C2 Domain Ontology within Our Lifetime

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C2 Concepts, Theory, and Policy

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Abstract: Agile Command and Control (C2) requires agile information sharing with an increasingly wide variety of military and non-military partners. While current "net-centric" approaches may improve information sharing within a particular niche of C2, they do not support information sharing across the larger C2 domain. Although not a silver bullet, the development and application of a C2 domain ontology to improve C2 data and service integration appears to be increasingly realistic. In fact, there are several examples of successful ontology applications in domains such as medicine, biology, and engineering, and the new discipline of *Applied Ontology* is emerging. C2 data, architecture, and conceptual modeling activities which bear a close resemblance to applied ontology activities are also beginning to take shape, and there are several efforts with near to mid-term promise as elements of a C2 domain ontology. This paper provides an overview of ontology, examples of existing ontologies, key C2 data, architecture, and modeling efforts with applicability to a C2 domain ontology, and recommendations regarding the way ahead. It is the authors' conclusion that development of a practical C2 domain ontology is necessary and feasible in the near to mid term, and that efforts should commence following the principles and best practices of the applied ontology community.

Background

In May 2003, the United States (U.S.) Department of Defense (DoD) published the DoD Net-Centric Data Strategy [1], which officially launched the quest to transform DoD information sharing from a producer-centric to a consumer-centric approach in support of the emerging concept of net-centric operations and warfare. This document was followed by the North Atlantic Treaty Organization (NATO) Net-Enabled Capability (NNEC) Data Strategy [2] and the DoD Net-Centric Services Strategy [3], and the same approach is being adopted by many other coalition and inter-agency partners. Whereas a producer-centric information sharing approach is characterized by stove-piped systems, point-to-point interfaces, and a "need-to-know" information sharing philosophy, a consumer-centric information sharing approach is characterized by open standards, many-to-many interfaces, and a "need-to-share" information sharing philosophy where data and services are viewed as enterprise assets. Making data and services widely available in this manner improves access to information needed for situational awareness, better enabling warfighters at all echelons to understand and adapt to changes in the operational environment. This will continue to be important in the future Joint Operational Environment, where warfighters must innovate and adapt to counter a broad range of threats from often unpredictable adversaries. [4]

At the architecture and technology level, the approach to implementing a net-centric data and service strategy has been to mimic the phenomenal information sharing success of the Internet by leveraging web-based methods for describing and sharing data and services as well as the concept of Service Oriented Architecture (SOA). The eXtensible Markup Language (XML) and its associated family of standards have become U.S. DoD and NATO standards, the preferred method for exposing and accessing data is via web-services, and federated search methods for searching defense-related data stores are being implemented. The concept of SOA has taken hold in key C2 capability development activities such as the U.S. Net-Enabled Command Capability (NECC) and NNEC, and initial core enterprise services for storing, searching, and retrieving data, services, and associated metadata are in place.

At the management level, the approach to implementing a net-centric data and service sharing strategy in the U.S. DoD and NATO has been to divide and conquer the overall information sharing problem through Communities of Interest (COI), each focused on a specific operational need. COIs are formed by the relevant stakeholders to address a specific data sharing need, and each COI is responsible for determining which data is relevant and authoritative in the context of the COI, how to describe the data in a common format, and how to make data accessible to the members of the COI and the enterprise via web services. In the parlance of the net-centric data strategy, the COI's role is to make its data and web services "visible, accessible, and understandable".

While the concept of using individual COIs to tackle subsets of the overall data sharing problem was a necessary and good first step, over time it has become clear that COIs operating independently may not be providing the information agility that was initially expected, even when individual COIs are successful. This is because COIs operating independently with no overall conceptual, technical, or governance framework have resulted in multiple independent representations for the same data, making it very difficult to share data and services across COIs. Thus, while data and services may be visible, accessible and understandable within each COI, they are not necessarily understandable outside of the COI, nor interoperable across COIs and with legacy capabilities and standards. [5] A consumer that combines data and services from multiple communities, a characteristic of many C2 functions, must be able to interpret multiple data and service metadata artifacts and then mediate between them in order to make effective use of the data and services. This can be quite difficult and time-consuming, and is not quite the consumer-centric, agile approach to data sharing that was envisioned.

Given this reality, how can C2 data and services be more understandable and interoperable across the C2 domain? While the use of open standards such as XML to describe and share data may get us partially there, clearly there is much more to be done. Specifically, to promote data and service interoperability within the C2 domain, there is a need for common message structure, common semantics, and a common descriptive framework for C2. While data standardization and/or standard information exchange models have been used to support C2 data exchange and integration in the past, this approach has not proven successful and it is clear that large scale data standardization at the physical level, even as a data exchange model, is not feasible for the C2 domain. Fortunately, this problem is not unique to the C2 community, and we can learn from several other communities that are answering these questions through the use of domain ontologies.

Ontology Defined

There are many differing definitions and perspectives on the term "ontology", which is somewhat ironic because ontology is concerned with creating accurate descriptions of the world in order to have a shared understanding. Some of these different perspectives can be attributed to relative inexperience, however, there is also lack of a consistent definition of ontology, ontology terminology, and ontological relationships even amongst professionals who are engaged in applying ontology in various fields of study. [6] This section reviews some of the different perspectives on ontology and offers a working definition for a C2 domain ontology.

