An Analysis of the IOF Architecture – a Systems Integration Perspective

Boonserm Kulvatunyou[a], Minchul Lee [a] and Megan Katsumi [b]

[a] *National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899, USA*
[b] *University of Toronto, 35 St. George Street Toronto, Ontario M5S 1A4, Canada*

Abstract
The Industrial Ontology Foundry (IOF) describes its ontology architecture by referencing different types of ontologies. The architecture describes these types of ontologies at a high-level. Their relationships and purposes are not clear. This research performed literature review and use case analyses with the aim to clarify the meaning of these types of ontologies. The use case analyses focused on the purpose of these types of ontologies from the perspective of enabling systems interoperability. The research was presented at the IOF face-to-face meeting on December 4, 2019 and the conclusion included in this paper is the result of discussions at the meeting.

Keywords 1
Industrial Ontology Foundry; Semantics; Integration; Interoperability; Types of Ontology; Ontology Architecture

1. Introduction

The Industrial Ontology Foundry (IOF) engages a diverse community from industry, academia, and research institutes. Its aim is to produce open-access ontologies for the manufacturing domain. The notional architecture that outlines different types of ontologies the IOF will produce and curate is shown in Figure 1-Left[1].

In this architecture, five types of ontologies are indicated including 1) Foundation Ontology (FO); 2) Domain Independent Reference Ontologies (DIROs); 3) Domain Specific Reference Ontologies (DSROs); 4) Domain Dependent Ontologies (DDOs); and 5) Application Ontologies (AOs). The IOF intends to produce and curate the first three types. The IOF charter describes these different ontology types as follows.

"The intent of these reference ontologies is to allow extensions to be progressive to more specific or constrained sub-domains (e.g., particular industry 'verticals' or applications). To meet this intent the IOF ontologies are expected to have an architecture that starts from alignment with a domain neutral ontology, also referred to as an Upper Ontology or Foundational Ontology, from which subsequent IOF ontologies can be developed (newly or adapted from existing ones) that are ontologically consistent, coherent, and modular allowing for reusability.

"Building from an FO the first 'layer' of IOF ontologies will be a collection of Domain Independent Reference Ontologies covering notions and relations independent of specific industrial domains, including time, units of measure, logistics, information, geospatial, etc. The next layer will be a collection of Domain Specific Reference Ontologies covering notions specific to industrial domains. Extensions following the DSROs, Application Ontologies, will address more focused sub-domains of industrial and manufacturing.

"The following notional diagram (Figure 1-Left) suggests how the suite of pro-posed IOF ontologies and their progeny may evolve. The expectation is that the application and/or bridging ontologies would be private or perhaps licensed."

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EMAILserm@nist.gov (A. 1); minchul.lee@nist.gov (A. 2); katsumi@mie.utoronto.ca (B. 1)
ORCID: 0000-0002-7429-473X (A. 1); 0000-0001-7554-2347 (A. 2); 0000-0003-2490-9887 (B. 1)

From the abovementioned citation, we induced that both FO and DIROs are in-dependent of the manufacturing domain. DSROs and AOs are specific to the manufacturing domain. While FO is commonly known because only a few exist such as BFO, DOLCE, and PSL [2],[3], and there is an ISO 21838 standard [4], definitions given in the charter for DIROs, DDOs and AOs are high-level or missing.

In the next section, we provide definitions of terms and notions similar to these types of ontologies. Then we perform linguistics and integration use case analysis with the aim to characterize these ontologies in more details.

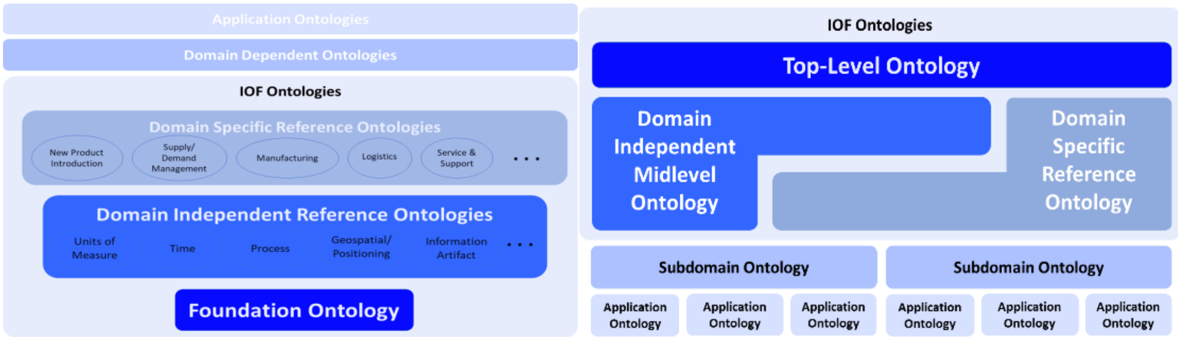

Figure 1: IOF ontology architecture - Left: before and Right: after – this analysis

2. Literature Search

In this section, terms and definitions from literature relevant to the ontology types identified in the IOF ontology architecture are provided. Next section analyzes them in the context of the IOF terms from the practical viewpoint of systems integration.

