pellet, ELK, Fact++, HermiT.

2.1.3 Semantics

Ontologies are capable of providing a greater degree of semantics than other knowledge modelling tools. "An ontology captures the semantics (i.e., data meaning) needed to allow data to be properly interpreted. One benefit […] is that it captures semantics not readily available", namely "often intrinsic knowledge captured in the minds of domain experts or documented in separate reports." [35]

The meaning of terms and data elements can be specified to varying degrees of abstraction and formality: from a set of defined concepts in an OWL file to a full logical axiomatization of all terms and their definitions. This translates to greater expressiveness. More knowledge can therefore be communicated and represented and to a higher level of detail.

According to [9], the advantages of encoding domain knowledge in ontologies are: facilitating the integration of heterogeneous data; guiding data mining algorithms via ontology constraints; and helping experts visualize and validate the extract units. We read that ontologies help create "models which play a role in the ongoing collection of human knowledge".

Limitations on expressivity depend, in part, on the formalization employed (the implementation language), time, and computing power.

2.1.4 Data Sharing and Integration

Ontologies are held to stimulate data-sharing and data-integration among disparate databases by providing a common vocabulary and semantics for each. According to Keller et al. [60] "One of the most important and challenging knowledge management problems faced by NASA is the integration of heterogenous information sources" and how "the information stored on these different data sources [and in different formats] are *semantically* [if at all] related". They list three specific problems: data sources may not capture meaning, the user's world view, and each source may store data in different formats or languages.

One approach to ontology-based data-sharing is developing a terminology or taxonomy at a higher level of abstraction than the terms, fields, or data elements in each actor's database. It provides terms that can classify or annotate database terms or terms from a more specific ontology. One challenge in this process is reaching agreement on the vocabulary.

According to [10], ontologies enable "mediation between systems in a Web Services model. When implemented with controlled vocabularies and taxonomic underpinnings, ontologies enhance reusability, search results, reliability, and knowledge acquisition."

We also read "The idea of creating ontologies to support the integration of diverse information models is the result of extensive research activity to find a solution to the problem, interoperability of the information, necessary for enabling integrated management. […] The use of ontologies is based on the assumption formal representations can enable computing systems to use any information that is relevant for a particular domain in other domain in mutual or individual benefit."[11]

3. Ontology in Astronautics and the Space Sciences

This section summarizes some ontology- and knowledge management-related projects for space-related data. Through these synopses we glean some insights into the perceived utility of ontology in knowledge architectures.

3.1 Orbital Space Domain Ontology Project (Space Situational Awareness Ontology)

The Orbital Space Environment Domain Ontology project† is an on-going project by Rovetto [12][13][18] to develop a domain reference ontology or set of ontologies for the orbital space domain, which includes space situational awareness (SSA) [14][17][18].

The formal ontologies and terminologies express and represent:

- fundamental orbital concepts (orbital dynamics)
- spacecraft, other orbital space objects, & their parts
- space systems
- sensor measurements
- SSA processes and networks
- astrodynamic models
- other relevant domain knowledge and entities

One goal of the project is to develop consistent, accurate and reusable terminologies, taxonomies or classifications of domain entities for the space domain community and interest users. Taxonomies for space objects in general, types of spacecraft and debris in particular, are examples.

For example, some high-level (generic) but domain-specific classes in the ontology include: Orbit, Keplerian Orbital Element, Orbital Inclination, Spacecraft, Spacecraft System, Spacecraft Component, Space Object, Orbital Object, Payload, Ground-Based Sensor, Space Object Detection Event, Space Object Observation Process, etc. Two sample ontologies under development are as follows.

The Orbital Debris Ontology (ODO) [15]‡ seeks to support orbital debris remediation by ontologically modeling orbital debris, developing accurate and reusable debris classifications, and facilitating debris data sharing and integration.