The term ontology originates in the realm of philosophy and translates roughly as “the study of being”, from the Greek “onto” (“of being”) + “logy” (“to study”).   Merriam Webster gives two definitions of ontology [7]:

> *1* **:** *a branch of metaphysics concerned with the nature and relations of being*
> *2* **:** *a particular theory about the nature of being or the kinds of things that have existence*

A more descriptive definition, still with a philosophical bent, is found in Wikipedia [8]:

> *The study of the nature of being, existence or reality in general, as well as of the basic categories of being and their relations. Traditionally listed as a part of the major branch of philosophy known as metaphysics, ontology deals with questions concerning what entities exist or can be said to exist, and how such entities can be grouped, related within a hierarchy, and subdivided according to similarities and differences.*

Per Smith and Klagges [9], the field of applied ontology has its roots with early philosphers such as Aristotle (384-322 BCE), who tried to make sense of a complex world by categorizing and documenting its entities and their relationships. Very well known ontologies are taxonomies of organisms, as well as hierarchical categories for the classification of diseases. Modern philosphers working in the field of ontology continue the pursuit of dividing, grouping, and describing the world within the discipline of applied philosphy, and wrestle with ideas such as realism vs. relativism, realist fallibilism, realist perspectivalism, granularity, partitioning, and what 'is_a' is[1].[11]

As the amount of data supporting a variety of scientific, medical, government, and business applications has exploded with automation, there is an imperative to better organize this information in order to make it more useful. Just as philosophy-based ontology tries to make sense of the world by categorizing and documenting its entities and their relationships, information managers also try to make sense of vast amounts of data by grouping, subdividing, and arranging it in hierarchies, as well as creating various relationships between entities and types of information. Thus, the term *ontology* has also found its way into the vocabulary of Information Science in areas such as data modeling, artificial intelligence, and knowledge engineering. In the Information Science domain, the Wikipedia definition [12] of ontology is as follows:

> *Ontology: a formal representation of a set of concepts within a domain and the*

1 'is_a' is one of the basic relations found in ontology, along with 'has_a'. It has been noted that there are at least 4 different types of 'is_a' relationships. [10]

relationships between those concepts. It is used to reason about the properties of that domain, and may be used to define the domain.

Another widely quoted definition in Information Science is that of Gruber [13]:

Ontology: "a formal, explicit specification of a shared conceptualization"

While not directly included in these definitions, it can be inferred that ontologies of interest in Information Science are represented via means suitable for automation, or are implemented directly within the underlying data structures or exchanges. In some circles, the term *ontology* is taken to imply only those formal specifications that are expressed in an ontological language such as the Ontological Web Language (OWL), a standard favored by the World Wide Web Consortium (W3C) [14]. However, a more general interpretation of the term is not limited to artifacts represented in an ontological language, and includes taxonomies, controlled vocabularies, data dictionaries, thesauri, conceptual models, and a number of other information modeling artifacts specified using a variety of tools. This type of perspective is reflected in the DoD Net-Centric Data Strategy, which refers to COI vocabulary, taxonomies, and XML schema artifacts as ontologies.

A notable difference between the philosophical and information science definitions of ontology above is that the philosophical definition stresses the modeling of *reality*, whereas the information science definition stresses the modeling of *concepts*. This is an important distinction in the philosophical realm, particularly to ontologists who are *realists.* That is, they believe there is one reality, and all ontology efforts should strive to represent reality vice concepts that may not reflect reality at all. The realist approach is strongly advocated by Smith [15], Grenon [16], and others.

One way of separating the difference between reality, concepts, and the artifacts that represent them is to divide entities into three levels as proposed by Smith [6]:

- Level 1 Entities (**reality**): *The objects, processes, qualities, states, etc. in reality.*
- Level 2 Entities (**concepts**): *Cognitive representations of this reality on the part of researchers and others.*
- Level 3 Entities (**artifacts**):*concretizations of these cognitive representations in (for example textual or graphical) representational artifacts.*

For the purposes of this paper, we are interested in ontology as applied to information sharing within and/or about the C2 domain via automated means. Drawing largely from Smith's proposed reference terminology for ontology in the biomedical domain[2] [6], our working definition of a C2 domain ontology is as follows:

2 Smith [6] defines ontology as "a representational artifact, comprising a taxonomy as a proper part, whose representational units are intended to designate some combination of universals, defined classes, and certain relations between them." He also notes that an ontology must be converted into a formalized representation if it is to be interpretable by a computer.

> ***C2 Domain Ontology**: A composite formalized representational artifact, comprising a taxonomy as proper part, whose representational units designate C2 universals, defined classes, and relations between them. The C2 domain ontology may be used as a reference to describe and reason about C2 in general, or about C2 particulars when applied to a dataset pertaining to these particulars.*

Thus, the C2 domain ontology is a collection of artifacts (level 3) that describe C2 entities, processes, qualities, etc. (level 1) based on how C2 subject matter experts collectively conceive of C2 (level 2). Further, these artifacts must be machine readable or otherwise suitable for automation. In this definition, the term *universals* refers to general types of entities (e.g., soldier, readiness level, personnel recovery), as opposed to instances of universals, or *particulars* (e.g., Sargeant Smith, 1st Battalion readiness level, recovery operation "OUT"). A *defined class* is a collection of particulars described by a general term (e.g., Charlie Platoon, Army readiness levels, Joint C2 processes*). Relations,* such as 'instance_of' and 'part_of', describe the correspondence between two entities via *tuples* (e.g., Sargent Smith *instance_of* soldier, Sargent Smith *part_of* Charlie Platoon, Sargent Smith *engaged_in* recovery operation OUT).

Per discussion in a recent C2 Ontology Technical Exchange held in the U.S. [17], there are three types of artifacts needed to describe the C2 domain: 1) A natural language vocabulary explicitly describing C2 representational units, 2) An OWL Description Logic (OWL-DL) instantiation of the C2 representational units, depicting universals, defined classes, and the relations between them, and 3) Rules (e.g. constraints) about the C2 representational units expressed in a logic language such as the Sematic Web Rule Language (SWRL) [18]. The use of OWL-DL and SWRL as opposed to any other ontological language is not absolutely necessary, but it is preferred for military use based on the designation of the W3C standards as DoD and NATO standards and their growing popularity. In addition, the DoD Metadata Registry (MDR) supports OWL-DL artifacts, although only the taxonomic relations of 'is_a' and 'part_of' are currently recognized. [19]

Ontology Types and Applications

Before discussing the feasibility of a C2 domain ontology, it is useful to review some ontology types and applications, as well as some real world ontologies that are in use in the biological, medical, and engineering domains.

