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Transforming Systems Engineering through Model-Centric Engineering

A013 Final Technical Report SERC-2017-TR-110

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The following is a list of the researchers and their affiliations. Each researcher may be involved in one or more tasks that are now mapped to a linked set of research use cases. These relationships are described in greater detail in Section 2.

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EXECUTIVE SUMMARY

This research task (RT-168) is addressing research needs defined by the United States (US) Army Research, Development and Engineering Command (RDECOM) Armament Research, Development and Engineering Center (ARDEC) in Picatinny, NJ. The purpose of this RT-168 Phase I final technical report is to document the refinement and expansion of those needs and the status of working sessions, demonstrations, presentations, and reports provided to the ARDEC team. These needs are characterized as overarching objectives and goals to elicit requirements for the Armament Virtual Collaboratory Environment (AVCE) integrated Model Based Environment (iMBE). The AVCE iMBE is ARDEC's envisioned concept of an integrated modeling environment - "the system for designing future ARDEC systems or systems-of-systems." The intent is to understand the relationships between Systems Engineering (SE) activities and methods in the context of a Digital Thread concept developed by ARDEC.

This research tasks focus on the ARDEC-relevant needs for a transformation for systems engineering enabled by model-centric engineering (MCE). Model-centric engineering[1] can be characterized as an overarching digital engineering approach that integrates different model types with simulations, surrogates, systems and components at different levels of abstraction and fidelity across disciplines throughout the lifecycle. Industry is trending towards more integration of computational capabilities, models, software, hardware, platforms, and humans-in-the-loop. The integrated perspectives provide cross-domain views for rapid system level analysis allowing engineers from various disciplines using dynamic models and surrogates to support continuous and often virtual verification and validation for tradespace decisions in the face of changing mission needs.

The path forward has challenges but also many opportunities, both technical and sociotechnical. It must include a modeling framework and consider the use of high performance computing (HPC) that enables single source of truth (SST), integration and interoperability of multi-domain and multi-physics models, and provide for methods for model integrity (trust in the modeling and simulating predictions). The modeling and infrastructure for AVCE iMBE is a critical step to enable a SST. While there are literally thousands of tools, with about 100 at ARDEC, they are often federated and there is no one single solution that is fully integrated that can be purchased. Every organization often has to architect and engineer their model-centric engineering environment. Most, like ARDEC have selected commercial tools that must be integrated with many specialized tools that they have developed for ARDEC-specific needs.

In order to better understand the requirements for the AVCE iMBE, ARDEC initially had three challenge areas, which has been extended to five challenge areas. The SERC research team is involved in four of the five challenge areas. A theme for a case study involves Unmanned Aerial Systems in which to investigate the following five tasks:

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[1] DASD has increased the emphasis on using the term Digital Engineering. A draft definition provided by the Defense Acquisition University (DAU) for DE is: **An integrated digital approach that uses authoritative sources of systems' data and models as a continuum across disciplines to support lifecycle activities from concept through disposal.** This definition is similar to working definition used throughout our prior research task RT-48/118/141/157/170 for Model Centric Engineering (MCE).

- Task 1: Framework/architecture of development and collaboration environment that support cross-domain integration of models to address the heterogeneity of the various tools and environments
- Task 2: Formalization of an information model for ARDEC-relevant domains to support capturing and sharing of data
- Task 3: Technology and domain-relevant modeling methodologies
- Task 4: Demonstrations in the context of ARDEC-relevant Challenge Areas relevant to Tasks 1, 2, 3 & 5
- Task 5: System Engineering Transformation Roadmap to roll out capabilities addressing all five perspectives in parallel:
  - Technologies and infrastructure
  - Methodologies and processes
  - People, training, competencies and framework viewpoints and interfaces
  - Operational & contractual paradigms for transformed interactions with industry
  - Governance

These five tasks have been mapped to a set of research uses cases, which are detailed in Section 2 of this report. Part II of this report, Sections 3 through 14 provide details on each of the research use cases. The specific accomplishments include, but are not limited to informing our ARDEC sponsors through five working sessions, one special session and 19 virtual meetings, where we have conducted presentation and demonstrations on many topics such as: Model Centric Engineering, modeling methodologies, Model Frameworks and Verification Tools for Cyber Physical Systems design, Multidisciplinary Design Analysis and Optimization, Decision Framework Approach and High Level Architecture (HLA) for Virtual Reality (VR) Forces demonstrations, mission and system simulations with upstream/downstream data interfaces demonstrations, and graphical CONOPS simulations with gaming technology. One of the high potential areas involves research in semantic web technologies and ontologies as a promising approach to enable cross-domain model through interoperability supporting the capability to enable a single source of truth.

Finally, this research is being conducted in collaboration with two SERC research tasks sponsored by the Naval Air Systems Command (NAVAIR) under RT-170 and RT-176, as well as Department of Defense (DoD) Digital Engineering (DE) Transformation initiative, and our relationship that we have fostered with National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL).

1 INTRODUCTION

The SERC team has conducted five working sessions, one special session and 19 virtual meetings with the United States (US) Army RDECOM-ARDEC in Picatinny, NJ to discuss the needs and scenarios for a System Engineering (SE) transformation enabled by evolving model-centric engineering (MCE) technologies and methods. Early meeting with ARDEC covered their prioritization of key areas to initiate such a transformation. We also discussed research needs characterized as five related tasks in the larger context of ARDEC's vision for an Armament Virtual Collaboratory Environment (AVCE) integrated Model Based Environment (iMBE). We refined those needs into sub-team-related research use cases that map to ARDEC's four of five challenge area. ARDEC is also working with their own Integrated Product Teams (IPTs) on some of these challenge areas. We are also fostering bi-directional sharing of research interests and results with our US Navy Naval Air Command (NAVAIR) sponsors who attended our working session in January 2017. Finally, we are collaborating in several MCE-related efforts to provide the opportunity to leverage and share with the Open Collaboration Group for MBSE and OpenMBEE, Semantic Technologies for Systems Engineering (ST4SE) initiative, DoD Digital Engineering Transformation Initiative, the Aerospace Industry Association (AIA) on Concept of Operations (CONOPS) for Government and Industry collaboration through MBSE and the National Defense Industry Association (NDIA) Modeling and Simulation group who are coordinating working groups to investigate approaches for using Digital Models for competitive down select.

1.1 ARMAMENT VIRTUAL COLLABORATORY ENVIRONMENT VISION

The AVCE iMBE vision portrayed by ARDEC reflects on their understanding of the research needed to advance to a future state of their integrated modeling environment. There are many enablers that relate to characteristics of a holistic approach that aligns with their vision such as (this list is not exhaustive, but represents advances in use today):

- Mission-level simulations that are being integrated with system of system (SoS) and system simulation that increasingly interoperate with distributed interactive simulation capabilities, augmented virtual reality, and gaming technology
- Computer-aided Design (CAD), behavioral techniques, physics-based/engineering simulations, decision analytics, Computer-aided Manufacturing (CAM), system architecting, prototyping, embedded in a knowledge management environment
- Enabling collaborative environments by leveraging social media technologies and operational metaphors in an engineering context
- Multidisciplinary Design, Analysis and Optimization (MDAO) for trade study analyses through more systematic design of experiments allows engineers to make many more excursions through both the problem and the design spaces
- Engineering affordability analysis, which is a risk-based approach that could be used to significantly reduce physical tests by focusing on those system uses that have the most uncertainty about margins of performance
- Decision analysis framework

- Risk modeling and Bayesian-relevant analysis
- Platform-based approaches with virtual integration
- Pattern-based modeling based on ontologies with model transformation and analysis
- Domain-specific modeling languages
- Set-based design for more concurrent engineering and to keep design options open longer
- Modeling and simulation of manufacturing and possibly early prototyping
- Explosion of interactive visualization, which we will need as we have a “sea” of data and information derived from a “sea” of models with HPC computing capabilities

The SERC’s research with NAVAIR Systems Engineering Transformation (SET) has provided considerable insights into the challenges associated with MCE [22]. That research suggests that there is no one instantiation of MCE. Each organization will have its own instantiation of its “Digital System Model” or Single Source of Truth (SST). A digital system model will increasingly support the integration of multi-domain and multi-physics models, and provides for a method for model integrity for ensuring trust in models and simulation, and including three critical items:

1. Cross-domain model integration, and the associated methodologies, which will also require and contribute collaboration
2. Technologies to establish and quantify model integrity (trust in model and simulation predictions)
3. High Performance Computing (HPC), which enables 1 and 2

The SST is an enabler for cross-domain interoperability needed for multidisciplinary design, analysis and optimization (MDAO) for problem and design space exploration. The SST requires that all information used to assess performance is semantically consistent with MCE technologies and methods used for assuring integrity and the orchestrated workflow is data-driven (not process driven). SST provides the basis for shared-data and a basis for real-time collaboration.

As a result of the NAVAIR research findings the Deputy Assistant Secretary of Defense (DASD) has initiated a Digital Engineering strategy. ARDEC and NAVAIR are both participating in this initiative. In addition, the SERC leadership confirmed and recommended that complementary research results can be shared across these research tasks. To the degree possible we are synergistically leveraging research completed or underway related to NAVAIR under SERC RT-157, RT-170, and RT-176 that includes other research collaborators Georgia Tech, University of Maryland, and the Naval Postgraduate School (NPS).

1.2 OBJECTIVES

The critical items gleaned from the ARDEC needs and our prior research resulted in the following set of proposed tasks:

- Task 1: Framework/architecture of development and collaboration environment that support cross-domain integration of models to address the heterogeneity of the various tools and environments

- Task 2: Formalization of an information model for ARDEC-relevant domains to support capturing and sharing of data
- Task 3: Technology and domain-relevant modeling methodologies
- Task 4: Demonstrations in the context of ARDEC-relevant Challenge Areas relevant to Tasks 1, 2, 3 & 5
- Task 5: System Engineering Transformation Roadmap to roll out capabilities addressing all five perspectives in parallel:
    - Technologies and infrastructure
    - Methodologies and processes
    - People, training, competencies and framework viewpoints and interfaces
    - Operational & contractual paradigms for transformed interactions with industry
    - Governance

We initially separated the five tasks into subtasks that provide better mapping to research expertise, but these are now defined as linked use cases, which are summarized in more detail in Section 2. These objectives underlying these tasks align with the theme that were presented at the NASA/JPL Symposium and Workshop on Model Based Systems Engineering held from January 25-27, 2017 at NASA/JPL in Pasadena California. The event brought together practitioners and leaders in MCE/MBSE to share information and ideas about the state of practice, challenges, recommendations, and future directions and strategies. Our ARDEC and NAVAIR sponsors were present at this event and should be able to resonate with their guidance on the direction of our research.

1.3 SCOPE

In the initial phase of the joint effort from August 2016 to August 2017, the SERC research should support ARDEC interests to:

- Streamline the process for using models, which is often done only in a relatively few areas ("pocket" as characterized by ARDEC)
- Understand the requirements for the AVCE conceptually at the stage of a Systems Requirement Review (SRR); this is not the requirements for a target system, rather these are the requirements for a system (of systems) for designing future ARDEC systems (i.e., AVCE iMBE)
- Understand the relationships between Systems Engineering (SE) activities and the decision framework (related to Dr. Matt Cilli's dissertation [41]); this is related to the 'digital thread wheel' that can show how to leverage analysis in each of the areas to develop a digital thread to support repeatable analysis, where a "fully" integrated operational analysis is missing currently.

The challenge areas continue to undergo definition, refinement and alignment. Four relevant challenges areas for RT-168 as characterized by ARDEC are:

- Challenge #1: Taking existing ARDEC models and combining them to form dynamic models at the system level, and to explore MDAO; this will help understand how the

models interact with each other and should allow for use of existing models to compose and solve the problem
  - Refinement by ARDEC Integrated Product Team (IPT) as presented at working session #2: Develop an integrated, cross domain, dynamic model of a system to assess its ability to achieve a specific operational scenario
  - IPT Lead: Rich Swanson
  - Status: completed at least initial concepts [9]
- Challenge #2: Trying to understand the more holistic process of solving a problem, including the people who are involved from more of a Concept of Operation (CONOPS) enabled by gaming technologies, and mission-level modeling and simulation that can ultimately feed information to a framework refined by Challenge #1
- Challenge #3: The focus here is on the data, and how it propagates throughout the lifecycle and be able to use standard-based and tool neutral technologies and methods to “integrate” modeling in analysis that are often heterogeneous and disparate
  - This includes how the data or metadata underlying those disparate modeling technologies and methods can be bi-directionally linked
  - Specifically concerned with design tools (e.g., 3D CAD, software development, electrical CAD, etc.) that integrates with analysis tools (Prism, IMO, MagicDraw etc.) that usually inputs design data and produce analysis data and results, all of which needs to be stored and managed
  - IPT Lead: John Campbell
- Challenge #5: This is a new challenge area defined in early January of 2017 to integrate crossdomain models (SysML model, Engineering Models, Performance Models, Cost Models, etc.) with decision support model based on Armament Analytics Multiple Objective Decision Analysis (AAMODAT) while executing Integrated Systems Engineering Decision Management (ISEDM) process
  - IPT Lead: Matt Cilli

This concept for these four challenges as shown in Figure 1, provides a simplified perspective on the elements in a more “traditional systems engineering” perspective. We notionally define:

- Concept of Operations (CONOPS) derived from simulation and gaming technologies
- “What” we want – requirements and constraints
- “How” (1 or more) – designs to achieve the “What”
- “How well” (usually many) to assess the “How” using analysis, testing, reviews and assessing how the design satisfies the requirements, given the constraints to achieve the mission concept
- The underlying Information Model links the data or metadata from many different domains
- The Decision Framework, we believe can demonstrate how data from the information model can be used to populate the Decision Framework in the form of the implementation of AAMODAT with potential refinements and extensions supporting a method to determine the Key Performance Parameters of the various stakeholders.

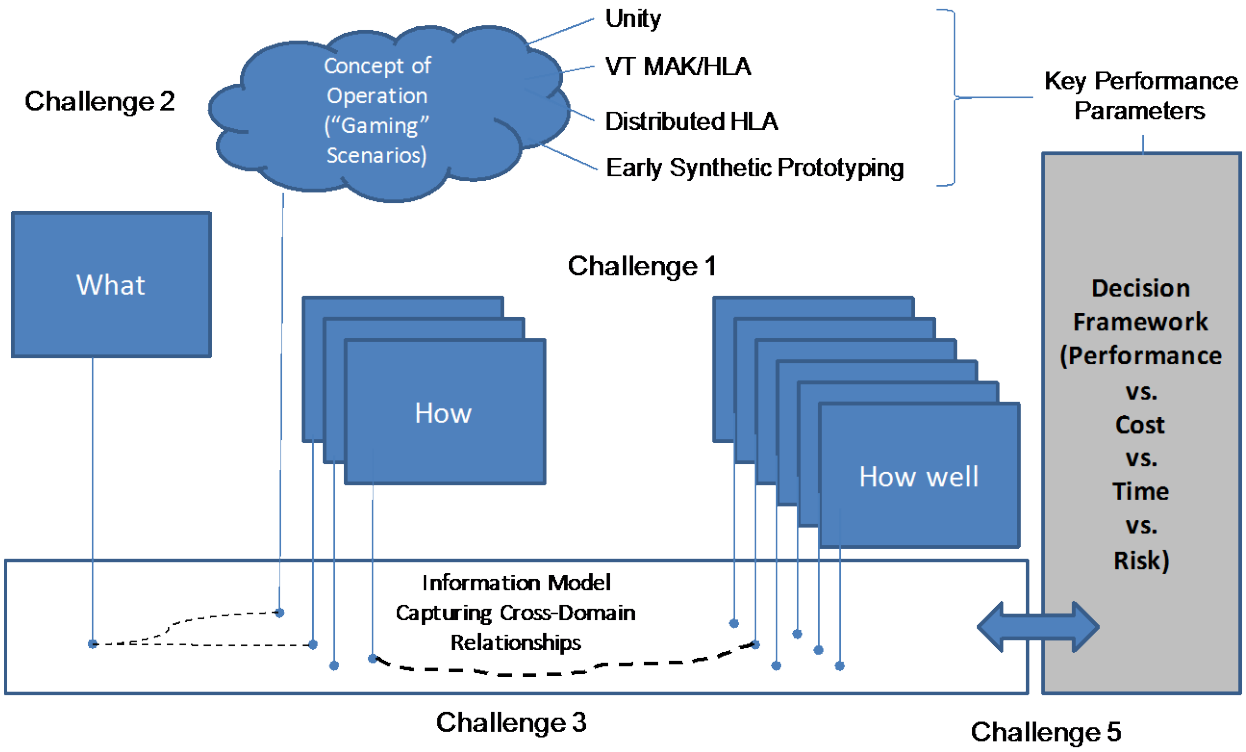

Figure 1. Context of System Engineering of Challenge Areas

MCE is enabled by computational technologies that now provide a means for using modeling and simulation in a transformed approach to systems engineering. A key problem is that most of these technologies are not integrated currently (and many may never be). The challenge area presentations at the January 2017 working session given by ARDEC confirmed this cross-domain tool integration is a challenging problem. This was further acknowledged in various talks at the NASA/JPL Symposium and Workshop on Model Based System Engineering held January 25-27, 2017. Therefore, we are interested in an approach that leverages tool-to-tool integrations where feasible, but the research is targeted on approaches to using data interoperability as a means (or surrogate) for accomplishing integration, when tool-to-tool integration is not feasible or cost-effective. This is challenge area #3 that we proposed. We plan to do research in the other two areas of Mission and Systems and understand the flow of information needed to be linked between them, and characterize those linkages in an Information Model. Our research efforts have made progress in this area that includes the development of an evolving Integration and Interoperability Framework (IoIF), which has been demonstrated to ARDEC at both working sessions and bi-weekly virtual events.

The new challenge area #5 is being coordinated with ARDEC's Dr. Matt Cilli who believes that information can be captured to drive the Decision Support Model Construct [41] (referred to as Decision Framework) in the AAMODAT tool developed and being evolved by Cliff Marini. Other research has provided evidence that semantic technologies (including ontologies) may support this belief of Dr. Chill. We believe Decision Framework with AAMODAT implementation serves many purposes and benefits:

- Provides senior management and program managers with visual representations of key tradeoff defined in terms of Key Performance Parameters (KPPs) such as Performance, Cost, Time and Risk
- As shown in Figure 2, scatterplot shows in a single chart how system level alternatives respond in multiple dimensions of stakeholder value
- Assessment Flow Diagrams (AFDs) trace the relationships between physical means, intermediate measures, and fundamental objectives
- Provides methodological guidance for identifying KPPs
- Can be used with uncertainty analysis as a measure for understanding maturing design
- Enables bi-directional analysis throughout lifecycle

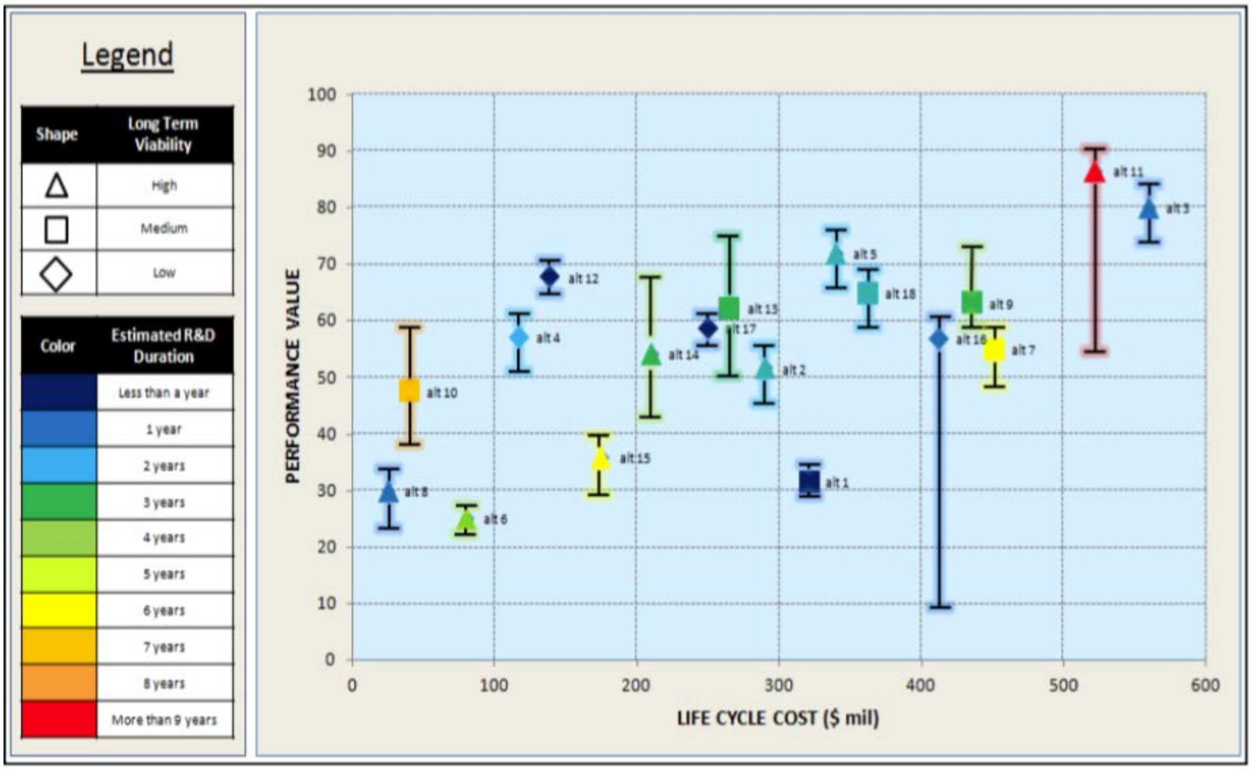

Figure 2. Decision Support Model Construct

The ARDEC leadership and SERC team agreed on the challenge area scenarios for using some examples related to counter unmanned aerial systems case study. The team has constructed several artificial UAS scenarios (use cases) and evolving scenario variants that demonstrate methods to address many of the cross-cutting concerns from CONOPS, mission and system engineering. Mission-level scenarios have been created and demonstrated using four different modeling and simulation capabilities ranging from low-cost and low-fidelity to high-cost and high-fidelity.

We fully assume that there will be practical limitations to fully automating the concept discussed in this section, however, given the objectives, a value and unique contribution proposed by this research is on the appropriate system (and SoS) methodological guidance in the context of specific technologies. Our sponsor has stated that they believe the efforts to date have helped ARDEC in making decisions on approaches to the development of requirements and architectures for AVCE iMBE.

We have obtained and use academic licenses for some of the most powerful commercial tools in order to address research questions in the context of these types of tools; these are the types of tools used by both ARDEC and industry. This approach also addresses some organizational and domain-specific concerns. Through digital means we can now also encode historical knowledge in reference models, model patterns to embed methodological guidance to support continuous orchestration of analysis through new modeling metrics, and automated workflow to accelerate concepts to prototypes, deployment and foster event-driven collaboration. Therefore, the deliverables include reports, demonstrations, meetings, meeting notes, and examples of models without violating any of the academic licensing guidelines.

1.4 ORGANIZATION OF DOCUMENT

Section 1 provides an overview of the context for the needed research, objectives, scope and organization of this report.

Section 2 provides a summary of the current set of research use cases, our Phase I efforts, status, and recommendations based on our increased understanding of the research objectives. For purposes of understanding the evolving efforts and status, the overview presented in Section 2 should provide that level of information.

Part II describes the detailed research use cases.

Section 3 discusses the concept of the Information Model underlying the AVCE; the fundamental purpose is to provide a means to link information and metadata from disparate sources across the various domains.

Section 4 describes the concept for researching the use of Graphical CONOPS, including the potential relationships with the Early Synthetic Prototyping under research at University of Southern California (USC) Institute for Creative Technologies (ICT).

Section 5 describes research into the use of mission and system modeling and simulation, and its relationships to graphical CONOPS and MDAO.

Section 6 discusses modeling methodologies, including examples and demonstrations created to illustrate mission, system, enterprise and reference models, including example and methods for MDAO.

Section 7 provides an overview of the approach for developing system models using Model Based System Engineering (MBSE), but more importantly for understanding the ways to linking MBSE models through the MCE toolchain as it relates to requirements for AVCE.

Section 8 provides an overview of the approach for relating system models using MBSE, Model Based Engineering (MBE), but more importantly for understanding the ways to link MBE models through the MCE toolchain as it relates to requirements for AVCE. Some of the details of the Courter UAS are covered in this use case, and a new section on Automated Concurrent Engineering.

Section 9 discusses the research approach to leverage information captured through all of the phases and types of modeling into the information model to systematically populate the Decision Framework as implemented currently in AAOMDAT.

Section 10 discusses potential contributions of modeling to support verification and validation (V&V).

Section 11 is a use case to develop and assess the operational elements of the entire framework in the context of a Chief Engineer Role.

Section 12 describe tradeoff analysis of technologies for integration or interoperability as a way for representing and analyzing the architecture trades for the requirements of AVCE. In addition, this section reflects on some of the most advanced integrated modeling environment identified through the NAVAIR related SERC research tasks. This task has been extended to consider Windchill, which builds off of a prior SERC RT-152, other commercial tool examples, and involvement with the Open Collaboration Group for MBSE and OpenMBEE.

Section 13 discusses the use of Semantic Web Technologies applied to AAMODAT for the newly defined challenge area #5.

Section 14 provides a new use case for assessing the AVCE iMBE requirements and model.

Section 15 provides a description of some of the SERC research synergies that are relevant to the ARDEC research objectives.

Section 16 provides a summary of Part II.

2 IN-PROCESS SUMMARY

This section provides context into the scope and approach to this research. The research continues to evolve as we have more in-depth discussions and demonstrations with ARDEC about the research and potential benefits. For example, Eddie Bauer's briefing for a Digital Engineering Working Group meeting stated: "*Research in Data Ontology/Information Model using semantic web ontologies is promising and could support model and simulation integration." [9]*

Some of the research results are emerging as elements of ARDEC's concept and architecture for AVCE iMBE. There is understanding that semantic technologies provide potential to better understand the detailed information model in a semantically precise way and enables underlying computation capabilities to automate reasoning about systems engineering tasks. In addition, the semantic precision and cross-domain linkages of information enables more computational analytics about consistency, completeness and well-formed of captured information.

We are using a Model Based System Engineering (MBSE) approach to model our project, and also to assist ARDEC in assessing their AVCE iMBE models. We started to elaborate the research tasks using high-level use cases as shown in Figure 3, relating those use case, and associating the use case with the stakeholders involved in the research. The relationships between stakeholders and use cases reflects on the interactions and dependencies between the team's research.

