The Orbital Space Environment and Space Situational Awareness Domain Ontology – Toward an International Information System for Space Data

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ABSTRACT

The orbital space environment is home to natural and artificial satellites, debris, and space weather phenomena. As the population of orbital objects grows so do the potential hazards to astronauts, space infrastructure and spaceflight capability. Orbital debris, in particular, is a universal concern. This and other hazards can be minimized by improving global space situational awareness (SSA). By sharing more data and increasing observational coverage of the space environment we stand to achieve that goal, thereby making spaceflight safer and expanding our knowledge of near-Earth space. To facilitate data-sharing interoperability among distinct orbital debris and space object catalogs, and SSA information systems, I proposed ontology in (Rovetto, 2015) and (Rovetto and Kelso, 2016). I continue this effort toward formal representations and models of the overall domain that may serve to improve peaceful SSA and increase our scientific knowledge.

This paper explains the project concept introduced in those publications, summarizing efforts to date as well as the research field of ontology development and engineering. I describe concepts for an ontological framework for the orbital space environment, near-Earth space environment and SSA domain. An ontological framework is conceived as a part of a potential international information system. The purpose of such a system is to consolidate, analyze and reason over various sources and types of orbital and SSA data toward the mutually beneficial goals of safer space navigation and scientific research. Recent internationals findings on the limitations of orbital data, in addition to existing publications on collaborative SSA, demonstrate both the overlap with this project and the need for data-sharing and integration.

1. INTRODUCTION

The orbital space environment is home to natural and artificial satellites, debris, and space weather phenomena. As the population of orbital objects grows so do the potential hazards to astronauts, space infrastructure and spaceflight capability. Orbital debris, in particular, is a universal concern: "[t]he current space debris environment is deteriorating due to an increasing number of orbital objects, despite worldwide efforts to reduce growth rates" [1, P.8]. This calls for a clearer picture of that environment and therefore more complete space situational awareness (SSA).

We can achieve this by a combination of activities: sharing orbital data among space actors and across international borders; and further developing the capability and physical infrastructure for space observation and scientific research. In other words, by exchanging data, increasing observational coverage, and expanding our knowledge of the near-Earth space environment in the process, we improve global SSA. This should minimize orbital hazards, making spaceflight safer. Although some actors participate in data-sharing agreements, "[n]o State in the world is currently able to provide a complete and constantly updated picture of the situation in orbit on its own. Thus, there is an objective need to combine capabilities in this area." [1, p.7]

This presents us with an opportunity for international partnerships, opening the door to innovation in collaborative SSA, or more generally collaborative space environment awareness. As more data is accumulated, and as space object catalogues grow, we should leverage this volume of data to draw forth the contained knowledge. Aggregating, analyzing, organizing, reasoning over, and disseminating various data-sets should simultaneously yield a greater comprehension of orbital space environment and afford safer space exploration. Furthermore, in contributing to the growing complexity of Earth orbits we arguably have a responsibility to better understand the causality at work.

Toward this, I have proposed researching formal and computational ontology as one potential means toward data-exchange and interoperability. To facilitate data-sharing among distinct orbital debris and space object catalogs, and

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SSA information systems, I offered ontology development concepts and offered specific ontologies in [2] and [3]. I continue this effort toward formal models of the overall orbital space domain. This paper explains the project introduced in those publications, as well as efforts to date. The research field of ontology engineering [4][5] is also briefly summarized. In short, I describe ideas for an ontological framework for the orbital space, near-Earth space environment and SSA domain. An ontological framework is conceived as part of a potential *international information system* for space data. The purpose of such a system is to consolidate, analyze, reason over and make available various sources and types of orbital and SSA data. Recent internationals findings on the limitations of orbital data management [1][9][10], in addition to existing publications on collaborative SSA [7][8], demonstrate both the overlap with this project and the need for orbital data sharing and integration. That is, they support the basic premise: sharing orbital information toward the mutually beneficial goals of safer space navigation, scientific research, and the preservation of peaceful spaceflight for future generations.