The applications of ontology are as varied as the number of information domains that exist and are limited only by knowledge of the domain, the quality of the ontology artifacts and associated tools, and the creativity of the user in applying the ontologies to the problems within a given domain. Common ontology applications are to organize information within a domain, to integrate disparate information representations within a domain or across domains, and to infer new information about a domain by applying the ontological relations within and across datasets[3]. The process of developing ontologies also advances knowledge of the domain, which

3 For example, if we know from one dataset that Nutmeg *is_a* dog, and from another dataset that a dog *is_a* mammal, we can combine this information and infer that Nutmeg *is_a* mammal if we know that the 'is_a' relation

is then captured in the ontologies and can become powerful learning aids for others. The ontologies may then serve as a focal point for refining, extending, or otherwise further advancing knowledge of the domain. Overall, ontologies support information sharing and understanding within and across domains, whether it is the general information about the domain, or the particulars within the domain when the ontology is applied to data about these particulars.

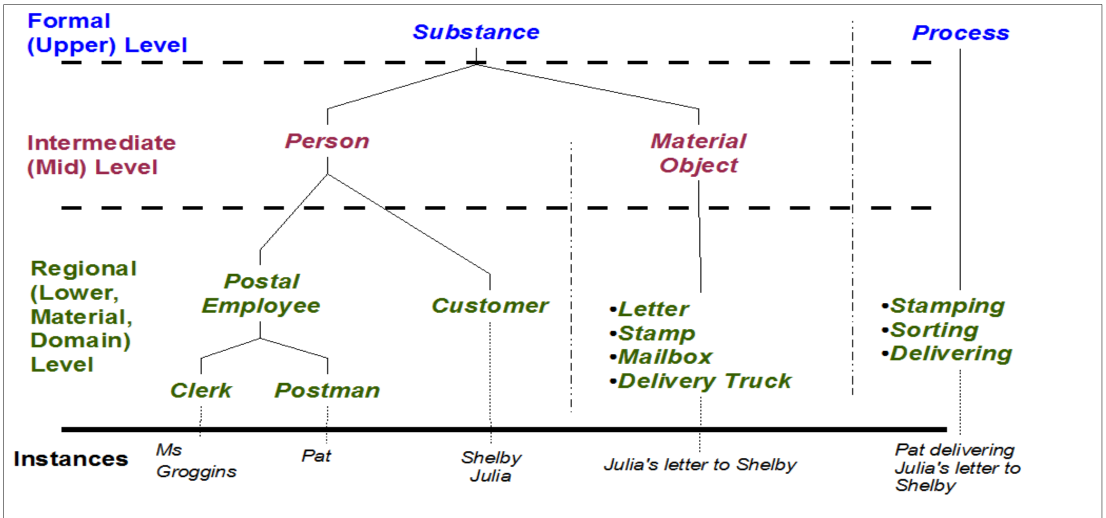

Figure 1: Ontological Levels *(Adapted from [16], p68)*

There are several distinct types of ontologies, and multiple ontologies are used in combination to describe a particular domain relative to the larger world in which it resides Some may refer to a set of ontologies in the singular, e.g., as we have above with respect to the C2 Domain Ontology. However, it should be noted there are usually multiple ontological artifacts required to describe a domain of any substance, particularly one as complex as C2. This is because there are a number of different perspectives to address, all of which may be valid in a particular context[4]. In addition, one ontology artifact may leverage several others to fully describe an entity. Ontology types commonly referred to include *formal ontologies, upper-level ontologies, intermediate ontologies, mid-level ontologies, regional ontologies, lower-level ontologies, domain ontologies, material ontologies, reference ontologies,* and *application ontologies*. Depending on what type of formal or upper-level ontology may be in use, there is also a distinction between ontologies that describe *continuents* (i.e., entities that have substance and a presence, such as a person or a rock), and *occurents* (i.e., entities that do not have substance or presence, such as a process or an event). [21]

Figure 1, adopted from [16], depicts the concept of ontological levels for a post office application based on the Husserl [23] distinction between *formal level ontologies* characterized by being

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is transitive.

4 The term realist perspectivalism captures the idea that we can obtain knowledge of reality through multiple valid views of reality, all of which can be partitions of an ontology. For example, C2 ontologies representing the structure of C2 organizations, objects on the battlefield, and c2 processes are all valid perspectives of C2. Collectively these different perspectives contribute to a robust and realistic representation of the C2 domain.[20]

domain-neutral, and *regional level ontologies,* characterized by being domain-specific[5]. As shown, the most general and domain-neutral ontology is at the formal level, and the specificity of the ontologies to a given domain increases downward through the intermediate and regional levels. There can be multiple intermediate levels, with the requirement that an *intermediate ontology* applies to two or more regional level ontologies. Actual instances of universals (particulars) are shown along the bottom of the diagram and map to the regional level ontology. The first vertical line from the left delineates between ontologies for persons or material objects, and the second vertical line delineates between ontologies pertaining to substances (continuents) and those pertaining to processes (occurents), thus depicting that it is possible to have multiple ontologies in use at the intermediate and regional levels. Formal level ontologies are also called *upper level* ontologies, and *intermediate level* ontologies are also called *mid level* ontologies. Regional level ontologies are referred to as *lower level* ontologies, *material* ontologies, and *domain* ontologies. *Reference* ontologies are those that describe universals, and *application* ontologies are those that describe particulars through application of a reference ontology.

The number of ontologies required to describe a domain is unlimited, depending on the complexity of the subject matter and the scope of each ontology that is employed. In this layering concept, there is one formal level, but it could conceivably include multiple formal ontologies if the intermediate ontologies stem from multiple formal ontologies. Below the formal level there may be multiple intermediate levels, and each intermediate level may include multiple ontologies depending on the scope of the domain and the number of intermediate level ontologies that are applicable. There may also be multiple regional or domain ontologies, but each is characterized as being specific to the domain in question and collectively they define the domain. An important point to note is that the categorization of ontologies as intermediate or regional is a function of the granularity of the analysis. A regional ontology in a coarse grained analysis (e.g., at the organism level in biology) may be an intermediate ontology in a finer grained analysis (e.g., at the cell level). Characterization of ontologies as being in the formal level appears to be more absolute, although not all ontologies that claim to be upper-ontologies or formal ontologies actually meet the requirements. [16]