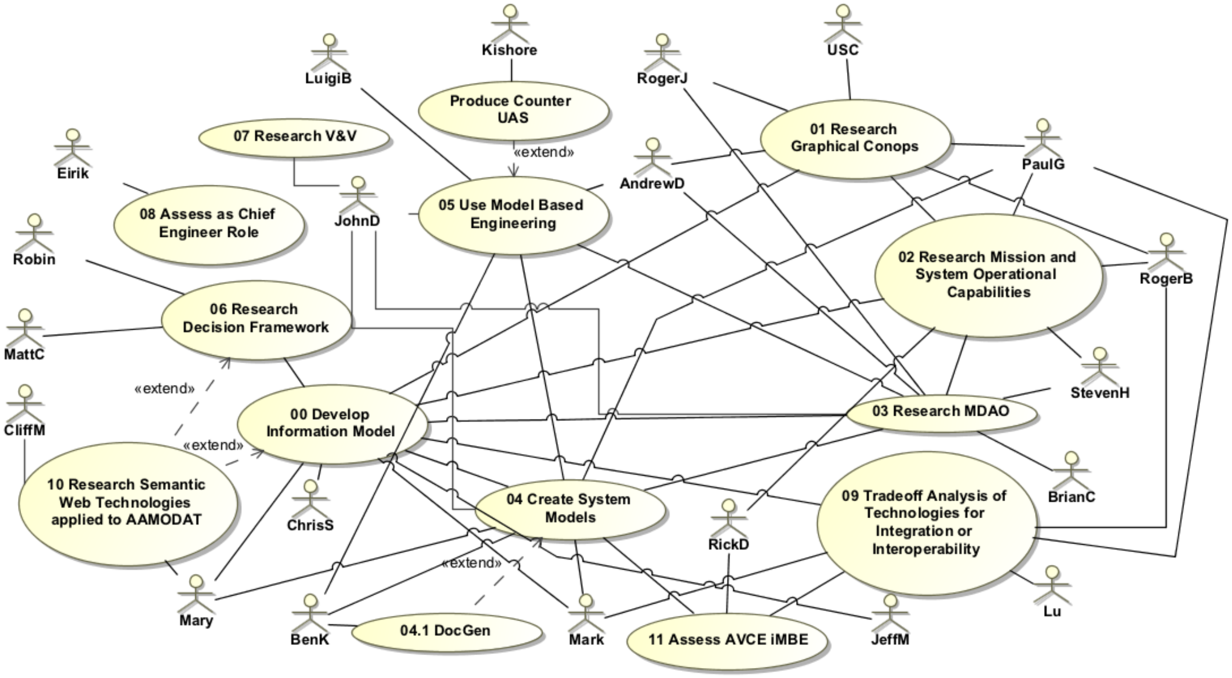

Figure 3. High-level Research Use Cases

2.1 ARDEC CHALLENGE AREA #1 PRELIMINARY FINDINGS

The status presented at the second working session given by Rich Swanson who is leading the ARDEC team on the challenge area #1 focused on integrated, cross domain, dynamic model of a system to assess its ability to achieve a specific operational scenario. The efforts to date are identifying the linkage between those domain areas by executing a conceptual scenario of counter UAS requirements to help inform the team about gaps and challenges associated with requirements needed for the AVCE iMBE requirements and architecture. The lessons learned confirms that, while technically feasible, there are challenges in achieving cross domain models integration to facilitate sharing of relevant data between specialties in order to assess performance within the scenario.

The following provides a few of challenges and concerns derived from the briefing material and presentation provided by the ARDEC challenge area #1 lead (non-exhaustive):

- Automation leading to a lack of applied subject matter expertise and granularity of assessment within each step of the analysis, can lead to incorrect analysis and assumptions
    - People have access to tools and data, but may not understand the methods to effectively use the tools
    - Tools may not have been created with adequate checks such as input data validity; again this relates to methods and types of checks that could be performed in an information model through semantic web technology (see NASA/JPL example)

- Working across domains, both from a technical and socio-technical perspective is challenging; if the tools worked better across domains, would this help with the socio-technical ("people")
    - Shows the need for both the iMBE objective framework (see new challenge area #5)
    - There are concerns that integrated modeling will not improve the timeline dramatically, because integration of models takes time, especially when emerging scenarios or technologies are included
    - Simulations can take long time to run, but uncertain if simulations are "structured/programmed" to leverage high performance computing
- Cost of integration and automation must be weighed against value it can provide. Consider:
    - Integration of models versus integration derived through interoperability using standardized (format) data (i.e., data/information model)
    - Digital thread provided by traceability between models versus single source of truth

These findings were also characterized in a different way in a briefing given by Eddie Bauer at the Digital Engineering Working Group that is approved for public distribution [9]:

- Culture
    - Uncovered lack of understanding across Integrated Product Team (IPT) specialties for the detail, and sometimes value that other IPT members provide
    - Lack of trust that data/models will be used appropriately
        - NAVAIR generally refers to this as Model Integrity (trust in the models/simulation results)
    - SME involvement must never be overlooked as integrated models can easily lead to incorrect analyses and assumptions
    - Do the SME's want to be integrated? Need to better understand value of Dynamic System models
- Model Integration
    - Technically possible
    - Domain understanding is very important
    - Physically passing data to appropriate SMEs is not the time-sink; it is developing new or modifying existing models for a new scenario - assessing and validating results is a concern
    - Dynamic Model Complexity = Greater Run Time and Need for High Performance Computing
- Authoritative Source of Truth
    - Need a common library of models/integrated models
    - Requires rigor in documenting M&S details that are normally in the analyst's head
    - Results of analyses need to retain input from the SMEs involved in its development and execution

Many of these concerns align with the findings from the NAVAR research as summarized in technical reports for RT-118/141/157 [22] [23] [25].

2.2 USE CASE SUMMARY

This section provides a high-level summary of each use case and recent results. Part II (starting with Section 3) of this report provides additional details on each use case (UC). As shown in Figure 3, there is considerable emphasis on understanding many of the cross-domain dependencies of the research use cases, and understanding the methods that must be used to guide the production of this information across the various domains and lifecycle phases.

We are developing an Integrating and Interoperability Framework (IoIF) as part of UC09 as shown in Figure 4. We are working with other use case teams to provide a demonstrations of the Decision Framework (UC06) enabled by semantic technology (UC00). We envision using semantic web technologies (SWT) in the context of the Decision Layer process with AAMODAT (UC10) highlighted in orange oval to be in this part of the concept. In collaboration with NAVAIR and NASA/JPL, we would also like to bring in the Integrated Model Centric Engineering (IMCE) ontologies [91] for systems engineering. We are considering using tool-to-tool integration as discussed in UC09, Data Acquisition and Aggregation in research to integrate Graphical CONOPS (UC01), and Mission and System Operational Capabilities (UC02).

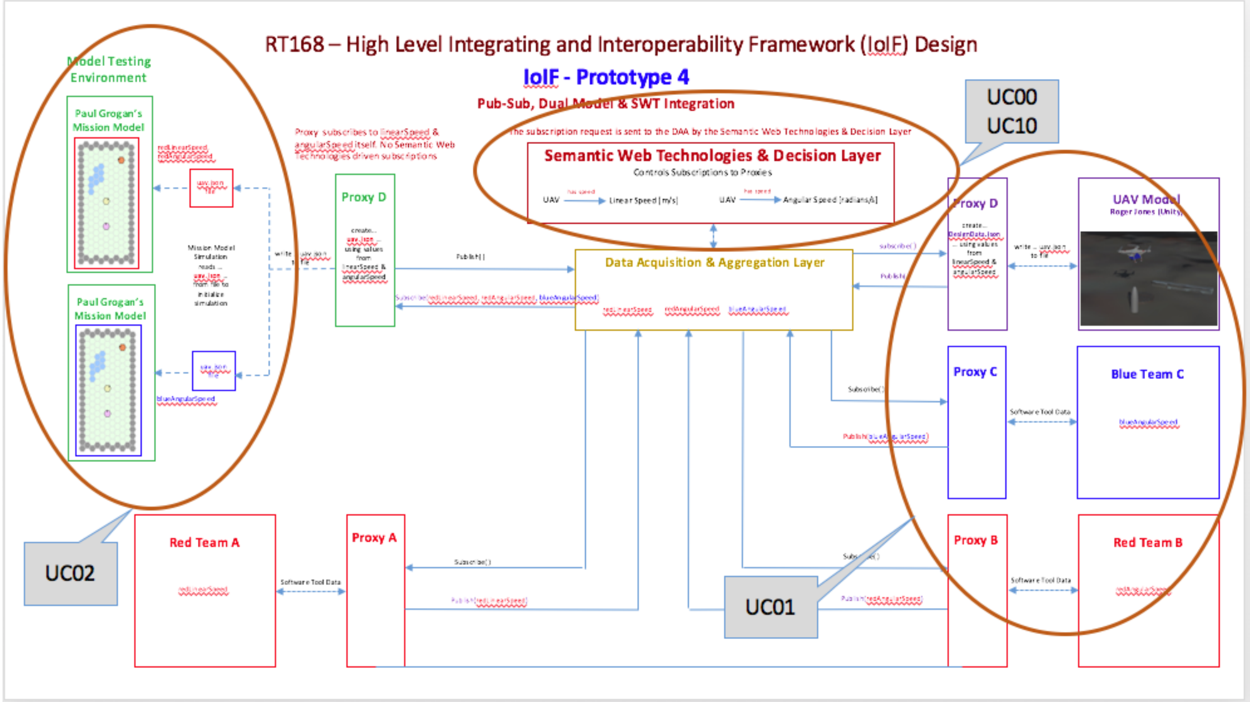

Figure 4. Integrating and Interoperability Framework (IoIF)

00. Develop Information Model. This information model characterizes the underlying information and relationships to "everything" that might need to be produced by the tools of AVCE, although we are using tools available to our Stevens laboratory. This has significant relationships to challenge #3 and #5. We are using the SWT language the Web Ontology Language (OWL) [179] as the primary means for characterizing the information model across many of the use cases. As reflected in Figure 1, the challenge is to characterize this information for each of the various domains, including requirements, risks,

designs (e.g., electrical, mechanical, etc.), and analyses. This reflects why there are so many associations from the other use cases. In addition, we (including our ARDEC IPT) fundamentally believe that it is technical feasible to capture this information and provide it as input to the Decision Framework (UC06). The research demonstrated the use of SWT to demonstrate the concept to both characterize the data and information as well as rules, and query language for processing and data exchange during working session five (5).

- Several demonstrations have illustrated the feasibility of this concept in both working sessions and webinar sessions. Challenge area #5 has been defined and the prioritization of the information model will align with the objective to characterize the information and rules associated with inputs to AAMODAT; as such, this is now defined as a new user case UC10.
- The SWT is being architecturally represented in the Integrating and Interoperability Framework (IoIF) as part of UC09, which was also demonstrated.

01. Research Graphical CONOPS. Investigate the use of Graphical CONOPS technologies such as gaming environments. The team has created demonstrations using the Unity gaming engine [170] for simulating two autonomous UAS interacting in an environment. Our research collaborators USC/ICT have been evolving a technology called Early Synthetic Prototyping (ESP). We are fundamentally interested understanding if there is an underlying metamodel of the information that can be captured, regardless of the domain, and the methods that would be used to ensure that information is fully captured. This information would be mapped to the Information Model (UC00) and be provided as input to UC02. In addition, we are interested in how the parameters of simulation entities can be used in MDAO (UC03).

    - The metamodel provided by ICT represents information and metrics captured while observing the users of the gaming technologies; processing this information in real-time has shown to be difficult, but having this type of information stored in SWT (UC00) could enable better and real-time analytics, which has been stated as a desire by our ARDEC sponsor.
    - There have been nine updates to the graphical CONOPS, which provides two types of missions for red/blue surveillance missions for autonomous quadcopters. The updated simulations include more realistic battery and flight models (UC05), and current research is using MDAO (UC03) for this level of the mission analysis.

02. Research Mission and System Operational Capabilities. Investigate the methodological and relevant technologies for mapping the Graphical CONOPS into Mission and System modeling and simulation capabilities. The current research involves the use of VT MAK [103] and other 2D modeling and simulation environments for distributed simulations. We envision that information from UC01 would provide parameter information that can be refined or expanded. Therefore, like UC01, we want to understand the underlying information (e.g., metamodel) that would be mapped to the Information Model (UC00), and the associated methods for how to develop models at this level. This use case is also researching the relationships of these simulation models and system models in languages such as SysML.

- We have created a simple ontology as the basis to demonstrate information sharing through SWT to illustrate transfer of information through the SWT components of the IoIF. The demonstration also illustrated the use of triple stores and SPARQL [181] queries to store, extract or transform data in the SWT. The next planned demonstration will use these IoIF capabilities to transfer data between the Graphical CONOPS simulation and low fidelity mission-level analysis on a 2D plane with spatial positions of entities.
- This use case is also researching the relationships of these simulation models and system models in languages such as SysML.

03. Research MDAO. Investigate the methods to trace capabilities to the relevant design disciplines and perform cross-domain analyses through MDAO for problem and design tradespace analyses. In addition, to characterizing elements of the framework, cross-domain relationships, but also characterize the methods used to support MDAO in a tool independent manner (we obtained academic licenses for ModelCenter, because we know that ARDEC uses that tool; these license can be used to provide examples, but not contribute to any ARDEC-specific work).

- Recent updates of UAV model using MDAO workflows in ModelCenter show more realistic results in terms of weight and size, including use of Computational Fluid Dynamics, results of Design of Experiments (DOE) for range vs. cruise altitude vs wingspan, and a Pareto frontier for range, payload, and endurance as KPPs, new visualizations provided by version 12 of ModelCenter
- Another model that was used Phoenix Integration MBSE Analyzer to integrate MagicDraw SysML with ModelCenter
- Current efforts are:
    - Researching use of ModelCenter/MDAO to the Graphical CONOPS (UC01)
    - Investigating the use of using MBSE Analyzer/MagicDraw SysML with ModelCenter to formalize the Assessment Flow Diagrams (AFD) for the Decision Framework (UC06)

04. Create System Models. This applies MBSE to the case study examples and looks at how metamodels or metadata is represented in the Information Model (UC00) to provide traceability through the other forms of modeling for UC01, UC02, UC03 and UC05. This use case is developing different variants of UAS system models at both the system and mission level.

- Demonstrations include the use of the OpenMBEE Model Development Kit (MDK) DocGen to a number of models including the AVCE iMBE and Rotocopter UAV
- We have an evolving SysML model for the RT-168 IoIF framework (UC09) to formalize the architecture, which has been provided to ARDEC
- We are near completing setup of the OpenMBEE environment, including the Model Management System (MMS) and View Editor components that have been open-sourced by NASA/JPL at: http://www.openmbee.org/ this is planned to be integrated with the IoIF framework

- We are trying to leverage work with the SERC RT-176 led by Kristin Giammarco to use Monterey Phoenix (MP) for demonstrating the potential to perform early V&V requirements and architecture models [70]. Currently, MP is a language, but we believe we can develop a graphical language using SysML activity diagram (maybe profiled), and then use DocGen to extract information in order to translate into MP. This tasks benefits ARDEC, because RT-176 is funded by NAVAIR.

05. Use Model Based Engineering. This applies Model-Based Engineering (MBE) typically associated with the different design disciplines (e.g., electrical, mechanical, controls) and will focus on some related research associated with counter UAS. Like UC04, we are interested at how metamodels from these various domain or metadata are represented in the Information Model (UC00) to provide traceability. It is currently acknowledged that, except for a few exceptions there is a gap in mapping from these types of modeling technologies to MBSE models.

    - Presented a session on “Representation Methods, Model Frameworks and Verification Tools for CPS Design” for UAS
    - Current investigations include bringing MBE design information into the SWT using an architecture and prototyping of system simulation with semantic data exchange; this will look at discipline-specific ontologies for cross-domain integration [29]

06. Research Decision Framework. As discussed in Section 1.3, we have had discussions with the ARDEC leads, who are intimately familiar with this framework and the evolving tool called AAMODAT. This use case is now aligned with challenge area #5. Fundamentally, a key goal for UC00 is to capture information that can be used to provide input to the Decision Framework (UC06). This would provide senior leaders and program managers the type of information they need to consider technology capability tradeoff using Performance, Cost (Affordability), Time (delivery schedule) and Risk. Fundamentally, if a particular answer was unacceptable, using the concept discuss herein, we could trace linkages through the Information model back to all other related perspectives on the system (UC01, UC02, UC03, UC04, UC05).

    - We provided demonstrations using SWT to get example data from DBpedia (which is a crowd-source effort to extract structured information from Wikipedia and make this information available on the Web) of a simple aircraft ontology and properties to show semantically rich data extracted from DBpedia using SWT tools (Protégé, OWL Viz, RDF)
    - Investigating the use of Phoenix Integration MBSE Analyzer plugin to MagicDraw SysML with ModelCenter to formalize the Assessment Flow Diagrams (AFD) for the Decision Framework (UC06) using an updated UAV case study [42]
    - Working on templates for different type of objective hierarchies (e.g., portfolio, product)

07. Research Verification and Validation (V&V). This use case was not considered in the original plan, but MCE does provide some unique opportunities to be more effective at contributing V&V evidence in early design. Rigorously defined models can directly support V&V, and this could both subsume cost and risks. This use case can likely identify candidate requirements for AVCE.

- As discussed in UC04, we are trying to leverage work with the SERC RT-176 led by Kristin Giammarco to use Monterey Phoenix (MP) for demonstrating the potential to perform early V&V requirements and architecture models [70].

08. Assess as Chief Engineer Role. This use case is created so that one of our researchers, experienced in actual systems engineering can provide some level of assessment of our overarching approach and contribute to the requirements for AVCE. We too want to bring as many technologies as possible into our lab at Stevens in order to assess the gaps, but are also interesting in bring in Masters students to using methods derived from this research.

09. Tradeoff Analysis of Technologies for Integration or Interoperability. This use case has been renamed and expanded due to information learned about other technologies that provide a means for looking at alternative technologies and approach to support either tool integration or some type of equivalent interoperability approaches that can be used for AVCE. Specifically, we are looking at the technologies and tools used by ARDEC and used in the case study to focus this research. In addition, this tasks revisits some of the most advanced tool integrations that have been developed by NASA/JPL [59] [10], the DARPA META projects [8] [7], Engineered Resilient Systems [81], Airbus [76], and generalization of commercial and industry integrated modeling environments. We added a team member assess Windchill as part of this use case. We learned of Syndeia by Intercax, and coordinated a demonstration with our ARDEC sponsor. We have joined Open Collaboration Group for MBSE and OpenMBEE [132].

- As discussed at the beginning of this section, the IoIF as shown in Figure 4, brings a number of use cases together:
  - The SWT is being expanded to support interoperability from Graphical CONOPS (UC01) to Mission-level simulation (UC02)
  - We are modeling this architectural framework (UC04)
  - We are expecting disciplines specific information to be integrated through the SWT component (UC05)
  - We expect this same architectural element to be used to support exacting information to populate the Decision Framework (UC06) and AAMODAT (UC10)
  - We will also look to integrate these capabilities with OpenMBEE

10. Challenge area #5 has been defined and the prioritization of the information model will align with the objective to characterize the information and rules associated with inputs to AAMODAT. This use case is related to both UC00 and UC06.

- We discussed how AAMODAT is usually something that happens early on for ARDEC, and all over the project. It has helped to identify Key Performance Parameters (KPPs) at the mission level and the elements from the sub-domains that are relevant to those KPPs. ‘All requirements are tradeable,’ but looking at how much they contribute to the KPPs, is a different way of thinking.
- As discussed in UC09, we expect this same architectural element to be used to support exacting information at populate the Decision Framework (UC06)

11. Assess AVCE iMBE. We were asked to provide a more detailed analysis of the AVCE iMBE requirements. We initially looked at the requirements, but in attempt to do the analysis started to identify additional use cases not reflected in the model as shown in Figure 11. ARDEC then did deliver the AVCE iMBE model, and we developed a set of View and Viewpoints for the model to allow for us of MDK/DocGen. While the model is well structure, the View and Viewpoints modeling process revealed some minor inconsistencies, which we shared with ARDEC. While ARDEC has finished the Systems Requirement Review (SRR) for AVCE iMBE. Rick Dove joined the RT-168 research team.
    - Rick Dove has done some research through the INCOSE's Agile Systems Engineering Life Cycle Model (ASELCM) project, and specifically in terms characterized by the ASELCM Pattern of Three Concurrent Systems. Rick will use this context to look at the AVCE iMBE model from this three-system perspective

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2.3 WORKING SESSIONS AND SPONSOR-SUPPORTING EVENTS

A component of the research and required deliverables are conducting working sessions that inform the ARDEC team about progress against the plan. These working session also inform the team about relevant information and feedback to scope the deliverables in the context appropriate for ARDEC; this approach has been especially important for working other SERC research task, such as with NAVAIR given the recent changes under SE transformation. In addition, NAVAIR joined for the second half day meeting for the first working session, and a number of members of the NAVAIR team have been attending working sessions and the bi-weekly meetings.

- Working session #1: 21, 22-Sep-2016 held at ARDEC
    - The SERC team provided an overview elaborated from the proposal discussing an approach to use case study scenarios to address the lifecycle concerns from CONOPS, mission and system analysis, using MDAO for tradespace analysis, Model-Based System Engineering linking to risk and the decision framework. This was presented in the context of their Digital Thread concept. The SERC team also discussed the potential synergies with NAVAIR Systems Engineering Transformation and the Digital Engineering Strategy initiative coordinated by Deputy Assistant Secretary of Defense (DASD). Discussed the concept for developing the ontology underlying the requirement manager (top-level priority)
- Working session #2: 10-Jan-2017 held at ARDEC
    - This session covered the broad objectives identified by ARDEC, to:
        - Discuss progress in research areas
        - Share lessons learned from their own efforts on Challenge Areas
        - Identify areas for enhanced collaboration
        - Engage in general model-based engineering discussions
    - A number of presentations and demonstrations from ARDEC, SERC, and NAVAIR were given to inform the audience and to stimulate further discussions, including:
        - Status of AVCE-iMBE Project – ARDEC, Cliff Marini
        - Dynamic Model Challenge Overview – ARDEC, Rich Swanson

    - NAVAIR SE Transformation Overview – NAVAIR, Jaime Guerrero
    - Overall Status of RT-168 Transforming Systems Engineering through Model-Centric Engineering - SERC, Mark Blackburn
    - Demonstration: Graphical CONOPS – SERC, Roger Jones
    - Demonstration: VT-MAK Mission Simulation – SERC, Roger Blake
    - Integrated Mission Modeling: Approach and Initial Results – SERC, Paul Grogan
    - Demonstration: Multidisciplinary, Design, Analysis and Optimization – SERC, Steven Hoffenson
    - Overview of Integrated Model Based Engineering Environment (iMBE-E) Data Challenges - ARDEC, John Campbell
    - Data Ontology/Information Model - SERC, Mark Blackburn
    - Decision Framework Approach and AAMODAT, ARDEC, Matt Cilli
- Working session #3: 30-Mar-2017 held at Stevens
  - ARDEC AVCE-iMBE Update, Cliff Marini
  - NAVAIR Progress update, Mark Blackburn
  - RT 168 Progress update, Mark Blackburn
  - Semantic Web Technologies Demo & Discussion, Mary Bone
  - Semantic Web Technologies Demo and Discussion… continued
  - USC ICT Research Presentation, Edgar Evangelista
  - MBE Tools: Syndeia, OpenMBEE, Jeff McDonald, Mark Blackburn
  - Mission-level simulation using High Level Architecture (HLA) Demo, Roger Blake, Paul Grogan
- Working session #4: 13-Jun-2017 held at ARDEC
  - ARDEC updates, Christina Jauregui, Cliff Marini, Greg Nieradka
  - OpenMBEE, Mark Blackburn
  - OpenMBEE MDK/DocGen for the AVCE model, Benjamin Kruse
  - SysML/MDAO/MBSE Analyzer, John Dzielski
  - MDAO updates, Brian Chell
  - Graphical CONOPS update and demonstration, Roger J.
  - Semantic Technology for SE Working Group/ NASA/JPL Integrated Model Centric Engineering (IMCE) Ontologies and SWT, Mark Backburn, Mary Bone
  - Integration and Interoperability Framework (IoIF) – Demonstration, Roger B, Roger J, Paul)
  - NAVAIR RT-170/RT-176 updates, Modeling for the Surrogate Pilot, Mark Blackburn
  - Requirement V&V through Monterey Phoenix (Mark Blackburn)
- Special Session: 31-July-2017 held at Stevens
  - This special session invited our sponsors from ARDEC, NAVAR, and DASD(SE), but also other organization Naval Surface Warfare Center, Digital Warfare Office, and MITRE, and industry guests from Raytheon working on Semantic Web Technologies and Ontologies
  - Objectives included: “Provide Big Picture – Mental Model”

    - Use historical context of research investigating ”the most advanced and holistic approaches and technologies supporting state-of-the-art in Model Centric Engineering” aka Digital Engineering
    - Summarize expanse of research thrusts dating back to initial NAVAIR air research in 2013
    - Discuss alignment with sponsors’ evolving needs, transformation, and goals of digital engineering initiative
    - Provide awareness of collaborations with other initiatives, industry, government, academia & open communities
  - “Past – Why” – Historical perspectives – How we got here and why
  - “Present – What” - Aligning the research gaps and challenges for a Systems Engineering Transformation
  - “Future – How” - Blending and evolving our research results with Digital Engineering (DE) Transformations across the DoD to be in a Future State by Computationally Enabled DE
  - Deep Dive a Few Research Topics
  - Integrated Systems Engineering Decision Management (ISEDM) Process Enabled by Digital Engineering Technologies, presented by Dr. Matthew Cilli
  - Semantic Technologies and Ontologies Research to enable Trade Space Analytics for Engineered Resilient Systems, presented by Dr. George Ball
  - Breakout Session discussing
    - Risk for Digital Engineering Transformation
    - Priorities for Digital Engineering Transformation
  - Forward Planning and Actions
- Working session #5: 1-August-2017 held at Stevens
  - Perspectives on July 31 Session: Systems Engineering Transformation through Model Centric Engineering
  - ARDEC challenge updates
  - Presentation and demonstrations on Integration and Interoperability Framework (IoIF) overview and demonstration (UC09, UC00, UC01, UC02, UC04), and IoIF model and workflow representation
  - Overview of OpenMBEE plan for integration into the IoIF
  - Decision Framework (UC06) and Formalizing Assessment Flow Diagram through MDAO (UC03)
  - Status updates of the Graphical CONOPS (UC01) integration with MDAO (UC03)
  - Status update from UCE/ICE
  - Next steps for Phase II

2.4 TENTATIVE SCHEDULE FOR MEETING, DEMONSTRATIONS AND DELIVERABLES

Table 1 provides a list of the deliveries, demonstrations and discussions for our bi-weekly status and other meetings involving our ARDEC sponsors.