The Space Situational Awareness Ontology (SSAO) [15] is tentatively§ a broader ontology whose domain coverage is all space objects in the orbital space environment together with relevant SSA entities. These include space object observations, SSA networks, etc. The SSAO has been used in the Ontology-Oriented Orrery [36] by D.A. O'Neil of NASA Marshall Spaceflight Center, demonstrating how to generate an ontology-driven interactive visualization of a solar system. This project will, in part, show data scientists, programmers and users how to apply ontology to create web-based space mission visualizations [61]. It does so by using the ontology's content (orbital parameter categories), instance data from external files (such as orbital parameters), and knowledge modelling editors. It has continued to serve as a research topic in the NASA Datanauts Open Data initiative [37][62].

With an appropriately demarcated domain, the resultant modular ontologies will answer user-defined queries, such as whether a particular set of orbital parameter values implies a certain orbit type. By formalizing domain knowledge and declaring rules (e.g., using SWRL), automated inference is afforded. The ontologies under development are being implemented in OWL using Protégé editor. Future implementations will be in Common Logic Interchange Format or CLIF. These ontologies can be tailored to serve as application-specific ontologies and domain ontologies.

† https://purl.org/space-ontology

‡ https://arxiv.org/abs/1704.01014

§ Ontology name and structure are subject to change as scope and demarcation of sub-domains are specified.

The project has been an unaffiliated and independent one from its inception, but the author seeks partners, subject-matter experts, and funding for its sustainable development.**

3.2 NASA Taxonomy

The goal of the NASA Taxonomy was to enable knowledge discovery [19], providing easy access to NASA Web resources, information integration, improving search results, and facilitate records management.

The 2.0 taxonomy is dynamic and modular, and represented "first steps towards the unification of the NASA information space by documenting a high level set of terms that can be used for mapping together varying data structures" [20]. Files available at https://github.com/nasa/dictionaries

Various terminological and information architecture tools, including taxonomies, controlled vocabularies and ontologies are mentioned. We read: "Once terms are defined through the use of taxonomies and RDF statements, their relationships to other terms can be specified through the use of ontologies. Ontologies for the Semantic Web are most commonly composed of a taxonomy tailored for the data and a set of inference rules." [10]. An ontology is therefore a more complex artifact for expressing meaning, than a stand-alone taxonomy.

3.3 NASA SWEET Ontologies

The NASA Semantic Web for Earth and Environmental Terminology (SWEET) ontologies are a set of approximately 200 modular ontologies, collectively consisting of approximately 6000 category terms [22]. It is intended to provide a knowledge base to represent Earth science data and knowledge.

According to [9], its taxonomy stems from NASAs Global Change Master Directory (GCMD), a *controlled vocabulary*. SWEET was originally developed to improve search of NASA Earth science data. Other goals were to:

- help integrate data from Earth & environmental communities
- improve the discovery of satellite data products
- improve understanding of web resources used for Earth science data, e.g., by enabling the same concept to be represented in various phrases
  - SWEET semantic annotations are used to reconcile the difference in semantics of terms from distinct Earth science data resources

The ontologies are formalized in OWL, and can be extended by more specific ontologies. The most general terms are: Representation, Process, Phenomena, Matter, Realm, Human Activities, Property, State, and Relation. *In totto*, it contains many classes that overlap with other disciplines.

** Interested parties, including professors (for studentship opportunities), should contact the author.

3.4 ODISEES

The Ontology-Driven Interactive Search Environment for Earth Sciences (ODISEES) [23][24] project was designed to achieve data discovery, search and organization. [23] notes the challenge of "storing, managing and distributing vast amounts of data and providing user-friendly tools" to do so.

The ontology-based approach in ODISEES sought to offer a method to address that challenge. Toward the goals of allowing layman and researchers access, find and compare data products, ODISEES was designed to:

- model Earth science concepts, objects and the corresponding interrelationships toward a common Earth science domain model;
- map defined terms from Earth science user groups to that model; and
- create computable definitions of community-based terms. [23].

It has inferential capabilities through a logic-based model.

ODISEES "was structured with the intention of merging a controlled vocabulary with useful deductive reasoning systems that can support semi-intelligent applications." A positive feature of ODISEES is its *flexibility*: "even if the application requirements change, the model can be easily adapted" accordingly.