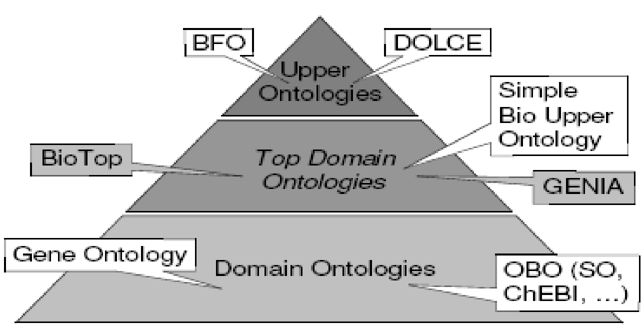

Figure 2: Ontological Layering in the Biological Domain (Stenzhorn [37])

Numerous real-world ontologies have been created and are in use in various fields of study, most notably in biology and medicine where ontology applications appear to be very prevalent, fairly mature, and widely accepted. Well known upper-level or formal ontologies include the Basic Formal Ontology (BFO) [24][25], the Suggested Upper Merged Ontology (SUMO) [26], and the Descriptive Ontology for Linguistics and

5 In this discussion, the term *domain* refers to the specific topic area that the ontologist seeks to describe via the ontology.

Cognitive Engineering DOLCE [27].

Notable domain ontologies include the Genome Ontology (GO) [28], the Unified Medical Language System (UMLS) Semantic Network [29], and the large collection of ontologies that are part of the Open Biological Ontology (OBO) Foundry.[30] These are very comprehensive artifacts that represent a vast amount of domain knowledge and which are in active use. The GO provides approximately 24,000 terms organized into 3 ontologies to describe gene products according to their associated biological processes, cellular components, and molecular functions. The UMLS is a thesaurus-like ontology that facilitates biomedical information retrieval and understanding and comprises over 1 million biomedical concepts and 5 million concept names stemming from over 100 incorporated controlled vocabularies and classification systems. Finally, the OBO Foundry includes over 60 biomedical ontologies from participating members, with the vision that a core of these ontologies will become fully interoperable by virtue of a common design philosophy and implementation. Figure 2, from Stenzhorn [37], illustrates the relationship between upper level ontologies, mid level ontologies (referred to as “top domain” ontologies in the diagram) and domain ontologies in the biological domain.

Another significant ontology effort is the National Aeronautics and Space Administration (NASA) Exploration Initiatives Ontology Models (NexIOM), supporting the NASA Constellation program. NeXIOM is a family of approximately 140 ontologies working across hundreds of datasets. NexIOM formalizes the way computers and people refer to NASA Elements, their Scientific and Engineering disciplines, related work activities, and their interrelationships throughout the NASA Constellation Program As a result, information can be found, aggregated and reasoned over to generate products, enable interoperability between systems and tools, and inform decisions. Figure 3, illustrating the NASA ontology architecture, gives a hint as to the scope and complexity of this work supporting multiple domains, disciplines, and organizations. [31]

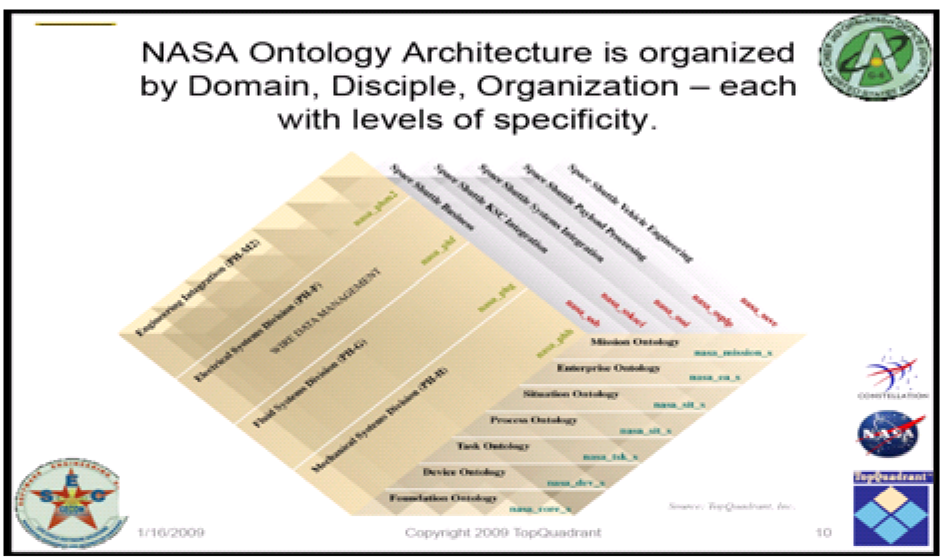

Figure 3: NASA Ontology Architecture (from Hodgson [31])

As further evidence of the growth in the use of ontology, libraries of ontological artifacts and ontology search engines are now available on the world wide web. [32][33] While this illustrates that ontology is poised to hit the main stream of information management, at least for web applications, it should be noted that not all ontology is good ontology. In the compilation *Applied Ontology, an Introduction* [11], multiple authors make the case that many ontology development efforts are using ad hoc methods and are not following basic principles for developing ontology as practiced by ontological engineers in the emerging field of Applied Ontology[6]. For example, "casual" ontologists are not likely to: follow best practices for defining vocabulary terms and creating useful classifications [35], understand the basic ontological relations and their meaning [36][10], understand how to partition a domain [20], nor understand the benefits of realism. [15][16] Furthermore, they may not be aware of work that others have done and/or whether it is suitable for reuse. As a result, many existing ontologies do not accurately represent domain knowledge, do not leverage accepted ontologies from other domains, and do little to solve the existing knowledge management and interoperability problems that resulted from equally ill-conceived information management approaches in the past. If C2 domain ontology development were to proceed in this manner, the C2 community would be no better off using ontology technology than with the current approach to COIs. That is, there would be multiple, disparate ontologies developed independently with no standard relations, no agreed to partitioning of the mission space, inconsistent adherence to doctrine or existing standards, etc. In that case, we would need still more ontologies to integrate these ontologies after the fact in a never ending spiral. Information management and interoperability problems would continue to persist, or perhaps even worsen.