Table 1. Schedule for Demonstration and Deliverables

Date	Demo / Presentation / Reports	Status
Sep 21 & 22, 2016	1st Working Session at ARDEC – see meeting notes.	Done
Nov 4, 2016 (Fri)	Mission Level Modeling and Graphical CONOPS (2 approaches) • *Paul Grogan* • *Roger Blake* • *Roger Jones*	Done
Nov 7, 2016	Interim Report/Bi-Monthly Status • Expand on all tasks that are mapped to Use Cases project model	Done
Nov 22, 2016	Decision Framework Approach by *Matt Cilli / Robin Dillon*	Done
Dec 2, 2016	MDOA presentation and demonstration by *Steven Hoffenson* *Discussion of Mission/System Simulations Roger Jones, Roger Blake, Paul Grogan*	Done
Dec 16, 2016	Design of a Systems Representation Framework for Counter UAS Operations by *Kishore Pochiraju*	Done
Dec 20, 2016	Information Model/Ontology by *Mark Blackburn / Mary Bone / Gregg Vesonder*	Done
Jan 10, 2017	2nd Working Session at ARDEC – see meeting notes.	Done
Jan 15, 2017	Update Interim Report/Bi-Monthly Status • Expand on tasks that are mapped to use cases in project model	Done: This report
Jan 25-27, 2017	NASA/JPL Symposium and Workshop on Model Based Systems Engineering	Meeting notes delivered
Jan 28-31, 2017	INCOSE International Workshop	Meeting notes delivered
Feb 10, 2017	Demonstrations of Graphical CONOPS ▪ Roger Jones – Unity gaming of competing autonomous quadcopters ▪ Todd Richmond – Video of Unity gaming for Early Synthetic Prototyping	Done
Feb 24, 2017	Automatic Concurrent Engineering and Knowledge-Based Product Design and Manufacturing (Kishore Pochiraju)	Done
Mar 2, 2017	Semantic Web Technologies (Mary Bone / Mark Blackburn)	Done
Mar 7, 2017	Syndeia Demonstration (Manas Majaj / Jeff McDonald)	Done
Mar 9, 2017	ARDEC sponsor Eddie Bauer participated in NAVAIR, RT-170 working session #29 at NAVAIR.	Done
Mar 10, 2017	Update on HLA approach (Roger Blake / Paul Grogan)	Done

Mar 15, 2017	Update Interim Report Expand on tasks that are mapped to use cases in project model	Done: Prior version of this report
Mar 24, 2017	Mary Bone gave a talk on ontologies as it related to AAMODAT and Challenge area #5	Done
Mar 30, 2017	Working Session #3 at Stevens – see meeting notes. There were over 25 attendees, including nine (9) from ARDEC	Done
Apr 7, 2017	Kishore gave a talk on Design Automation	Done
Apr 18, 2017	Two related talks on OpenMBEE model in SysML to support analysis of requirements development/review for AVCE iMBE (Mark Blackburn)	Done
Apr 21, 2017	Broader aspects of OpenMBEE (Mark Blackburn)	Done
May 15, 2017	Bi-monthly status report • Expand on tasks that are mapped to use cases in project model	Done
May 19, 2017	Model Centric Engineering Architecture (Roger Blake / Paul Grogan)	Done
Jun 2, 2017	Overview on Model Development Kit (MDK) DocGen View and Viewpoints that were added to AVCE requirements model to illustrate the DocGen capabilities (Benjamin Kruse)	Done
Jun 13, 2017	Working Session #4 at ARDEC – see meeting notes.	Done
Jun 30, 2017	Two talks on Model Centric Engineering Architecture and the Prototype of the Integration and Interoperability Framework (IoIF) and demonstration interoperability using semantic web technologies and ontologies (Paul Grogan, Roger Blake, Mary Bone, Chris Synder, Harsh Kevadia)	Done
Jul 14, 2017	Decision Framework update with discussion of use of semantic web technologies and concept for modeling the Assessment Flow Diagram (Matt Cilli, Robin Dillon-Merrill, Mary Bone, John Dzielski)	Done
Jul 15, 2017	Updated Interim Report • Expand on tasks that are mapped to use cases in project model	Done
July 31, 2017	Systems Engineering Transformation through Model Centric Engineering Past, Present, and Future – Special Session at Stevens (Mark Blackburn, Dinesh Verma)	Done
Aug 1, 2017	Working Session #5 at Stevens	Done
Aug 8, 2017	Final Technical Report	Done: This report

PART II: TASK DETAIL SUMMARY

The material in Part II provides additional detail on the latest status on the tasks in the context of the research use cases, including information shared during some of the working sessions and bi-weekly meetings. An extensive amount of material covered in Part II of the RT-141 final report [22] and RT-157 final report [23] still provides relevant information to this research, but has not been integrated into this report.

Each of these sections has a team of researchers, which are reflected by Figure 3. We are adding the information from the different perspectives, and will continue to integrate the story as the research results evolves through Phase II (August 2017 – August 2018).

3 INFORMATION MODEL (UC00)

MCE is enabled by computational technologies that now provide a means for using modeling and simulation in a transformed approach to systems engineering. A key problem is that most of these technologies are not integrated (and many may never be). Therefore, we are interested in an approach to using data interoperability as a means (or surrogate) for accomplishing integration. This is challenge area #3, which has now been extended to incorporate this concept under challenge area #5, and defined in more detail under UC10 (see Section 13).

This information model characterizes the underlying information and relationships to "everything" that might need to be produced by the tools of AVCE. We are using OWL and SWT to represent the information. Our efforts with ARDEC are also complemented by our efforts with NAVAIR and the Semantic Technologies for Systems Engineering initiative (ST4SE) that was established in April 2017.

3.1 SEMANTIC TECHNOLOGIES FOR SYSTEMS ENGINEERING

Briefly, the SWTs are based on a standard suite of languages, models, and tools that are suited to knowledge representation. Figure 5 provides a perspective on the SWT stack, which includes eXtended Markup Language (XML) [129], Resource Description Framework (RDF) [180] and Schema (RDFS), Web Ontology Language (OWL) [179] (i.e., OWL2), the SPARQL Protocol And RDF Query Language (SPARQL) [181], and others. RDF can describe instances of ontologies – that is, the data for particular model instances, where OWL relates more to metamodels describing the class of information that can be characterized as RDF instances. RDFS extends RDF and provides primitives such as Class, subClassOf, and subPropertyOf. The SWT was created to extend the current Internet allowing combinations of metadata, structure, and various technologies enabling machines to derive meaning from information, both assisting and reducing human intervention. This technology is generally applicable to many different applications, and our research is beginning to reflect that from the demonstrations of the IoIF, to the Decision Framework, and communicating the uses of SWT by NASA/JPL, and how such capabilities can be integrated within a model based engineering environment, like OpenMBEE to provide additional reasoning on the information that is captured such as completeness, consistency and well-formedness.

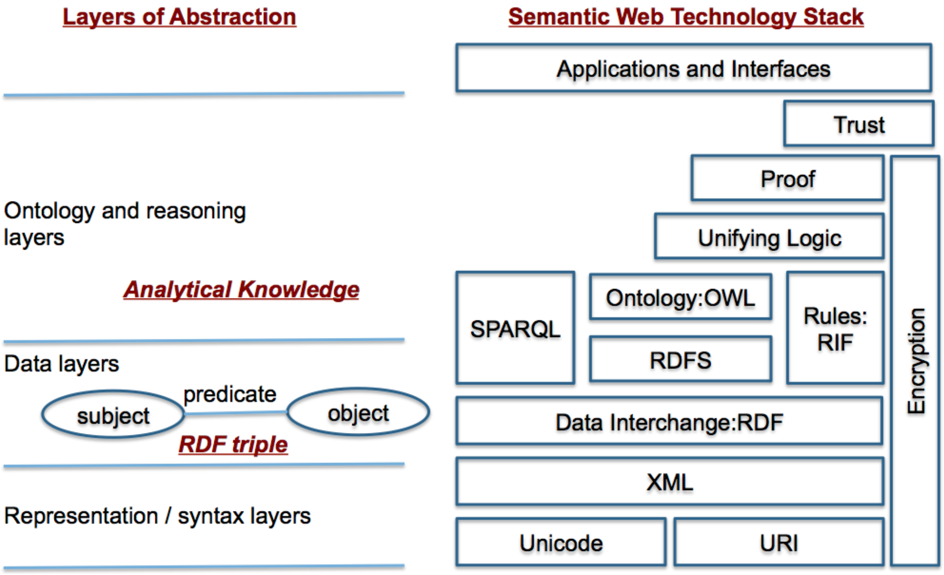
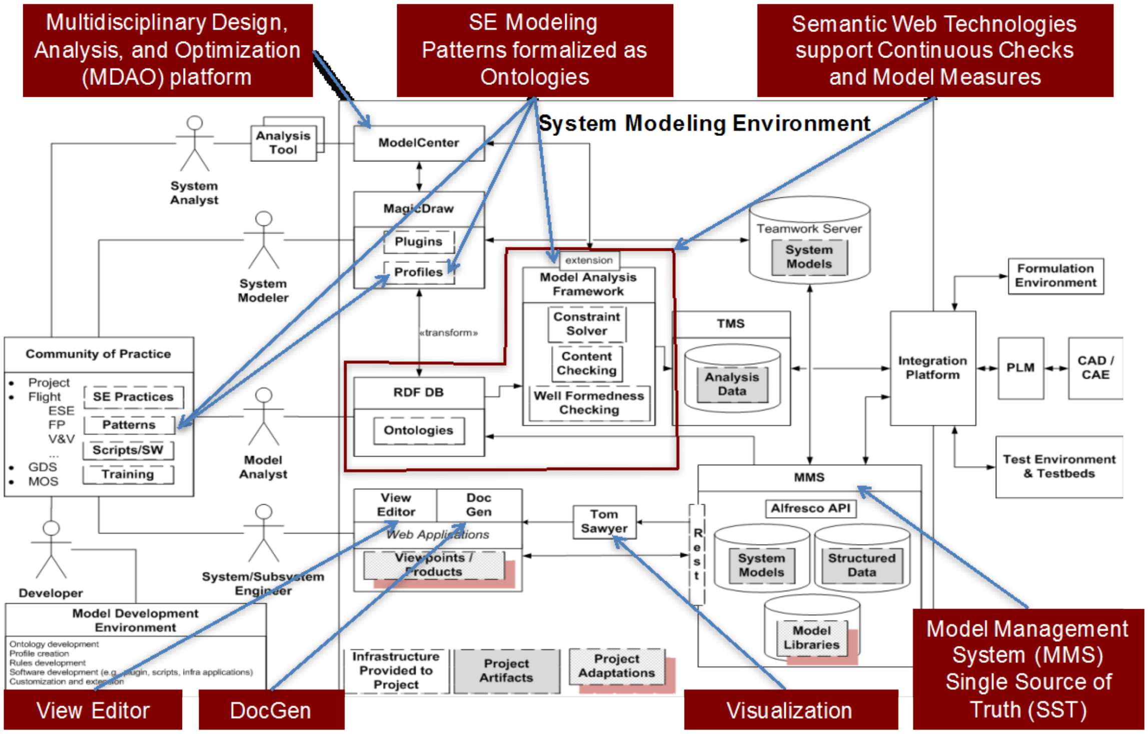


Figure 5. Semantic Web Technologies related to Layers of Abstraction

Figure 6 provides another perspective using an instantiation created by NASA/JPL, which reflects a number of the pieces we are interested in using:

- Three core elements of View Editor, DocGen and Model Management System (MMS)
- MagicDraw client (in which the MDK/DocGen) plugin works
- Teamwork Cloud server from NoMagic is used with MMS
- The NASA ontologies for Systems Engineering used to check constraints (e.g., consistency, completeness, well-formedness) [90] related to the model is shown in Figure 7
    - These are being open-sourced
    - We would like to opportunistically leverage these capabilities both with NAVAIR and ARDEC through our efforts with the ST4SE
    - These ontologies have grown out of a history of work, including the INCOSE modeling patterns group

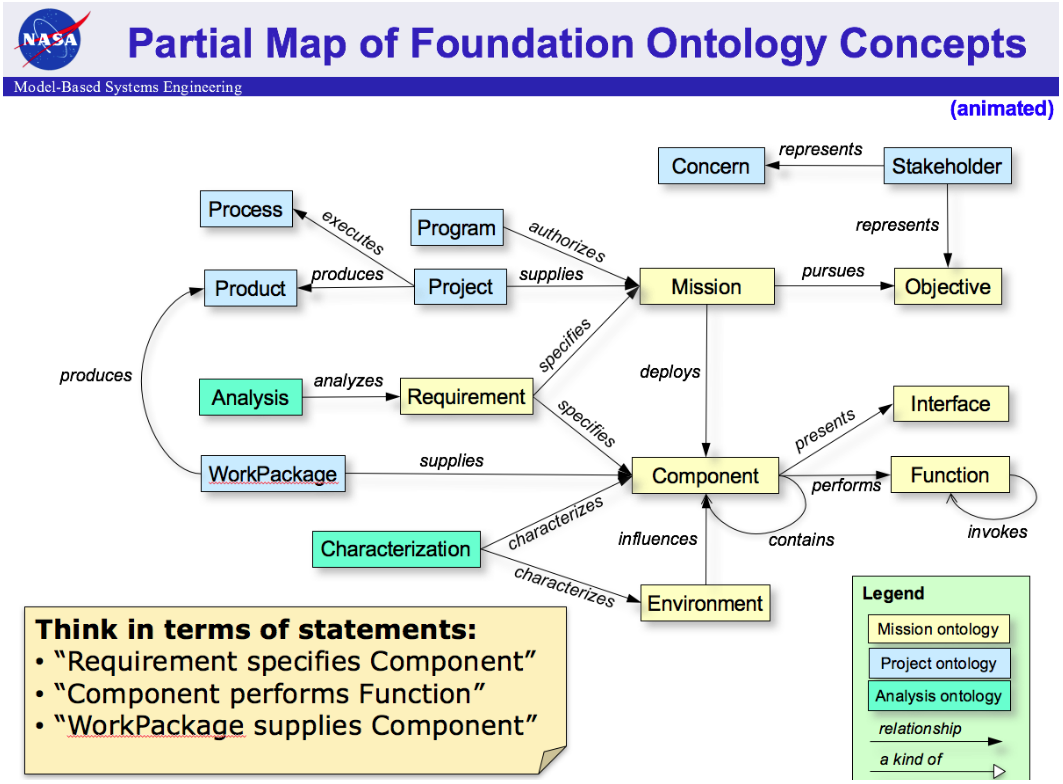


*An Integrated Model Centric Engineering (IMCE) Reference Architecture for a Model Based Engineering Environment (MBEE), NASA/JPL, Sept, 2014.

Figure 6. NASA/JPL Instantiation of OpenMBEE (circa 2014)

The following figures have been taking from Model-Centric Engineering, Part 3: Foundational Concepts for Building System Models [91]. Figure 8 shows the Integrated Model Centric Engineering (IMCE) concept that is being developed. The process involves:

- Creating ontologies for foundational systems engineering derived from the modeling patterns (reflected in Figure 7)
  - This can be done in any OWL modeling tool such as the open source Protégé
  - The ontologies are turned into SysML profiles
  - The SysML profiles are loaded into a modeling tool for creating models
  - The profiled SysML models are exported back into OWL statements
  - Checks for completeness, consistency and well-formedness can performed



Partial Map of Foundation Ontology Concepts

Model-Based Systems Engineering

(animated)

Think in terms of statements:

- "Requirement specifies Component"
- "Component performs Function"
- "WorkPackage supplies Component"

Figure 7. NASA/JPL Foundational Ontology for Systems Engineering

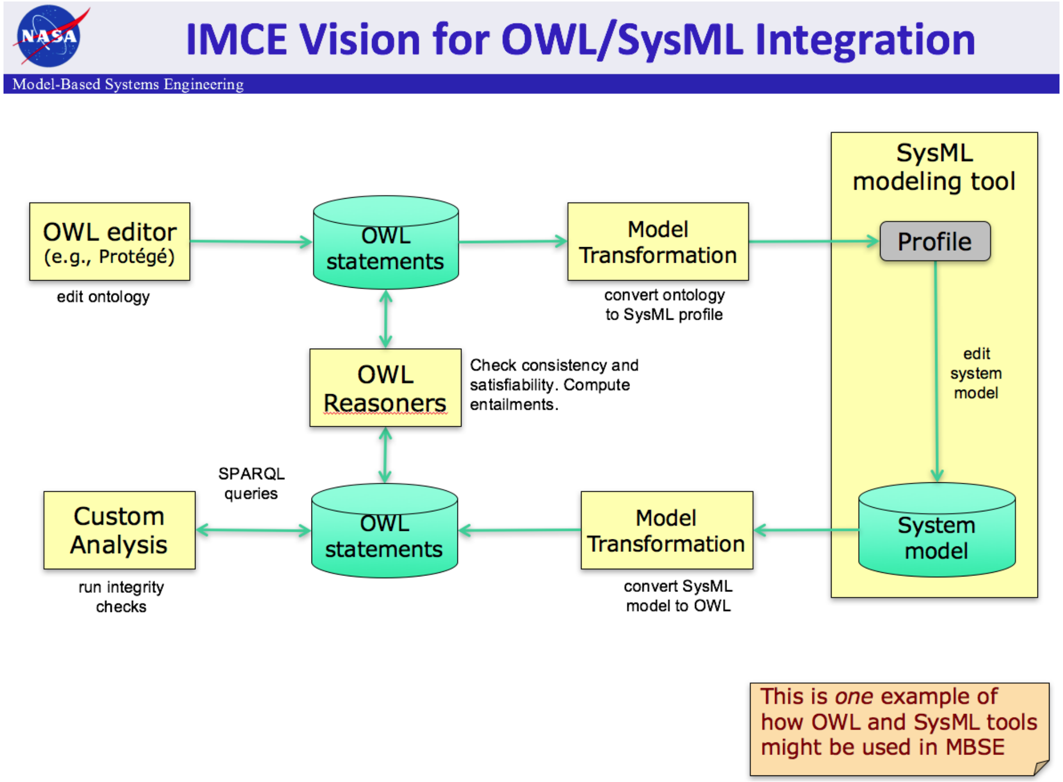
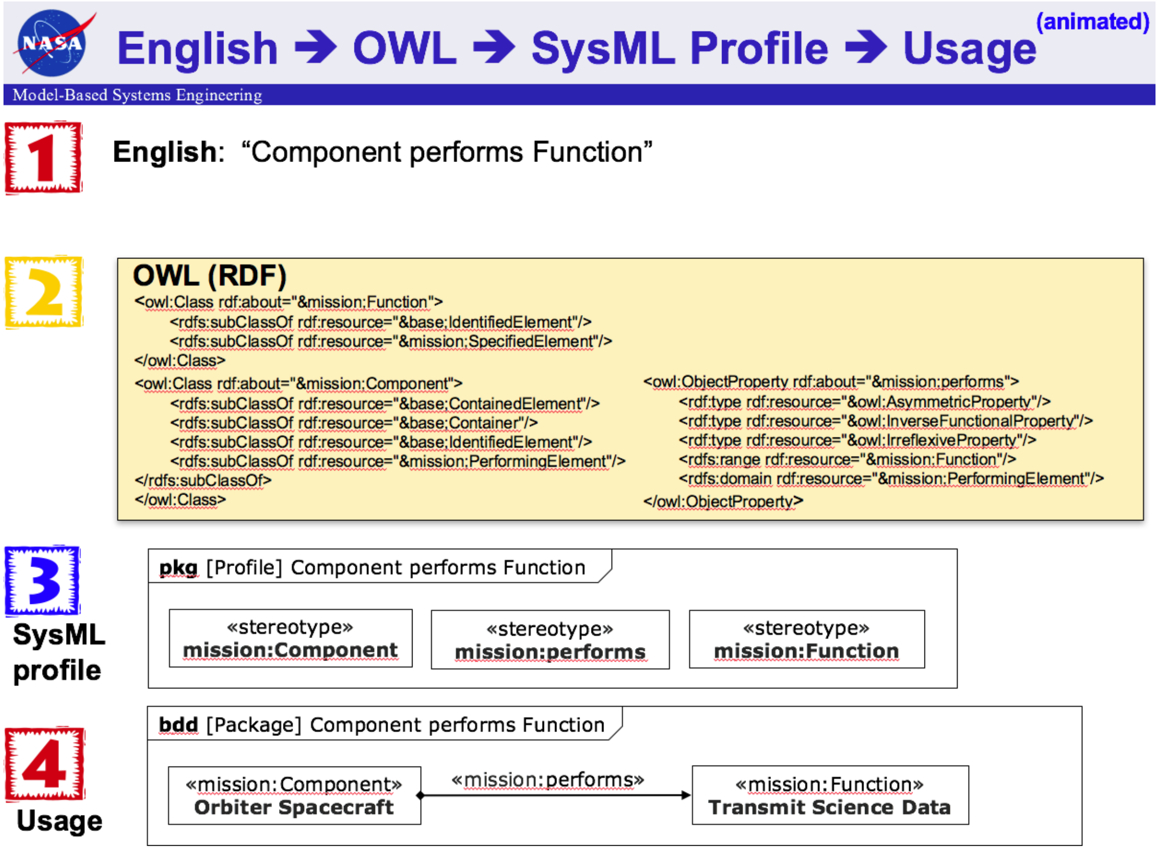


Figure 8. From Ontologies to SysML Profiles and Back to Analyzable OWL / RDF

Figure 9 shows the various representations associated with the concept described in Figure 8:

1. The modeled statement in English is: “Component performs Function”
2. The OWL/RDF representation of the statement in low-level XML for this same statement
3. The Profile and Stereotypes used in the model (loaded into a SysML model)
4. The Stereotypes used in a SysML Block Definition Diagram (BDD)



English → OWL → SysML Profile → Usage (animated)

Model-Based Systems Engineering

1 **English**: “Component performs Function”

2 **OWL (RDF)**

```
<owl:Class rdf:about="&mission;Function">
      <rdfs:subClassOf rdf:resource="&base;IdentifiedElement"/>
      <rdfs:subClassOf rdf:resource="&mission;SpecifiedElement"/>
</owl:Class>
<owl:Class rdf:about="&mission;Component">
      <rdfs:subClassOf rdf:resource="&base;ContainedElement"/>
      <rdfs:subClassOf rdf:resource="&base;Container"/>
      <rdfs:subClassOf rdf:resource="&base;IdentifiedElement"/>
      <rdfs:subClassOf rdf:resource="&mission;PerformingElement"/>
</rdfs:subClassOf>
</owl:Class>
```

```
<owl:ObjectProperty rdf:about="&mission;performs">
      <rdf:type rdf:resource="&owl;AsymmetricProperty"/>
      <rdf:type rdf:resource="&owl;InverseFunctionalProperty"/>
      <rdf:type rdf:resource="&owl;IrreflexiveProperty"/>
      <rdfs:range rdf:resource="&mission;Function"/>
      <rdfs:domain rdf:resource="&mission;PerformingElement"/>
</owl:ObjectProperty>
```

Figure 9. Multiple Representations in Process

We believe that SWT has the potential to contribute significantly to challenge #3 and challenge #5. As reflected in Figure 1, the challenge is to characterize this information for each of the various domains, including requirements, risks, designs (e.g., electrical, mechanical, etc.), and analyses. The use case diagram in Figure 3 reflects why there are so many associations from the other use cases. In addition, we believe that it is technically feasible to capture this information and provide it as input to the Decision Framework and AAMODAT tool. The research approach is to use SWT to demonstrate the concept to both characterize the data and information as well as rules, and query language for processing and data exchange. Several briefings on SWT concepts (e.g., ontologies) and example uses have been provided in both working session and webinar sessions. Challenge area #5 has been defined and the prioritization of the information model will align with the objective to characterize the information and rules associated with inputs to AAMODAT; as such, this is now defined as a new user case UC10.

The third and fifth working session demonstrated showed evolving capabilities to illustrate broader viability of the concept of using data interoperability defined by ontologies as a means for collecting, managing and composing information collected across domains. This is a strategic thrust area moving into Phase II.

We are evolving an Integrating and Interoperability Framework (IoIF) as part of UC09 as shown in Figure 4. We are working with other use case teams to provide a demonstration of Decision Framework enabled by semantic technology (UC00). We envision SWT and Decision Layer (UC10) highlighted in orange oval to be in this part of the concept. In collaboration with NAVAIR and NASA/JPL, we would also like to bring in the IMCE ontologies for systems engineering. We are considering using tool-to-tool integration as discussed in UC09, Data Acquisition and Aggregation in research to integrate Graphical CONOPS (UC01), and Mission and System Operational Capabilities (UC02).

3.2 UC00 MAPPING TO OTHER USE CASES

We plan to continue research in the other two areas of Graphical CONOPS (UC01) and Mission and Systems (UC02) to understand the flow of information needed to be linked between them, and characterize those linkages in an Information Model. The information produced under the following use cases has begun to characterize elements of the metamodels, for example:

- Parameters in the Graphical CONOPS
- High Level Architecture (HLA) metamodel for both VT MAK [103] and Distributed Simulation
- Early Synthetic Prototyping (ESP) Data Structures and Reasoning
- Lack of “acceptable” representations and transformation using SysML
    - Graphical diagrams specified at multiple abstractions
    - Oriented towards concrete design (=very detailed)
    - Likely to be missing relevant mission/scenario parameters
    - XMI difficult to ‘query’ for structural parameters
    - Low-level with extensive unique IDs difficult to interpret/parse
    - Behavioral diagrams cannot easily be transformed to scripted code (e.g. Lua script)

As discussed by the ARDEC challenge area #1 team, which relate to UC03, UC04, and UC05 involve the need to improve the integration of architectural, system and component models across the domains, and better link with other modeling and simulation capabilities targeted to specific disciplines. At the system level they may be developed using MBSE methods and be represented in standard modeling languages such as SysML [131]. The linkages between the MBSE and design disciplines, usually referred to as Model-Based Engineering (MBE), is often not precisely represented, with a few exceptions. When it is done using tool-to-tool integration, such integrations can be rather susceptible to tools updates [36]. We believe there are opportunities to address this need in more tool agnostic ways using SWT. See UC09 and UC10.

A key reason for the need for cross-domain model integration is the underlying complexity needed to accomplish the scenarios associated with Figure 10. In addition, our research as illustrated by the DARPA META project [8] has shown that methods are needed to ensure that the tools provide the expected automation, efficiencies, and produce the desired information. This points to the need for both methods (Task 3), and because many of the modeling and simulation capabilities that may be integrated into an MDAO workflow can be modeling and simulation capabilities, they require some type of assessment to ensure the integrity of the predictions.

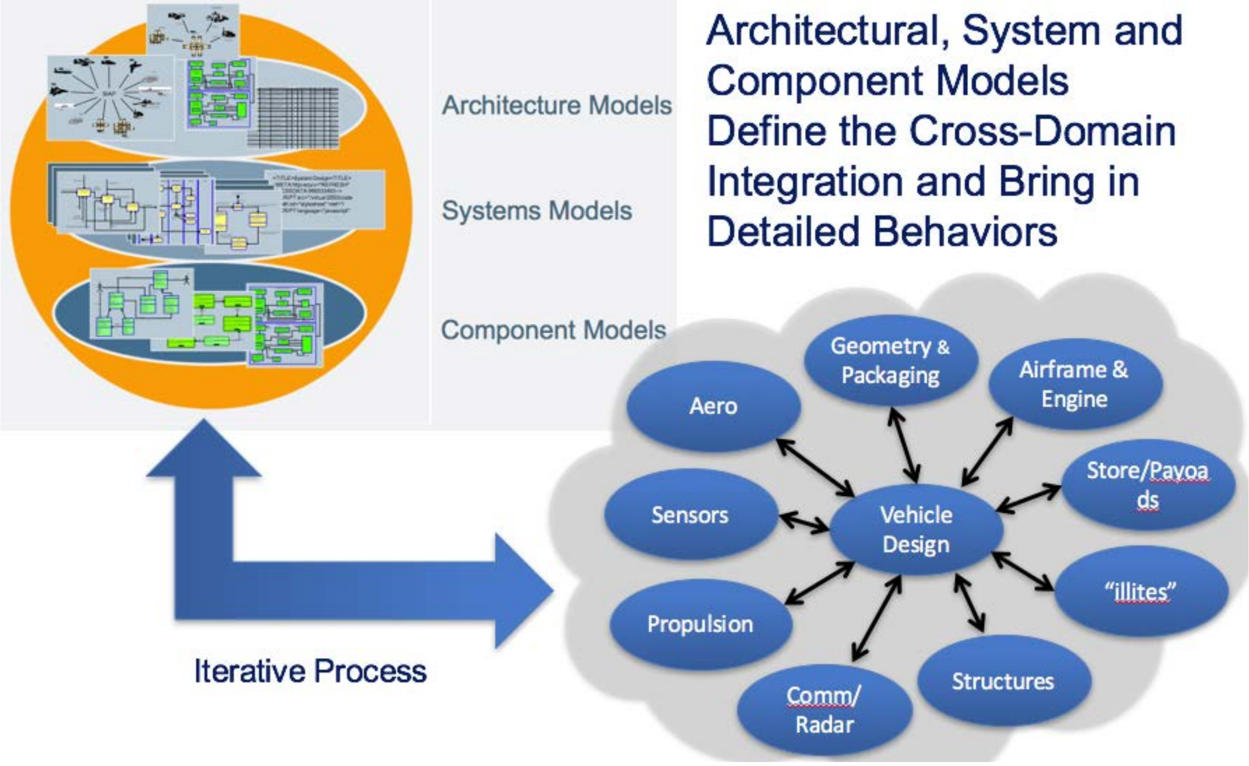


Figure 10. Integrate Multiple Levels of System Models with Discipline-Specific Designs

We believe there are research challenges to better quantify design margins, parameter uncertainties, and system performance sensitivities associated with physics-based digital models. There are opportunities and challenges in integration of relevant multi-physics modeling and simulation, need for earlier high-fidelity models, and means to assess reduced-order models. In addition, there are needs for determining optimal risk/cost tradeoff for continual Verification, Validation and Accreditation (VV&A) or alternative means for assessing trust in model and simulation predictions.