In a helpful and succinct passage on the historical context of ontologies, the authors state that although ontologies have more recently been understood as "controlled vocabularies that are used to provide semantic content for marking up data objects for the Internet", "the term 'ontology' continues to be subject to multiple interpretations", ranging from terminological resources/languages such as taxonomies, relational models, and XML (which do not provide a semantics) to detailed logical theories. They also note that ontologies can be developed to various scales and scopes.

Finally, supporting ODISEES is the NASA OlyMPUS project, a data access, delivery, and metadata provisioning tool. It's goals are "to enable researchers to seamlessly find and retrieve variables of interest from multiple disparate datasets and create custom data subset" [25] It provides "an Ontology-based data model implemented as an RDF triplestore" with additional objectives being to "enhance [the] search functionality" of ODISEES, and "populate [the] ontology with semantically rich metadata".

3.5 NASA Planetary Data System Ontology

The Planetary Data System (PDS) is an archive of data and metadata for the planetary science community, started in the 1980's. Its subject matter involves "dynamic contexts within which the data is collected - orbiting target bodies, moving instrument platforms, and a plethora of reference frames" [26] The PDS "is tasked to ensure long-term preservation and usability of big scientific data" [27] in disciplines such as Planetary Plasma Interactions, Rings, Small Bodies and Atmospheres.

During a redesign of the PDS [27], semantic approaches were taken, including an ontology of the PDS model [28]. The PDS model, intended to be independent of its implementations, contains mission, spacecraft, and instrument metadata. Using RDF/XML, the ontology contains classes such as Data_Set (and sub-classes), Mission, Person, Instrument, and Target.

We read these actual and potential benefits. "The capture of the data model as an ontology has resulted in a more formal and richer specification of the planetary science domain model. It reveals both known and unknown weaknesses in the model and provides alternate methods for analyzing and documenting the model." [26]

Ontology editor tools, they explain, will "help convert unstructured knowledge into a formal specification that describes the 'things' in the domain. Domain knowledge is captured in these tools in a language or notation that is expressive enough to capture the majority of the information that can be depicted in a Unified Modeling Language (UML) class diagram."

"Semantic Web technologies also suggest the means to support correlative science across science disciplines, missions, and instruments since they were designed to support inter-operability among digital assets."

Storing information about properties "will make migration of future data simpler. The mapping simply has to be done once between the data and the ontology."

Finally, toward the claim that "NASA requirements to support interoperability across […] archives will require the integration, and in some cases development, of domain ontologies" [29], we read the following. "Large scale data system interoperability can be now be envisioned where 'semantically aware' software agents reason about and process distributed science data repositories." [26]

3.6 ESA Earth Observation

The European Space Agency (ESA) Earth Observation (EO) Knowledge Navigational System is a knowledge management system for EO imagery (and other) data. It was "field-tested in the Remote Sensing Exploitation Department" at the EO Observation center and "offers an EO application-related knowledge-based system on the Internet."[30]

EO is a field "where data and terminology need to be presented to users in an understandable language and customised to meet particular requirements." The EO ontology elaborated in the project models "the major EO science, engineering and user components".

The project's knowledge model includes three layers: a user concepts layer; a semantic network (or conceptual knowledge model) layer composed in part of classes and their associations; and finally a layer consisting of instances of each class, taxonomies defined by the previous level, and rules for search. "The conceptual model links to the real objects at the instance level which is implemented according to the specific internal/physical model of the database system."

3.7 IVOA Ontology of Astronomical Object Types

The International Virtual Observatory Alliance (IVOA) has an Astronomy ontology [31], with work by Dr.Shaya of the University of Maryland [32]. The ontology captures knowledge about types of astronomical objects, and draws from the SIMBAD database [33].

Some relational and non-relational terms used to describe Astronomical entities include: AstrObject, CompoundObject, AstroPortion, Galaxy, DoubleStar, EMSpectrumRange, Morphology, Measurement, Process; hasPortion, hasComponent, hasMorphology, hasProcess, hasProgenitor, isClassifiedBy.

