Ontology Architectures for the Orbital Space Environment and Space Situational Awareness Domain

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Abstract. This paper applies some ontology architectures to the space domain, specifically the orbital and near-earth space environment and the space situational awareness domain. I briefly summarize local, single and hybrid ontology architectures, and offer potential space ontology architectures for each by showing how actual space data sources and space organizations would be involved.

Keywords. Ontology, formal ontology, ontology engineering, ontological architecture, space ontology, space environment ontology, space object ontology, space domain ontology, space situational awareness ontology, data-sharing, astroinformatics.

1. Introduction

This paper applies some general ontology architectures to the space domain, specifically the orbital space environment and the space situational awareness (SSA) domain. As the number of artificial satellites in orbit increases, the potential for orbital debris and orbital collisions increases. This spotlights the need for more accurate and complete situational awareness of the space environment. This, in turn, requires gathering more data, sharing it, and analyzing it to generate knowledge that should be actionable in order to safeguard lives and infrastructure in space and on the surface of Earth. Toward this, ontologies may provide one avenue.

This paper serves to introduce the space community to some ontology architecture options when considering computational ontology for their space data and space domain-modeling needs. I briefly summarize local, single and hybrid ontology architectures [1][2], and offer potential space domain architectures for each by showing how actual space data sources and space organizations would be involved. For all figures, each node represents a distinct ontology or ontology suite (ovals), vocabulary, or data-source (rectangles). As the paper provides a cursory discussion, details, both technical and methodological, are left to existing publications and future work.

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2. The Space Domain

The domain of interest encompasses the phenomena in orbit, in near-Earth and deep-space environments relative to Earth. These entities are of interest because we should (i) protect persons and property in orbit and on the planetary surface, (ii) increase our scientific knowledge of the space environment, and (ii) ensure the future of safe and peaceful space flight. The domain includes observation, detection, identification, tracking, and propagation (prediction of future motion and behavior) of orbital objects [4]. As such, the sensors, sensor networks, accumulated data and the processes by which we attain knowledge of the entities under study are part of the domain of interest. Collectively, this domain has been described as the *space situational awareness* (SSA) domain. Given a focus on the regions of space where objects orbit, the domain can also be called *the orbital space environment domain*, which could arguably have a wider scope and have SSA as a part. If spatial zones from Earth are delimited, this may be distinct from other space environment ontologies. Various permutations are possible, depending on scope or domain demarcation.

Whereas astronomy studies all astronomical phenomena, the SSA domain or space domain awareness is concerned with those objects in closer proximity to Earth and the processes by which we achieve awareness of them and their environment. SSA is essentially about the space phenomena in relation to Earth, i.e., their potential effect on Earth and our space-related assets.

Both SSA and astronomy are data-intensive disciplines. Ground- and space-borne sensors accumulate data on natural and artificial objects in orbit, and in the further reaches of our solar system. Optical, radar, and infrared sensors individually provide one (or more) aspect(s) of the observed orbital or near-Earth object (NEO). Collectively, they provide a broader picture of these space objects. Catalogues or databases of satellites, orbital debris, near-Earth objects and space weather phenomena are maintained from this data. Example sorts of data include: the orbital parameters used to describe an orbit, positional and motion data (as in the Two-line Element Sets), and physical property data (shape properties, reflectance, mass, etc.). As the volume of datasets grows, *big data* and ontology engineering research and applications may serve to achieve the goals of space data-exchange for improved SSA.

3. Ontology and Ontology Architectures

Ontology is the general study of a given subject matter, universe of discourse or domain. A computational or applied ontology is a computable terminology with a formal semantics, the totality of which expresses a theory or understanding of the given domain. Ontology terms annotate data from space data sources toward fostering data-exchange and interoperability. A variety of ontology development and engineering architectures [1][2], and methodologies [6][7] exist for the space community to consider. I summarize three architectures.

A local (or multiple) ontology architecture is one in which “each information source is described by its own ontology” [1]. Each ontology can then be interconnected, creating a link between distinct databases, thereby facilitating data-exchange. A method to interconnect local ontologies is by mapping ontology terms to one another. A single ontology architecture has one ontology providing a shared terminology to annotate data from multiple databases, has been called a ‘global ontology approach’ [3], and can “be a combination of several specialized ontologies" [1]. A hybrid architecture is one that incorporates design features from each. "Similar to multiple ontology approaches the semantics of each source is described by its own ontology."[1]. Local ontologies directly annotate data, while also having a shared vocabulary. Each of the three architectures can use parts (selected terms) of, or the entirety of, other ontologies. In the next section I offer a potential space ontology architecture for each of the above three general ontology development architectures.