As shown in Figure 11 [50], there can be a very large set of tools that can be used to develop the needed data and information across all of the domains. Therefore, it is important that appropriate methods are applied to the selected tools that are assembled for use on a project or program. As a secondary objective that is being demonstrated as leading edge approach by NASA/JPL is to ensure models are created that comply with established modeling patterns. We provide information at the second working session on the NASA/JPL approach, which transforms the model information into a tool-neutral SST based on ontologies, and then uses standard SWT to apply checks to ensure completeness and consistency [90].

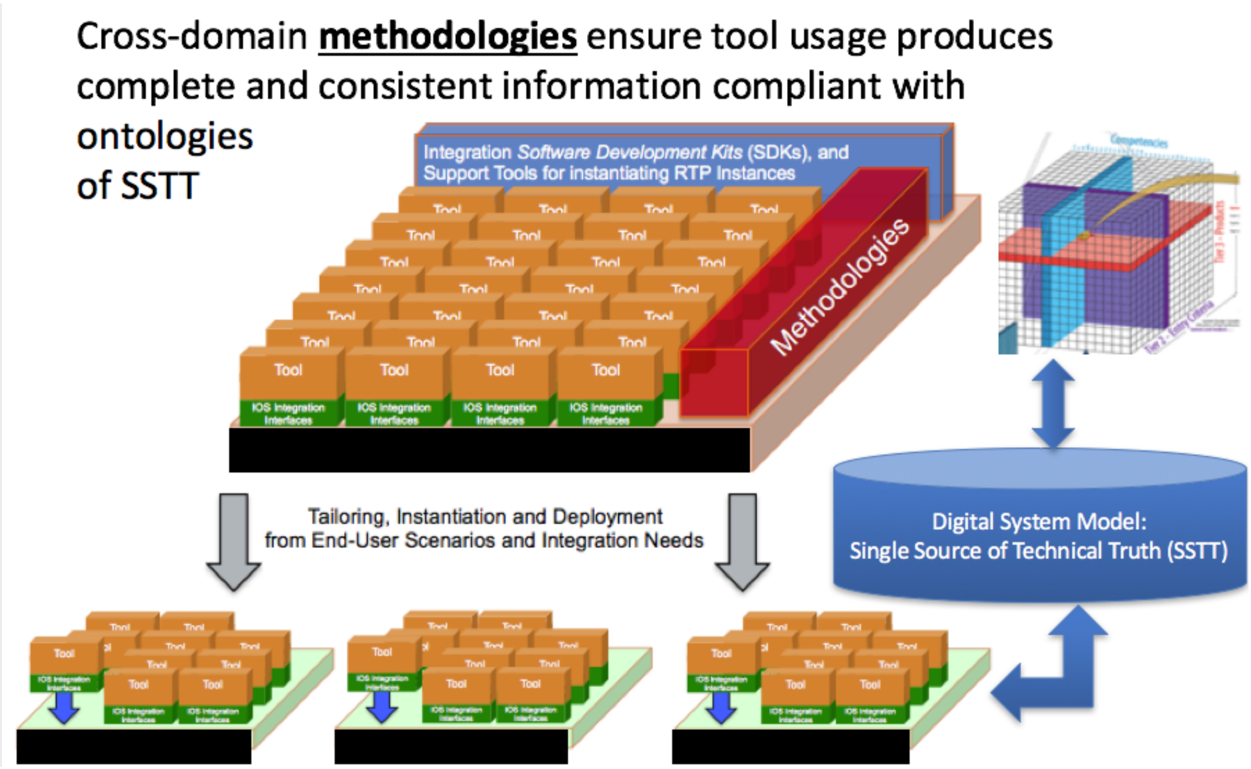


Figure 11. Appropriate Methods Needed Across Domains

3.3 UC00, UC07 AND UC10 (DECISION FRAMEWORK AND AAMODAT)

As shown in Figure 3, this task relates to UC07 and UC10. We have confirmed with Dr. Matt Cilli that we believe the information captured can be used to drive the Decision Support Model Construct [41] (referred to as Decision Framework) as shown in Figure 2. We believe that this concept and process has been demonstrated to provide senior management and program managers with visual representation of key tradeoff defined in terms of Performance, Cost, Time and Risk.

The key concept associated with the information model and the decision framework is to work with Matt Cilli, Cliff Marini (developer of AAMODAT) and Robin Dillion-Merrill on exploring potential enhancements and extensions to the Integrated Systems Engineering Decision Management (ISEDM) process and the related decision support tool AAMODAT. Some of the objectives for the new challenge area #5, focused on how to integrate cross domain models (SysML model, Engineering Models, Performance Models, Cost Models, etc.) with decision support model (AAMODAT) while executing ISEDM process. This is specifically where ARDEC requested us to demonstrate ability to create Domain Ontology via AAMODAT views, which is discussed in more detail in UC10 (see Section 13).

4 GRAPHICAL CONOPS (UC01)

There are nine different modeling and simulation examples that are being developed to support UAS and Counter UAS analysis case study. These different approaches involve different researchers, and look at the problems using different technologies, both in terms of types of abstractions, level of fidelity, no human-in-the-loop, and humans-in-the-loop, which also have an impact on trading off cost and value of the simulation. Each approach is described in the subsection below. Fundamentally, we are also interested in the information (metamodels, which map to OWL) and associated methods to produce and analyze this information in order to integrate with the other models in use cases UC01, UC02, UC03, UC04, and UC05.

4.1 UAV CONOPS USING GAMING ENGINE SIMULATION (JONES VIEW)

Engineered systems have advanced to the stage in which they share many properties with biological and sociological systems. Engineered systems can have systems embedded in them, and those subsystems can have subsystems embedded in the subsystems. This is reminiscent of the layered level of complexity in biology. Molecular processes form cells; cells form organs; organs form organisms; and organisms form societies. In some cases, engineered systems are a part of sociological systems. A city is a combination of a social system and many engineered systems, from traffic systems to the power grid.

Nature has solved many of the problems that systems engineers are struggling with. These problems include incompatibility of systems, multidisciplinary integration, incompatible time scales, systems of systems, and more. Can we examine the manner in which Nature solves many of these problems to inform the design and optimization of complex engineered systems? This use case addresses at least this question.

Biological and sociological systems are not designed in the traditional sense. The designs emerge from interaction with each other and with the system environment through a process of evolution and natural selection.

The goal of this research is to identify a general systems framework that can be used as a backend for Graphical CONOPS in support of MDAO as well as provide inputs to other types of modeling and simulation, such as both 2D and 3D approaches to mission and system simulation. Since Nature has solved many of the systems problems, the framework will be organically-based. The framework will be able to create models of a very large class of systems and systems-of-systems. As shown in

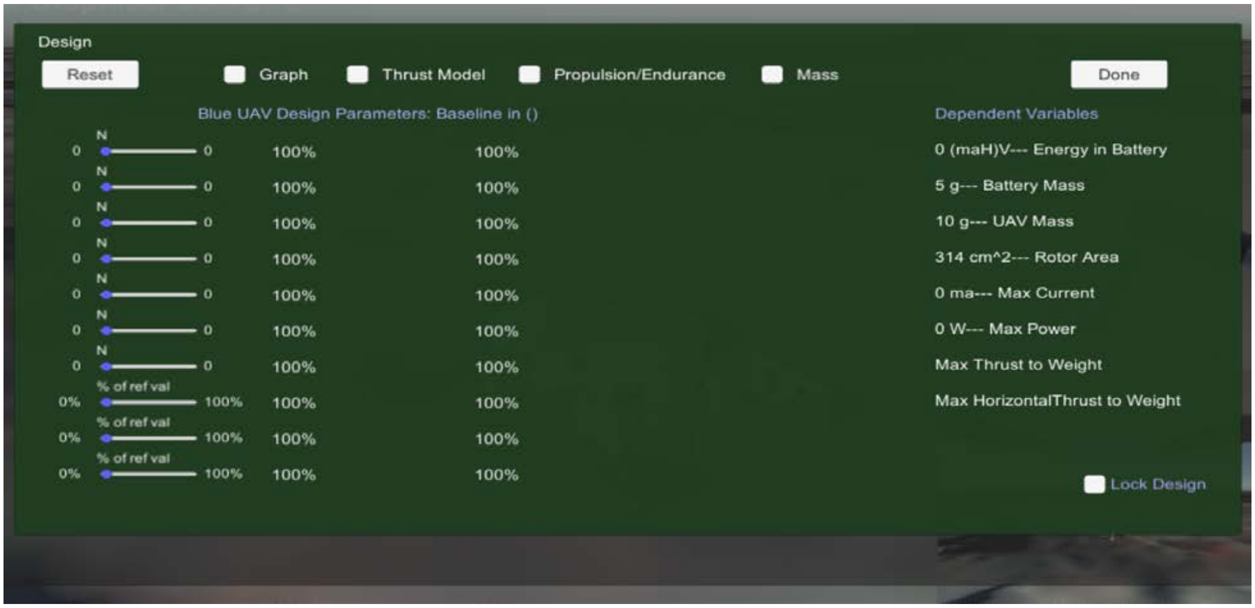
Figure 12, we have created an example that has demonstrated the use of this concept in an environment involving UAS mission scenarios using the Unity Gaming Engine; this will be the canonical example.

Roger Jones has demonstrated a Graphical CONOPS created using the Unity game engine that that provides Monte Carlo simulation feedback to MDAO. There are two possible surveillance missions for a blue quadcopter. In scenario one, the blue quadcopter searches for an object, and mission is unimpeded. In the second mission, a red quadcopter actively tries to prevent the blue copter from succeeding at its mission, as shown in Figure 12. Both quadcopers are fully autonomous. There are options to change different parameters related to the two UAVs in a dynamic manner. As shown in

Figure 13, there are also tabs that can be used to parametrically modify the capabilities of the two different UAVs.

- The latest version (1.09) provides to feature:
    - Communication with other software through JSON files
    - Plan to use MDAO is performed in Excel, which writes to JSON that is read by the Unity gaming engine
    - Has more realistic battery and flight models
    - Enhanced design interface that allows user to quickly explore design space around an optimum determined by static MDAO software
- The planned next steps include:
    - Complete analysis and optimization modules and integration with ModelCenter or other simulations through JSON files
    - Integrate a synchronized simulation with the output from the graphical CONOPS being published through the SWT and be consumed (subscribed) through the SWT by the 2D simulation
    - Demonstrate integrated simulation as part of the IoIF

Figure 12. Unity Gaming Engine Simulation of Two Moving UAV with Camera



Blue UAV Design Parameters: Baseline in ()

N 0 — 0 100% 100%
N 0 — 0 100% 100%
N 0 — 0 100% 100%
N 0 — 0 100% 100%
N 0 — 0 100% 100%
N 0 — 0 100% 100%
N 0 — 0 100% 100%
% of ref val 0% — 100% 100% 100%
% of ref val 0% — 100% 100% 100%
% of ref val 0% — 100% 100% 100%

Dependent Variables

0 (maH)V--- Energy in Battery
5 g--- Battery Mass
10 g--- UAV Mass
314 cm^2--- Rotor Area
0 ma--- Max Current
0 W--- Max Power
Max Thrust to Weight
Max HorizontalThrust to Weight

Figure 13. Unity Gaming Engineering Simulation MDAO

4.2 GRAPHICAL CONOPS (USC ICT – RICHMOND VIEW)

The USC Institute for Creative Technologies (ICT) will support this use case by investigating various aspects of Early Synthetic Prototyping (ESP) capability that has been developed for RDECOM-ARDEC. They too use the Unity gaming platform with other technologies that integrate and study humans-in-the-loop. The scope of work includes, but is not limited to:

- Visualization of tradespace and alternatives
- Graphical CONOPS improvements
- Assess collaboration opportunity with TRADOC's ESP
- Provide recommendations for Collaborative Design Infrastructure

The ESP project explores options to leverage emerging synthetic immersive environments to foster innovative design and testing as shown in Figure 14. ESP seeks to bring the Soldier (i.e. the end user) into the design and testing process during initial planning stages, helping to connect those that design/build (engineers) and those that employ (Soldiers). ESP also is being designed to enable testing of nascent concepts and explore not only the art of the possible for today, but also the innovations of tomorrow. The concepts of *early fidelity* and *minimum viable model* are critical for speed and agility and the ideation design and testing process. There are some videos available to illustrate more aspects of the ESP capabilities:

- https://vimeo.com/145230112
- https://vimeo.com/139283830
- https://vimeo.com/139283668

Figure 14. Early Synthetic Prototyping Video Example

The proliferation and maturation of tools supporting virtual environments combined with emerging immersive capabilities (e.g. Oculus Rift and other head mounted displays) point towards the ability to take nascent ideas and realize them in engaging ways through a virtual/synthetic prototyping system. In effect, “bend electrons before bending metal,” enabling Soldier (end-user) feedback early in the design process, while fostering an atmosphere of collaboration and innovation. Simulation has been used in a variety of ways for concept, design, and testing, but current methods do not put the user into the system in ways that provide deep feedback and enable a dialogue between Warfighter and Engineer (as well as other stakeholders) that can inform design, and more broadly, the entire acquisition process. The key is to fail early when it is cheap, rather than late in the process.

ESP is different from existing game/simulation engines. Current synthetic environments track fairly traditional metrics giving data largely as scores around easily quantifiable outcomes. At the core of ESP moves towards a new generation of metrics and analytics that focus on the wants and needs of the user, tracking not only their in-game performance – what they did – but also their inner motivations how and why they did things and how they feel at specific points in time during the interaction. In order to provide useful and untapped information back to a designer/engineer, ESP will need to assess a number of softer metrics such as user frustration. In addition, deeper granularity will be tracked as well as challenges such as: sources of frustration for stakeholders.

ESP is currently in the early prototype stage, and in fact, is creating ESP by using an evolving ESP conceptual model, understanding the requirements that enable creativity and innovation through virtual engagement. These exploratory environments are multi-player and are exploring the design of next-generation vehicles as well as their use in a variety of contexts.

Users can make modifications on-the-fly, and help find new ways to not only design and build, but also employ the systems. Play can enable emergent behaviors to arise and be tracked, teased out, and assessed. The broader ESP effort also includes research work at Naval Postgraduate School (NPS), collaboration with various Army Research Development and Engineering Center (RDECs), and other Army partners. The initial prototypes are undergoing iteration and testing and will inform the ESP design and requirements, as well as facilitate ongoing research into four vectors: analytics, idea ingest, emerging interfaces, and community.

The vision for ESP is an integrated ecosystem where community stakeholders may propose, develop, test, discuss and refine ideas, capabilities, and concepts of operation within a virtual prototyping environment. These can connect to ideation platforms (on the left), and to higher fidelity modeling and simulation (on the right).

Edgar Evangelista showed a video at the third working session on the work they were doing at USC-ICT, bringing soldiers early in the design. They are developing army games to deploy with soldiers in a multi-player environment. The key point is getting early prototype systems into the hands of the soldiers. The virtual world allows soldiers to play around with new concepts that we don’t want to build in the physical world.

4.2.1 TRADESPACE FOR EARLY SYNTHETIC PROTOTYPING (ESP)

Previous Army Capabilities Integration Center (ARCIC)-funded efforts resulted in a series of prototype applications centered around the concept of Early Synthetic Prototyping. ICT created multi-player game (Unity3D engine) with a red vs. blue “capture the flag” game mechanic. The environment allowed players to choose and modify vehicles, and a wide variety of data was captured during play, including biometrics (https://vimeo.com/135100689). In order to visualize the data, a Post Exercise Analysis (PEA) application was developed that ingested game logs and provided interactive replay and analysis (https://vimeo.com/139283668). The results of these prototype applications led to current work by Army Game Studio (AGS) to develop the next iterations of ESP.

ICT has been working to identify and analyze the gameplay data from ESP systems. ICT is currently working with the AGS to collect player gameplay for the ESP system. There are tradeoffs between different data storage formats, as well as effort needed to translate between formats for post-game analysis. ICT’s current research has led them to store all the data of the ESP multiplayer system so that they may analyze the data post-game. They currently allow for replay of the system. However, they do need to investigate how to organize the data to direct it toward experiment objectives. Currently, they are relying on AGS’s Operation Overmatch to bring in enough participants and gameplay recordings, so that they can help researchers develop and run experiments on the efficacy of certain systems. ICT has been working with AGS to identify methods of storing thorough gameplay data for analysis.

There are differences between the AGS’s data storage format and ICT’s data storage format which poses certain translation issues as well as introducing interesting tradeoffs. Currently, AGS’s data storage format relies on a fixed logging rate with an implicit format versus ICT’s variable log rate with an explicit format. Their fixed logging rate stores the position of each unit every timestep, while not actually recording the timestamp. The timestamp is implicit. This also implies that AGS will store events within the order they occur. The data format designer is required to be consistent in implying event (e.g., firing, damage) ownership of the particular unit so that certain events can be tracked and replicated. This requires thorough documentation for other parties to ingest the data. Further, in the case that a unit stays still, this adds redundant data for its position since it is stored every timestep. This method is sound as long as other developers who'd like to use the data are well informed of the implied data.

Conversely, ICT's PEA data format uses timestamps for variable log rates and explicitly states event ownership and damage states. Although this requires documentation as well, the explicit data format does make it easier to ingest initially. However, it does have a slightly larger memory footprint. Variable log rates also cover frame skipping issues, in which the simulation computer may not be able to log the status of a certain frame. However, an issue with variable log rates also requires certain playback to account for the variability. If certain physics events, like projectiles, are to be replicated, they need to check the timestamp and interpolate the position.

Both methods are found to be sufficient in storing requisite event and status data for gameplay replication. Either method requires analyzers to develop translation middleware to fit the data format into their analysis software. AGS has also developed an easy way to deliver gameplay results to analyzers. They have set up a protected website that allows analyzers to download batches of gameplay. This gives ICT, as well as other partners, easy access to the results at any time.

ICT has found that there are other data format considerations dependent on the type of gameplay being recorded. They are also tasked with developing design considerations for ESP: Higher Echelon (ESP:HE). ESP:HE is a turn-based strategy game aimed at educating captains on troop movement, capabilities, and other facets of directing larger units in battle. Because this is a turn-based game and not a first-person game, ICT is more concerned with recording events, rather than states at each timestep.

Further, not only should ICT be concerned in storing diegetic gameplay events, as they do in ESP: Small Unit and Operation Overmatch, they must also be concerned with storing non-diegetic gameplay events. ESP:HE is a much more complex strategy game with a more diverse set of units and commands. Therefore, the interface is also more complex in presenting users with numerous capabilities in leading their command. This requires a more substantial training period for users as well as introduces usability issues with the interface. Storing certain non-diegetic gameplay events, such as time spent on a dialogue window to time spent between unit actions, can provide insight on player motivation and player issues. We can infer that if a player spends a lot of time going through certain dialogues without committing to an action that the player is either collecting various information before acting or is struggling with the interface. It is possible that the success of that action may help to distinguish this.

One of the main objectives of ESP is to analyze gameplay to answer research questions regarding military systems, equipment, and tactics. ICT must identify key data points that are pertinent to certain stakeholders, while also identifying issues that might allow for misinterpretations. For example, they might want to identify weapon effectiveness in certain scenarios, so they can capture the percentage of hits and misses a weapon generates in gameplay. This would give us the accuracy of the weapon. However, it is important to identify if accuracy stems from user control, modeling error, or the weapon's given ability. This may require further research to receive more accurate analysis.

Further, game designers may develop game mechanics that may incentivize players to play towards creating gameplay data that pushes the research question. For example, selecting to use certain weapons can be rewarded. However, certain game mechanic modifications can change player motivation and, in turn, change the accuracy of the data. So, versions of games as well as game types must be stored with the data.

4.2.2 BIOMETRICS DURING GAMEPLAY

ICT has also been researching methods for collecting biometric data that is concurrent with the subjects' gameplay. One issue that arises is an inconsistent synchronization of the biometric data with gameplay, especially considering the various peripherals which produce different signals. Latency arises since they run multiple hardware peripherals from different manufacturers with different software. Synchronizing the timesteps of the signals is not always possible due to third party code and different temporal formats. Further, there can be a latency associated with the signal causing certain effects associated with a particular event. This may require error tolerance and/or calibration built for custom synchronization.

ICT has investigated Lab Streaming Layer (LSL) which allows them to synchronize streaming data from various sensors with custom Unity Engine simulations. LSL allows them to synchronize multiple data and time marker sources. It also accounts for network and transmission latency. Although LSL allows for (near) real-time data access, they also rely on post-game analysis to synchronize the signals.

Furthermore, there may be an issue of signal trustworthiness wherein the ground truth may not be represented. The player may not be a reliable subject. Although they may not be able to directly monitor each player, they may be able to use audio and gameplay recordings to find a baseline to determine that the player is actively participating.

4.2.3 DISTRIBUTED INTERACTIVE SIMULATION INTERFACE WITH GRAPHICAL CONOPS

ICT is also collaborating with ARDEC to provide a Graphical CONOPs in the Unity Engine application with a Distributed Interactive Simulation (DIS) [84] interface to explore federation of large-scale simulation (OneSAF). The task involves translating OneSAF DIS packets into the creation of a BLUFOR (i.e., blue force) and OPFOR (i.e., opposing force) entities into a given environment. A BLUFOR player will interact with ARDEC's Gunner Protection Kit and ARDEC's Virtual Testbed, which ICT will ingest into their visualization, so the player can interact with the OneSAF entities. This research is interested in the ability to ingest input from other simulations to drive our visualization and ICT will document the development of this interface as well as the networking protocol. The IoIF capability may provide a new approach to accomplish this need.

4.2.4 MIXED REALITY PROTOTYPING/COLLABORATIVE DESIGN

ICT, particularly the Mixed Reality Lab (MxR), continues to work broadly within a construct known as Mixed Reality Prototyping (MxRP). This approach leverages the combination of virtual environments, immersive hardware and software (i.e., Augmented Reality, Virtual Reality), and machine learning to enable design and user testing to happen first in synthetic environments, then in mixed reality spaces (including real-time synchronization between virtual and physical, as well as collaboration with distributed teams - https://www.youtube.com/watch?v=D0WhSW0phx4). As training and operations increasingly merge, due largely to the increase in virtualized operations, the ability to design, prototype, test, iterate, and deploy in mixed reality will become increasingly important. This has significant overlap with the needs and desires for MBSE, and as such, that synergy can hopefully be amplified moving forward.

4.2.5 DATA STRUCTURES AND REASONING

From the overall integration of graphical CONOPS to the other modeling and simulation environments, we need more information about the underlying data and information that is captured. Given that this was the first iteration of ESP design, ICT went through a series of rapid prototypes to tease out both conceptual framework as well as concrete issues that arise during the design of the ESP system. Inevitably that types and amount of data tracked is a tradeoff based on inherent capabilities of the game engine, performance, and particular the ability to track user actions.

In particular ICT was interested in trying to understand user intent within the game. ICT firmly believes that current game metrics are inadequate to assess why a user takes certain actions within the game/simulation. This data and knowledge is less critical for entertainment experiences, but is critical when considering that ESP is focused on innovation and understanding a wide variety of issues around design and implementation. As such ICT spent time experimenting with various biometric markers and sensors in addition to more tradition game metrics. It is clear that true “next generation” game analysis will be some combination of in-game data aggregation, manipulation and visualization, along with a robust “user model” where each individual user is tracked for not only a history of their in-game actions but also they emotional and mental state.

It is important to remember that these initial ESP prototypes are just that – prototypes to explore the problem space and understand how ESP can actually be done effectively. In future versions of this report additional detail on the data will be included.

4.2.6 METADATA AND METAMODEL FOR GRAPHICAL CONOPS

We received information about the underlying metamodel of the information that can be captured, regardless of the domain, and the methods that would be used to ensure that information is fully captured. We hope this information would be mapped to the Information

Model (UC00) and be provided as input to UC02. In addition, we are interested in how the parameters of simulation entities can be used in MDAO (UC03).

- ICT will try to help Stevens classify any data and analysis captured from ESP so it can be sent to an Information Model to inform decisions. It might be possible for ICT to also help inform how our data and analysis could best be visualized to inform other parties.
- USC began working with Tobii Eye tracker and found how to capture eye tracking data to coincide with gameplay from CounterStrike.
- USC began talking with Army Game Studio (AGS) to design both data schemas and data capture/retrieval from AGS's Operation Overmatch (ESP) for future analysis.
- USC began working with ARDEC on Game Engine integration with OneSAF.

This is ongoing research, but the following provides a list of some lessons learned and tradeoffs:

- Memory (and human Readability)
    - We chose to prioritize minimizing memory over time
        - We only recorded continuous parameters when the delta between the last recorded value and the current value exceeded some threshold – fewer data points if a player/entity was sitting still but added complexity for parsing/playing back the data.
    - We could have made other choices, but given that this protocol was intended for transmission over the network, we maintain that a light, memory-optimized protocol was the right choice
- Design time vs. Post-processing
    - We chose to save low-level data (position, orientation, field of view) with an eye towards building higher-level features by post-processing.
        - For example visibility – “entity 0x123 has entity 0x234 in its field of view at t+11.2 sec” – we could compute this by playing back the log data and adding additional events to the event stream
    - Post-processing is still pending do to other priorities
    - We were looking for information about the level, i.e., “this area is cover,” “this area is a corner” – two potential ways to get this:
        - Post-process how players use the level
        - At design time, program-in literal “this area is cover” etc. data.
- Format
    - ICT chose to use JSON [93] because it is pretty succinct in comparison to something like XML (which has verbose closing tags, etc.)
    - Organizing events by logging information about entities (ID, array of timestamped events, event references)

ICE is working to define a taxonomy of the data for a post exercise analysis using JSON. This will be important to characterize the information model associated with graphical CONOPS.

4.3 UNITY COMPARISON

While both of the CONOPS scenario that use the Unity gaming engineer, the concept described in 4.1 is an experiment on simulating drones being used for surveillance as well as drones being used as a counter-UAS. This allows a user to play around with drone characteristics to see how it changes their efficacy, even as the drone movement is automated.

The ICT experiments with the ESP hover pallet vision piece investigate the pallet as a viable option to transport material across short distances while bypassing any local dangers and obstacles quickly. This only allow different choice of route, however the ICT pallet movements are controlled by the user, as well as its weapon systems.