Term	Description
Foundation Ontology	"A small, upper level ontology that is designed for use in supporting information retrieval, analysis and integration in scientific and other domains. BFO is a genuine upper ontology. Thus, it does not contain physical, chemical, biological or other terms which would properly fall within the coverage domains of the special sciences." [5] "The primary purpose of top-level ontologies lies in providing a broad view of the world suitable for many different target domains." **Erreur ! Source du renvoi introuvable.**
Top-Level Ontology	"Ontology that is created to represent the categories that are shared across a maximally broad range of domains." [4]
Upper Ontology	Upper ontologies define top-level classes such as physical objects, activities, mereological and topological relations from which more specific classes and relations can be defined. Examples of upper ontologies are SUMO, Sowa upper ontology, Dolce, CliP, and ISO 15926-2. [6]
Upper-domain ontology	"An upper-domain ontology holds the essential core domain classes as an interface between both top-level and domain ontologies, like Organism, Tissue or Cell in the case of biology. An upper-domain ontology can also include more specific relations and further expand or restrict the applicability of relations introduced by the top-level ontology. An example for this kind of ontologies is BioTop." [8]
Generic ontology	"Generic ontologies are valid across several domains. For example, an ontology about mereology (part-of relations) is applicable in many technical domains." [9]

Domain Ontology	"Domain ontologies and task ontologies describe, respectively, the vocabulary related to a generic domain (like medicine, or automobiles) or a generic task or activity (like diagnosing or selling), by specializing the terms introduced in the top-level ontology." [10] "Ontology whose terms represent classes or types and, optionally, certain particulars (3.3) (called 'distinguished individuals') in some domain" [4] "A domain ontology includes a multitude of low-level, domain-specific classes that comprehensively describe a certain (aspect of a) domain of interest, like, Antisense RNA Transcription or DNA Replication from the Gene Ontology." [8] "Domain ontologies capture the knowledge valid for a particular type of domain (e.g. electronic, medical, mechanic, digital domain)." [9]
Domain Specific Ontology	"A domain-specific ontology of concepts within a certain field, along with their relations and properties, is a new medium for the storage and propagation of specialized knowledge." [11]
Reference Ontology (RO)	"ROs are designed to describe a certain domain adequately. They are called Reference ontologies, since they have a realist bias. Indeed, Reference ontologies contain the implicit claim that they are true about a certain portion of reality and not just that they express a more or less broad consensus among a community of experts." [12] "Domain Reference ontologies represent knowledge about a particular part of the world in a way that is independent from specific objectives, through a theory of the domain." [13] "ROs are an emerging ontology type that attempt to represent deep knowledge of basic science in a principled way that allows them to be re-used in multiple ways, just as the basic sciences are re-used in clinical applications." [14] "ROs target the structuring of ontologies that are derived from them." **Erreur ! Source du renvoi introuvable.**
Application Ontology	"AOs describe concepts depending both on a particular domain and task, which are often specializations of both the related ontologies. These concepts often correspond to roles played by domain entities while performing a certain activity, like replaceable unit or spare component." [10] "AOs contain all the necessary knowledge for modelling a particular domain (usually a combination of domain and method ontologies)" [9] "AOs are suitable for direct use in reasoning engines or software packages." **Erreur ! Source du renvoi introuvable.**

3. Analysis

3.1. Foundation ontology (FO)

Foundation (or Foundational), top-level, and upper ontology are referring to the same notion. Because the ISO standard calls it Top-Level Ontology (TLO), the IOF community has agreed at the face-to-face (F2F) meeting to replace FO with **TLO** and also flip its architecture diagram upside down (Figure 1-Right).

In addition, we proposed to add to the ISO definition, from a practical ontology development viewpoint, that "TLO provides a common ground/framework to model domain ontologies across domains (e.g., common across industrial manufacturing domain and biomedical domain)." For example, when an IOF working group (WG) tried to formalize the term "Product Model", one of the first few tasks in the formalization process was to classify the term into a category in the TLO. BFO 2.0 as the TLO, currently used by IOF, helped to establish whether the working group agreed to think of the term as a physical entity or information about it. Part of the working group argued that it should be classified as BFO's Independent Continuant; others said they should be Generically Dependent

Continuant. This resulted in a refactoring task where the “Product Model” notion was captured by both “Product” as a physical entity and “Design” as an information entity.

3.2. Domain Independent Reference Ontologies

We found that the term “domain independent ontology” was commonly used in literature without definition. “Generic ontology” in [9] provides a good basic definition for DIRO. However, it is not distinguishable from TLO, which is also domain independent. The key difference is only relative in that classes and properties in DIRO are subsumed by TLO’s concept, yet still applicable to multiple domains. For that reason, it was agreed at the IOF F2F meeting to change the name to “Domain Independent Mid-level Ontologies” (**DIMO**). From the ontology development perspective, IOF will have to determine whether a notion and the ontology of it shall be classified as a DIMO. For that a practical competency question is whether such notion is applicable even in a remote domain outside of the manufacturing domain, e.g., banking. If so, the term would be classified as a DIMO term. An example dilemma posted at the F2F meeting was whether the notions like “system” and “resource” should be in DIMO. Definitionally, they are widely applicable to many domains; and the IOF Core Ontology WG has specialized them into “engineered system” and “manufacturing resource” as notions specific to the manufacturing domain.