4. Space Ontology Architectures

I now apply each ontology architecture to the orbital space and SSA domain, offering potential scenarios for space community data-sharing and inter-organizational cooperation. Space agencies and SSA databases are included as actors and data sources. These architectures are subject to revision, but draw upon [5] and [4]. The potential or actual ontologies discussed may be distinct ontologies in their own right, or may forming modules of a larger ontology.

4.1 Local Orbital Space Domain Architecture

Figure 1 portrays a cooperative scenario in which four space actors use an interconnected system of locally developed ontologies to share data. They are: the European Space Agency with its SSA and near-Earth object data; the National Aeronautics and Space Administration with its orbital debris data, one or more universities with, say, asteroid, comet and other NEO data; and satellite operators with their own satellite and observational data. An ESA NEO ontology may be part of a broader ESA SSA ontology, and likewise for the local ontologies of other space actor partners.

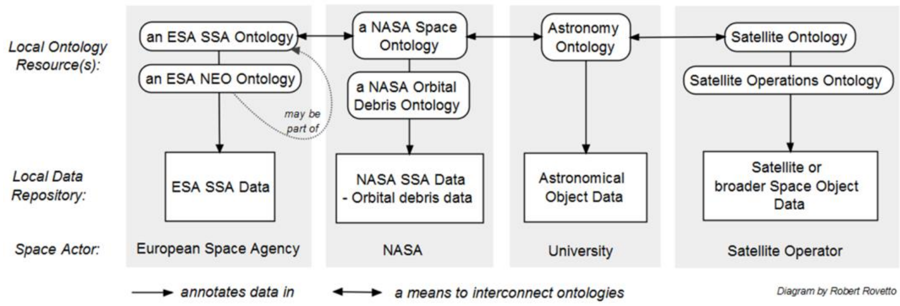

Figure 1. Local space environment ontology architecture (v1). Scenario: European Space Agency, NASA, universities & satellite operators exchanging data via interconnected local ontologies that annotate local databases.

This is an architecture in which each space actor has sovereignty to design, develop, and test their own ontology (or ontology library) to represent and annotate their data. As such, a local SSA ontology architecture is helpful where space actors seek to exchange information without a mediating or bridging resource. By developing together, they can make the interconnection (e.g. via mappings) and interoperability of their ontologies and systems smoother. Given the space community's shared scientific knowledge (astrophysics, astrodynamics, etc.), and given that some space actors will observe and track the same (numerically identical) orbital object (e.g. a GPS satellite), concepts, terminology and semantics will overlap.

Figure 2 adds ontologies with broader domain concepts, as well as sub-domain and other related content. Additions include: an astrodynamics standards ontology, which may consist of data formats, and computational models; science reference ontologies, the space situational awareness domain ontology (SSAO) [4][2], and event and object ontologies that may be modular parts of the latter. They provide some of the common knowledgebase for local ontologies. Other demarcations of the overall domain (and individual ontologies) include the SSAO being equivalent to or, alternatively, part of what I call the Orbital Space Environment Ontology (OSEO) (or some variation thereof). As a part, the SSAO would primarily represent the activities and object involved in achieving and maintaining awareness of the space environment, e.g. observational, tracking, and computational processes.

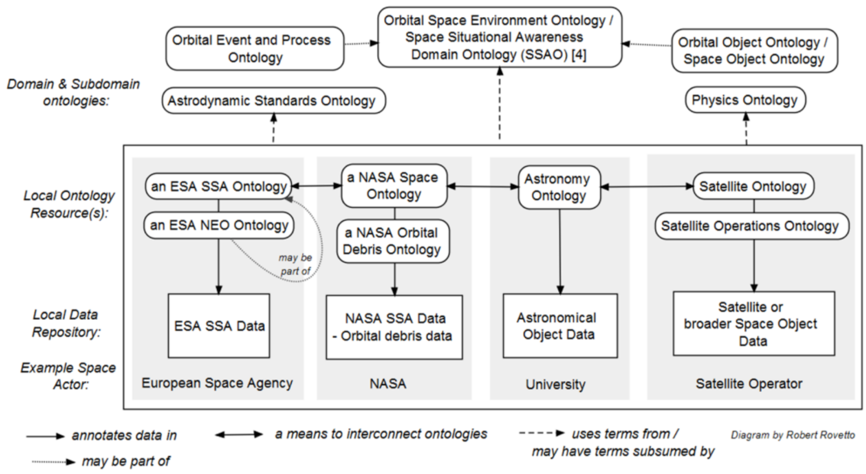

Figure 2. Local space ontology architecture (v2): local ontologies using generic ontologies.