The technical publication characterizes ontologies as *structures that represent and formalize knowledge*. Applications and functions of ontology for astronomical data include:

- new ways to share information between astronomers and machines;
- allowing inference engines to reason over astronomy knowledge bases;
- classification; semi- and fully-automatic semantic consistency checks of database entries;
- building/refining queries

Other noteworthy aspects of ontology development they mention are as follows. First, they imply that automated reasoning is hindered by lack of formal definitions. To more fully realize the *semantically-rich* potential of ontologies, developers should utilize the definitional capabilities available to them. Second, we read: "[…] when the astronomical knowledge evolves, one just has to update the ontology accordingly and the systems exploiting it will take the changes into account". This reflects the need for a dynamic knowledge system. Third, different implementations offer different capabilities and limitations. Some dimensions are: the choice of implementation language, the choice of inference engine, the ontology editor program, and the naming conventions.

Some considerations, consequences and tradeoffs when making implementation decisions and when testing the ontology are:

- the complexity of the logic;
- formal restrictions that may require more CPU processing;
- and that the greater the complexity of the ontology (e.g., the size and detail), the more challenging it is for reasoning, maintenance and use.

Some implementation choices may increase reasoning time, which may or may not be manageable in real world conditions. Three ways to resolve unmanageable reasoning times are: reducing the ontology size, using simpler logics and writing simpler formal (property) restrictions. This may reduce expressivity and possibility domain accuracy, however.

Fourth, the choice of definition (for a given concept/class) may depend on the *use* of the ontology. In other words, "having multiple definitions can be either a good or a bad thing". It depends, in part, on whether definitional parts are formalized and used in the ontology (see their example on DoubleStar).

Fifth (related to the third point): "there is no unified procedure for building ontologies". Ontology development is at least an iterative process.

Finally, Astronomy is a *big data* field, requiring processing of various astronomical data-sets. In that regard astroinformatics [34] is relevant, and may make use of ontologies.

3.8 Space Surveillance XML Schema

Pulvermacher et.al.[35] developed a space surveillance schema using the Extensible Markup Language (XML). They describe their XML "[…] approach invented to capture data structure, content, and semantics in a targeted military domain of space surveillance [...] as a step toward achieving data interoperability for military space data across domains". This was in the context of the 2000 military Joint Vision 2020 document. and define an ontology as being "[...] the mechanism that captures the definitions of information elements, the individual data items, and the associated interrelationships".

Although XML schemas are not ontologies [50], the terms 'space surveillance schema' and 'Space Surveillance Ontology' were used interchangeably. We read that their "ontology approach […] captures data structure, content, and semantics [metadata and data definitions] all in the XML Schema vocabulary", resulting in a Space Surveillance Ontology.

Its purposes included understanding the applicability of XML for space information objects; and whether it could be expanded upon by other efforts. Emphasis is placed on the fact that ontologies capture data meaning. They state that understanding the meaning of data is necessary to achieve interoperability. The Extensible Stylesheet Language (XSL) is used to transform XML-tagged data to a human-user readable form.[††] XML Documentation annotations are also used to express the meaning.

Schema files for the military space surveillance domain included those for Satellites, Sensors, Element Sets, Observations and Tasking. The authors make good points explaining the separation of these areas. For example: element set information is (more) dynamic than satellite information. Additionally, declaring something as an attribute or an element is an open question. The latter is important because it communicates the various *modelling possibilities* in semantic approaches and knowledge representation. A final noteworthy point is that "[o]bject representation and content will vary depending upon the domain perspective", which partially reflects that objects can be grouped in different ways, some of which may contrast with how data is operationally used.

3.9 Semantic Data Grid for Satellite Missions

In [38], semantic technologies are applied to grid[‡‡] technologies. A semantic layer with ontologies is added to a grid system for satellite mission analysis.

They describe the aerospace domain as having "a strong need to share both data and computational resources for complex processing tasks" in part because of the domains "heterogeneous network of facilities and institutions". This highlights the often-mentioned function of ontologies to facilitate data sharing.

The ontology services "store and provide access to the conceptual models representing knowledge", whereas the reasoning services "[…] support computational reasoning with those conceptual models" and metadata services "store and provide access to semantic bindings" and finally "the annotation services generate metadata from different types of information sources, like databases, services and provenance data" [38].