2. PROJECT SYNOPSIS AND GOALS

The project[2] aims to develop and apply ontology for the orbital space environment and space situational awareness domain in order to solve contemporary domain data management deficiencies. The ontology development process includes concept development, theoretical/philosophical ontology, computational ontology development, and informatics, data management and artificial intelligence applications. The ontology, or ontology suite, itself may be part of a potential international information system. We see concepts of the latter expressed in [2] and [7-10] (discussed in section 3). As expressed in [2][3][6], the ontological part of a joint orbital information system has the following functions or goals. Note that many of these apply to any unified, joint or international information system for orbital space data, regardless of whether ontologies are used.

I. To formally represent the relevant astrodynamic, astronautical, and astronomical domain(s). To offer one or more formal models of the domain: knowledge models, conceptual models, data models, etc.
II. To form one or more orbital space domain terminologies/vocabularies and taxonomies
III. To annotate orbital data
IV. To foster data integration and data-sharing
V. To foster interoperability among individual orbital debris, space object or other SSA information systems
VI. To form a working international orbital debris object, space object, or SSA database
VII. To expand our knowledge of the near-Earth space environment
VIII. To stimulate international cooperation across borders and disciplines
IX. To stimulate innovation in collaborative SSA, knowledge engineering, and ontology development

The ontological component is intended to provide one formal representation (sometimes called a 'knowledge model') of the domain. *In toto*, project functions include: aggregating, managing, and computationally reasoning over SSA data representing orbital objects, the orbital environment, and other relevant entities.

A rationale is to (XI) help remediate orbital debris hazards, and (XII) improve peaceful global SSA. Some of these goals may (XIII) contribute to astrodynamics standards as well. Related to the latter, ontological analysis of the domain may help provide insights into the simplifying assumptions made by some astrodynamic models. As such, this interdisciplinary effort stands to contribute to the philosophy of science in astrodynamics, SSA, and space environment modeling.

Additionally, integrated orbital data should allow computer simulations with a graphical user interface to provide a more complete and higher-fidelity visualization of the global orbital environment. Ontology can be applied to a global orbital space environment simulation or real-time space environment computer visualization by annotating the graphical modeling elements. Consider [19], an existing space environment simulation, and [20], which describes its use of ontological approaches.

The potential benefit transcends disciplines. Due to the goals and nature of such a project, fields ranging from astrodynamics to informatics and computer science are required to realize it. It is effectively an interdisciplinary cooperative endeavor. This is necessarily true for a large-scale international information system for orbital data sharing and integration.

[2] No claims to completeness are made, and concepts are subject to revision.

Very briefly, ontology is the general study of some universe of discourse or domain of interest ('domain' for short) as well as a branch of philosophy. An ontology is a general theory of some domain. Formal ontology is the application of formal methods, concepts and logics to ontology, yielding generic representations, conceptualizations or models of the objects, events, concepts and phenomena of some domain. Both involve identifying, asserting or prescribing categories to represent types of those domain entities. Computational ontology, or ontology engineering [4][5], yields *computational ontologies*, which are computable and structured terminologies or taxonomies with a formal semantics. They consist of a structured vocabulary (e.g., ontology category terms) and corresponding definitions. Ontology in information and computer science is often used in semantic technologies and artificial intelligence. Ontologies have been applied in other disciplines such as geography, biology, and enterprise architectures, toward semantic interoperability, data-sharing, data annotation, automated reasoning, decision support, data-mining and knowledge discovery.

The domain to ontologically represent is that of the objects, occurrences and other phenomena (weather or otherwise) in orbital space; the environment itself; the causal interactions among them; the processes and infrastructure by which we observe and attain information on them; the knowledge we attain; orbital data itself; orbital data message formats; computational models; and so on. It is the SSA, orbital space and near-Earth space environment domain. Although there are various ways to demarcate and name the domain (and sub-domains), these sorts of entity are critical.

Domain demarcation and clearly specifying extensions and definitions of corresponding terms, names or labels are typically part and parcel of the ontology development process. For example, although space weather may occasionally be primarily associated with 'space environment' labels, it need not be. The space environment includes not only weather phenomena, but space artifacts such as debris objects, active spacecraft, and how they interact. In coming to more acute knowledge of those interactions we improve SSA. Similarly for 'SSA', as expressed in [3].

