# From Why to How through Knowledge Capture


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## ABSTRACT

The complexity of many engineered systems continues to increase, with literally millions of design permutations. System designs can take many years to complete and have become immensely expensive. As part of an effort funded by the Defense Advanced Research Projects Agency (DARPA), Raytheon has been working with Georgia Tech and MetaMorph Inc. to extend approaches and toolsets for design, testing and manufacturing of complex systems. At this level of complexity, relationships between cost, performance, and design models become extremely important; we are capturing expert knowledge of these relationships to link computational models. This paper describes our efforts to use knowledge capture approaches to move from why to how, from the basic science that underlies expert understanding across domains to computable representations that can be used to cost-effectively deliver reliable, complex engineered systems. We describe the challenges we face in capturing the critical expertise necessary to do cross-domain reasoning of engineering disciplines.



### Categories and Subject Descriptors
I.2.6 [**Learning**]: Knowledge Acquisition; J.2 [**Physical Sciences and Engineering**]: Engineering

### General Terms
Design, Languages

### Keywords
Ontology, knowledge engineering, engineered systems


## 1. INTRODUCTION

Computational models in the engineering environment include cost, performance, mechanical, and electrical, that address guidance, navigation, power, propulsion, control, and communication. Managing the connections between these models across the life cycle is what system engineering is and does, but computationally, the links are weak between the individual models and the whole. The current work by Raytheon, Georgia Tech, and MetaMorph Inc. attempts to link these models more strongly to reason across engineering disciplines and interconnected system components.[1] We are using a lightweight ontology to inform automation between models, and using an iterative knowledge engineering approach to build the ontology. A major challenge comes from dealing with the range of basic science information and its deep application in the engineering domain of engineering design. Making the connections between why and how could reduce cost and speed implementation, both by reducing the design space quickly and intelligently, and by making choices that are cost-effective and producible.


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## 2. BACKGROUND

DARPA has conducted an exploratory digital design exercise on a next generation amphibious vehicle using a suite of tools developed under the Adaptive Vehicle Make (AVM) portfolio. The AVM portfolio of programs focused on developing revolutionary approaches for design, testing and manufacturing of complex systems [1]. Vanderbilt University was the primary technical lead in the development of the integration and information architecture under the META program, which enables a design to evolve from concept stage to deployment phase in a model based virtual environment [2]. A metamodel integration language, CyPhyML, provides semantically precise integration of domains and open source tools for OpenMETA, with both structural and behavioral semantics supported [3].

The effort proved the AVM concept to have great potential and identified some possible improvements in the technical approach and service architecture for systems design. The attributes of digital design analysis and simulation coupled to manufacturing is an area in which Raytheon has been working, including ontology-based model integration to support preliminary design analysis that links small sets of physics-based models. MetaMorph Inc.'s tool suite implements progressive, constraint-based design space refinement. Having a design method or tool that helps sort through the complexities, reduces the design cycle and can focus the design effort on a much smaller set of potential designs that meets performance, manufacturing and cost requirements, has the potential to improve our ability to get proven, cost effective systems more quickly.

The development of next generation information architectures to support large scale integrated environments is an ongoing Raytheon effort, and the authors have been developing ontology-based component descriptions for engineering components for the last two years in an information library [4]. This component library reflects the attributes of the product design, in addition to performance, manufacturing and cost attributes. In this DARPA funded effort, Raytheon is using its knowledge of missile design and incorporating the technical work accomplished within the META program to extend AVM into a new domain. The effort will use a new domain space (air vehicle design) to test the tool suite's capability to handle several components, as well as system performance and environmental models to assess the cost and performance trade-offs of known versus potential designs. Part of the effort is to link the AVM tool suite to relevant manufacturing and cost models in order to enhance the design iteration with design for manufacturing as an integral component of the chosen design.

The main objective of this effort is to demonstrate that the AVM tool suite could be used to design products in a domain other than the amphibious vehicles, and to show that the tool suite could be transferred to other industries and product domains to assist in new product design. This effort could prove the generalizability of the approach and use of the tool suite.