The information model of the architecture classifies ontologies as knowledge entities. We read: "In this system we had a single ontology including classes for times, planning systems, macrocommands, satellite instruments, and the details of the various plan and product file metadata. Ultimately there needs to be a set of ontologies to cover the whole satellite mission domain."

By "[…] having an ontology which included instruments and types of events as objects independent of the individual events which they classify" the system was augmented with knowledge about which event types used which type of instruments [38]. In other

[††] By contrast, contemporary ontologies have built-in ability for human readability.

[‡‡] A grid system is described as a system of distributed but connected resources.

words, developing an ontology allowed representation of *general knowledge* and *generic domain conceptualizations*, not only information about individual things, such as a particular satellite.

We read: "The addition of [this] 'generic' information […] allows us to have semantically rich annotations. This semantic approach to queries where they are moved up to greater levels of abstraction gives us much more flexibility and robustness over time, as we are querying what the users need to know (usage of the instrument) rather than what we traditionally have recorded (the list of codes used for the event types)." [38]

3.10 NASA NExIOM Ontologies

The NASA Exploration Initiatives Ontology Models (NExIOM) was "a semantic approach to knowledge reuse within NASA" during the Constellation program. Some goals include the "creation and maintenance of consistent terminology; enabling translations of concepts across multiple autonomous vocabularies; improved specification of queries for information retrieval; and improved integration of data and interoperability of processes and tools across the lifecycle." [39]

The vision of NExIOM was a "NASA–wide, lifecycle-aware knowledge infrastructure". It consists of at least 126 ontologies implemented in OWL, with 81 namespaces each representing a distinct subject area.

NExIOM ontologies "formalize the way machines (and people) refer to NASA Elements, their Scientific and Engineering disciplines, related work activities, and their interrelationships in the Enterprise." [40] They were developed in a modular architecture with reusable models[§§], and to different degrees of specificity. They were intended to connect enterprise architecture systems to systems engineering models.

These ontologies characterize devices in functional hierarchies, one ontology being the NASA System Ontology. There were category terms for engineering, process, and enterprise knowledge. An example formal statement (in subject-predicate-object form) is: *Tool analyses MissionRisk*. The architecture also involved an ontology-based grammar engine for naming and rules.

In totto, the NASA Constellation Data Architecture defines "consistent, unambiguous data representations and implement repeatable processes for data exchange in order to enable data sharing within and across Constellation Systems, Organizations, and Missions", [41]. Ontologies were, thus, explored as a tool in this architecture.

Finally, related to NExIOM are the QUDT (Quantities, Units, Dimensions and Data Types) ontologies, which were developed for NExIOM [42].

[§§] E.g., the Orion Model, named after the spacecraft.

3.11 International Space Station Schema

Bonasso et al. [44] claim that a challenge to "use of automation techniques for operations is capturing and maintaining the domain models needed to support such techniques" and so they "seek to develop a framework for consistent ontological modeling across domains".

They describe an editing system allowing NASA subject-matter experts to create and maintain ontological information that is usable by automation [43]. Ontologies were developed to support *space systems*, such as the International Space Station (ISS), with a modelling focus on *procedures*. They model relationships between systems and locations of components, as well as procedures.

More specifically, a domain ontology for automation systems was developed to capture the relevant types of entities, "their possible states and configurations and the relationships" among them. The base ontology, for example, contains ontological information about all ISS systems. Other ontologies are considered extensions for distinct flight disciplines, including electrical power systems and extra vehicular activity (EVA).

Some ontology classes include: Abstract Entity, Physical Entity, Geometry, Configuration, State, Location, Object, Station-object. Relation terms include: component, attached-to, startboard-of, port-of, contains.

The Procedure Representation Language (PRL), proposed for NASA's Constellation program for procedure automation was used to help represent spacecraft procedures. They identified these benefits:

- a domain model usable for each automation project;
- unification of disparate EVA and non-EVA information
- fast updating of ISS configuration information (affording automation applications to output results based on recent data); and
- semantic mapping between external data sets and user-created ontologies.

One of three difficulties in the ontology development process they cite is: that subject-matter experts think in terms of their subject, not in terms of formal logics used in ontology-authoring applications. This is important because it should make ontologists aware of (and take care with regard to) the differences in expressivity; the potential loss of expressivity, and the difficulty, in translating subject-matter conceptualizations to (perhaps more rigid) formalisms.