The conceptual analysis and development, and formal and philosophical ontology involved are goals in themselves, regardless of whether the more practical data goals are achieved. These specific efforts stand to contribute to the philosophy of the SSA and orbital domain, philosophy of science, and may offer distinctions and concepts to better conceptualize and understand the domain.

Additionally, although the focus is on SSA and the space environment *relative to Earth*, the general scientific knowledge, e.g., celestial mechanics, astrodynaimcs, etc., is applicable to any planetary body. We have universal physical principles or general laws of nature that can be ontologically represented for computational reasoning with data about individual/particular objects and events subject to those principles. The implicit distinction, drawn from philosophy, is that of the general and the specific, or the universal and the particular. The ontology development involves formally representing the particular orbital entities about Earth in relation to the general astrodynamic and orbital principles/knowledge. To envision and speculate on future applications, consider a suite of planet-specific orbital space ontologies. Each would include the entities unique to their environment while drawing upon ontologically-represented general scientific knowledge. For example, along with a Near-Earth Space Environment Ontology (mentioned in [3]) or alternatively an Earth Orbital Space Ontology, we may have a Near-Mars Space Environment Ontology (or alternatively a Mars Orbital Space Ontology), which would represent particular objects in the Martian neighborhood, while using the formal models of orbital principles and concepts. Given that these planets are part of a larger astronomical system, the content of a suite of planet-specific ontologies would naturally overlap. In all, this ontological model would need to reflect the dynamic and causal interconnectedness of the astronomical system as a whole.

Some ontology-specific research questions for the project include the following.

- What are useful & scientifically accurate ontological representations and classification systems of the domain?
- Are contemporary & classical ontological categories and distinctions sufficient to accurately represent the domain? What novel ontological characterizations will better represent domain phenomena?
- What are helpful demarcations or delineations of the domain?
- What ontology architectures and methods are most helpful to achieve goals?
- What domain questions and computational queries can ontology-based applications answer? E.g., 'What's the origin and type of a debris object?'
- How can data-sharing, integration and systems interoperability be achieved with ontology applications for this domain?

- Is the current state of ontology engineering able to manage the: physics-intensive, predictive modeling, and dynamic data aspects of SSA?
- What are areas for philosophical analysis/inquiry?

Other important topics to investigate are the following.

- Prediction, e.g., potential orbital conjunctions, future orbital position
- Astrodynamic models
- Probability
- Dynamic ontologies

Finally, a simplification of the process is as follows: (1) Identify space data sources, (2) establish cooperative partnerships, (3) exchange and integrate the respective data, (4) analyze, structure, interpret and reason over the data. Although ontologies largely come into play between step 2 through 4 (thereby facilitating 3), the ontology development process begins as early as step 1. For example, between 2 and 3 they will provide terminologies, semantically-rich taxonomies, and annotations of instance data from the databases identified in 1.

The next section presents existing proposals for collaborative SSA, and contemporary international findings supporting data-sharing goals in this domain. I also demonstrate the similarity of these proposed efforts with my project, as well as the potential ontology applications to points mentioned in some proposals.

3. INTERNATIONAL MOTIVATION

There is international motivation for collaborative SSA. More specifically, there is reason for improving the state of data exchange, integration, management and processing therein. Members of the SSA community have proposed international platforms toward this—towards ameliorating the state of SSA and orbital safety.

In [7], Weeden and Kelso discuss the feasibility of creating "[…] an International Civil SSA (ICSSA) system where data from multiple actors, States, and commercial providers is voluntarily shared". Data-sharing is

> "[…] towards a central data clearing house. This data would then be shared with all participants, enabling each to perform their own analysis and decision-making. For those actors without indigenous analytical capabilities, the data clearing house would also offer analytical services".

In short, "In return for voluntary contributions of data to a central database, participants get access to all the contributed data." Such a system "[…] has the potential to fill in the gaps in the existing military SSA systems."

In [8] Kretzenbacher, Rathnasabapathy and Kamaletdinova state that

> "[o]ne possible approach is the creation of a neutral international organization and network that exists solely to facilitate the collection and sharing of SSA data. The proposed network would utilize the capabilities of already existing SSA infrastructure".

