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An Overview of the Common Core Space Domain Ontologies

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Prepared by:
CUBRC, Inc.
4455 Genesee Street, Suite 106, Buffalo, NY 14225
POC: Alexander P. Cox, Ontologist
716-204-5100 ext. 5248
alexander.cox@cubrc.org

1 Introduction – The Common Core Ontologies

In this paper, we describe the content and structure of the Common Core Space Domain Ontologies and the ontologies that they extend from in order to provide an overview of their scope and utility. In this section, we introduce the Common Core Ontologies (CCO) and describe the basic ontology design structure.

The CCO adopts a modular approach to ontology development, according to which different ontologies are responsible for representing reality at different levels of granularity or in different domains. Ontologies are categorized as upper-level, mid-level, or domain-level ontologies:

- An uppe*r-level ontology* is one that identifies those generic types of entities which belong to the formal structure of the world, together with formal specifications of how those types of entities are related to others.
- A *mid-level ontology* is one that adds general content to the structure outlined in the upper-level ontology by identifying types of entities which directly specialize the upper-level types, but which are also common to many domains of interest. Classes in mid-level ontologies are still fairly basic with respect to particular knowledge domains and often require further specialization to be useful for more detailed data modeling.
- A *domain-level ontology* is one that identifies additional types that further specialize the basic types from one or more mid-level ontologies. Domain ontologies describe objects, events, and relationships of interest to a more limited number of knowledge domains.

The CCO is designed as a mid-level extension of the Basic Formal Ontology (BFO) and the Relation Ontology (RO) that jointly compose an upper-level ontology framework widely used to structure and integrate knowledge in the biomedical domain (Arp, et al., 2015). BFO aims to represent the most generic categories of entity, and RO the most generic types of relations that hold between them. The CCO extends from BFO-RO in that every class in the CCO is asserted to be a subclass of some class in BFO, and CCO adopts the generic relations defined in RO.

Designing ontologies in this modular, extendable format reduces the cost of representing new domains of knowledge. For example, the Spacecraft Ontology does not need to define classes for standard radios or engine components because it imports the Artifact Ontology as part of the CCO and therefore inherits these and many other classes that have already been defined. This methodology also increases the interoperability of data – even data from seemingly disparate domains – because it is modeled using a common higher-level framework. For example, consider how different an outboard motor on a speedboat is from an ion thruster on a satellite. Since the Spacecraft Ontology represents 'Ion Thruster', the Watercraft Ontology represents 'Outboard Motor', and both ontologies import the Artifact Ontology where 'Engine' and 'Propulsion System' are defined, it is trivial to determine that both are engines that are designed to be part of propulsion systems. In this way, the rigorous design of the CCO and Space Domain Ontologies facilitates the fusion of data across domains.

The Common Core Ontologies comprise eleven ontologies designed to represent and integrate taxonomies of generic classes and relations across all domains of interest. The twelfth CCO ontology, the All Core Ontology, is designed to simplify the importation of the most commonly used portions of the CCO (see §5) and does not introduce new content.

The ontologies that comprise the Common Core Ontologies are:

1. Agent Ontology
2. Artifact Ontology
3. Currency Unit Ontology
4. Event Ontology
5. Extended Relation Ontology
6. Geospatial Ontology
7. Information Entity Ontology
8. Modal Relation Ontology
9. Quality Ontology
10. Time Ontology
11. Units of Measure Ontology
12. All Core Ontology

They are available here: https://github.com/CommonCoreOntology/CommonCoreOntologies

Each member of the CCO is developed in accordance with a rule-based methodology, see "Best Practices of Ontology Development" (Rudnicki, et al., 2016). For more information about the content and design of the Common Core Ontology suite, see "An Overview of the Common Core Ontologies" (CUBRC Inc., 2019):

An Overview of the
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Additional, more domain-specific, content is added to this growing body of knowledge through the construction of domain ontologies that extend the CCO. The Space Domain Ontologies – together with their imports: the Common Core Ontologies, the Military Ontologies, and the other supporting domain ontologies discussed below – provide more than 3,500 carefully curated and logically structured terms that represent a diversity of entities of interest to the space domain.