The authoring tool they constructed allows domain experts to form ontological models without needing skills in implementation languages or inference patterns. Their PRONTOE editor application allows users to author class hierarchies, instances and relations in order to populate an ontology.

The graphical display of the editor is helpful from both a pedagogical and general user-interface perspective. It allows the user to visualize each component of the ISS, and taxonomies can be seen alongside what the terms are intended to represent.

3.12 Spacecraft components in XCALIBR

The XML Capability Analysis Library (XCALIBR) mentioned in [51] is “a spacecraft ontology, used for the ‘plug and play’ assembly of spacecraft” that describes relations between components. It is described as supporting “designers in determining the dependency of component on other[s]” Neff et al. [52] describe XCALIBR as a spacecraft taxonomy and ontology database, providing “a common data vocabulary that uniquely defines a finite set of spacecraft components and their structural and functional relationships.” It could help non-experts to define “the bus and payload for rapid-response spacecraft”, and “automatically defining component interfaces”.

3.13 ProjectChronos

A SpaceApps Challenge participant, called ProjectChronos, describes their project as integrating information about space missions from NASA, ESA, and JAXA by their learn-by-playing paradigm. It involves the development of RDF ontologies [52]: one for aerospace engineering concepts; astronomical objects; astronomical objects specific to our solar system; spacecraft and their systems; one for subsystems of a spacecraft; detectors; and space exploration and mission design. Classes and object properties are inherited from sources such as OpenCyc[***], DBpedia, and Umbel sources.

3.14 ULISSE

The European Commission funded project, USOCs Knowledge Integration and dissemination for Space Science and Exploration (ULISSE) [45][46][47] “aimed at improving preservation, valorisation and exploitation of the data produced across multiple domains by European scientific experimentation […] on the International Space Station (ISS) and other space platforms.” [48]

The USOCs (User Support and Operations Centre’s) around Europe are part of a decentralized architecture handling space data. The final report [48] states that “[s]pace data and experiment results are presently dispersed over numerous archives and databases in Europe”, and that the overall situation "represents a bottle-neck for the complete exploitation of the scientific data of ISS experiments”.

ULISSE, then, aimed to address this via a system that included semantic technologies. We read: "to ensure the usability of space data in the future, it is necessary to provide also a description of the data (metadata), technical information about the experiment equipment and the space platform and knowledge about environmental conditions.” “Knowledge management in ULISSE is based on the Topics Maps approach” and used XML metadata. “The structure of a Topic Map is represented by an ontology; any subject in the knowledge domain ontology is represented by a topic. Each topic may have a type, structured in a hierarchy.”

Knowledge engineering tasks were knowledge representation through ontologies, and “creating metadata and knowledge for a subset of experiment data”.

Two ontologies were developed: (1) "an experiment ontology representing the metadata structure that is common to all disciplines and that includes information on the data and on the experiment” and (2) “an ontology of the scientific domain […] which captures some main concepts […] enabling the association among them.” "Topics of an ontology are linked through associations; each association is characterized by a name and other features".

They used the ScienceCast web-based browser tool to edit topic maps and their ontologies, and to make natural language queries over the topic maps. ScienceCast was developed for browsing, editing and sharing scientific research data. It is a “flexible way to represent disparate sources of information” [49]. In all, they sought to determine “the feasibility and the usefulness of a data e-infrastructure for ISS.”

Some positive results includes the following. "The use of semi-formal knowledge representation and of semantic technologies allows […] users that are not acquainted with the ISS research domain to access the information in an easy and natural way”, which makes the data usable to a wider audience.

Two very interesting points are worth mentioning. First, “a major impact has been recognised for education; the knowledge captured in the ULISSE Topic Maps can be used to construct dynamically explanations of phenomena or instruments, linking also these explanations to experiment data for a better comprehension. These features allow a fundamental level of knowledge transfer from space specialized research to students.” Second, the project also explored both Augmented Reality and Virtual Reality tools to visualize the metadata. In all, this represents helpful pedagogical methods.