Finally, a 2016 United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) presentation [9], along with the corresponding working paper [10] by the Russian Federation, outlines the limitations and deficiencies of contemporary orbital information management. Among them are the following.

Deficiencies in orbital information exchange

i. Low accuracy of publicly-accessible orbital information
ii. No unified international mechanism for catalogues and identifying space objects
    - Multiple databases; Varying levels of data quality and completeness; Potentially conflicting information
iii. Distinct data sources are not integrated
iv. Many false alarms

Deficiency *i* and *iv* can be addressed, in part, by developing technologies and methods for higher fidelity data. Deficiencies *ii* and *iii* are most directly relevant for this communication, and related to the following passage, which demonstrates the similarity to the present ontology-based project. Emphasis is added to mark the overlap.

"The fact that there is no common database of space objects (spacecraft plus debris) virtually guarantees that there will be **duplication of space objects across the several databases** now maintained by different nations, differing degrees of information on objects that are registered in **multiple databases**, uncertainties of information on objects that are registered in multiple databases, **different identifying names for the same object** in multiple databases, and an assortment of other data quality and completeness issues with which actors in the space arena must reckon." [1,p.28, emphasis added]

4. OVERLAP WITH THE PROJECT

The preceding quotations not only demonstrate similar ideas to the present ontology-based project, but they also support some of its goals and purpose. First, the limitations mentioned above (*ii* and *iii*) are some that ontologies seek to resolve. More to the point, I have intended this project to use ontology to help address such problems[3]: data-sharing among multiple databases; address data-entry duplication and multiple identifiers for the same referent satellite or piece of orbital debris; etc. As stated, ontology engineering is often aimed at achieving interoperability among information systems and data-exchange between data silos (isolated databases). Ontologies can provide common space domain terminologies for use by databases that have distinct names for the same space object.

Second, in [2, p.70-71] I proposed the idea of a joint international orbital debris ontology or catalogue serving to, among other things, foster data-sharing between distinct orbital debris databases; and aggregate orbital debris data from those sources. I mentioned two scenarios (Fig. 1): databases sharing data with a joint international system (scenario B, Fig. 1), and databases exchanging data amongst themselves (scenario C). In each, an orbital debris ontology would annotate that data with general ontological categories. A backbone generic domain vocabulary and taxonomy would do so.[4] Ontologies, in Fig.1, would be found in the dotted arrows in C and as well as in the joint system in B (represented by the octagon).

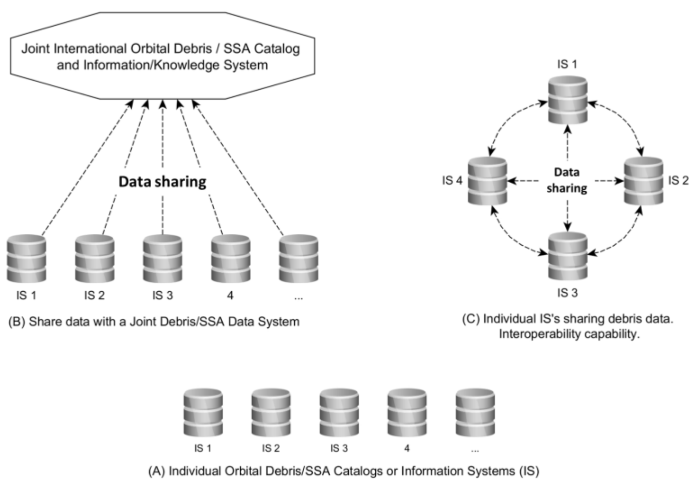

Fig. 1 reproduced from [2]. Data-sharing among orbital debris databases

We read a similar idea expressed by [9] and [10], but which do not mention ontologies, for:

"establishing **a centralized international database** as a functional addition to the existing national and integrated international capabilities in the area of monitoring and assessment of the situation in outer space. The conclusion is obvious: **the collection and fusion of multi-source information** should not be neglected"[10Z,p.6, emphasis added]

"An international mechanism for collecting orbital information from different sources" [10Z,p.21]

[3] Note that whether ontological applications can and will do so successfully, or whether they will do so without sacrificing essential functionality is a central question. For the benefit of the community and the safety of our astronauts and space assets, other non-ontology approaches that can achieve the same results towards an improved comprehension and safer state of orbital space should be pursued as well.
[4] Example category terms include Orbit, Orbital Object, Orbital Debris Object, Orbital Debris Field, etc.