2 The Space Domain Ontologies

The suite of Space Domain Ontologies began as a single ontology – the Space Object Ontology. Due to the complexity and uniqueness of the space domain, the Space Object Ontology quickly became quite large and covered a wide range of entities. In keeping with the modular design of the CCO and the design principle of establishing clear boundaries on the scope of each ontology, the Space Object Ontology was refactored to create a suite of five space domain ontologies. Each space ontology focuses on its own space sub-domain while preserving the established logical relations between their respective content. The Space Domain Ontologies consists of: (1) the Outer Space Ontology, (2) the Space Event Ontology, (3) the Space Object Ontology, (4) the Spacecraft Ontology, and (5) the Spacecraft Mission Ontology. An overview of the scope and purpose of each ontology is provided in §2.1-2.5. For a more in-depth discussion of the earlier iteration of the Space Object Ontology, see "The Space Object Ontology" (Cox, et al., 2016):

The Space Object
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2.1 Outer Space Ontology

The Outer Space Ontology is designed to represent entities relevant to the spatial and temporal positions of objects and events in outer space. It imports the CCO and its content includes: astronomical temporal regions, regions of space, spatial coordinate systems, orbital paths, and orbital parameters. As such, the Outer Space Ontology provides the basis for locating and characterizing entities in space at the most general level.

2.2 Space Event Ontology

The Space Event Ontology is designed to represent processes that are commonly participated in or caused by objects located in outer space. It imports the Outer Space Ontology and adds content about many naturally occurring processes in space including: orbits, solar radiation pressure, space weather, atmospheric drag, precession, occultation events, and space object collisions. The representation of orbits is especially robust with approximately 70 orbit types defined. (Additional, spacecraft-specific, orbit types are represented in the Spacecraft Mission Ontology.) As such, the Space Event Ontology provides the means for representing celestial and orbital mechanics and the basis for characterizing spacecraft behavior.

2.3 Space Object Ontology

The Space Object Ontology is designed to represent physical objects located in outer space. It imports the Space Event Ontology (and, by extension, the Outer Space Ontology) and is focused on representing astronomical bodies and orbital debris as well as the properties that are common to many or all objects in space, such as their albedo and magnitude. (Note that intact artificial satellites are the domain of the Spacecraft Ontology.) As such, the Space Object Ontology provides the final components needed to characterize and track space debris and natural space objects.

2.4 Spacecraft Ontology

The Spacecraft Ontology is designed to represent spacecraft and related entities. It imports the Space Object Ontology and significantly expands upon it by representing many types of artificial satellites along with their parts, capabilities, vulnerabilities, and design specifications. Types of spacecraft are represented at a generic level based on their size and primary function, e.g. cubesats, communication satellites, and Earth observation satellites. An extensive array of spacecraft parts – including their modules, subsystems, propulsion systems and components, communication systems and components, thermal control systems, power systems, sensors, fuel types, and more – enable finer-grained representations of individual spacecraft. In addition to identifying which parts a satellite of a given design should have, a satellite model can provide significantly more information about a satellite by specifying what its configuration, capabilities, performance specifications, communications frequencies, and other attributes should be. The Spacecraft Ontology also represents relevant entities on the ground, including: satellite ground communications facilities, launch sites, and launch vehicles.

Each artifact – whether it is a ground facility, a spacecraft part, or an entire satellite – is linked to one or more functions that it is designed to perform. This enables users to easily extrapolate additional information about many entities based on limited inputs. For example, a user can infer information about a satellite's capabilities based on information about its parts or, vice versa, infer information about what parts a satellite is likely to have (or not have) based on its demonstrated capabilities. Similarly, given information about blue or gray assets in a specific orbit, users can reasonably infer a lot about red assets that are in the same type of orbit and have similar observational measurements. In general, as the amount and variety of ontologically structured data increases, the extrapolative power of the ontologies becomes more evident and can be leveraged with increasing confidence. As such, the Spacecraft Ontology is a powerful tool for characterizing satellites and evaluating the space-based capabilities and vulnerabilities of nations.

2.5 Spacecraft Mission Ontology

The Spacecraft Mission Ontology is designed to represent entities relevant to the operation of spacecraft as well as other agential interactions that occur in or through outer space. It imports both the Spacecraft Ontology and the suite of Military Ontologies (discussed in §3) and adds content to represent *what* these spacecraft are doing. This includes: spacecraft missions, space-based mission objectives, mission-specific actions, and spacecraft launch, landing, and rendezvous events. Mission-specific actions encompass both "standard" and aggressive operating behaviors and include: telemetry, ISR, orbital maneuvers, station-keeping, transfer orbits, harassing actions, and the employment of space weapons. As such, the Spacecraft Mission Ontology provides the final component needed to characterize satellite behavior, inform mission planning, and assist in the identification of optimal courses of action. The richness and rigor of the Common Core and Space Domain Ontologies together with the doctrinally-informed Military Ontologies makes them a powerful tool for supporting space situational awareness.