C2 Domain Ontology

The C2 community can clearly benefit from the use of ontology because of the need to organize, integrate, and understand large quantities of information in order to make effective decisions. This is true whether the ontology is used to support C2 concept development, C2 capability management, C2 materiel development, C2 training, or real-time C2 decision making and information integration during operations. While the full-scale development of an authoritative C2 domain ontology has not been directed by the C2 governance bodies in the U.S. or NATO[7], both bodies have begun exploring the practical application of ontology to C2. For example, NATO hosted two ontology workshops in 2008 and a third in March 2009, the NATO Semantic Interoperability Group is investigating the applicability of ontology to facilitate semantic interoperability, and the forthcoming NATO Data Strategy Implementation Guidance will include a volume on "Ontology and Vocabulary". In the U.S., the U.S. Joint Forces Command, U.S. Army Software Center of Excellence, and the Buffalo University National Center for Ontological Research held a C2 Ontology Technical Exchange in February 2009 to assess the state of the art of C2 ontology efforts, and there are several independent efforts underway exploring the use of ontology for a variety of C2 applications. Collectively, these activities show that the idea of

6 Applied Ontology is "a branch of applied philosophy using philosophical ideas and methods from ontology in order to contribute to a more adequate presentation of the results of scientific research." [34]

7 The formal U.S. C2 governance body is the C2 Capability Integration Board (C2 CIB). The formal NATO C2 governance body is the NATO C3 Board (NC3B).

applying ontology to C2 has taken hold, and undoubtedly there are similar activities underway in other nations. As further evidence, there have been a steady stream of C2 ontology papers presented at the ICCRTS, Simulation Interoperability Standards Organization (SISO), and elsewhere regarding C2 ontology, many of which explore the use of the Joint Consultation, Command, and Control Information Exchange Data Model (JC3IEDM) as discussed below.

Given the strong interest in the use of ontology for C2, how far is the C2 community from creating a C2 domain ontology that can support C2 capability development and management, C2 data and service interoperability and integration, operational decision making, training, or any type of practical application? Based on our working definition of a C2 domain ontology in a previous section, one might argue that the C2 community is already well on the way to creating a C2 domain ontology. That is because many C2 architecture, data, and modeling initiatives may be considered forms of ontology, or at least promising candidates for contributing to a C2 domain ontology. In addition, the formal description of C2 entities, vocabulary, and processes within doctrine can also serve as strong contributors to a C2 domain ontology. Several of the most relevant C2 ontology-like efforts and artifacts are described in the following paragraphs.

Joint Capability Areas (JCA) and Universal Joint Task List (UJTL)

5.3	**Planning**
5.3.1	Analyze problem
5.3.1.1	Analyze Situation
5.3.1.2	Document Problem Elements
5.3.2	Apply Situational Understanding
5.3.2.1	Evaluate Operational Environment
5.3.2.2	Determine Vulnerabilities
5.3.2.3	Determine Opportunities
5.3.3	Develop Strategy
5.3.3.1	Determine End State
5.3.3.2	Develop Assumptions
5.3.3.3	Develop Objectives
5.3.4	Develop Courses of Action
5.3.4.1	Assess Available Capabilities
5.3.4.2	Understand Objectives
5.3.4.3	Develop Options
5.3.5	Analyze Course of Action
5.3.5.1	Establish Selection Criteria
5.3.5.2	Evaluate Courses of Actions

Figure 4: C2 Planning JCA (Tier 2-4)

The JCAs are a U.S. DoD construct for partitioning DoD capabilities into separate functional areas. The JCAs are described by a taxonomy and a set of definitions for each element in the taxonomy. [41] At the top level (Tier 1), there are 9 JCA's, one of which is Command and Control[8], and the hierarchy of capabilities extends several levels, providing 4 levels for C2. JCAs have become an important organizing construct for management purposes, e.g., within the Joint Capability Integration and Development System (JCIDS) [42], and should also be an important part of a C2 domain ontology. This is because the JCA construct provides a taxonomy and vocabulary for defining C2 from the process perspective, and the Tier 1 JCAs could be considered part of an intermediate ontology which relates C2 to the larger scope of the DoD capability domain. Figure 4 shows an excerpt of the C2 JCA taxonomy for arguably the most important Tier 2 capability, Planning. The DoD Core Taxonomy, an OWL taxonomy in the DoD Metadata Registry, is based on the JCA structure. A similar product to the JCAs is the Universal Joint Task List (UJTL). The UJTL is a common language and reference system arranged in a hierarchical manner that enables users to unambiguously describe and communicate U.S. military missions and tasks. [43] While the best known functions of the UJTL are to support the Joint Training

8 The remaining 8 Tier I JCAs are: Force Application, Battlespace Awareness, Net-Centric, Building Partnerships, Logistics, Force Support, and Corporate Management and Support

System and readiness reporting, the UJTL also serves as a description and taxonomy of the types of tasks that are performed in the conduct of C2 or other capabilities, and is therefore an important component of a C2 domain ontology. The U.S. Joint Chief of Staff J7, which owns both the JCAs and UJTLs, maintains a mapping between the two.

C2 Core

The C2 Core is a U.S. DoD effort led by U.S. Joint Forces Command (USJFCOM) and the Office of the Assistant Secretary of Defense for Networks and Information Integration (OASD(NII)) in their role as co-leads of the C2 Capability Portfolio. The intent of the C2 Core is to enable greater information interoperability within the C2 domain through the use of a common structural and semantic foundation for the creation of XML-based C2 information exchanges.[9] The C2 Core is currently under development with a baseline version to be available in Jun 2009 that will include a C2 conceptual model and vocabulary as well as XML reference schemas that are C2-specific extensions to the U.S. Universal Core (UCore)[10].[5][44] The conceptual model and vocabulary components of the C2 Core are highly relevant to the creation of a C2 domain ontology because they will describe the universals that are of interest within the C2 domain, such as organizations, individuals, weapons, vehicles, plans, orders, and effects. These are the continuents of the C2 domain and can form the basis for more sophisticated occurrent or process ontologies. The close relationship of the C2 Core to the UCore is also important to an eventual C2 domain ontology because the UCore, if coupled with additional semantics, will then be an intermediate ontology for the C2 domain ontology. In fact, there are reportedly efforts to create a UCore Semantic Layer (UCore-SL) represented in OWL, and possibly to map the UCore to a true upper ontology[11]. In that case, the upper ontology, UCore-SL, and the C2 Core, if represented as an ontology, would form a hierarchy of ontologies for C2 and the basis for further work at the COI-level. Figure X shows the hierarchical relationship between the UCore, C2 Core, and COI-specific extensions within a C2 Core compliant Information Exchange Specification (IES).