The drone automation (Section 4.1) allows for a more controlled analysis, and we would further like to integrate with Simulink-based control from UC05. The drone automation system does allow the user to experiment with different properties of the drones by allowing the adjustment of Length, Width, Height, Drag, Mass, Propulsion, and battery size. The ESP Multiplayer and Vehicle Tuning Demo also allowed the user to change similar properties such as Engine Torque, Max RPM, Leg Length, Leg Rotation, Battery Size. The ESP exposed common vehicle properties, but also purposefully exposed certain properties that highlighted specialties of each vehicle (i.e. Spider tank could be armored, yet crippled spatial awareness), so that we could encourage more experimentation and emergent gameplay that could arise.

These approach are different and illustrate why the same underlying platform can support different types of analysis. The drone automation system currently relies on small quick single player scenes/experiments where they try to focus on developing UAS capabilities in incremental iterative steps. It was developed rather quickly, and has been incrementally evolved. In contrast, the ESP development process does have incremental iterative steps, but allows for more emergent and immersive gameplay in our multiplayer setup that not only tests capabilities, but also techniques using the equipment. This makes the ESP more approachable for the end user, such as the soldiers.

The next two approaches discussed in Sections 4.4 and 4.5 are also very different, yet very complementary to the Unity-based approaches.

4.4 SIMULATION TECHNOLOGIES FOR GRAPHICAL CONOPS (GROGAN VIEW)

Graphical CONOPs engages stakeholders in an interactive, immersive environment to develop a CONOPS [47] [97] [115]. It aims to improve communication between users and developers by providing a common platform on which to express issues, similar to the concept of a single text in negotiation [140].

Another element of this research is investigating the use of standard simulation technologies for graphical CONOPS. Standards are crucial to enable interoperability and data exchange across model boundaries. The two most common standards for distributed simulation are IEEE Std. 1278 Distributed Interactive Simulation (DIS) [84] and IEEE Std. 1516 High Level Architecture (HLA) [85]. DIS defines common data structures (protocol data units, PDUs) which are exchanged between simulation members in real time. HLA defines a common application programming interface (API) to a runtime infrastructure (RTI) which manages data exchange and time synchronization among simulation federates. Other related standards include IEEE Std. 1730 Distributed Simulation Engineering and Execution Process (DSEEP) [86], SISO Std. 001 Real-time Platform Reference Federation Object Model (RPR FOM) [160], SISO Std. 007 Military Scenario Definition Language (MSDL) [161], and SISO Std. 011 Coalition Battle Management Language (C-BML) [162].

In contrast to other combat modeling activities and broader military operations research (the typical application of the above standards), graphical CONOPS directly supports system design activities and, as such, does not incorporate as much detail. Instead, it seeks to identify fundamental characteristics of the target problem. The outcome of a graphical CONOPS activity produces a set of scenario parameters to describe the environment in which a system will be used. In addition, we investigate a potential interface between a SysML model and an integrated mission model.

To support this research another capability has been created and demonstrated. This is a simple scenario with UAV, Counter-UAV as a two-dimensional model of a two UASs, one “friend” and the other “foe,” with emphasis on distributed simulation using HLA to synchronize model state across simulators using internal interface within the mission model.

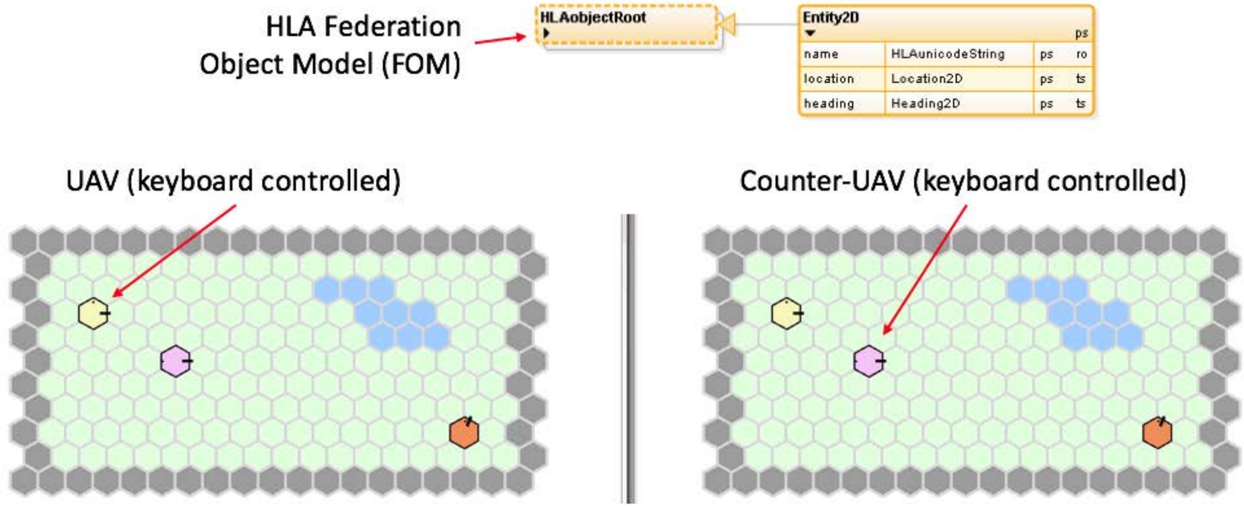


Figure 15. Mission Model using High Level Architecture (HLA) to Enable Distributed Simulation

4.5 MISSION MODELING USING HIGH FIDELITY SIMULATION VT MAK (ROGER BLAKE)

We have also secured an academic license for the VT MAK / VR-Forces tool as a high-end alternative to the two-dimensional simulation discussed in Section 4.4. VR-Forces is a high fidelity simulation environment that implements Computer Generated Forces (CGF) and a Simulator Development Environment using a HLA framework. VR-Forces contains a multitude of federate models that can be used to create interactive simulation environments to analyze various situations and behaviors of desired scenarios. We have decided to use VR-Forces as a tool in our research in order to show the effects of our research and implementations. Since each VR-Forces federate model can be communicated with using a Lua [101] scripting language, we can change model parameters flexibly. The idea is that as the design tools change value, we can theoretically enter the new design parameter values into the simulation models to observe the new behaviors within the high fidelity simulation scenario. This again provides another way to use MDAO to consider different optimization (see Section 6).

We developed a demonstration for a simple UAV simulation. This is being expanded into a counter UAV mission. The scenario that we demonstrated was one which included a UAV that was scanning various entities that it encountered as shown below in

Figure 16. As we continue to build this scenario, we plan to include counter measures to the UAV like a Surface-to-Air Missile System also shown below. As the UAV flies to, and around its targets, nearby Surface-to-Air Missile Systems will fire on the UAV if the UAV flies into their kill zones as demonstrated by the green RADAR beams that illustrate the area of coverage in the Surface-to-Air Missile System shown below in Figure 17 and Figure 18.

Figure 16. UAV Scanning Targets

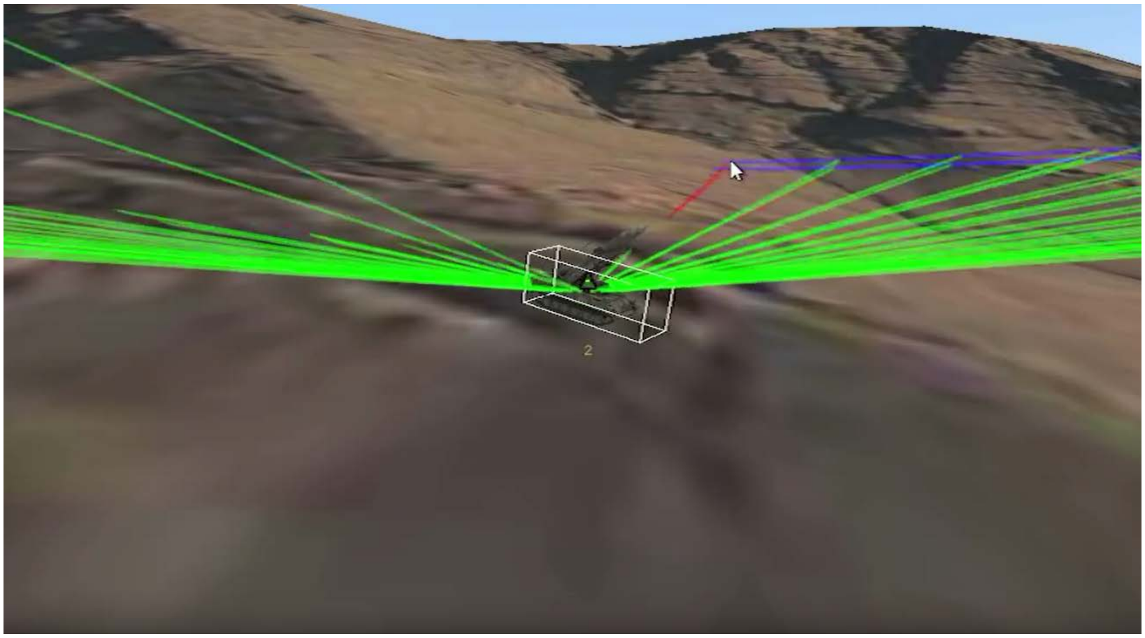


Figure 17. Surface-to-Air Missile System

By furthering this research, we hope to be able to use a publish/subscribe system that is implemented in the IoIF that utilizes tool proxies to aggregate design tool data which can be routed to the recipient design tool though the implementation of an ontology layer, as discussed in Section 12.8. By doing this, we hope to be able to facilitate the transfer of design tool parameter data though this network by using the SWT layer as the control point that decides where design parameter data is needed. We can then link the design parameter data into the federate model in our simulation to be able to observe the new model behavior in the simulation environment based on the new design tool parameter changes.

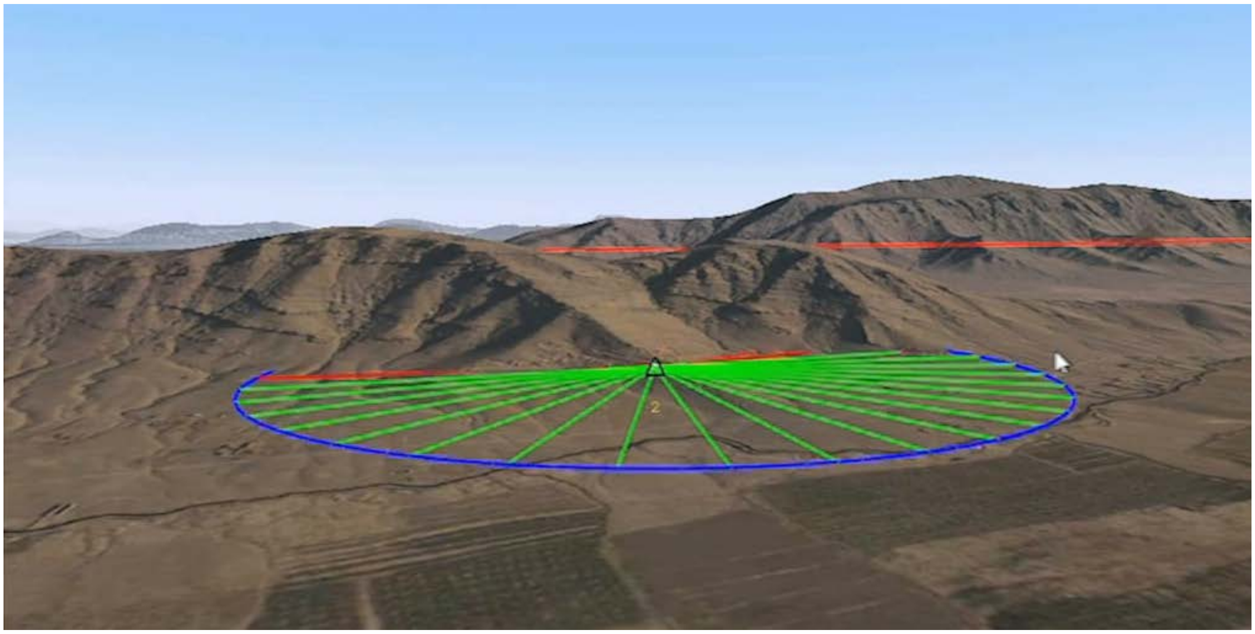


Figure 18. Surface-to-Air Missile System Area of Coverage

5 MISSION AND SYSTEM CAPABILITY ANALYSIS (UC02)

A mission model is a dynamic simulation model which evaluates the application of a system in the context of a scenario. It simulates the system operation to integrate and compute key performance metrics (KPMs) and assess system value over operational timescales. A mission model may either be controlled manually or executed autonomously provided adequate behavior scripting. The system model evaluates static functional capabilities for a particular system design. A system model evaluates and optimizes functional capabilities for a set of objectives and constraints.

This section extends the research discussed in Section 4 to investigate automatic transformation and exchange of data between the mission model, graphical CONOPS, and system model. As reflected in Figure 19, inputs to the mission model include scenario parameters and system functional capabilities. KPMs output by the mission model can be used to revise and alter scenario definitions and system designs as needed.

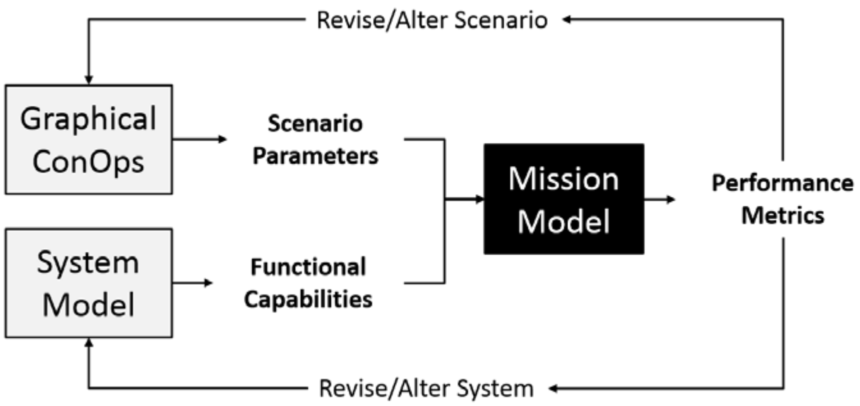


Figure 19. Scenario parameters and functional capabilities are inputs to a mission model which computes performance metrics.

This project uses an application use case scenario to study the MCE approach described above. This notional case is purposefully simplified to allow rapid modeling without proprietary or sensitive details, as discussed in Section 4.4. The use case scenario considers the conflicting operations between a UAV and a counter-UAV system. Both platforms exist in space and are equipped with sensors and engagement devices.

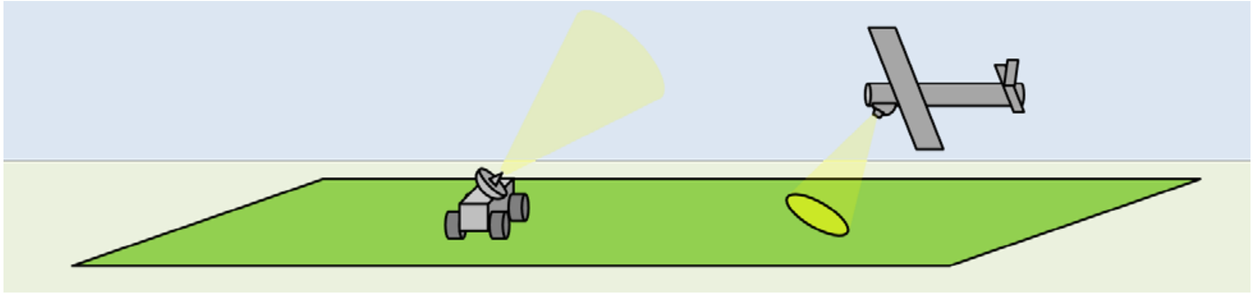
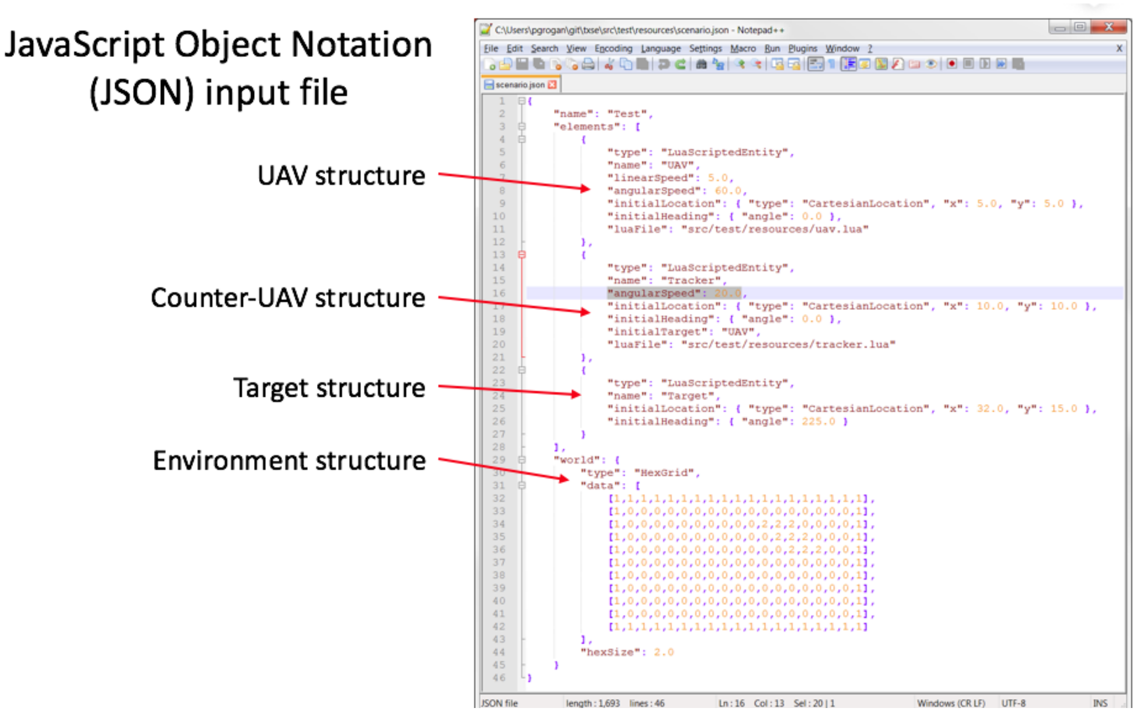


Figure 20. UAV and Counter-UAV systems participate in the scenario.

Initial work has focused on development of a simplified mission model for the UAV/Counter-UAV scenario described above. The mission model is a Java executable which imports scenario and system information from external interfaces. Context parameters defining the spatial region are loaded from JSON file. System parameters defining the functional capabilities (max speed, etc.) are also loaded from JSON file and system behaviors can be expressed Lua scripts conforming to an internal API.

5.1 MISSION MODEL MAPPING TO SYSTEM MODEL

Paul Grogan investigated creating a representation in SysML and mapping the parameters from the simulation into SysML. We use the mission model and can extract out data about individual system elements, as well as environmental information. An example of the structural aspect of the model is shown Figure 21. Notionally, there is a logical mapping from the JSON to the SysML model structure shown in Figure 22.



```
{
    "name": "Test",
    "elements": [
        {
            "type": "LuaScriptedEntity",
            "name": "UAV",
            "linearSpeed": 5.0,
            "angularSpeed": 60.0,
            "initialLocation": { "type": "CartesianLocation", "x": 5.0, "y": 5.0 },
            "initialHeading": { "angle": 0.0 },
            "luaFile": "src/test/resources/uav.lua"
        },
        {
            "type": "LuaScriptedEntity",
            "name": "Tracker",
            "angularSpeed": 20.0,
            "initialLocation": { "type": "CartesianLocation", "x": 10.0, "y": 10.0 },
            "initialHeading": { "angle": 0.0 },
            "initialTarget": "UAV",
            "luaFile": "src/test/resources/tracker.lua"
        },
        {
            "type": "LuaScriptedEntity",
            "name": "Target",
            "initialLocation": { "type": "CartesianLocation", "x": 32.0, "y": 15.0 },
            "initialHeading": { "angle": 225.0 }
        }
    ],
    "world": {
        "type": "HexGrid",
        "data": [
            [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1],
            [1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1],
            [1,0,0,0,0,0,0,0,0,0,0,2,2,2,0,0,0,0,1],
            [1,0,0,0,0,0,0,0,0,0,0,0,2,2,2,0,0,0,1],
            [1,0,0,0,0,0,0,0,0,0,0,0,0,2,2,2,0,0,1],
            [1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1],
            [1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1],
            [1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1],
            [1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1],
            [1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1],
            [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1]
        ],
        "hexSize": 2.0
    }
}
```

Figure 21. Mission Model – Structure

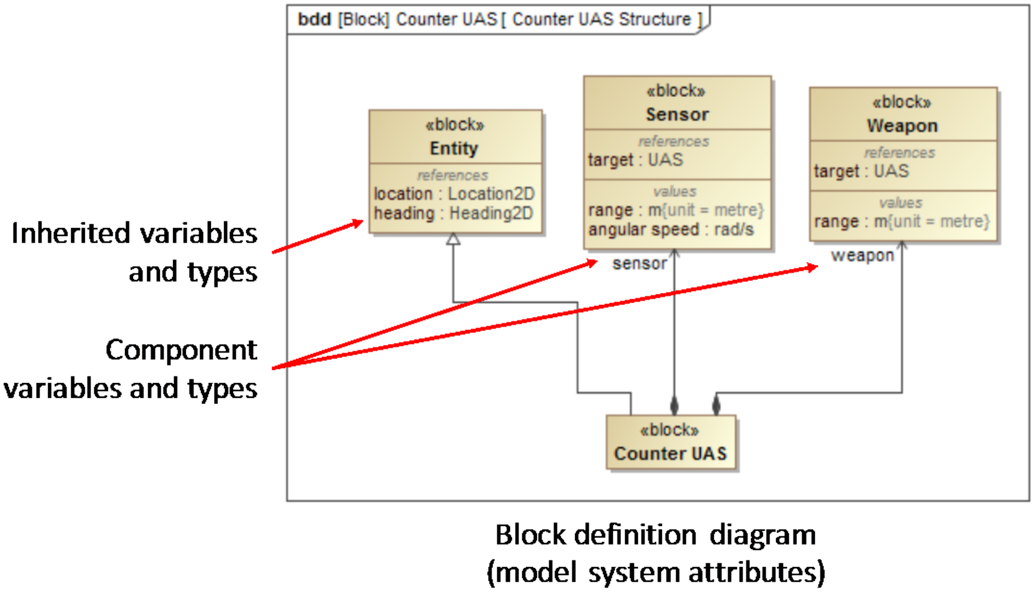
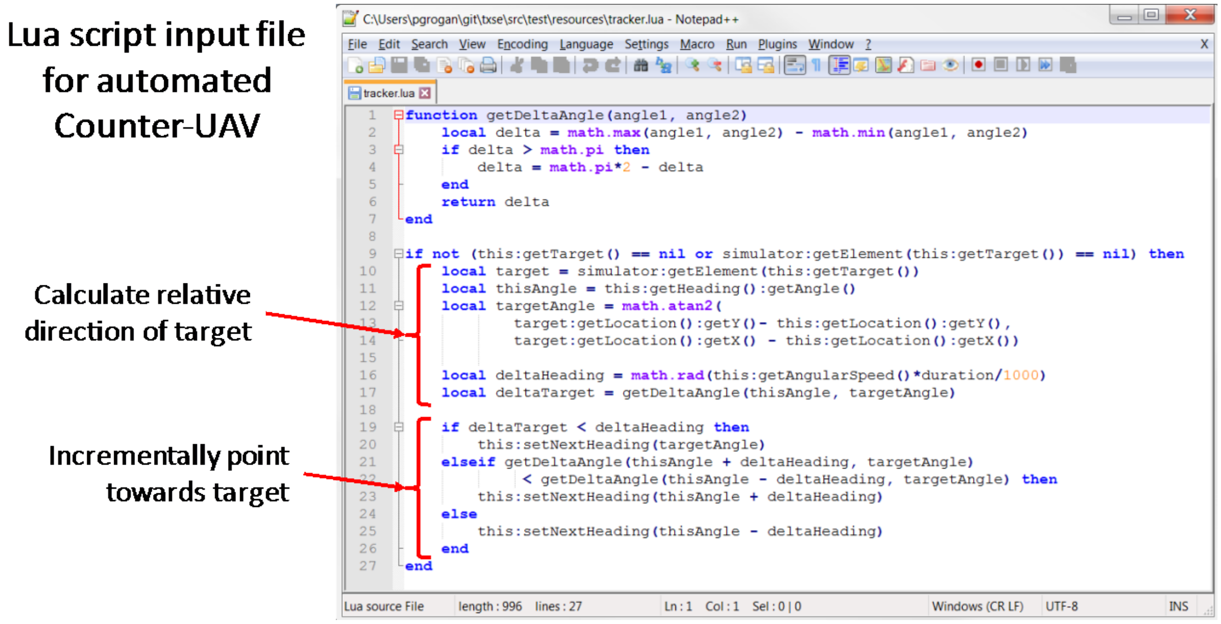


Figure 22. SysML Model – Structure

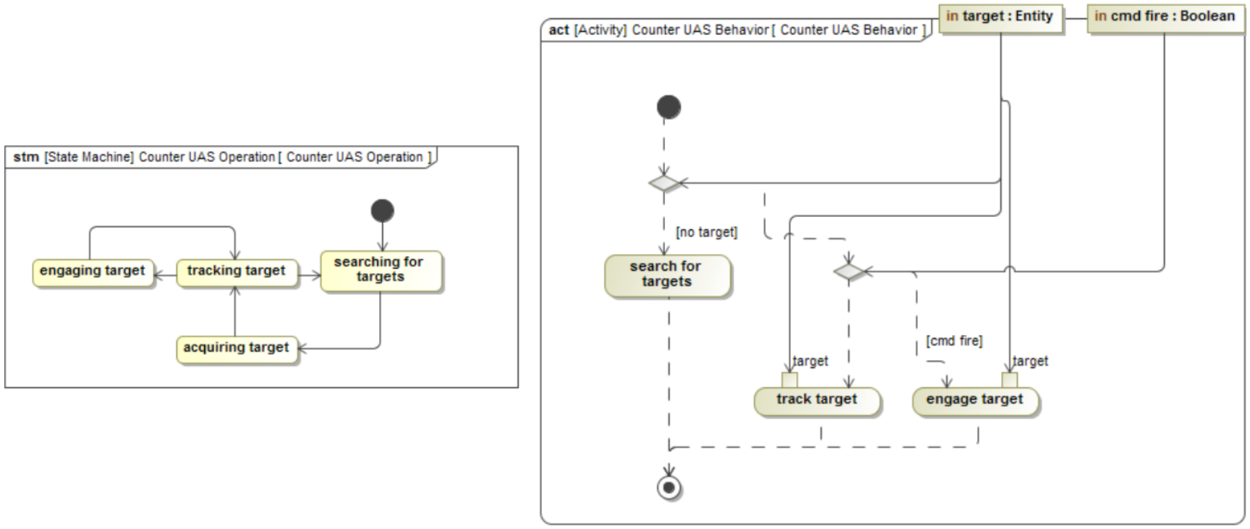
Representing behavioral information in mission modeling can be done with Lua [101] scripts as shown in Figure 23. Lua is a lightweight, embeddable scripting language (e.g., in Java). It supports procedural programming, object-oriented programming, functional programming, data-driven programming, and data description.



```lua
function getDeltaAngle(angle1, angle2)
    local delta = math.max(angle1, angle2) - math.min(angle1, angle2)
    if delta > math.pi then
        delta = math.pi*2 - delta
    end
    return delta
end

if not (this:getTarget() == nil or simulator:getElement(this:getTarget()) == nil) then
    local target = simulator:getElement(this:getTarget())
    local thisAngle = this:getHeading():getAngle()
    local targetAngle = math.atan2(
            target:getLocation():getY()- this:getLocation():getY(),
            target:getLocation():getX() - this:getLocation():getX())

    local deltaHeading = math.rad(this:getAngularSpeed()*duration/1000)
    local deltaTarget = getDeltaAngle(thisAngle, targetAngle)

    if deltaTarget < deltaHeading then
        this:setNextHeading(targetAngle)
    elseif getDeltaAngle(thisAngle + deltaHeading, targetAngle)
             < getDeltaAngle(thisAngle - deltaHeading, targetAngle) then
        this:setNextHeading(thisAngle + deltaHeading)
    else
        this:setNextHeading(thisAngle - deltaHeading)
    end
end
```

Figure 23. Mission Model of Behavior

In SysML behaviors can be represented in state machine (stm) or activity (act) diagrams as shown in Figure 24. SysML behaviors can also be represented in sequence diagrams (not shown here). While these are intuitive abstractions, the diagrams cannot easily be transformed to scripted code (e.g. Lua script), because they are usually more abstract to facilitate documentation; this could notionally double the effort to implement and completely document the models.