Ontology terms annotate instance data about space objects in this potential international database. Annotations indicate the meaning of the data that users can access. An orbital space domain ontology would provide a higher-level but domain-specific general terminology for annotating, classifying, representing and describing orbital data, objects, events, causal relationships and phenomena, as well as the interrelationship therein. This should provide us with a generic picture of the orbital space environment, whereas instance data indicates specific objects, states and events (what have been called 'particulars' in philosophical ontology and metaphysics). Given that some databases are siloed—and therefore isolated from, or non-connected to, others—a spotty view of individual orbital objects and events is the result. Fusing and integrating orbital data should generate a more continuous and complete understanding of the situation in orbit.

Ontologies therefore have the potential to expanding our scientific knowledge of the near-Earth space environment in arguably a variety of ways. First, by formally representing current scientific domain knowledge (and the objects they describe), we may glean insights not previously conceived. That is, conceptual analysis of domain concepts, scientific principles, and orbital objects may yield helpful distinctions, classifications, and conceptual constructs. Second, translating this formal representation into a computable format affords data-annotation, automated reasoning and knowledge discovery over various data-sets. Note that limitations in expressivity exist partly due to the interrelations between categories specified by the formal semantics. Despite this, by using a well-made ontology we can determine (to some degree of accuracy) the relationships between an individual space object and other entities in the orbital environment.

Toward resolving the orbital information deficiencies listed above, [10] proposes an **information platform** for the aforementioned **international database**, and lists a variety of information content to include. We read:

> "the platform database should cover all **information categories** relating to space launches, space objects, in-orbit operations and events in near-Earth space that would be included in the set of guidelines for ensuring the longterm sustainability of outer space activities." [10, p.20, emphasis added]

The proposal mentions an **information model** (consisting of the information content) as one requirement, and includes **metadata** [10, p.24] as part of the content. Ontology can contribute to the formation of an information model and the use of metadata by providing a semantically rich model of the SSA domain. Moreover, information models and metadata are related to ontology development in general. The content for the information platform includes the following [10, p.20-28], some of which were mentioned in [2][3] as necessary content to ontologically represent.

Information on…

- Type of launch vehicle
- Unique identifier of a launch
- Launch location (launch site, launch facility, launch complex)
- Name of each space object
- Approximate dimensions and mass
- An independent orbital flight,
- reference to the State which has jurisdiction and control over each of the objects, contact information for communication with the entities responsible for space object (spacecraft)operations
- The trajectory of motion of space objects, e.g., planned parameters of the orbit of each space object
- the change of status of a space object (cessation or resumption of operation)
- predicted and actual conjunction, or de-orbiting of a space object
- Assessment of boundaries of the time interval of the breakup
- The number of spacecraft, launch vehicle stages and accompanying operational fragments
- a new space object detected by near-Earth space monitoring means
- Information providers
- Date and time of…
    - compilation of the information by the provider
    - receipt of the information in the platform database
    - the launch (time intervals for different dates)

Each of these is to be ontologically modeled by asserting corresponding category terms, their definitions and interrelationships. This will provide us with a broader conceptualization to understand the SSA picture. For example, in beginning an ontological analysis of the desired content, we will need: temporal categories for representing times, dates, durations; terms for physical and geometric properties; terms for names or identifiers; event categories for, say, launches; and for particular actors, agents or organizations. Finally, we will need terms for predictions, predictive information, and modality; as well as spatio-temporal concepts.

One challenge is to represent the orbital environment and its phenomena in an accurate manner, while taking into account the expressive limitations of logical and computational formalisms (and computational models themselves) and the need to search and reason over data.