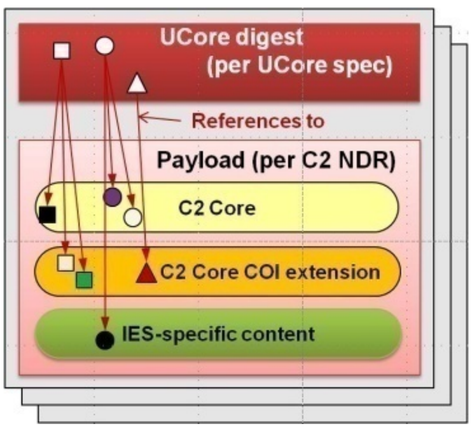

Figure 5: C2 Core-based IES

JC3IEDM

JC3IEDM is a product of the Multilateral Interoperability Programme (MIP) and is endorsed by the NC3B as NATO Standard Agreement (STANAG) 5525.[46][47] The JC3IEDM is important to the C2 domain ontology because it is a very comprehensive representation of the data that is

9 While the emphasis on the C2 Core is on XML-based messages due to the emphasis of current standards, the C2 Core Conceptual Model and Vocabulary may also apply to other types of messages.

10 The UCore is a U.S. DoD, Department of National Intelligence, Department of Justice, and Department of Homeland Security common framework for XML-based messages that includes the basic concepts of “who”, “what”, “when”, and “where”

11 MITRE investigated the use of upper ontologies for government and military applications in [45].

shared between coalition partners to perform C2 functions, and it codifies at least 20 years of work by C2 domain experts based on C2 doctrine. Important components of the JC3IEDM that may contribute to a C2 domain ontology include the conceptual data model, logical data model, an extensive vocabulary, and many controlled vocabularies. In addition, the JC3IEDM documentation includes extensive rules governing the relationships between JC3IEDM entities as well as their allowable values, which is invaluable for verifying whether a given message or information artifact is valid. There have been many papers regarding the value of JC3IEDM as a C2 ontology, most finding that while there is goodness, it is not a ready made solution for a C2 domain ontology. [48][49][50] Recently the Institute for Defense Analyses created an OWL-DL version of the JC3IEDM for the MIP community. An important finding was that while OWL-DL was able to capture much of the model, an additional rules language such as SWRL is needed to fully capture the relationships of the JC3IEDM.[51] It is expected that the JC3IEDM conceptual model and vocabulary will have a significant role in the emerging C2 Core. However, there are many other sources of similar information that will be considered to include Tactical Data Link standards, Message Text Format standards, and the work of C2-related COIs to the extent that they are accurate representations of C2 vocabularies, entities, and relationships.

COI and Program Vocabularies and Taxonomies

As described previously, COIs are the stated U.S. and NATO approach to implementing a net-centric data sharing approach for a specific operational need. Examples of C2-related COIs in the U.S. include the Time Sensitive Targeting COI, the Blue Force Tracking COI, the Joint Air and Missile Defense COI, the Air Operations COI, the Maritime Domain Awareness COI, and the Global Strike COI. In accordance with U.S. DoD guidance [52], each of these COIs is producing semantic products that describe the data shared within the COI, to include vocabularies, XML schemas, taxonomies, and sometimes additional components such as logical data models, Business Process Language (BPL) artifacts, and U.S. DoD Architectural Framework (DoDAF) [53] products that describe the processes of the COI. While none of these COIs is concerned with developing a C2 domain ontology in and of itself, they are important nonetheless because they may share entities with the C2 domain, model part of the C2 domain, or represent the lower ontologies that build from the C2 domain. Thus, the work of the C2-related COIs can help define the C2 domain ontology from the “bottom up”, whereas the UCore and the JCAs help build the C2 ontology from the “top down”. In addition, COIs such as Logistics, Distribution, Global Force Management, Meteorology and Oceanography (METOC), and Measurement and Signal Intelligence (MASINT) can provide important insights on domain ontologies that are outside of the C2 domain but may be leveraged by the C2 domain ontology. A quick review of the unclassified version of the DoD MDR [19] in March 2009 revealed that there are very few COIs or programs registering taxonomies, the basic type of ontology supported by the MDR. Of the approximately 140 namespaces, only 6 have registered taxonomies for a total of 180 taxonomies, with 151 attributed to one namespace (Focused Logistics). C2 taxonomies appear to be limited to the NECC-C2 namespace, where there are 18 artifacts, most of which are multiple versions of capability taxonomies based on the NECC program structure. Of particular interest is a C2 objects taxonomy which appears to be based on objects in the Military Standard (MIL-STD) 2525, *Military Symbology*.

C2 Architecture Products

Over the last decade or more, there has been a push toward creating extensive architectural documentation to uniformly describe a given capability and how it fits into the bigger picture of an operational process or a domain such as C2 or Logistics. The DoDAF and the NATO Architectural Framework (NAF) [54] offer guidelines for creating specific architectural products. Of primary interest to a C2 domain ontology are the Operational Views (OV's) of the architecture, because they define C2 universals: operational entities, the relationships between them, the information that is exchanged, and the relevant processes[12]. While many architecture products describe a single capability or a single operational process vice a domain, there are more comprehensive "integrated" architectures as well. A notable effort is the USJFCOM-developed Joint Task Force Headquarters (JTF HQ) architecture, which describes the operational nodes of a JTF HQ, the relationships between these nodes, the functions they perform, the information that is exchanged, and many other aspects of JTF C2. Additional Joint C2 architecture products offer detailed descriptions of important C2 processes, to include Joint Close Air Support (JCAS), Joint Personnel Recovery Activity (JPRA), and Crisis Action Planning (CAP). The JTF HQ architecture products are extensively documented, map back to authoritative references such as policy or doctrine, and include a vocabulary that describes the entities of the architecture (AV-2), as well as information exchange requirements (OV-3) that describe the data entities (e.g., reports, messages) exchanged by the operational entities. Because the function of the JTF HQ is C2, these integrated architecture products may be considered a form of a C2 domain ontology in that they describe C2 entities and the relationships[13] between them, as well as important C2 processes. These architecture products have been mapped to key external products such as the JCA taxonomy, the Joint Common Systems Functions List[14] [55], and the UJTL, and there are efforts underway to make the architecture products and mappings available as UCore and C2 Core compliant XML artifacts via web services.