State machine diagram (model system states)

Activity diagram (model system actions)

Figure 24. SysML Models of Behavior

The following lists some of the challenges with the integration to SysML:

- Lack of “acceptable” representations and transformation using SysML; we are planning to investigate this more deeply in UC04
- Graphical diagrams specified at multiple abstractions
- Oriented towards concrete design
- Likely to be missing relevant mission/scenario parameters
- XMI is difficult to ‘query’ for structural parameters
- Low-level with extensive unique IDs difficult to interpret/parse
- Behavioral diagrams cannot easily be transformed to scripted code (e.g. Lua script)

These finding are different from those of the Challenge Area #1 effort, but yet with similarities. The overarching challenge is the difficulty of tool-to-tool integration. This is again the reason for our belief that we will need to use interoperability using the underlying information model (Challenge Area #3).

5.2 USING SEMANTIC WEB TECHNOLOGY FOR MISSION MODELING AND SIMULATION

In support of UC00, this use case is being extended to research the use of centralized shared information using the IoIF and specifically the use of SWT by:

- Populating the system model represented in the SWT using sensor data from other simulations
- Query the system model (i.e., SWT, SPARQL) to retrieve specified design attributes (e.g. retrieve system attributes as inputs to the mission analysis)
- Store analysis results for later use by other modules (e.g. store mission analysis results for use in downstream decision support modules)

The current research extends the 2D modeling and simulation environments for distributed simulations to integrate through the components of the IoIF as shown in Figure 4. As discussed in Section 4.1, we demonstrated this concept for our sponsors using the IoIF SWT. As shown in Figure 26, we created a simplified version of a use case to demonstrate data exchange, which demonstrates a subset of the functionality of the IoIF:

- UAV model: output system performance attributes
- C-UAV model: output system performance attributes
- Mission model: evaluate system performance in context of simulated mission

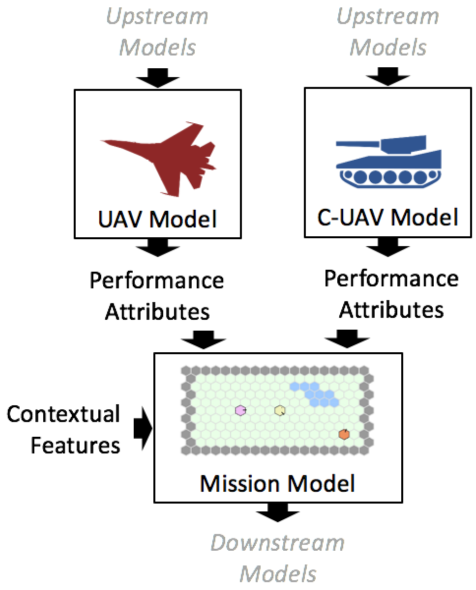


Figure 25. UC01-UC03 Prototype Application Case

We created a simple ontology, not for the purpose of illustrating how to develop a "proper ontology," but more as the basis for showing examples of using SWT for interoperability using the IoIF. The small ontology describes class of shared information using OWL, object properties, and data properties, as shown in Figure 26. The model instances corresponding to the red and blue systems are produced in RDF, and then added to a triple store. SPARQL queries retrieve and update values to create a dynamic interaction through the Data Acquisition and Aggregation layer (DAA) in conjunction with the SWT as shown in Figure 27.

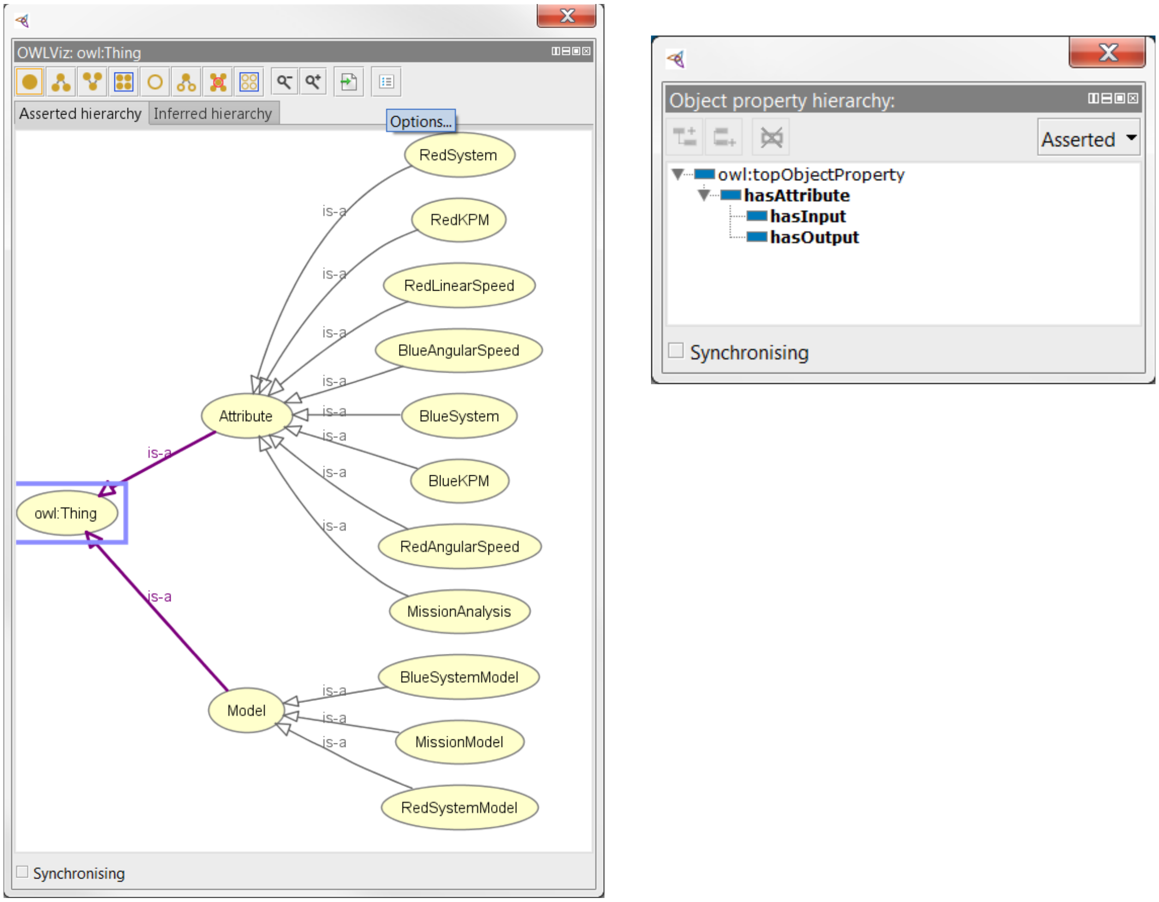


Figure 26. Simple Ontology for Experiment of Simulation Integration the SWT

Some examples of the underlying details of the information described in the ontology are shown below in the Terse RDF Triple Language (Turtle). The Subject-Predicate-Object triples are easier to read in Turtle than the underlying XML. For example ":Attribute is a rdf:type of the owl Class." In general, most user of this type of underlying technology never see this level of detail, and we refer interested readers to other sources [182].

```
:Attribute rdf:type owl:Class ;
           rdfs:subClassOf [ rdf:type owl:Restriction ;
                             owl:onProperty :hasUnits ;
                             owl:someValuesFrom xsd:string
                           ] ,
                           [ rdf:type owl:Restriction ;
                             owl:onProperty :hasValue ;
                             owl:someValuesFrom xsd:double
                           ] .
:hasUnits rdf:type owl:DatatypeProperty ;
          rdfs:subPropertyOf owl:topDataProperty ;
          rdf:type owl:FunctionalProperty ;
          rdfs:domain :Attribute ;
          rdfs:range xsd:string .
:hasValue rdf:type owl:DatatypeProperty ;
          rdfs:subPropertyOf owl:topDataProperty ;
          rdf:type owl:FunctionalProperty ;
```

```
                rdfs:domain :Attribute ;
                rdfs:range xsd:double .

        :UAV rdf:type owl:Class ;
             rdfs:subClassOf [ rdf:type owl:Restriction ;
                               owl:onProperty :hasMaxSpeed ;
                               owl:qualifiedCardinality "1"^^xsd:nonNegativeInteger ;
                               owl:onClass :MaxSpeed
                             ] ,
                             [ rdf:type owl:Restriction ;
                               owl:onProperty :hasTurnRate ;
                               owl:qualifiedCardinality "1"^^xsd:nonNegativeInteger ;
                               owl:onClass :TurnRate
                             ] .
        :MaxSpeed rdf:type owl:Class ;
                  rdfs:subClassOf :Attribute .
        :TurnRate rdf:type owl:Class ;
                  rdfs:subClassOf :Attribute .
        :hasMaxSpeed rdf:type owl:ObjectProperty ;
                     rdfs:subPropertyOf :hasLinearSpeed ;
                     rdf:type owl:FunctionalProperty ;
                     rdfs:range :MaxSpeed .
        :hasTurnRate rdf:type owl:ObjectProperty ;
                     rdfs:subPropertyOf :hasAngularSpeed ;
                     rdf:type owl:FunctionalProperty ;
                     rdfs:range :TurnRate .
```

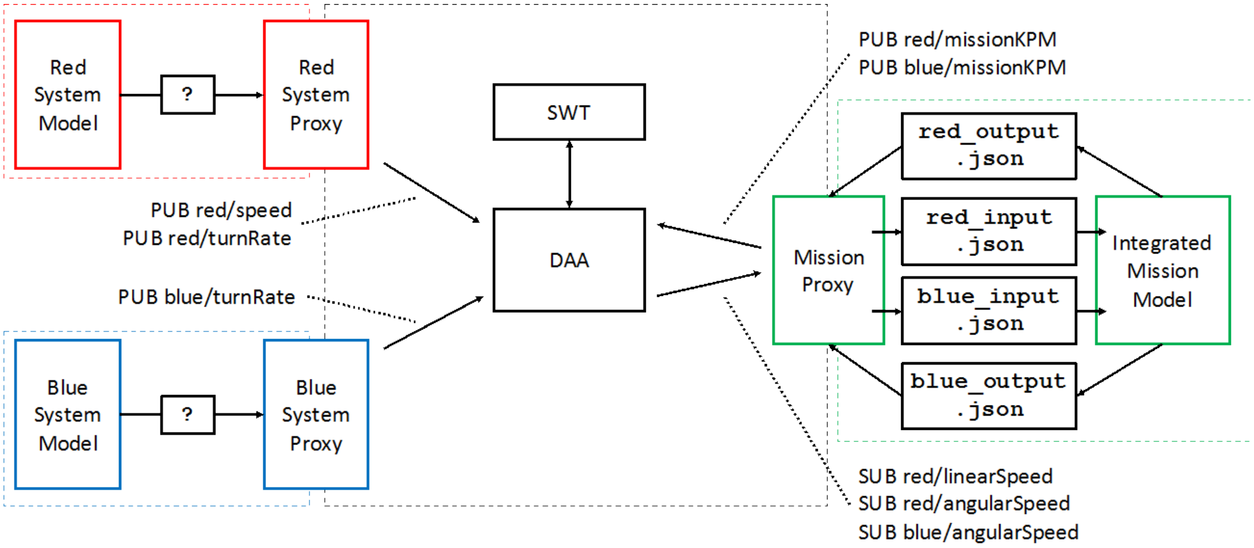
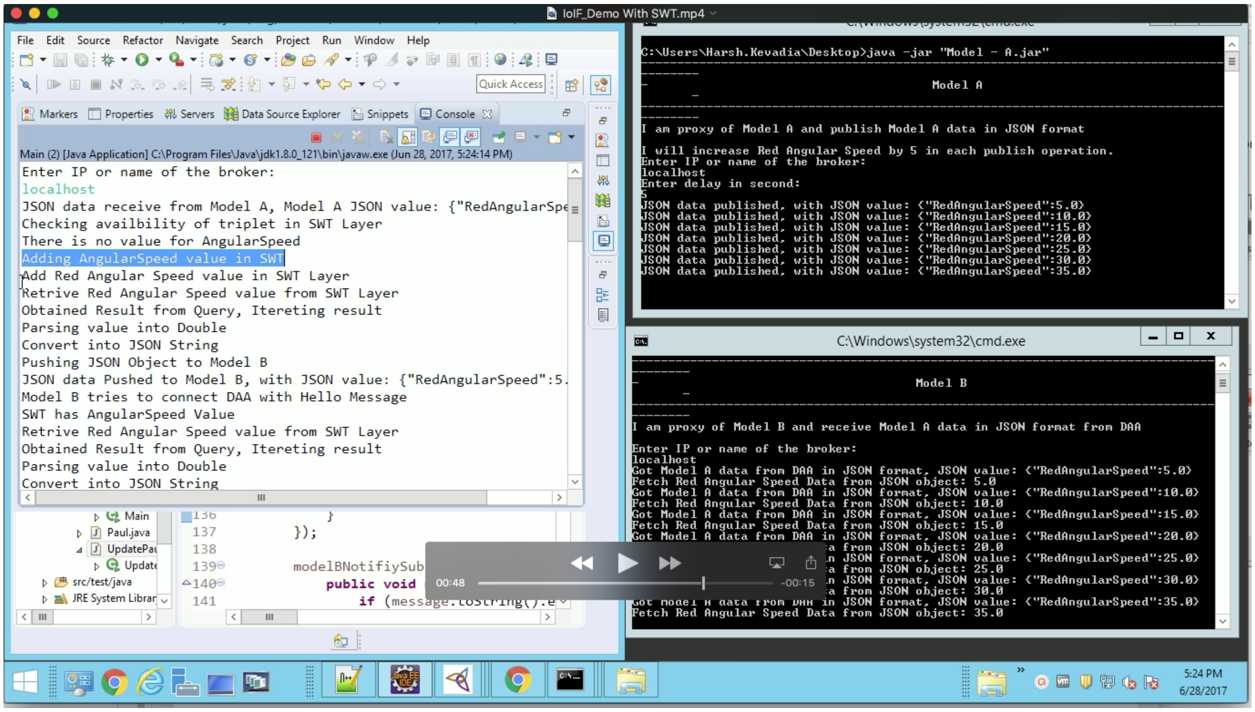


Figure 27. Multi-fidelity Mission Simulation using Semantic Web Technology and Data Acquisition and Aggregation

There is a video of a simplified version of this demonstration as shown in Figure 28. The video was shown to our ARDEC sponsors. In this simple demonstration, Model A publishes data to the DAAL using its proxy, which inserts the data into the triple store using a SPARQL query (note: a SPARQL query can read or write to a triple store). Model B subscribes to the “RedAngularData.” The DAAL subscribe method performs a SPARQL query to retrieve the data and send to Model B proxy.



```
Main (2) [Java Application] C:\Program Files\Java\jdk1.8.0_121\bin\javaw.exe (Jun 28, 2017, 5:24:14 PM)
Enter IP or name of the broker:
localhost
JSON data receive from Model A, Model A JSON value: {"RedAngularSpe
Checking availbility of triplet in SWT Layer
There is no value for AngularSpeed
Adding AngularSpeed value in SWT
Add Red Angular Speed value in SWT Layer
Retrive Red Angular Speed value from SWT Layer
Obtained Result from Query, Itereting result
Parsing value into Double
Convert into JSON String
Pushing JSON Object to Model B
JSON data Pushed to Model B, with JSON value: {"RedAngularSpeed":5.
Model B tries to connect DAA with Hello Message
SWT has AngularSpeed Value
Retrive Red Angular Speed value from SWT Layer
Obtained Result from Query, Itereting result
Parsing value into Double
Convert into JSON String
```

```
            }
        });

        modelBNotifiySub
            public void
                if (message.toString().e
```

```
C:\Users\Harsh.Kevadia\Desktop>java -jar "Model - A.jar"
------------------------------------------------------------------------------
--------
-                                    Model A
       -
------------------------------------------------------------------------------
--------
I am proxy of Model A and publish Model A data in JSON format

I will increase Red Angular Speed by 5 in each publish operation.
Enter IP or name of the broker:
localhost
Enter delay in second:
5
JSON data published, with JSON value: {"RedAngularSpeed":5.0}
JSON data published, with JSON value: {"RedAngularSpeed":10.0}
JSON data published, with JSON value: {"RedAngularSpeed":15.0}
JSON data published, with JSON value: {"RedAngularSpeed":20.0}
JSON data published, with JSON value: {"RedAngularSpeed":25.0}
JSON data published, with JSON value: {"RedAngularSpeed":30.0}
JSON data published, with JSON value: {"RedAngularSpeed":35.0}
```

```
------------------------------------------------------------------------------
--------
-                                    Model B
       -
------------------------------------------------------------------------------
--------
I am proxy of Model B and receive Model A data in JSON format from DAA

Enter IP or name of the broker:
localhost
Got Model A data from DAA in JSON format, JSON value: {"RedAngularSpeed":5.0}
Fetch Red Angular Speed Data from JSON object: 5.0
Got Model A data from DAA in JSON format, JSON value: {"RedAngularSpeed":10.0}
Fetch Red Angular Speed Data from JSON object: 10.0
Got Model A data from DAA in JSON format, JSON value: {"RedAngularSpeed":15.0}
Fetch Red Angular Speed Data from JSON object: 15.0
Got Model A data from DAA in JSON format, JSON value: {"RedAngularSpeed":20.0}
                         a from JSON object: 20.0
                         n JSON format, JSON value: {"RedAngularSpeed":25.0}
                         a from JSON object: 25.0
                         n JSON format, JSON value: {"RedAngularSpeed":30.0}
                         a from JSON object: 30.0
Got Model A data from DAA in JSON format, JSON value: {"RedAngularSpeed":35.0}
Fetch Red Angular Speed Data from JSON object: 35.0
```

Figure 28. Video Demonstrating Integration and Interoperability Framework

The latest instantiation of the research involved five of the researcher to execute a demonstration as reflected in Figure 29. This version of the IoIF uses two active models and passes published data through the SWT layer before delivering the data to the subscribing model. The published data that is passed into the SWT is extracted in different units and by different name. The example demonstrates the ability of the IoIF to convert both units and name, through the following steps:

- SysML Model used to model Red Team linear speed
- DocGen transforms SysML model data to xml format
- Proxy A captures and transforms xml data to RDF
- Proxy A publishes red team linear speed (in m/s) to DAA
- Linear speed variable name and units will not match what is needed for Proxy B
- Mission Model Proxy B subscribes to red team linear speed
- DAA handles publish and subscribe from proxies
- SWT resolves the differences in the variable naming of Red Team linear speed and also the units
- When Proxy A (DocGen) publishes a new linear speed then the DAA initiates a request to the SWT to get the needed information for the subscribers of that data (Mission Model) and sends the updated information to the subscriber (Mission Model)
- DAA stores RDF instance data
- For the Demo, the team manually changed SysML model's linear speed and re-ran Mission Model simulation to demonstrate automated propagation of data change through system

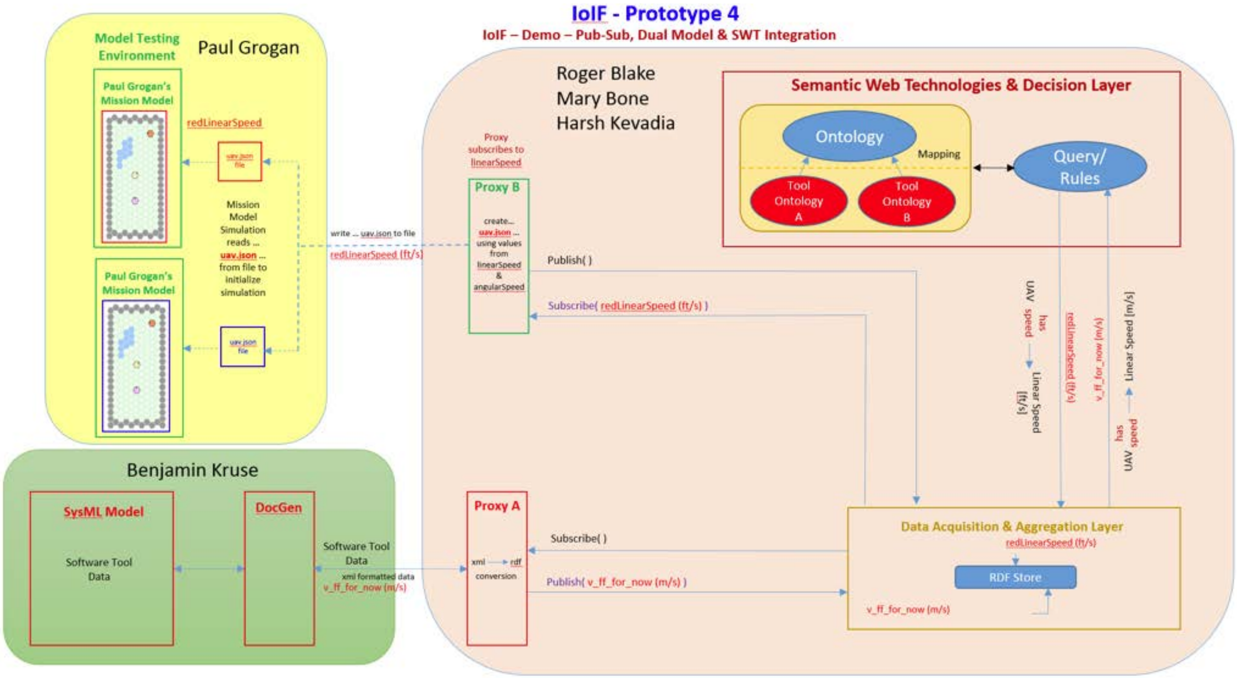


Figure 29. Integrating System Model Data through SWT to 2D Simulation

6 MULTIDISCIPLINARY, DESIGN, ANALYSIS AND OPTIMIZATION (UC03)

This use case investigates the methods to trace capabilities to the relevant design disciplines and perform cross-domain analyses through Multidisciplinary Design Analysis & Optimization (MDAO) for problem and design tradespace analyses. In addition, to characterizing elements of the framework, cross-domain relationships, but also characterize the methods used to support MDAO in a tool independent manner.

MDAO is an approach for calculating optimal designs and understanding design trade-offs in an environment that simultaneously considers many types of simulations, evaluations, and objectives. For example, when designing a vehicle, there is typically a trade-off between maximizing performance and maximizing efficiency, where calculating either of these objectives require multiple disciplinary models (geometry, weight, aerodynamics, propulsion). MDAO prescribes ways to integrate these models and explore the necessary trade-offs among the objectives to make a design decision. While the theoretical foundations of MDAO are well-established by academics, a number of barriers to practical implementation exist. Chief among these is the lack of model integration, which prevents designers of one subsystem from easily assessing how changing a design variable affects the results of other subsystems' models or simulations. The overarching objective of this use case is to understand these challenges and develop recommendations for overcoming them and effectively applying MDAO to add value in a large, distributed, organization such as ARDEC.

As illustrated by some of the examples in UC01 and UC02, we can extract the key parameters in these various mission and system simulations. These parameters are fundamental to the MDAO workflows. We need to combine those parameters for different elements of a workflow, but we must also characterize our key performance parameters (KPP); for example, a surveillance UAV range or endurance would be KPPs. These KPP are modeled as the outputs from running the MDAO through different optimizations. The other aspect of the method involves identifying the constraints that must be characterized with respect to KPPs (i.e., outputs) with respect to selected inputs. As discussed in Section 9, we believe that the decision framework (see Figure 1) use case UC06 provides a methodological approach to identify the KPPs.

6.1 MDAO OBJECTIVES

More specific objectives include:

- Assessing the impacts of individual design changes on system capabilities
- Supporting early-phase (conceptual design), system-level trade-off analysis using previous evaluation results from existing models
- Develop strategies to transform the contracting process so that requests for proposals (RFPs) can be designed more flexibly toward value-based (rather than target-based) design

In pursuit of these objectives, the research activities entail:

- Develop generic multidisciplinary models of an UAS, including analyses of the geometry, structure, aerodynamics, propulsion, and performance capabilities, to be used as an example case
- Explore using systems representations (e.g., SysML, Domain Specific Models) to map all inputs (parameters and variables) and outputs (objectives, constraints, intermediate parameters) among the individual models
- Conduct trade studies on the UAS design using established approaches and tools for MDAO, exploring different approaches, tools, and visualization techniques to most effectively display information and uncertainty for decision-makers
- Explore ways that previous trade study results on detail-phase product design can be useful toward new conceptual design of products with varying mission capability requirements
- Work with ARDEC project leads to understand the barriers to implementing this type of MDAO, culturally and practically/theoretically
- Explore more general ways to map and coordinate subject matter experts (SMEs) and data, models, and meta-models for improved (1) requirements setting for RFP or CONOPS, and (2) value-driven design

Interfaces with other sub-tasks include:

- Explore ways to more seamlessly associate parameters from mission and system modeling and simulation for UC01 and UC02
- Receiving and using model structures from “Use Model Based Engineering”, “Develop Information Model”, and “Create System Models” portions
- Feeding and matching capabilities and needs with the “Research Mission and System Operational Capabilities” and “Research Graphical CONOPS” portions of the project, as well as the “Research Decision Framework” portion

- Investigate how MDAO outputs can be further used to calibrate mission and system modeling and simulation
- Investigate if MDAO can be used to formalize the Assessment Flow Diagram (AFD) for the Decision Framework (UC06)

One of the objectives of this project is to leverage the most powerful tools that are often used by industry as well as government organization. We have secured academic licenses to Phoenix Integration's ModelCenter [138]. Further, while research to date examines the use of MDAO at the systems level. We have received additional academic licenses to ModelCenter to investigate the use of MDAO at the mission and subsystem levels.