3 The Military Ontologies

The Common Core Military Ontologies are a suite of military domain ontologies that are based on Joint Doctrine and are built in compliance with the CCO and its design principles. These ontologies are designed to represent data from every branch of the military in a common structure that can be extended as needed to meet the specialized requirements of each organization. In this way, the richness of the CCO is available to provide representations of entities that are too generic to warrant explicit coverage by doctrine while the Military Ontologies provide the representation structures necessary to ensure that military-specific data can be readily aggregated and leveraged. The suite of Military Ontologies consists of: (1) the Military Operation Ontology, (2) the Military Intelligence Ontology, (3) the Military Command and Control Ontology, (4) the Military Planning Ontology, and (5) the Military Occupations Ontology. An overview of the scope and purpose of each ontology is provided in §3.1-3.5.

3.1 Military Operation Ontology

The Military Operation Ontology is designed to provide a Common Core representation of military operations, missions, and general military actions as described by Joint Doctrine, especially the Joint Publication 3-0 series. Its content includes: operational environments as well as offensive, defensive, air, space, land, maritime, cyber, and support operations. As such, the Military Operation Ontology provides the basis for a common representation of military operations.

3.2 Military Intelligence Ontology

The Military Intelligence Ontology is designed to provide a Common Core representation of information and intelligence as described by Joint Doctrine, especially the Joint Publication 2-0 series. It imports the Military Operation Ontology and adds content about types of military information and military intelligence categorized based on its source, importance, classification level, and its subject matter. As such, the Military Intelligence Ontology provides the basis for identifying and grouping key characteristics of information as well as for tracking its progression through the processes of requesting, collection, processing and exploitation, analysis and production, and finally dissemination.

3.3 Military Command and Control Ontology

The Military Command and Control Ontology is designed to provide a Common Core representation of military command and control entities as described by Joint Doctrine. It imports the Military Operation Ontology and adds content about operational limitations, acts of commanding, and the directive contents of these acts – such as planning directives and tasking orders. As such, the Military Command and Control Ontology provides the basis for representing the use of C2 in the space and other domains.

3.4 Military Planning Ontology

The Military Planning Ontology is designed to provide a Common Core representation of military planning procedures as described by Joint Doctrine, especially the Joint Publication 5-0 series. It imports both the Military Command and Control Ontology and the Military Intelligence Ontology. Its content includes: military operation plans, courses of action, end states, measures of effectiveness and performance, commander's intent, as well as the procedures for creating and selecting courses of action. As such, the Military Planning Ontology enables users in to represent COAs and other aspects of the planning process in a doctrinally consistent manner.

3.5 Military Occupations Ontology

The Military Occupations Ontology is designed to represent occupational roles that are realized by civilians or military personnel within the context of their work for a military organization. Personnel can have and lose many such roles at any given time as well as throughout their careers. The Military Occupations Ontology enables users to assign and keep track of these roles for each individual. This is useful in many contexts including: command and control, information management, and personnel tasking.

4 Other Ontologies Relevant to the Space Domain

In addition to the CCO and the Military Ontologies, the Space Domain Ontologies have access to a wide range of CCO-compliant domain-level ontologies (see §6 for a partial list) that can be imported to instantly expand the types and level of detail of data that can be represented. In particular, the Space Domain Ontologies currently import the Atmospheric Feature Ontology, the Sensor Ontology, and the Cyber Ontology. These additional supporting ontologies are discussed briefly in §4.1-4.3.

4.1 Atmospheric Feature Ontology

The Atmospheric Feature Ontology is designed to represent the atmosphere, meteorological events, and related entities. Its content includes: regions of the atmosphere, precipitation events, severe weather events, natural illumination environments, and other atmospheric conditions. As such, the Atmospheric Feature Ontology provides the means to represent features relevant to performing actions in or through a portion of the atmosphere. This is of particular importance to the space domain for characterizing operational conditions that may impact launching, landing, observing, or communicating with spacecraft.

4.2 Sensor Ontology

The Sensor Ontology is designed to represent sensors and related entities. Its content includes: sensor processes, capabilities, and platforms as well as an array of sensors and sensor systems of varying complexity – such as gyroscopes, imaging sensors, and radar systems. As such, the Sensor Ontology provides the basic set of sensors used in the space domain (with the Spacecraft Ontology adding more specialized sensors) as well as the means to better represent sensor data.