NATO C2 Conceptual Model and Referent Tracking

In 2003, the NATO Research and Technology Office formed a Systems Analysis and Studies panel (SAS-050) to explore new approaches to command and control. [56] The primary goal of the group was to build a conceptual model of C2 that would capture knowledge about C2 and then serve as a point of departure for others to explore, analyze, and evaluate alternative approaches to C2. The result is a C2 conceptual model consisting of a Reference Model, a Value View, and a generic C2 process view. Whereas the architecture products above tend to describe a classic, hierarchical approach to C2 based on current doctrine, the SAS-050 product is a more

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12 Operational Views are of 'primary interest' because they describe the universals of a domain or process, whereas Systems Views and Technical Views describe specific instances of a process, or the particulars. Per our definition, the C2 domain ontology is composed of universals, but it can be used to describe and reason about particulars. This is exactly how the operational, system, and technical views in the architecture work together.

13 The integrated architecture products include approximately 50 types of relations, which could serve as the basis for a standard set of C2 relations.

14 The JCSFL is a very extensive 3-level taxonomy of the basic capabilities that systems provide in support of military capabilities. While not limited to C2 functions, the JCFSL include a very detailed list of C2 system functions that map to the architecture products and could be part of a C2 domain ontology applied to the requirements or acquisition processes.

general C2 model that supports the development and analysis of many working models of C2 using subsets of variables and relationships from the Reference Model. From an ontology perspective, the SAS-050 work is of interest on many levels. For example, the generic process view of C2 can serve as an overarching process model for C2 that is not specific to Land, Air, Maritime, Space, Cyberspace, or any other operational domain. Of particular interest is that it includes provision for human dimensions of C2 such as the differences between individual and unit characteristics, behaviors, awareness, and knowledge. In addition, the C2 Reference Model contains a wealth of information regarding C2 variables and relationships that may be the basis for developing sub-ontologies within the C2 domain. A very interesting perspective on the value of the SAS-050 model was presented by Cuesters [57] at the U.S. C2 Ontology technical exchange, where it was shown that the SAS-050 work aligns well with the applied ontology layered framework of reality, concepts, and representational artifacts. In addition, Cuesters also demonstrated how the SAS-050 generic process model, when combined with a suitable upper ontology and the concept of Referent Tracking[15] [58], can model the state of reality at points in time, including the difference between reality, what is perceived as reality by a human observer, and what is captured as reality in a C2 system (and thus the foundation for shared situational awareness). This is a powerful perspective that creates a bridge between entities in the real world and the human-centric process of C2 that seeks to understand and act upon them over time. Figure 6 illustrates the concept of referent tracking, where objects in reality are mapped to the ontology through a situational model consisting of referents. The situational model changes over time as the situation changes, while the ontology remains a constant.

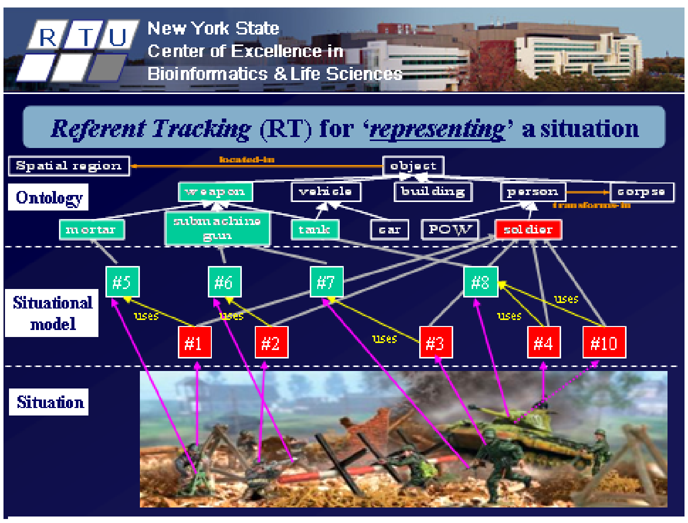

Figure 6: Referent Tracking, Cuesters [58]

Summary

The previous section demonstrates that there are already numerous C2 artifacts in existence or under development that can help form the basis of a C2 domain ontology and/or give insights on the development of C2 domain ontology. In addition, there is a wealth of applicable doctrinal publications available such as those describing military terminology, C2 concepts and processes, and various types of materiel, organizations, and individuals that are the objects of C2.[59][60] Figure 7 shows the approximate relationship of these C2 products to the levels of ontology described in the previous section. Of course, this is not to say that each of these products follows the principles of applied ontology and are thus "good ontology", nor that the products are

15 The concept of referent tracking is that each particular in the real world has a unique identity (a reference) that can be mapped to its corresponding universal in a domain ontology. The status of the referent and its relationship to the ontology may change over time.

mutually compatible. In fact, they are certainly imperfect from an applied ontology perspective, and are known to be incompatible in many regards because they are each developed independently from different perspectives using different entities, vocabularies, and relations. However, what it is very promising is that the C2 domain is being modeled extensively and in some cases rigorously, and the C2 community is looking toward ontology as a future solution. Thus, there is a great opportunity to shape the way ahead.