The SSAO or OSEO includes general terms that can be applied to any of the local ontologies. These terms may subsume local terms, be asserted as equivalent (depending on the intended meaning of corresponding terms), or may be imported into the ontology. They help annotate data about individual orbital parameters, Two-line Element Sets, observations, various objects in orbit, orbital events (e.g. collisions), and so on. Examples of common terms include: orbital debris, launch vehicle, orbit, circular orbit, inclination, asteroid, optical sensor, orbital conjunction, Hohmann Transfer Maneuver, etc. More general domain-specific terms include: orbital occurrence, orbital object, space object, space artifact, and orbital property. Scientific discipline ontologies, e.g., physics, orbital dynamics, are developed to provide the formal representations of the relevant scientific knowledge and principles.

4.2 Single Orbital Space Domain Architecture

[2] Under development. URL=https://github.com/rrovetto/space-situational-awareness-ontology/

A single orbital space ontology architecture (Fig.3) can take the form of the SSAO or OSEO directly annotating space data from distinct data systems from similar space actors. Given that the data is about objects in space, a variety of their properties and observations thereof (among other things), the ontology should have domain terms for: orbits, orbital parameters, orbital objects such as debris and satellites, physical features, satellite operations activities (e.g. launches, navigation, maneuvering); tracking, propagation, and so on.

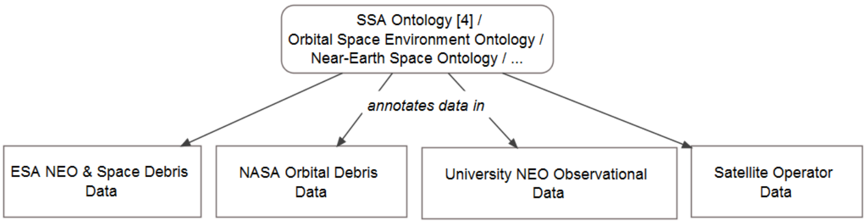

Figure 3. Single space ontology architecture (version 1): National, academia and company space actors utilize a more general domain ontology such as the SSAO from [4] or some variation.

The single ontology used for the domain would itself be domain-specific. Without other ontologies, this architecture avoids mappings, but faces the challenge of agreement on the structure and content of the ontology. Figure 4 depicts a variation of this architecture, adding other potential ontologies, or alternatively, decomposing the single ontology into sub-domain ontology parts (similar to Fig.2) to form a more complete picture of the domain. Some include the Orbital Debris Ontology [5], Astronomical Object Ontology (e.g. similar to [8]), and physics ontologies. Terms from each could be imported into the single ontology. Local data elements are described with the semantics and formalisms of these ontologies.

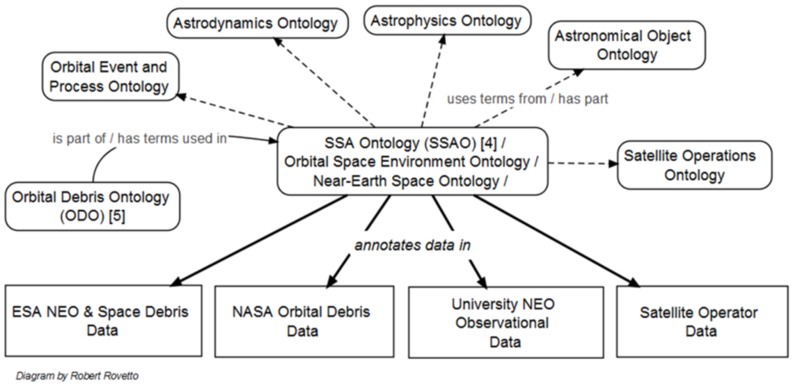

Figure 4. Single space domain ontology architecture (version 2): added other ontologies that may be modularized parts of the single ontology or distinct.