4.3 Cyber Ontology

The Cyber Ontology is designed to represent entities relevant to the cyber domain. Its content includes: types of computers, computer parts, computer networks, computer languages, computer programs, malware, computer processes, cyber-attacks, computer functions and vulnerabilities, as well as digital files, formats, and data structures. As such, the Cyber Ontology provides a solid framework for representing computers, digital information, and cyber activities. This is useful to the space domain for many purposes, including representing sensitive satellite components, data transfers, and the cyber capabilities and vulnerabilities of space assets. For more information about the Cyber Ontology, see (Donohue, et al., 2018).

5 Ontology Import Structure

A roadmap of the import structure for the Space Domain Ontologies is illustrated in Figure 1.

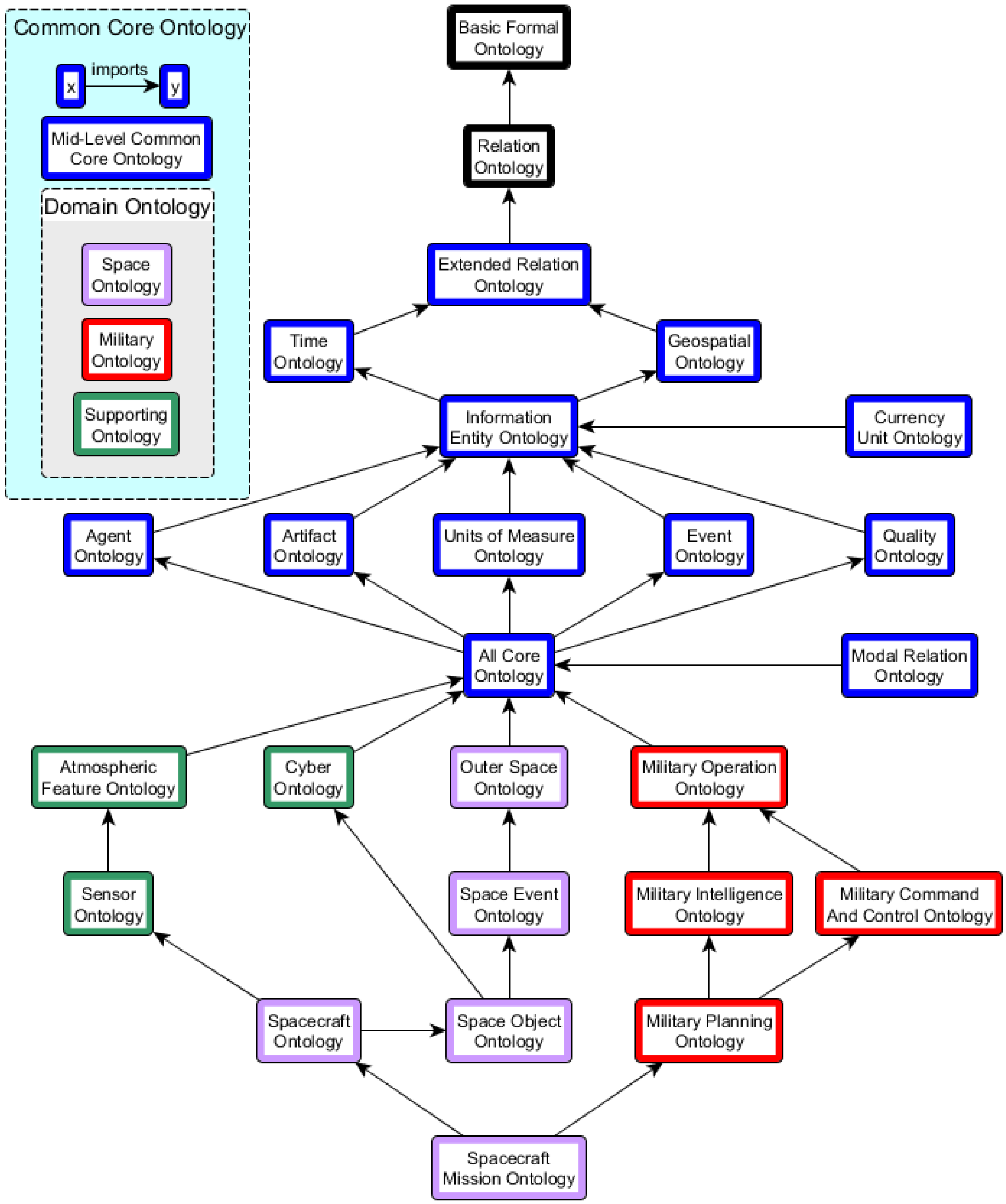

Figure 1: The import structure of the Common Core, Space Domain, Military, and supporting ontologies