Finally, we read: “A common representation of the specific domain, through semi-formal knowledge representation languages and through the development of domain ontologies for a structured data representation and semantic coherence, would allow the integration of different pieces of information enabling the possibility to deploy new services for the users.” [48]

[***] http://www.opencyc.org/

3.15 Systems Analysis

Using spacecraft design as an example of an area that might benefit from State Analysis methods [8], a State Analysis Ontology is developed on a set of base ontologies describing "organizational and engineering context in which State Analysis is performed."

They describe generic domain concepts such as *project mission*. Fundamental concepts of physical system modelling are reflected in one layer of the ontology. Concepts for control system modelling is expressed in another layer. Mappings relate concepts from the ontology to SysML elements.

Classes in the first layer include: Affected, StateVariable, and Measurement. Those in the second layer include Estimator, Controller, ControlSystemComponent, and Achiever.

3.16 Functions of spacecraft systems/applications

Erica Wick [53] created "an ontology of functions specific to the modeling system of the navigation system of a spacecraft". It is an ontology of the functions of SPICE[†††], an information system "to assist NASA scientists in planning and interpreting scientific observations from space-borne instruments". This was part of a project to develop the Integrated Spacecraft Analysis software architecture "to aid in deploying discrete subsystem models."

Function classes had multiple parents, which, interestingly, were visualized using a hyperbolic viewer, i.e., a graphical display showing "tree-structured hierarchies on a non-Euclidean" plane. However, since SPICE functions are not necessarily hierarchical "a hierarchy was forced on them that separated the functions by keywords associated with each function".

The ontology served to: "search for relevant or useful functions, output the necessary function calls in any available language, quickly generate code to convert data types, or simply as a way of viewing and learning the SPICE functions". Additionally:

- from a single webpage, users can search the ontology for words appearing in documentation
- "the ontology can provide the correct pseudocode for translating each data type"
- the ontology acts as documentation for the functions

Prior to this function ontology, the project began by ontologically modeling an *attitude control system* (ACS), and included terms such as 'ConstraintChecker', 'hasOutput', and 'InertialVector'. A subsequent iteration resulted in a more general ontological model consisting of fewer terms, e.g., ProgramInput, UserInput, isInput, FlightSoftware, ACS.

[†††] https://naif.jpl.nasa.gov/naif/spiceconcept.html

3.17 JAXA spacecraft fault knowledge

From the Japan Aerospace Exploration Agency (JAXA), Kato and Tsutsui [54] [‡‡‡] use ontology engineering for developing a framework to capture fault knowledge for spacecraft systems. They state that "knowledge sharing is crucial for a sound and efficient development or operation of a space system".

3.18 A Mar Rover ontology for tele-robotic science

Wales, Shalin and Bass [55] development a naming convention, and a related ontology, to represent action in the tele-robotic context of the NASA Mars Exploration Rover. The naming convention was to request Rover action. They sought "to identify general issues for an ontology of [...] requests for action", one that "must take into account a dynamic environment, changing in response to natural physical events as well as intentional actions. This domain required a changeable ontology that was context-sensitive: it needed to "reflect the influence of context on the meaning of action." [56] The project employed a human-centered, cross-disciplinary approach, to include ethnography, cognitive science, engineering, and psychology.

There was little pre-existing knowledge of both ontology and the domain, which resulted in a dynamic learning environment that called for a flexible ontology. We read: "in the dynamic, environment of Martian tele-robotic science, terms require semantics that are not just internally consistent within the software. Rather, they must also support action with an on-going, dynamic external environment. […] those terms must adjust to users who are themselves changing, that is, learning over time. [...] as leaning takes place, new conceptualizations will develop." Thus, "ontologies require extensibility, or the ability to adapt to the needs of users and projects" and "the ontologist should expect dramatic, frequent revisions and have the capability to capture and support those revisions." [55] They hold that "ontological change is a key property of knowledge creation" and discovered that "a greater focus on work process and work practice and consideration of how they are related to" expert knowledge enabled us to identify relevant ontological categories."