3.3. Domain Specific Reference Ontologies

There are three terms in the literature review that are relevant to DSRO, namely “Domain Ontology”, “Domain Specific Ontology”, and “Reference Ontology” (RO). Key notion of “Domain Ontology” and “Domain Specific Ontology” according to the literature is that the ontology is **low-level** and **domain-specific**. The notion captured by these two terms cannot be directly mapped to DSRO in IOF because IOF also has Domain Dependent Ontology (DDO), i.e., the notions subsume both DSRO and DDO.

The notions described in the term RO also express characteristics of DSRO. In particular, [12] stated that it is “**true about a certain portion of reality**” and a “**consensus among a community of experts**”; [13] indicated that an RO should be “**independent from specific objectives**”; and [14] said it “**represents deep knowledge**” but can be “**reused in multiple ways**”. We propose a definition of DSRO, synthesized from the above three terms, as “a low-level ontology about a specific domain but still can be reused across multiple applications in the domain.” Note that in the case of IOF, the domain is manufacturing. For example, a supply chain (SC) RO for manufacturing should be reusable for SC design, SC planning, and more. It should also be independent of types (e.g., push, pull), strategy, or industry. In addition, DSRO shall be subsumed by the union of TLO and DIMO.

3.4. Domain Dependent Ontologies

The only clue from the charter about DDO is that it is not intended to be maintained by IOF; therefore, it is quite specialized. From the linguistic analysis perspective when compared to DSRO, it is specific to a domain like DSRO, but it is not a “reference” ontology (i.e., it is not a multi-purpose ontology). Based on this analysis we proposed that the ontology be called **Subdomain Ontology** (SO) instead. Next, we analyze what the purpose of SO might be from the standard-based systems integration perspective. Since SO is not maintained by the IOF as a standard according to the current architecture, to achieve interoperability, a SO shall only include notions derived from the notions in IOF reference ontologies. In other words, SO shall be a **specialization** of **IOF ontologies** (note that this includes TLO, DSRO, and DIMO). We specifically define **specialization** using the OWL language [15] as follows. An SO is a specialization of IOF ontologies if it satisfies the following conditions 1) SO reuses some classes, properties, and axioms from IOF ontologies; 2) a new class in SO shall be a defined class with only conservative axioms[1]; 3) there shall be no new properties asserted; and 4) axioms added to classes

[1] Conservative axioms are axioms containing only classes and properties from IOF ontologies

and properties of IOF ontologies must be conservative axioms (**refinement**). The following examples[2] provide simple illustrations of two SOs called Inventory Valuation SO (IVSO) and Inventory Management SO (IMSO). IVSO imports classes Component, Inventory, Work-in-Process, Stock, Unit Cost, Sale Amount, and Purchase Amount from IOF ontologies. Inventory is refined to be a union of Work-in-Process and Stock. In addition, it defines new classes Unit Cost of Sale and Unit Cost of Purchase as a subclass of both Unit Cost and Sale Amount and a subclass of both Unit Cost and Purchase Amount, respectively. IMSO imports Component, Inventory, Unit Cost, and Work-in-Process. It, however, refines Inventory to include Stock but exclude/disjoint-with Work-in-Process. Here it can be seen that another characteristic of SOs is that they can be inconsistent with each other. We will term this horizontal inconsistency; as the inconsistency is between the same type of ontologies.

3.5. Application Ontologies

The definition given by [10] is well aligned with the systems integration perspective. The definition indicates that AOs describe notions for **particular tasks** and often correspond to **roles** played by domain entities while performing those tasks.

Based our experiences in systems integration, we hypothesize that AO could be an ontology that refines terms with respect to specific software application interfaces or data sources to be integrated. It refines (see refinement in 1.3.4) terms from an SO. AOs refined from the same SO could also be inconsistent. Such condition would indicate possible interoperability issues. Take, for example, a requirement for an OEM Cost Estimation Application and a Supplier PLM Application to exchange Unit Cost of Material (UCM) data. Each of them could create AOs to declare their precise semantics. The OEM AO might state that UCM is a Last Month Average cost, while Supplier AO might state that that it is a 6-Month Average cost. Ontology reasoner should be able to automatically detect such a conflict through logical inference.

4. Conclusion and Remark

This analysis was presented at the IOF F2F meeting at NIST on Dec 4, 2019. Attendees agreed that the research topic is essential, and that further work is needed. In the interim, this analysis resulted in a rearrangement of the architecture diagram as shown in Figure 1-Right. New questions were raised to whether more layers will be needed and whether SOs will be maintained by IOF. The community also would like to have more guidance to what kinds of axioms should be given in these different ontologies. We planned to work with IOF WGs through additional use cases, particularly addressing the general knowledge discovery in addition to the systems integration perspective.

5. Disclaimer & Acknowledgement

Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST. Special thanks to Evan Wallace and Melinda Hodkiewicz for their reviews and comments.

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