6.2 MDAO METHODS

Using tools like ModelCenter, we have investigated, demonstrated and described methods for apply such tools, and also identify the relevant research questions in the context of those advanced tools. For example, the steps for an MDAO method may be characterized as:

- Describe a workflow (scenarios) for a KPP (e.g., range, notionally similar to surveillance time)
- Determine relevant set of inputs and outputs (parameters)
- Illustrate how to use a Design of Experiments (DoE) and use analyses such as sensitivity analysis and visualizations to understand the key parameter to use with optimizations
- Illustrate Optimization using solvers with key parameters and define different (key objective functions – on outputs) to determine set of solutions (results often provided as a table of possible solutions)
- Use visualizations to understand relationships of different solutions

A number of methods can be applied to formulate multidisciplinary optimization problems, develop useful surrogate models, and calculate optimal and Pareto-optimal solutions. Optimization problems can be formulated with a number of different objectives by converting some objectives to targets or constraints, summing the objectives with value-based and unit-consistent weighting schemes, or multiplying and dividing objectives by one another. Surrogate models are often used to quickly simulate the behavior of a more computationally-intensive simulation model, and some common methods include interpolation, response surface using regression models, artificial neural networks, kriging, and support vector machines. Finally, numerical optimization can be performed using a number of different algorithms and techniques, including gradient-based methods, pattern search methods, and population-based methods. For each of these, different techniques have been found to be more suitable to different applications, and part of this research directive will be to identify and demonstrate the best tools for this MCE architecture.

6.3 INTEGRATIONS WITH RELATED TASKS

While the theoretical foundations of MDAO are well-established by academics, a number of barriers to practical implementation exist. Chief among these is the lack of model integration, which prevents designers from easily assessing how changing one design variable affects the outputs from different models or simulations. Through this project, and the creation of an MCE architecture that follows a Single Source of Truth and a consistent ontology, we will be able to leverage MDAO techniques in the design decision-making process. From an academic perspective, the major contributions will be to build a roadmap for integrating MDAO practices into complex existing and new organizational structures.

A solid framework for MDAO can enable multi-objective optimization, showing product developers how different design objectives compete with one another. For example, we know that improving an objective like “minimize weight” typically requires a sacrifice in the objective to “maximize power.” The magnitude of that improvement-sacrifice relationship, which often involves different units and requires human judgement to make a mission-appropriate decision, can be revealed by combining different simulation models, surrogate models, and optimization routines. As this may involve balancing a large number of objectives, one of the key challenges is in visualization of the results to enable informed decision-making. This fits into all five tasks of the project, as the entire information architecture must be built to support cross-disciplinary analysis, and specific tools and techniques can be integrated and tested at different stages of the transformation.

6.4 MDAO UAV EXAMPLES AND USE CASES

Demonstration covering several of the objectives have been presented in several working sessions as well as several bi-weekly status meetings. The demonstrated workflow shown in Figure 30 was developed using ModelCenter, or in conjunction with SysML and the MBSE Analyzer that provides an integration from MagicDraw SysML models to ModelCenter. This section provides a summary of the evolving use of MDAO and different workflows.

6.4.1 MDAO EXAMPLE FOR FIXED WING UAV

The first demonstration covered several aspects of the objectives discussed in this section, including:

- Describe and execute a workflow analysis of UAS capabilities (e.g., range, velocity, and fuel consumption)
- Map relationships among parameters (inputs/outputs) in disciplinary models
- Illustrate use of Design of Experiments (DoE), sensitivity analysis, and visualizations to understand capability relationships/trade-offs
- Optimize using different solvers to find sets of Pareto-optimal solutions
- Take advantage of previous model analyses for use in early-phase design with new mission capability requirements

- Currently links 5 equation-based models
  - Geometry
  - Weight
  - Aerodynamics
  - Propulsion
  - Performance
- Future work
  - More advanced, simulation-based models
  - Add mission capabilities

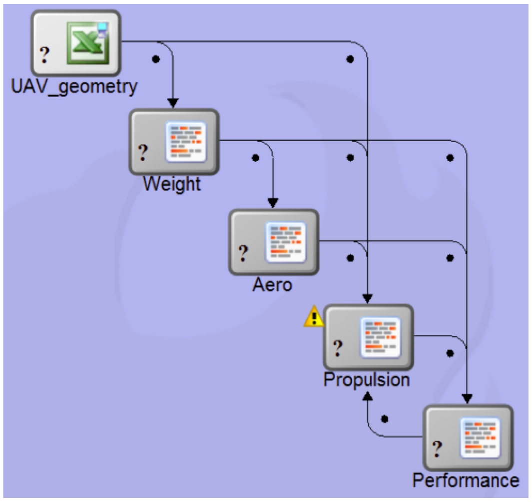


Figure 30. MDAO Example Workflow

As shown in Figure 31, the Pareto frontier (Pareto optimal set) shows the trade-off between range and propulsion. The blue points show the Pareto frontier/non-dominated solutions. The Pareto frontier was calculated using a bi-objective optimization using NSGA-II algorithm to:

- Maximize range
- Maximize propulsion
- Given 5 design variables
  - Wing area (ft2)
  - Wing span (ft)
  - Altitude (ft)
  - Speed (knots)
  - Efficiency factor

These results reflect on how much range one would have to give up in order to increase the propulsion by some amount. Based on the current set of equations characterized in the workflow, the sensitivity analysis shown in Figure 32 indicates that the wing area is the variable that exhibits the clearest trade-off. The wing span has the largest effect on range, but does not present a trade-off between these objectives.

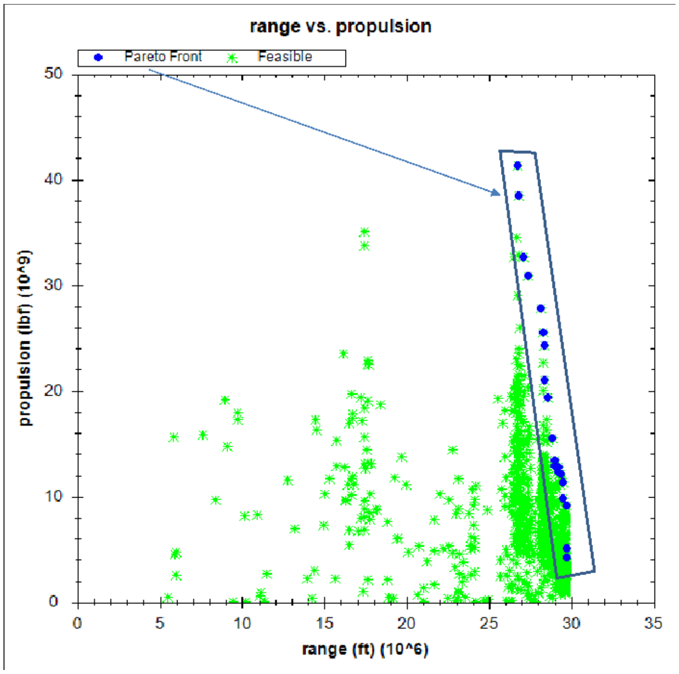


Figure 31. Pareto frontier (Pareto optimal set) Shows Trade-off Between Range and Propulsion

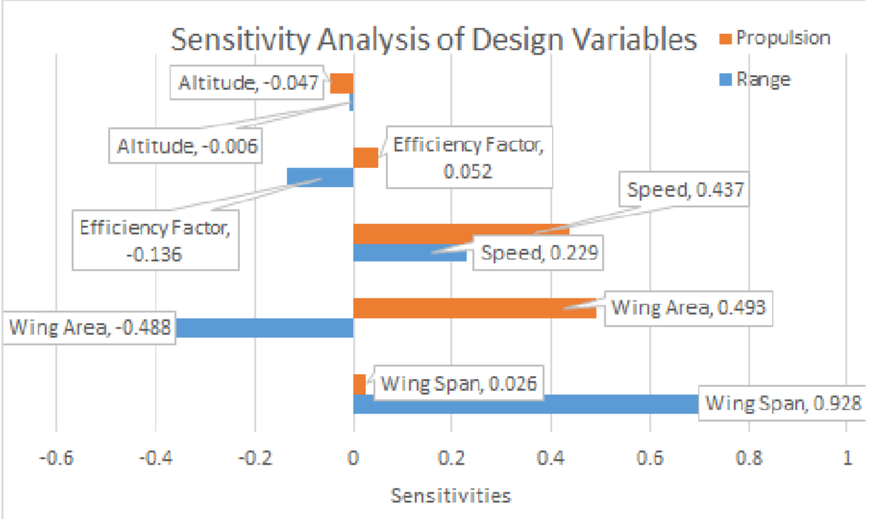
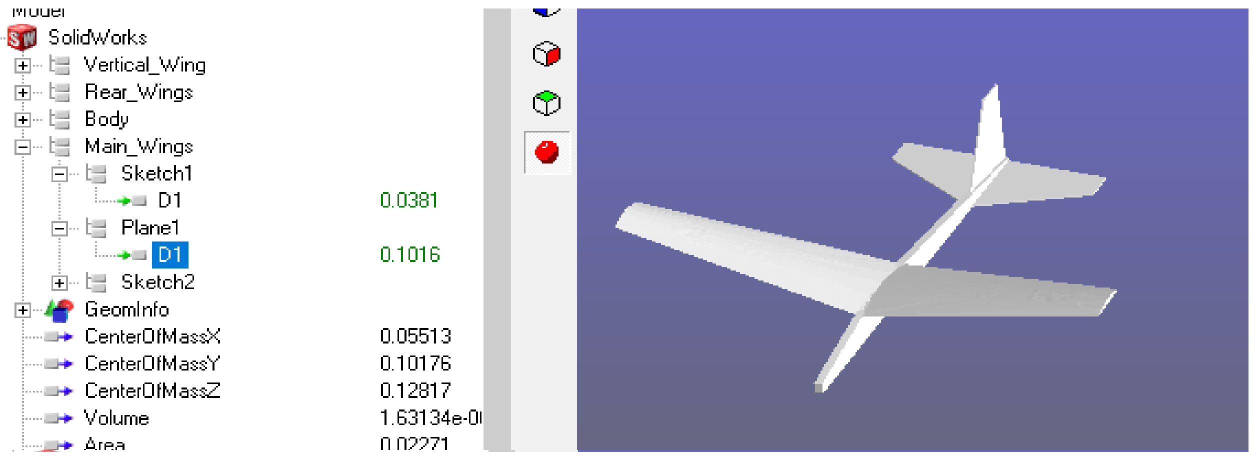


Figure 32. Sensitivity of Objectives to Design Variables

6.4.2 EXTENDING THE MDAO UAV EXAMPLE 1

Brian Chell is a new PhD student working with Steven Hoffenson. Brian has produced a number of updates to the initial model. The efforts produced alternative workflows that leverage other types of solvers for different aspects of the problem including multi-physics problems. For example, one of the first steps looked at bring SolidWorks [165] into ModelCenter as shown in Figure 33. This provides a way to bring in detailed geometries.



Model	
SolidWorks	
Vertical_Wing	
Rear_Wings	
Body	
Main_Wings	
Sketch1	
D1	0.0381
Plane1	
D1	0.1016
Sketch2	
GeomInfo	
CenterOfMassX	0.05513
CenterOfMassY	0.10176
CenterOfMassZ	0.12817
Volume	1.63134e-0
Area	0.02271

Figure 33. MDAO Workflow with SolidWords Computer Aided Design Model

There were a few challenges with the more complicated geometries, as well as:

- Open-source geometry validity is questionable
- Model variables
    - Most SolidWorks files found so far do not import variables into ModelCenter automatically
    - We assume that we can set the variables within SolidWorks, but this might be more difficult because manually setting values may not align structures (e.g., wing connect to fuselage to meeting correct)
- More complex
    - Computations solver (e.g., CFD) take longer to run on the laptops provide to students

This has led to the following investigations:

- Equation-based models derived from the model shown in Section 6.4
    - Uses DLR Unmanned Combat Air Vehicles (UCAV) [100] parameters
    - Model is fully operational
    - Based on weight fractions that are more scalable, and easier to change than DLR UCAV model
    - Model starting with payload weight vs. range vs. endurance tradeoffs

    - Looking at the potential to merge with future Computational Fluid Dynamic (CFD) results
- Simulation-based models
    - Difficulties
        - Still problems with importing variables into ModelCenter
        - Very large number of variables automatically imported (12,000+)
        - Under construction
    - OpenVSP [133] vs. Solidworks (CFD)
        - OpenVSP is a parametric aircraft geometry tool
        - OpenVSP allows the user to create a 3D model of an aircraft defined by common engineering parameters. This model can be processed into formats suitable for engineering analysis.
        - OpenVSP commonly used with ModelCenter
        - SolidWorks has stronger analysis capabilities
        - OpenVSP is limited to a standardized shape library
        - SolidWorks Flow Simulation can handle turbulence
        - OpenVSP CFD is most valid at nominal flight conditions (e.g. low angle of attack)
        - OpenVSP should be sufficient for conceptual design phase

OpenVSP is being used for CFD. It is easier to use with limited library of shapes of quadcopters and fixed wing, and can run ‘headless’ (i.e., without GUI) to make computations less expensive. NASA has been using this with ModelCenter. The current status is:

- Integrated parametric geometry and CFD into ModelCenter
- Performing optimization and DOE to characterize model
- Trying to find lowest-fidelity mesh that produces accurate results
- Challenges:
    - Takes some time to change between different aircraft
    - Future NASA wrapper will make this much easier
    - High-fidelity CFD simulations are very slow; we know it can run much faster, because we tested on Mark’s computer; we have not tried it on the server, because we don’t have enough licenses

Figure 34 show the CFD results from the same geometry under the same flight conditions with different fidelity meshes. The simulation on the left has a coefficient of lift many magnitudes higher than the one on the right. The next steps will:

- Investigate mesh balancing accurate results and low computing cost
- Start integrating structural analysis
    - First use built-in OpenVSP outputs for wings modeled as simple beams
    - Investigate using Finite Element Analysis (FEA)
    - While this is using an airplane in the example, the concept is relevant to things that ARDEC designs that must fly (e.g., quadcopters)

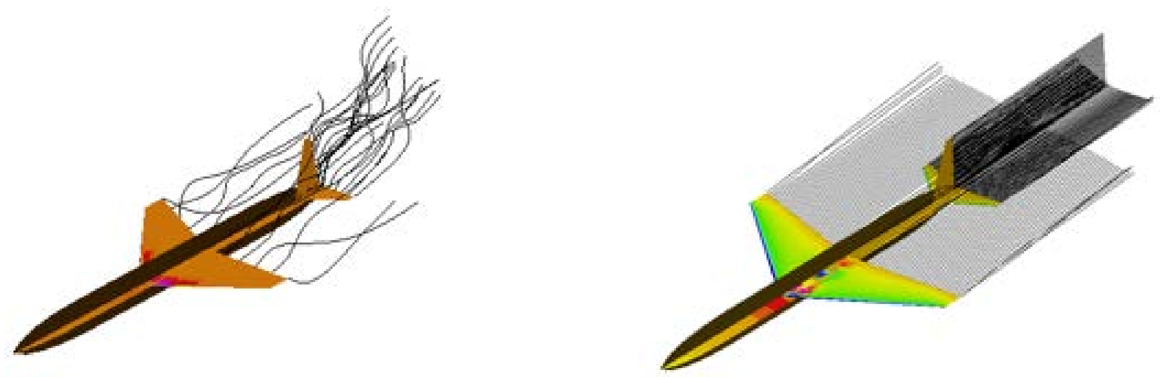
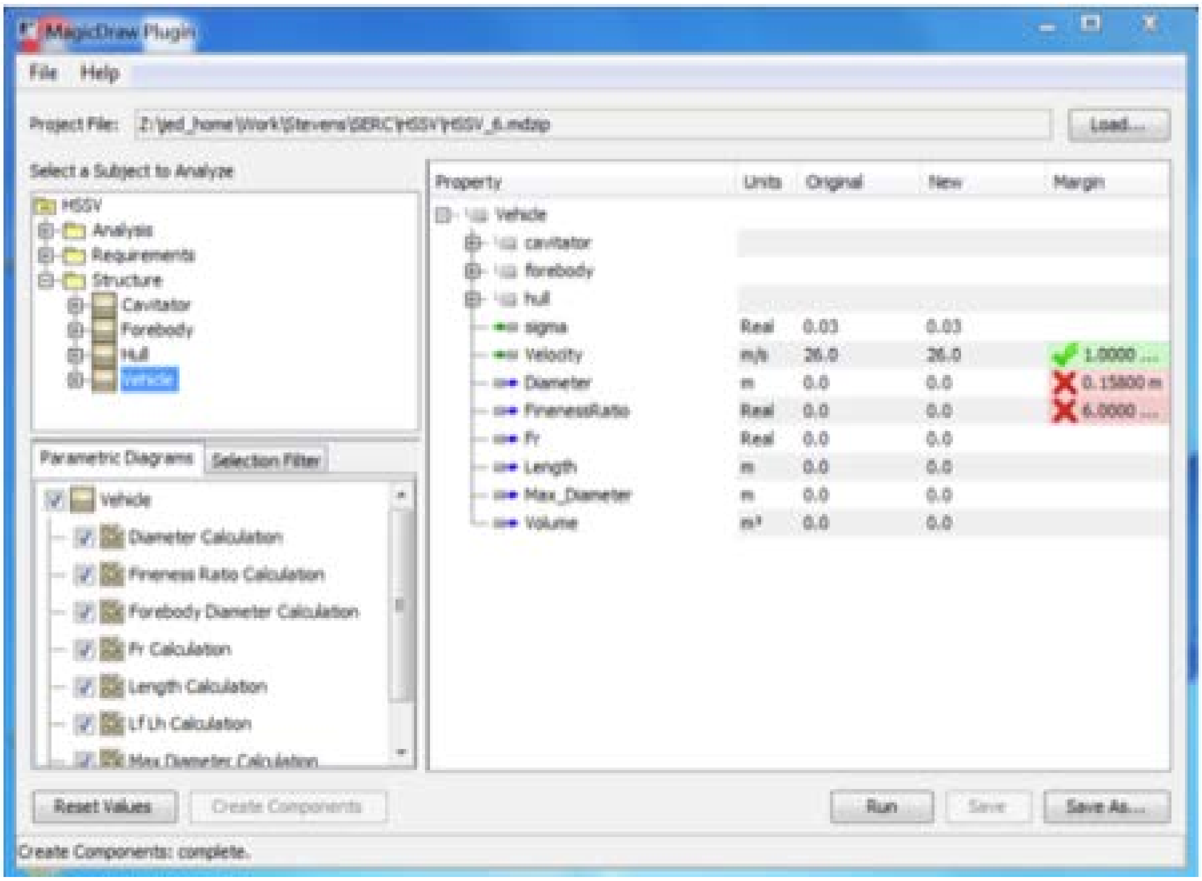


Figure 34. CFD Mesh Fidelity Importance

6.5 SYSML INTEGRATION TO MDAO THROUGH MBSE ANALYZER

This research investigated the use of the Phoenix Integration MBSE Analyzer that provides a way to integrate MagicDraw SysML models with ModelCenter for performing MDAO analysis. John Dzielski who performed this research primarily works in Matlab, and he used an example that was familiar to him related to underwater super cavitating modeling. The process covered the following steps:

- Defining requirements models in SysML
    - MBSE Analyzer works by adding a profile that includes a number of stereotypes to MagicDraw
    - Specify a constraint (=’s), upper and/or lower bounds, and units
- Properties are connected to requirements via the satisfy relationship
- Information is transferred to the ModelCenter through MBSE Analyzer plugin as shown in Figure 35
    - Requirements are shown in the Margin column of the plug-in.
    - The plug-in indicates whether the requirements are satisfied or not by a design
- MagicDraw Plug-In populates an analysis to create a workflow
    - Components correspond to constraint blocks
    - Constraints blocks are models or equations used in par diagrams
    - Constraint parameters correspond to component variables in ModelCenter
- Parametric (PAR) blocks are used to indicate to ModelCenter how to connect component I/O (values) to model values
- All of the other types of analyses discussed previous can then be applied in ModelCenter



Project File: Z:\jed_home\Work\Stevens\SERC\HSSV\HSSV_6.mdzip

☑ Vehicle
- ☑ Diameter Calculation
- ☑ Fineness Ratio Calculation
- ☑ Forebody Diameter Calculation
- ☑ Fr Calculation
- ☑ Length Calculation
- ☑ Lf Lh Calculation
- ☑ Max Diameter Calculation

Property	Units	Original	New	Margin
Vehicle				
cavitator				
forebody				
hull				
sigma	Real	0.03	0.03	
Velocity	m/s	26.0	26.0	✓ 1.0000 ...
Diameter	m	0.0	0.0	✗ 0.15800 m
FinenessRatio	Real	0.0	0.0	✗ 6.0000 ...
Fr	Real	0.0	0.0	
Length	m	0.0	0.0	
Max_Diameter	m	0.0	0.0	
Volume	m³	0.0	0.0	

Create Components: complete.

Figure 35. Example of MBSE Analyzer MagicDraw Plugin to Integrate with ModelCenter

The following reflects on some of the initial findings in his first exposure to MagicDraw, SysML, and ModelCenter:

- Found it difficult to learn SysML
  - SysML has a lot of documentation, but MagicDraw can be hard to learn (John learned MagicDraw without any formal training)
- ModelCenter is a little bit better
  - Extremely flexible, anything that can be modeled in ModelCenter can be used a constraint
  - Similar constraints will be found in ARDEC – in specific armament
  - MBSE Analyzer works by adding a profile that includes a number of stereotypes to MagicDraw
- It is easier to model in SysML and use the MBSE Analyzer to create the ModelCenter workflows
- ModelCenter doesn't understand generalization relationships as represented in SysML

6.6 MDAO NEXT STEPS

There are a few additional tasks planned for this MDAO use case:

- Provide a demonstration of MDAO applied to the graphical CONOPS use cases (UC01)
- Continue to add on simulation-based model
    - Propulsion
    - Internal components
    - Payload, engine, fuel tanks
    - Structural analysis
- Continue to look at the MDAO relationships to Design Structure Matrix (DSM)
- Investigate the use of MDAO for formalizing the Assessment Flow Diagram of the Decision Framework (UC06) and populating AAMODAT (UC10)

6.7 FORMALIZING ASSESSMENT FLOW DIAGRAMS AS MDAO WORKFLOW

For populating AAMODAT (UC10), we need to collect all of the elements of information. Mary Bone demonstrated at the third working session how this is feasible. However, we need to determine how/where to collect all of the information reflected Figure 36 from rigorously specified models. Matt Cilli, believes this is possible.

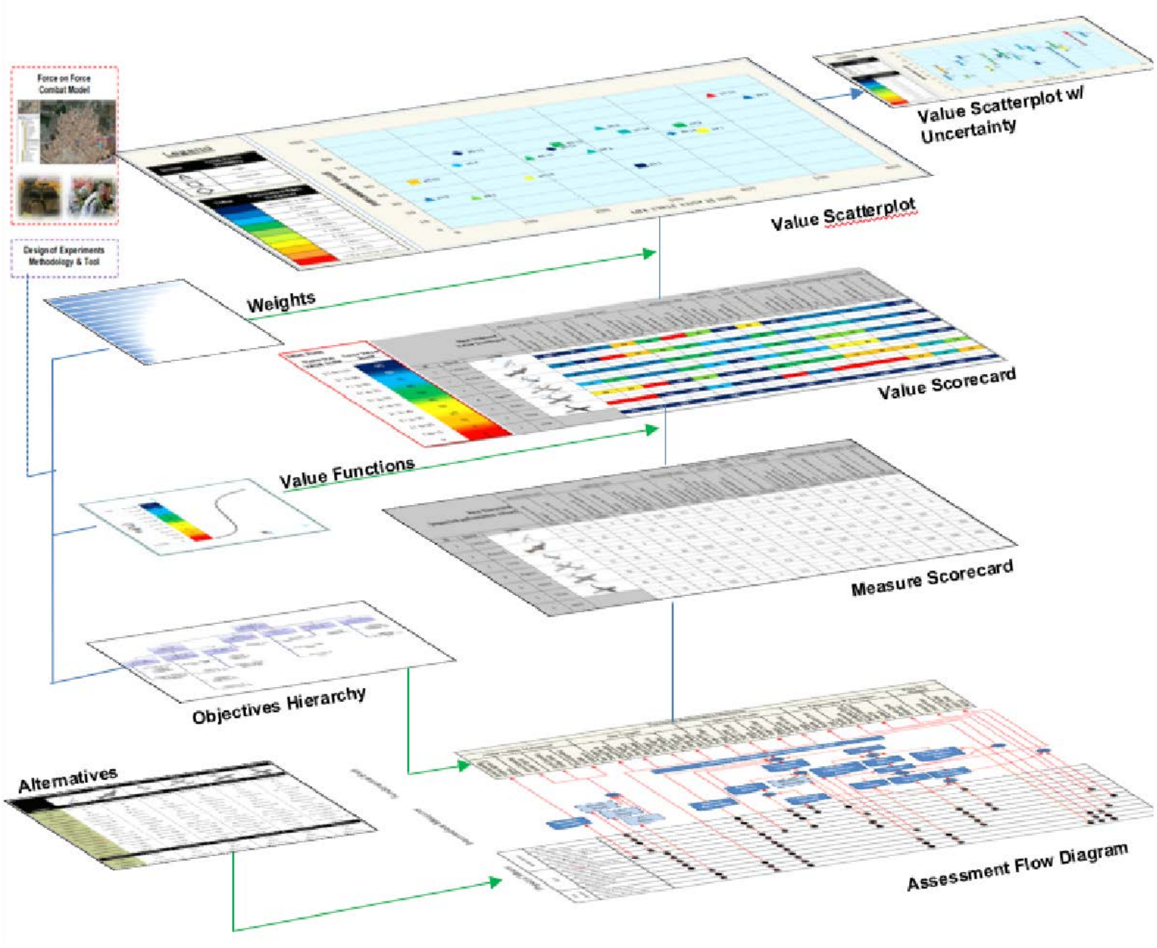


Figure 36. Decision Support Model Construct [41]

Matt Cilli has done a refinement from his book chapter, and created an Assessment Flow Diagram (AFD) as shown in Figure 37. The research investigates if we can formalize the AFD as an MDAO workflow, which will have a mapping into SysML. John starts with SysML and use the MBSE Analyzer to produce the MDAO workflow. Initial assessments reported at working session #5 suggest that this is possible, and we will next attempt to use MDK/DocGen (UC04) to extract that information from SysML and put it into a repository to be later loaded into AAMODAT. Figure 37 provides a basic conceptualization for researching this concept:

- Can MDAO represent Assessment Flow Diagram?
- Does AFD characterize needed MDAO workflows?