The ontology modeled, in part: the features and instruments of the Rover; its targets; objects in the environment; events; temporal constraints; actions such as rover movement and interaction with different terrains and satellites. They developed relationships between activity, observation, feature, target and instrument use terms. Relations included kind-of, part-of. Higher-order work actions were essential to capture, as they related evolving science work practice activities to aspects pertaining to the Rover.

[‡‡‡] In Japanese.

4. Discussion

The preceding was a non-exhaustive sample of space data projects with ontological aspects in their knowledge management architectures. Ideas for relating some, including partnership ideation, are as follows.

Note the overlap of domains in distinct projects: planetary and Earth-observation science; ISS structure and contents; application and system data; spacecraft and their components; and space situational awareness. It is possible, then, that ontologies with similar domains can be mapped or otherwise interrelated. Some pairs of projects that may be interrelated are as follows.

One, the IVOA astronomy ontology, the Planetary Data System Ontology, and the Earth Observation ontology have overlapping topics. The Astronomy ontology seems to have the broadest domain scope.

Two, the Orbital Space Domain Ontology (or SSA ontology) [12-18], and the Space Surveillance schema [35] will have similar terms. Given that the latter is an XML schema, a further collaboration idea is to implement it in contemporary ontology languages. Partnership potential should also exist with recent concepts for SSA projects like the ontology aspects in [56], which mirror [12-15, 17] in various respects. The ontology concept for [57], for instance, can begin by using those of [12-18]. Likewise, partnerships are feasible with those interested in quantitative taxonomies for satellites [58][59] given the similar subject. Finally, European spacecraft and SSA knowledge management architectures may employ [18].

Three, the distributed network for European ISS data described in the ULISSE project may be related to the Semantic Grid approach.

Four, ontologies that model spacecraft components (e.g.. on the ISS) may benefit from discussions on their classifications and ontological characterizations of various system and parts at multiple levels of abstraction.

Five, the topic of fault knowledge explored in JAXA’s project [54], may be related to orbital debris domain ontology [15]. It is conceivable to create an ontological model for: types of faults and their causes that may lead to spacecraft malfunctions, disasters, orbital conjunctions; and determining the origins thereof.

Although individual projects may have overlapping domains, creating distinct domain ontologies (e.g., multiple astronomy ontologies) may be helpful. They have the potential to offer different perspectives and models of the respective universe of discourse. Correlations and mappings between, together with analysis of the varying semantics, may yield novel insights into space data management as well as knowledge discovery in the domains, themselves. Additionally, delineating a domain or topic area, itself, brings with it challenges. Furthermore, in the context of scientific disciplines there are and will be distinct theories and sets of assumptions.

Summarizing some past and on-going projects has shown some general and context-specific space data challenges, as well as how ontological engineering is perceived as addressing some of those challenges. For example, flexibility, improving data search/access, and modelling of domain content are common goals.

Common goals of knowledge architectures with (and without) ontologies are:

- Improving data search, access, and retrieval
- Mapping between disparate data sets
- Classification and terminology development
- Translations among distinct vocabularies
- Conceptual modelling
- Knowledge representation and reasoning
- Knowledge and data sharing
- Knowledge discovery
- Data integration/fusion
- Decision support
- Automated reasoning
- Machine-to-machine communication

The disadvantages of, and alternatives to, ontologies are worth exploring for a fuller picture of the state of the art. “[O]ntologies are not good for every problem. [...] there are situations in which building the ontologies required for a specific task is more difficult or more costly that solving the task without ontologies.” [50] Some disadvantages include increased complexity, computing power, time requirements, reaching agreement or consensus on terms and meanings, etc.

In any case, challenges to leveraging space data in actionable ways that facilitate problem-solving include: various sources of data; limited data sharing; formats, terminologies, and languages; and the growing size and complexity of data sets, which may call for novel approaches to both data and knowledge management.

6. Conclusions

This paper discussed aspects of ontological engineering in knowledge management architectures for space data. In discussing some past and on-going astronautical and space science projects that utilize ontology, we not only identify goals of knowledge- and ontology-engineering, but some commonalities among the projects.

Whether terminologies, controlled vocabularies, ontologies, or other semantic technologies are used, managing space data for knowledge discovery, knowledge creation and knowledge sharing is important for current and future space operations.

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