The proposal also describes the platform as "A single international database of events in space"[9, p.21]. Ontological analysis can provide an *event type* terminology or categorization for orbital events, such as those mentioned: “termination of existence of objects in orbit, docking/separation of objects, break-ups”. Moreover, an ontology offers a semantics to capture various relationships (causal, functional, etc.) between the orbital event, the surrounding environment and other objects therein. For example, when an event is detected in orbit, or once the actors/satellites involved are identified, it can be categorized as an instance of a given ontology class which in turn may imply other relationships. Each particular event can be recorded and ontologically represented accordingly.

> "[T]he coverage of all the above-mentioned information categories by a single database of the platform should contribute to the successful implementation of the guidelines and to an increase in transparency and confidence in outer space activities" [9, p.20]

Although the need for sharing and integrating orbital and other SSA-related data has existed for years, the preceding points from [1][9][10] focus the attention to it on an international scale. The motivation and opportunity exists for members of the global space community to form more partnerships in data exchange towards safer and fuller state of SSA.

5. ORBITAL DATA – POTENTIAL FOR EXCHANGE AND INTEGRATION

If we are to achieve real-time responses to rapidly changing orbital events, and potential space environment threats, SSA data must be ***dynamically*** updated and available in real-time. It must also be ***actionable*** to secure the safety of astronauts and spacecraft. We read: "Information on the trajectory of motion of space objects should, as practicable, be updated with periodicity" [10, p.24] For example, impending orbital conjunctions must be identified and communicated to maneuver orbital assets into safer orbital regions. This preemptive and predictive ability will become more acute with greater knowledge. However, so long as we have a fragmental perspective of the situation in orbit, attaining this knowledge will be a challenge. The unification of orbital data itself is challenging, but data-exchange, integration and analysis gives us a leg-up. To more accurately assess orbital hazards we need a more complete perspective of orbital space. Data sources and potential partners toward this mutually beneficial goal include the following.

Potential space data-sharing partners

General

- Academia
- Observatories
- SSA networks
- Space agencies
- Satellite Operators
- Amateur observers
- Non-profit space associations
- …

Specific SSA organizations & Data Sources

- European Space Agency Database and Information System Characterizing Objects in Space (DISCOS) [11][12]
- International Scientific Optical Network [13]
- Canadian Space Surveillance System[14]
- Space Surveillance Network (SSN) [15]
- Russian Space Surveillance System
- Chinese Space Surveillance System
- Space Data Association [16]
- Celestrak [17]

To visualize real-world data-sharing scenarios, substituted some of these for the database images in Fig.1. In [18], I explored this by offering scenarios for space ontology architectures in which these space actors were a part.

6. EFFORTS TO DATE

Efforts to date on the ontology of the orbital space environment and SSA domain by the author include independent efforts such as: publications, ongoing concept development and ideation, computational ontology development, etc.

In "An Ontological Architecture for Orbital Debris Data" [2], I introduce the concept of an *orbital debris ontology* (ODO), i.e., using ontology to help address orbital data problems. The purpose is to represent orbital debris objects and data; and foster data-exchange among different orbital debris or space object catalogues. A working computational ontology of ODO has been in progress, and is conceived as a potential component within a multi-module ontological architecture for the overall domain. Each potential modular ontology was described as presenting a high-level theory of a specific portion of the domain with terms for key entities in that portion. For example, ideas for interconnected ontologies include: Satellite Ontology, Space/Satellite Operations Ontology, Space Systems Ontology, Astrodynamic Model Ontology, and the more general Orbital Object Ontology, Space Object Ontology, Orbital Event Ontology, Orbital Process Ontology, etc. ODO and any other related ontology provides an orbital debris domain terminology to annotate instance data; classify and provide a formal model of orbital objects, the orbital environment, and the relevant scientific knowledge.