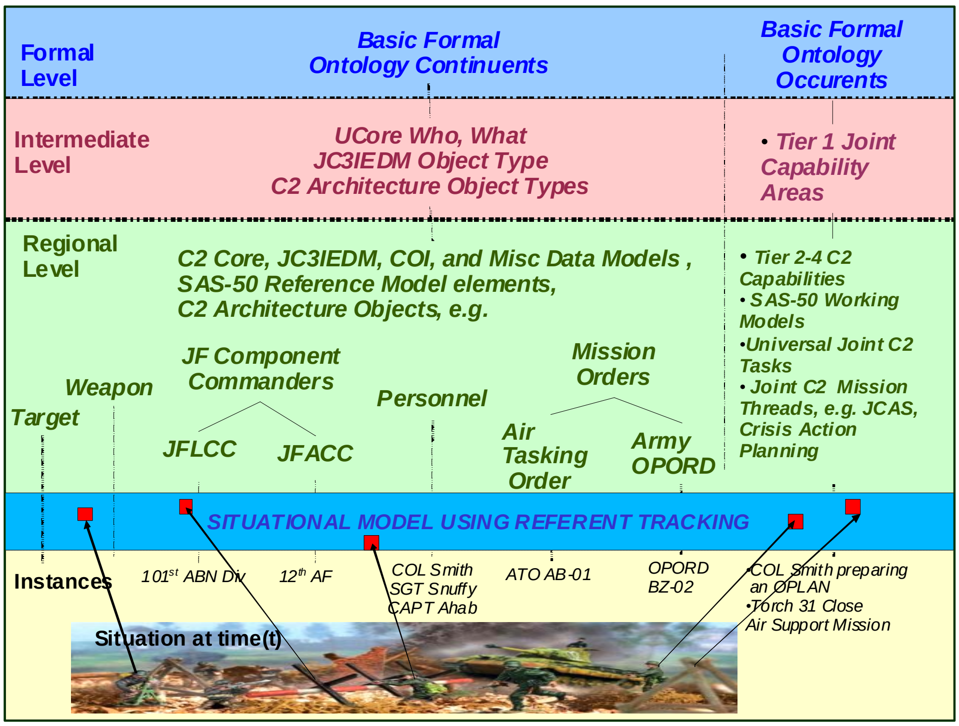

Figure 7: Ontological Layering of Candidate C2 Artifacts

Recommendations and Challenges

The previous sections described the need to organize and share C2 information in a more agile manner, what ontology is, how ontology is applied in other domains, and how some current C2 data, architecture, and modeling efforts may contribute to an eventual C2 domain ontology. Given this basis, what is the way ahead for successfully building and applying ontology to C2?

Recommendations

A number of basic recommendations for the development of a practical C2 domain ontology follow from the previous sections, from the discussions in the NATO and U.S. Ontology Workshops, and from the collective experience of the authors. Some of the most important recommendations are as follows:

• **Identify relevant and feasible applications of C2 ontology.** There is a wide variety of applications for C2 domain ontology, and it is important to focus initial efforts on applications that are the most relevant and feasible. Modeling the continuents of the C2 domain as a basis for information integration is a good place to start, e.g. within the C2 Core effort and/or within one or more C2-related COIs.

• **Establish a common approach to C2 ontology specification.** This would include a common vocabulary for describing the components of the ontology, a standard set of relations, a standard set of rules/constraints, preferred ontology and rules languages, and a set of best practices.

• **Adopt the Realist Perspective.** Reality is the true common denominator between independent ontology efforts, and thus ontology based on the realist perspective offers the best opportunity for interoperability. At a practical level, this will mean leveraging C2 Subject Matter Experts and doctrine in the ontology development process.

• **Leverage existing C2 ontology-like artifacts** such as the architecture products to the extent that they are accurate depictions of the C2 domain. This will avoid excessive duplication of effort, will assist with backward compatibility, and will accelerate the development curve.

• **Include key stakeholders in an open process** to include coalition and interagency partners to allow convergence on a common approach. The OBO Foundry approach of making ontology artifacts openly available with wiki-like configuration management may be a good model to adopt for the C2 domain.

• **Foster C2 community applied ontology awareness and expertise** through increased access to applied ontology workshops, short courses, tools, and training opportunities. This statement applies to ontological engineers, operators and others who would apply and benefit from the ontology, to include managers and decision makers.

Challenges

While the above steps sound reasonably straight forward, there are still a great number of challenges and open questions to resolve before an effective, large scale C2 domain ontology is in place.   These challenges include:

- Huge scope, complexity, diverse applications, and unclear partitions and boundaries of C2;
- C2's dependencies on other warfighting domains (e.g. force management, logistics, intelligence) that also do not have mature ontologies in place;
- The process-based nature of C2 and strong human element, which are very difficult to model;
- Significant time and resource requirements; and
- The constantly evolving nature of warfare.

While these are difficult challenges, the C2 community should take heart in the fact that these are similar challenges that the biomedical community, NASA, and others are successfully tackling.

The C2 community can benefit from the significant progress and lessons learned that have been made in applied ontology, as well as the C2 ontology-like artifacts already developed.

Summary and Conclusion

Agile C2 requires agile information sharing with an increasingly wide variety of military and non-military partners. While current "net-centric" approaches may improve information sharing within a particular niche of C2, they do not support information sharing across the larger C2 domain. Although not a silver bullet, the development and application of a C2 domain ontology to improve C2 data and service integration appears to be increasingly realistic. In fact, there are several examples of successful ontology applications in domains such as medicine, biology, and engineering, and the new discipline of *Applied Ontology* is emerging. C2 data, architecture, and conceptual modeling activities which bear a close resemblance to applied ontology activities are also beginning to take shape, and there are several efforts with near to mid-term promise as elements of a C2 domain ontology. Given this state of affairs, it is the authors' conclusion that development of a partial but practical C2 domain ontology is necessary and feasible in the near to mid term. At the very least, the U.S. and/or NATO C2 community should commit to some near term practical steps toward developing a basic, quality C2 domain ontology such as those outlined above, following the principles and best practices of the applied ontology community. These initial steps can then pave the way for follow-on activities to develop and grow a more sophisticated and comprehensive C2 domain ontology over time, capable of supporting a broad array of information integration and decision support activities for C2 developers, trainers, experimenters, and operational users.

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