4.1. Hybrid SDO Architecture

Finally figures 5 and 6 present the hybrid architecture, the latter adding additional ontologies. We see a higher-level shared space vocabulary, or alternative domain ontologies, e.g., the SSA domain or orbital space ontology. Space actors would use this common resource to provide a backbone terminology to relate to their local ontologies. As a shared ontology, it may subsume the local ontologies. The shared resource may also be compositional, consisting of distinct sub-domain ontologies. This architecture has the benefit that local domain professionals can help ensure veridical formal descriptions. It has the challenge of agreement on the terminology, definitions and formalization of the shared higher-level resource.

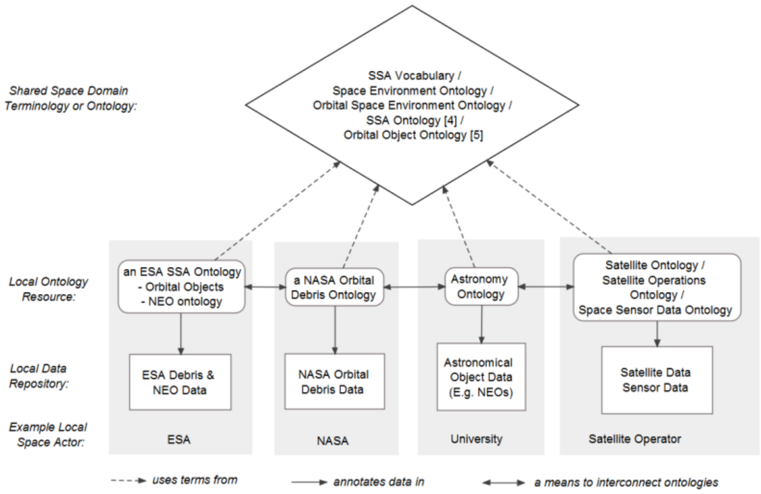

Figure 5. Hybrid space ontology architecture.

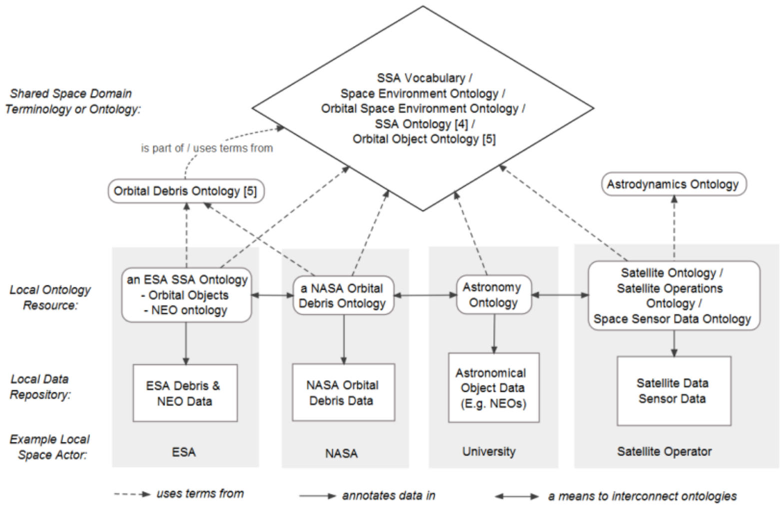

Figure 6. Hybrid Space Ontology Architecture (version 2): addition of other modular ontologies.

5. Other Considerations and Discussion

Other considerations in the development of an ontological framework are the ontology languages, i.e., the computable formalisms used to represent the domain. Each language has its own limits on expressivity. According to [1] "The role and the architecture of the ontologies influence heavily the representation formalism of an ontology." We also read "Depending on the use of the ontology, the representation capabilities differ from approach to approach." Whether to use other ontologies at different levels of abstraction is also a consideration.

As always, another option is to develop a novel architecture or approach (ontological or otherwise). Moreover, depending on the space community's needs, feasibility studies, and the ability of ontology engineering to address those needs, ontology may or may not be the best research direction. Each of the architectures would be an interesting pursuit for this domain, as would the development of a novel approach. In any case, the goals remain: to solve space data problems, improve SSA for space (and terrestrial) safety, and expand our knowledge of the space environment.

6. Conclusion

When researching ontology for space data needs, there are various possible architectures and methodologies the space community may consider. This paper applied the local/multiple, single and hybrid ontology architectures to space situational awareness and orbital space environment domain. I offered ideas for space domain ontology architectures toward stimulating both data-sharing and international and inter-institutional cooperation.

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