The component ontologies of the CCO and Space Domain Ontologies are connected to one another by the import relation (sometimes referred to in this document as the extension relation). When one ontology imports another, the content of the imported ontology is available for use in the importing ontology. Users can choose to import some or all of the ontologies from the mid-level Common Core Ontologies and domain-level Common Core Extension Ontologies to satisfy their needs.

For example, a user who wants to represent all of the ground vehicles used by a particular branch of the U.S. military might begin by importing the Artifact Ontology and then expand upon its existing representation of ground vehicles to develop a new domain ontology of U.S. military ground vehicles. If that user later wants to represent data about the performance of these types of vehicles in different environmental conditions while performing various tasks, the Sensor Ontology and Physiographic Feature Ontology along with the Atmospheric Feature Ontology and the main corpus of the CCO can be imported to immediately grant access to established representations of these environments, tasks, and measurements.

6 Additional Domain-Level Content

The goal of the mid-level Common Core Ontologies is to represent entities of common interest to a wide array of domains. Domain-level ontologies are built as extensions to the CCO and are designed to provide the greater level of granularity and specificity needed to capture all of the relevant data within their respective domains. Users can develop additional domain-level ontologies by importing content from the pertinent mid- and domain-level ontologies in a piecemeal or wholesale manner and then extend the inherited content as needed. In this way, users can readily reuse and enhance the shared knowledge representation. This significantly speeds up development and improves knowledge integration.

To date, more than 50 domain-level extensions of the CCO have been developed including:

1. Affective State Ontology
2. Agent History Ontology
3. Agent Information Ontology
4. Aircraft Ontology
5. Air Force Action Taken Codes Ontology
6. Air Force Aircraft Maintenance Ontology
7. Air Force How-Malfunction Codes Ontology
8. Air Force Maintenance Status Codes Ontology
9. Air Force Purpose Codes Ontology
10. Air Force Type Maintenance Designators Ontology
11. Air Force When-Discovered Codes Ontology
12. Army Universal Task List Ontology
13. Atmospheric Feature Ontology
14. Citizenship Ontology
15. Curriculum Ontology
16. Cyber Ontology
17. Ethnicity Ontology

18. Food and Allergy Ontology
19. Food Ontology
20. Hydrographic Feature Ontology
21. Joint Doctrine Ontology
22. Legal and Criminal Act Ontology
23. Maintenance Activity Ontology
24. Marine Corps Task List Ontology
25. Marine Corps Task List Metrics Ontology
26. Medical Information Ontology
27. Military Command and Control Ontology
28. Military Intelligence Ontology
29. Military Occupations Ontology
30. Military Operation Ontology
31. Military Planning Ontology
32. Modal Extension Relation Ontology
33. Occupation Ontology
34. Outer Space Ontology
35. Physiographic Feature Ontology
36. Planning Ontology
37. Sensor Ontology
38. Skills Ontology
39. Spacecraft Mission Ontology
40. Spacecraft Ontology
41. Space Event Ontology
42. Space Object Ontology
43. Transportation Infrastructure Ontology
44. Undersea Warfare Ontology
45. Watercraft Ontology

7 Conclusion

The Common Core Space Domain Ontologies are a set of domain-level ontologies that – together with the mid-level CCO, Military Ontologies, and supporting extension ontologies – provide an extensive vocabulary of more than 3,500 terms to describe both man-made and natural objects and events in space and on the ground. They also provide the means to express complex relationships between a rich array of entities that a mere taxonomy or vocabulary cannot. The Space Domain Ontologies were developed in adherence to principles designed to maximize interoperability and reduce costs associated with organizing and maintaining diverse and complex data. The ontologies are flexible, modular, and easy to reuse or expand to satisfy novel data and application requirements. They are grounded in doctrine, vetted against multi-source data, reviewed by subject matter experts, and subjected to quality tests. As such, the Common Core

Space Domain Ontologies are well-suited to support space situational awareness, mission planning, and many other space applications.

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