The early goals of this current work include:

- Ontological based design support for component/system development
- Model integration to support preliminary design analysis with system design closure
- Linking small sets of physics based models in a logical solution
- Early TRL/MRL assessment (Technical Readiness Level / Manufacturing Readiness Level)
- Early cost and performance trade analysis

The objectives of the work are to demonstrate:

- Enhanced model based engineering process
- Extensibility in multiple domains
- Tools for affordability and manufacturing modeling
- Advanced modeling and computer engineering
- Expanding aerospace component library and the ontology to support the library for better decisions
- Tool suite for designing aerospace vehicles in the virtual environment
- Capability to virtually design, test, and manufacture products faster and cheaper
- Reusable method for model based design

# 3. APPROACH

The approach taken was to conduct a series of expert interviews for ontology building, and proposed a crowdsourced mechanism for populating ontology instances. Methods described in the literature for knowledge elicitation (critical decision method, work domain analysis, concept mapping) were useful as guides [5, 6], but initially did not map easily to the goal of building a simple ontology that informed the trade space. The ontology development process followed the outline in [7], with the expectation that this iteration of the ontology would result in a relatively small set of elements. The primary goal was to determine whether the approach was worthwhile.

## 3.1 Ask the experts

The authors are using in-house experts on air vehicle design, propulsion, and navigation for their domain expertise. Through a set of interactive interviews, the team seeks to capture a portion of domain knowledge in a way that others can easily discover and make use of it. Although the scope of the interview questions was smaller, the semi-structured interview approach is similar to the one used in a case study of a large-scale product development program, described in [8].

When experts are asked about what elements should exist in the ontology to make tradeoffs, they often have very specific answers that exclude possibilities which a lay person might have included. When asked why certain things were excluded, they quickly respond with something akin to, “Well, that’s not reasonable to include.” For instance, when asked what should be included in a list of materials for an air vehicle, their list is fairly short. The reason is that the most preliminary design constraints, for instance, a vehicle speed or range constraint, eliminated a large set of design choices of materials. Those basic associations need to be captured in the set of tradeoffs, and while it may sound simple, making the mapping to the underlying models is not straightforward. One of the primary goals of the current work is to strengthen the link between computation models, a link that is fundamentally analogical, and a good candidate for expertise elicitation [9].

## 3.2 Building the ontology

The starting point was a lightweight ontology for a vehicle whose top-level classes are mapped to functional capabilities, including aerodynamics, control, propulsion, and guidance. A search for existing ontologies in these domain areas did not result in ontological representations of the important properties the experts were identifying to make system trades. The authors built upon the Semantic Sensor Network (SSN) ontology as a base [10], and utilize the QUDT, OWL-Time, WGS84, and SWEET ontologies as described in [11]. Efforts continue to provide meaningful linkages between an identified set of models currently used within the design environment.

Collaborating once a week over a month, the subject matter experts identified the specific elements that should be included, and were asked questions about the values of those elements:

A) Is there a *set* of values to choose the answer from? (If a set is known, “B” and “C” below can be answered.)
   a. Y/N is the simplest, but all finite, discrete sets can be useful for description and inference.
   b. Is there a public reference for this set?
B) What *kind* of value is this? (examples: mass, time, force, length)
C) What *unit* should be used to measure this? (examples: meters, kilograms, volts)
D) What *components” comprise this property? (example: propulsion is rocket motor)
   a. the two viewpoints of the architecture, physical decomposition and functional decomposition, are being represented

## 3.3 Populating ontology instances

Raytheon has 60 years of experience of building products, many of which are still in service today. There is a vast amount of information distributed across locations, products, businesses, and people. The information that could be used to populate instances for the ontology are not easily collected due to factors related to what information was considered to be important in the production of previous products. It



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was determined that the cost of trying to mine the existing data from the large set of knowledge experts via iterative interviews would be prohibitive. The proposed approach to populate the instance data is to crowdsource it over a large cross-section of the workforce yielding an emergent ontology.

At this point in time, there are less than 100 elements in the ontology with many of the elements having lists available for selection. An example is the list of materials that are available for air vehicle casings. Protégé is used for development, and OWL[2] (Web Ontology Language) is used for representation. Since Protégé is the current ontology authoring tool, the collaborative version of Protégé is under consideration for instance population experimentation [12], although the authors believe it would still have to be extended in some way to perform the matching activity, as ease-of-use is critical.

The matching exercise enables subject matter experts to perform a mapping between the ontology elements and products they are familiar with. Separately, results can be tallied. For instance, if 10 people make suggestions on which casing materials were used on a specific product, each material will be noted. The potential benefit is that the result will be a collection of important design choices that have been made associated with specific products. If the ontology could then be used as an index to product information, additional value could be derived by using the ontology as a navigation aid as part of an enterprise search function.

# 4. SUMMARY

This project used expert interviews to build a lightweight ontology to inform the linkages between computable engineering models, and crowdsourcing the instance data within the ontology to link it conceptual air vehicle models. One of the objectives was to extend the DARPA AVM toolset and demonstrate the generalizability of the approach to other engineering domains. Early results suggest that this work can make contributions to model-based engineering by establishing linkages between descriptive and performance models by embodying basic scientific and engineering principles.

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