In "Preliminaries of a Space Situational Awareness Ontology" [3], Dr. T.S. Kelso of the Center for Space Standards and Innovation at Analytical Graphics Inc., and myself, describe some requirements for an ontology of the SSA domain. We describe some general activities of SSA (observation, detection, tracking, identification, propagation, etc.); and purposes of SSA (producing a working catalog of orbital objects; predicting collisions and orbital paths; preventing collisions; detecting objects and malfunctions; etc.). Some ontological (philosophical) categorical concepts and distinctions; and some steps in the ontology development process were also discussed. Preliminaries of a working computational ontology (SSA Domain Ontology, or SSAO) were included and pointed to an online repository[5], subject to revision. The domain of interest includes orbital debris. ODO may therefore be incorporated as a part of a more general SSAO. Alternatively ODO may be distinct, while each ontology uses (imports) terms from the other. Given multiple interpretations of 'SSA' and its scope, SSA can be delineated in at least one of two ways. One, the SSA domain is the overall orbital or near-Earth domain of interest (including observation, tracking and modeling activities; orbital debris itself, environmental conditions, etc.). Two, the SSA domain is a part of the overall domain, i.e., as the awareness and knowledge of the near-Earth environment and the entities by which we attain and generate it.

As expressed, in both [2] and [3], a big-picture potentiality is the creation of a *joint international orbital debris/SSA/space environment ontology and data system*. As we noted above, [10][9][8][7] describe similar concepts with proposals for *neutral international or civil information platforms* for SSA data. While the present project is specific as to using ontology, they share the same fundamental goal: remediating orbital debris hazards and advancing knowledge and situational awareness of the orbital space environment via the consolidation and sharing of data. This research seeks to determine if ontology can help with achieving this, i.e., achieving safer space navigation by means of knowledge representation, data-exchange and systems interoperability.

In [18] I introduced some generic ontology architectures, and applied them to this domain. Single, Multiple, and Hybrid architectures were offered, exemplifying a strategic goal of this project concept: to *foster international cooperation and knowledge exchange*. Space actors from different countries and industries, such as those in the previous section, should be partners in developing a fuller understanding of the global space environment for the benefit of all. This collaborative potential is reflected in the scenario architectures, where the European Space Agency, and NASA, for example, are included to demonstrate the idea.

In-progress efforts include a variety of papers and ontology file development. Some include the following. Using data from an online-accessible satellite database I have begun an ontological representation of the database terms. Celestrak [17] and the DISCOS [11] system are other data sources to pursue the same in future work. These efforts will serve as case-studies and proof-of-concept, but in order to provide this fully, it should include at least logical formalizations of the terms and category system, and examples of computation over the data via querying[6]. In a

[5] https://github.com/rrovetto/space-situational-awareness-domain-ontology
[6] Asking formal and structured questions over the data annotated by the ontology to yield meaningful answers.

paper on space object ontology, I perform a conceptual analysis of the term 'space object'. I offer preliminaries of a generic space object terminology for the community. It also briefly mentions my work on computational ontology of a space object ontology. In yet another paper on formal representations of orbits, I began work on ontological models for orbits, to be expanded further.

Future work includes developing these and other papers further, and additional subject matter research, and researching (seeking) partnerships, interested parties, and opportunities for this project or similar projects/concepts. Collaboration with, or grants via, NASA, the ESA and other space organizations are of particular interest as inter-agency partnerships will help realize the project fully.

7. CONCLUSION

This paper summarized efforts to date for ontology of the orbital space environment and space situational awareness domain. I described some project [2][3] concepts and goals and compared them with those of proposals for international information systems by other authors. In doing so I demonstrated the similarity between them. Both call for integrating orbital data, fostering data-sharing and international cooperation. Existing limitations and deficiencies of orbital data management cited in one proposal provide justification and motivation for the effort. In short, one goal is for ontology engineering to resolve some limitations in the current state of SSA data management. In the context of an international information platform, an ontology would be one component which provides a standard terminology, one or more classification systems, a formal theory of the orbital space domain, and a knowledge model.

To return to the quotation at the beginning of the paper, if the orbital debris environment is deteriorating, then we must ask why. Assuming that nations are indeed striving to mitigate and remediate orbital debris formation, we need to understand what is happening in orbital space (or beyond it) that explains the deteriorating condition. With this knowledge, partly attainable via data-sharing, comes improved SSA and safer spaceflight.

There is reason to better share and integrate orbital data: to curtail orbital hazards such as debris formation, and advance our knowledge of the orbital environment. International motivation exists toward this end, and ontology development and engineering may provide one means.

> "effective sharing of information on objects and events in near-Earth outer space is to serve the general good of the whole international community (i.e. produce comprehensive benefits in terms of ensuring safety of space operations" [10, p.3]

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