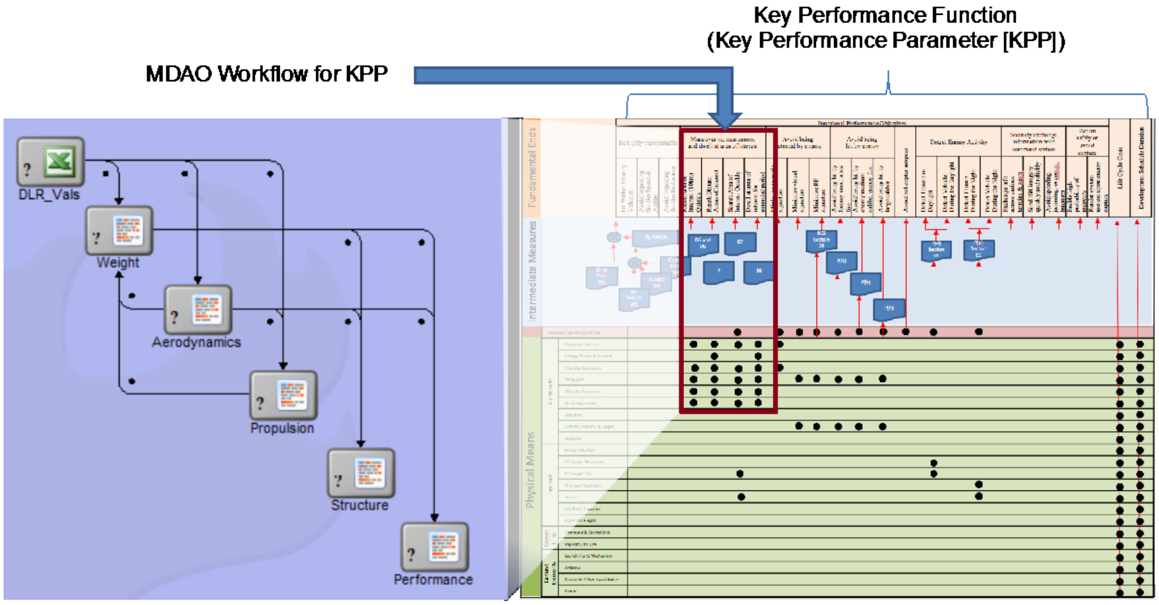


Figure 37. Formalizing the Assessment Flow Diagram

6.8 FUTURE RESEARCH FOR MDAO

At the request of David Allsop from Boeing, we also connected a few people from our NAVAIR visits to discuss the issue of deriving MDAO parametrics from high-fidelity models, or more generally having some type of bi-directionality between parametric models and higher fidelity simulations (which can "break" the parametric chains). Dr. Dave McCormick who runs the MDAO lab for Northrop Grumman gave an informative presentation at the April NDIA Modeling and Simulation bi-monthly committee meeting on some of challenges, which we believe are relevant to future research, such as:

- Rapid re-parameterization of completely new concepts
- Ability to incorporate static models
- Ability to bring in static changes "underneath" the parameterization
- Ability to incrementally add to parameterization
- Ability to rapidly alter the sizing logic behind models

7 SYSTEM MODELS AND MODEL BASED SYSTEMS ENGINEERING (UC04)

This use case applies MBSE methods and tools to the case study examples and also looks at how metamodels or metadata is represented in the Information Model (UC00) to provide traceability through the other forms of modeling for UC01, UC02, UC03, UC05, UC06 and UC10. This use case is developing different variants of UAS system models at both the system and mission level. We are also interested in using MBSE using SysML with MagicDraw [126] to investigate benefits and synergies through OpenMBEE [132], as discussed in Section 12.6. We used the Model Development Kit (MDK)/DocGen to generate visualization of the requirements from the AVCE iMBE model provide by the ARDEC sponsors. The use of MagicDraw also allows for integration to ModelCenter through MBSE Analyzer, as a means for modeling system constraints in SysML and integrating with MDAO as discussed in Section 6.5.

7.1 OPENMBEE AND MODEL DEVELOPMENT KIT

We have provided a number of sessions to our sponsor on the OpenMBEE that was developed and now is open-source by NASA/JPL. OpenMBEE has been evolving over the years, and we are participating in the OpenMBEE collaboration group (https://groups.google.com/d/forum/openmbee/), which has about 115 group members, including industry participation from Boeing, Lockheed and international organizations. We believe it will be an effective tool for our research, but can also provide us with insights that might be beneficial to AVCE iMBE.

As shown in Figure 38, OpenMBEE has three main components: MDK – with DocGen, Model Management System (MMS), and the View Editor. DocGen works from a View and Viewpoint hierarchy, which is a type of model embedded within a system model. In the absences of more rigorous checking such as the NASA/JPL ontologies [90], or validation rules from in MagicDraw, the use of the View and Viewpoint hierarchies can be used to enforce some methodological guidelines. For example, after generating a document using DocGen, blank sections reflect potential incompleteness in the model. While the generated documents can provide a type of specification, they are often used first as a means of checking the view of a model and then "pushed" into the MMS where they can be viewed through the View Editor, which runs in a standard browser. The View Editor allows:

- Access by person, roles, supporting review
- Can update information that can be pushed back into the model through the MMS

NASA/JPL hoped that the process of open sourcing OpenMBEE would encourage tool vendors to add capability into the commercial tools, and to some extent this has occurred. The updates created by NASA/JPL improve the practice of modeling. Details are provided on Github: *https://open-mbee.github.io/*.

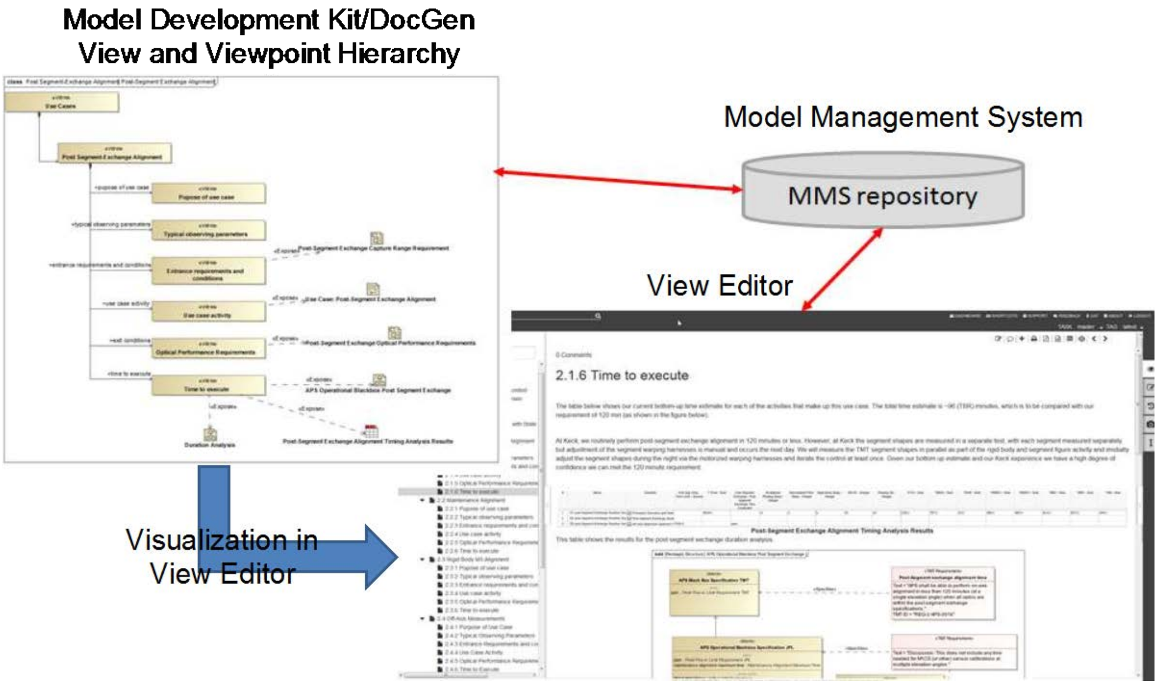


Figure 38. OpenMBEE Core Elements

7.2 MODEL DEVELOPMENT KIT AND DOCGEN

Benjamin Kruse has provided a number of talks and demonstration covering the following topics:

- Concepts for DocGen as architecturally represented in Figure 39
- View and Viewpoint Hierarchy
- Workflows
- Best Practices and considerations
- Model Findings and System Reasoner supported by MDK
- Usage & Purpose
  - Extracting information for various stakeholders
  - Demonstrated example for AVCE iMBE
  - Demonstrated example for UAV
  - Demonstrated example for NAVAIR Surrogate Pilot
  - Thirty Meter Telescope models has a number of example: https://github.com/Open-MBEE/TMT-SysML-Model/tree/master/Presentations

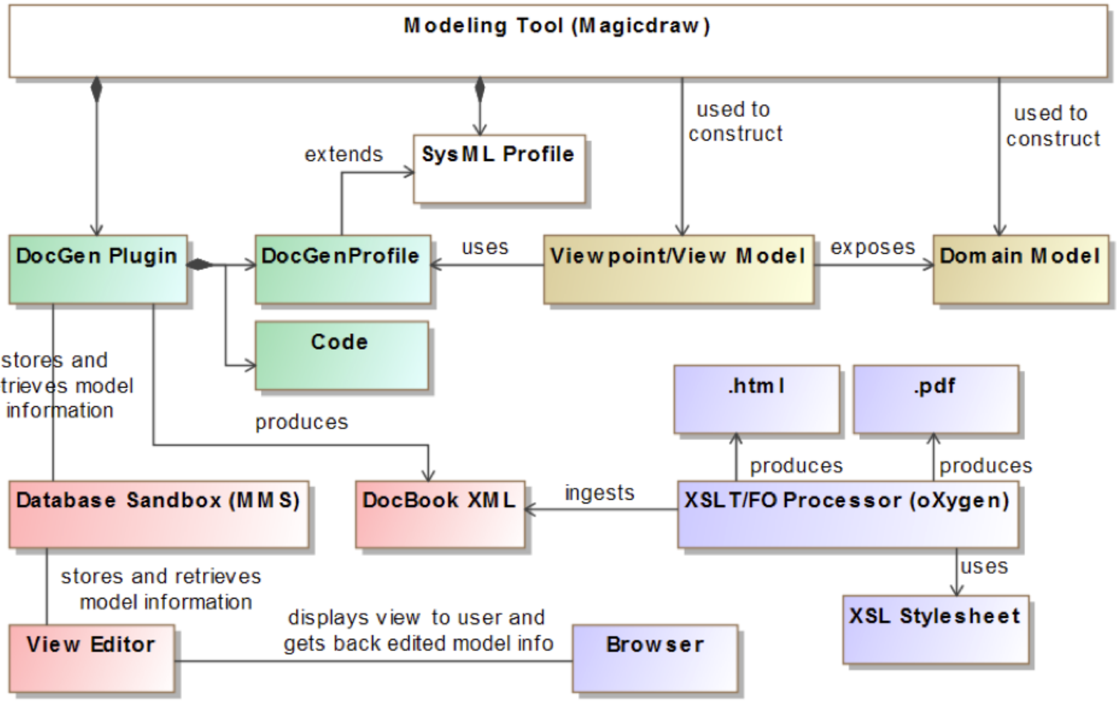


Figure 39. Concepts for DocGen

The basic concepts of a View and Viewpoint hierarchy are shown in Figure 40. There is a profile for DocGen, which includes <<Document>>, <<view>, and <<viewpoint>>. A Document contains one more Views. A View *exposes* Model Content, and *conforms* to a Viewpoint. A Viewpoint is a special type of profiled activity diagram, as shown in Figure 41 that provides a modeling language for extracting information from the exposed view. While this capability was developed to “generate documents” or visualizations from a model, we believe that it can be used for other purposes:

- Use concept to extract parametric values for translating into Monterey-Phoenix ‘language’ – related to RT-176
- Use concept to extract workflow information to support the Assessment Flow Diagram as discussed in Section 6.7

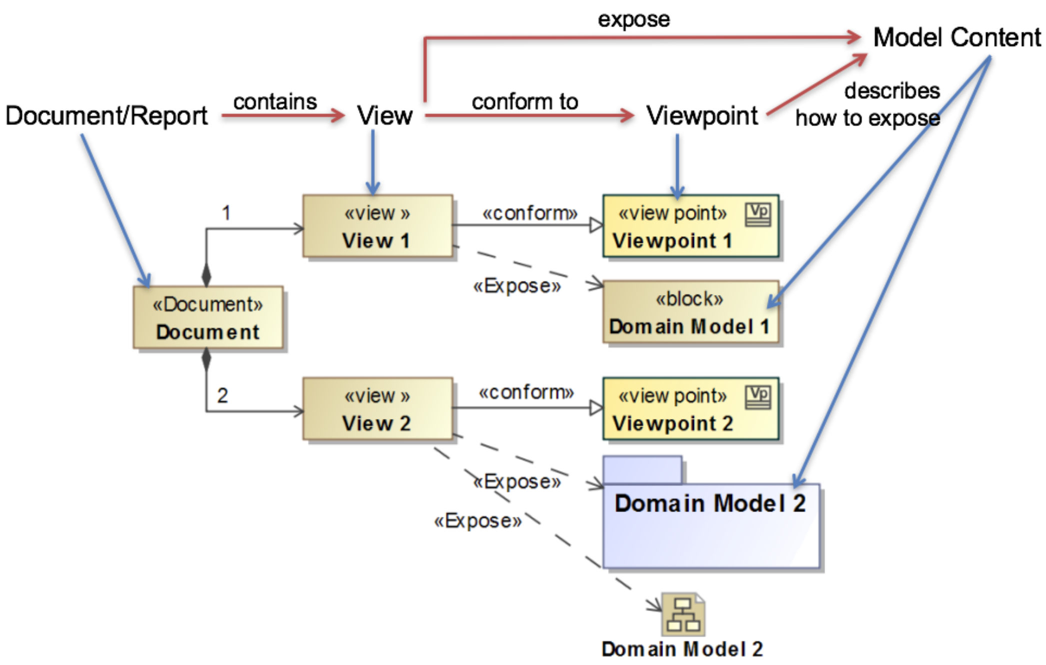


Figure 40. Concepts of View and Viewpoint Hierarchy

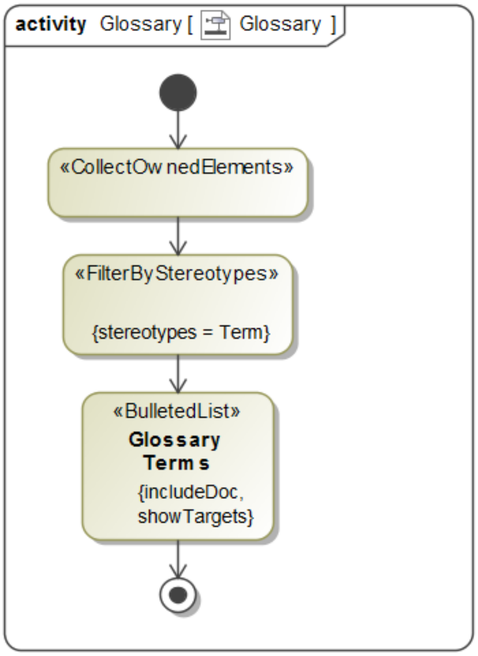


Figure 41. Simple Viewpoint Example

There are a few considerations and best practices for developing view and viewpoint hierarchies for use with DocGen

- There a number of pre-defined viewpoints, so review those provided in the profile to understand what is available, and to provide guidance in making custom viewpoints
- Expose model elements that align with viewpoints and vice versa

    - Required data must exist in model (e.g. traceability links between elements)
    - Consistent model structure makes data accessible (e.g. nested package structures or existing diagrams at expected position)
- Ordering of sections/views
- Order of sections/views conforms to order of a set of part properties as reflected in Figure 42, which shows partial representation of View and Viewpoint hierarchy for AVCE iMBE (DocGen plugin only displays it through numbered naming)
    - Create sub-chapters through nested views to reduce change impact
- Data representation
    - Produce SysML matrixes only as images or tables
    - There are issues to export simulation plot data
- There is a simulation capability
    - Expected use for web editor (e.g. to recalculate values)
    - Execution of simulation within SysML during report generation, not working as expected
- Viewpoints can be described with the Object Constraint Language (OCL) (as opposed to the activity diagram language)

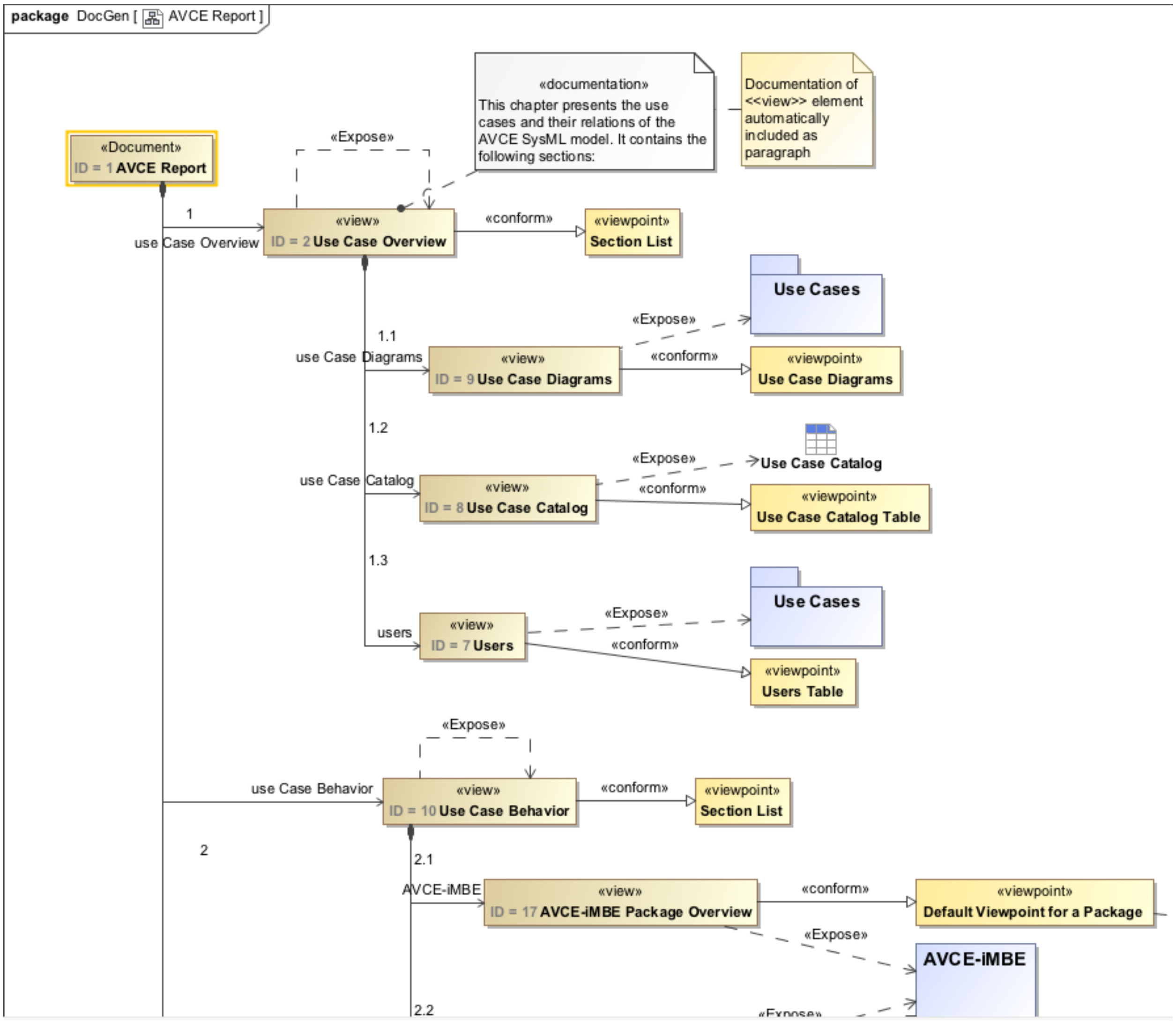


Figure 42. Partial Representation of View and Viewpoint Hierarchy for AVCE iMBE Model

7.3 SYSTEM MODEL IN SYSML

We are also using MBSE to model our project, as reflected in the initial use cases shown in Figure 3. We are developing UAV examples, both for this project as well as for our NAVAIR research. We plan to leverage models between the projects, where possible. For example, as shown in Figure 43, the system domain shows the various elements associated with surveillance, which is shown in a Block Definition Diagram (BDD). We will elaborate on parts of this domain that map back to both mission and system simulation in UC01, UC02, and UC03.

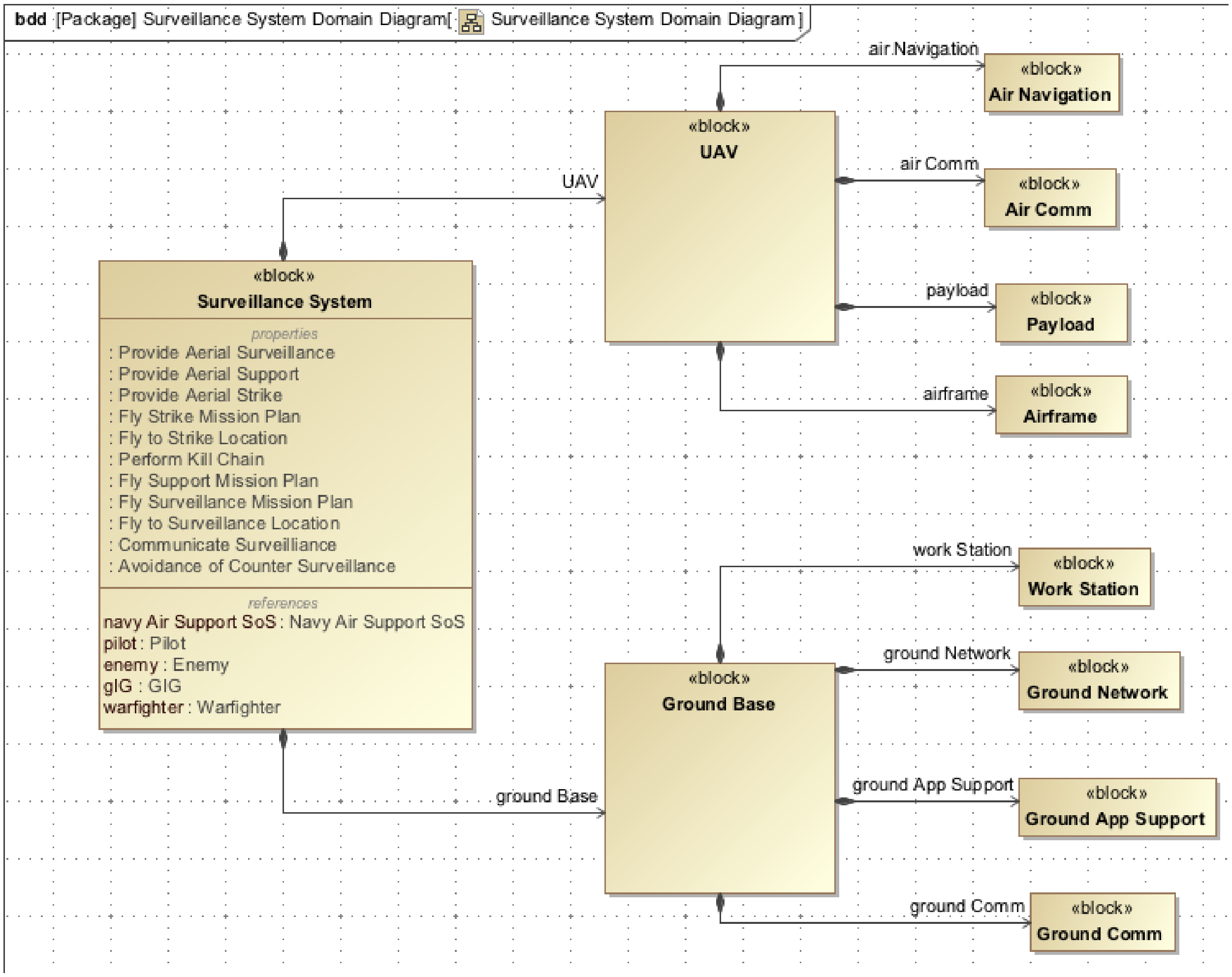


Figure 43. Surveillance System Domain Diagram

We also provided an example of Activity diagram of Mission Activity relating a Sensor Platform (UAV) and its interactions with Communication Platform(s) as shown in Figure 44 [168]. Note that this concept is presented from a logical perspective and shows both control flow (dash lines), and data flow (solid lines); this activity diagram also shows swim lanes that illustrate the different partitioning of the activities. NOTE: these are all examples.

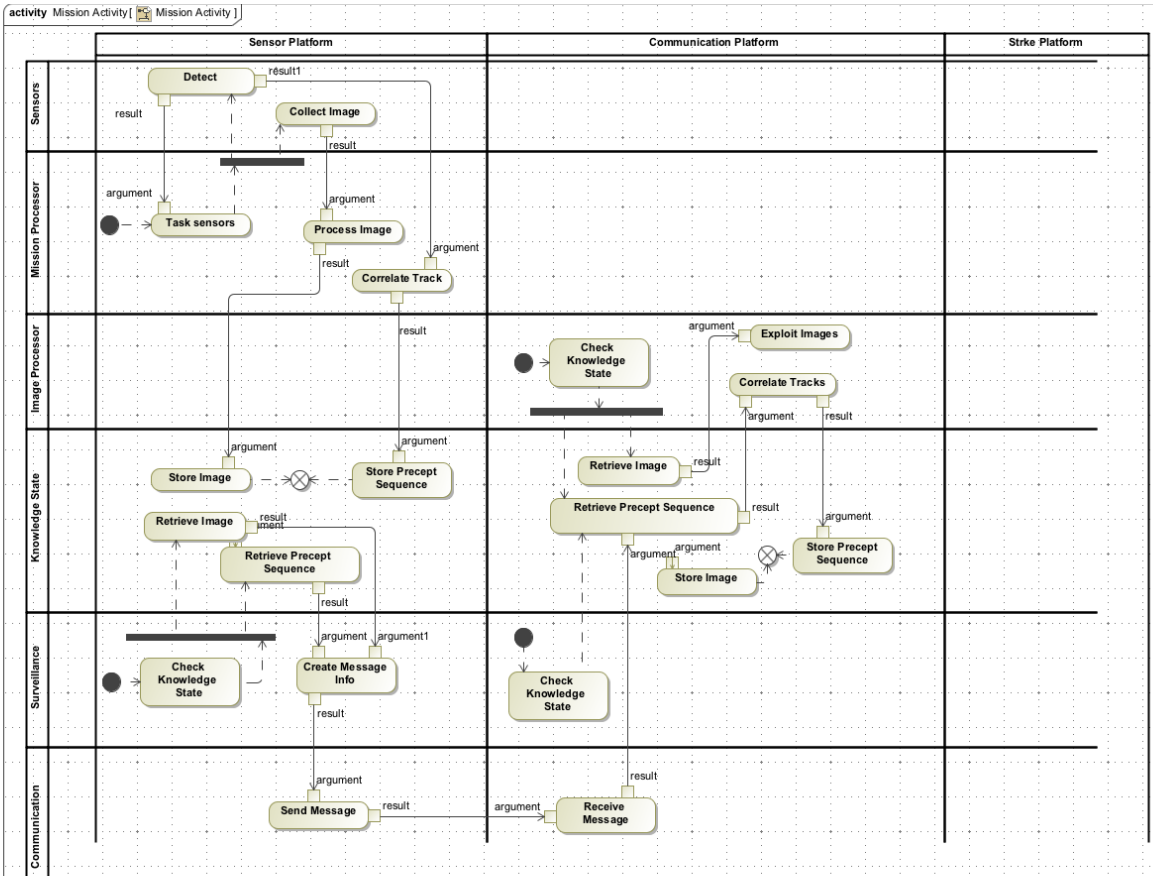


Figure 44. Mission-level Activity Diagram with Swim Lane Partitions

We can further refine the model, and we also have examples that are based on a product family of UAV being developed by our research collaborator Dr. Russell Peak under RT-170 that include:

- Rotor UAV 2.1 portfolio effectively completed
  - Includes optical camera option to original package delivery UAV squadron
  - Includes physics calculations via SysML parametrics (par)
  - Includes behavior simulation via SysML state machine (stm) / activity (act) / parametrics (par)
- Fixed-wing UAV 0.1 portfolio initiated
  - Inspired by fixed wing surveillance.
  - Applying ~same approach as for rotor UAV portfolio
- We could use Dr. Cilli's UAV example

Some of work in progress elements include the system model for the Fixed-Wing Refueling UAV. These are shown below in a SysML BDD, which shows some of the subsystems of the UAV that include: propulsion, fuel, and refueling subsystems.

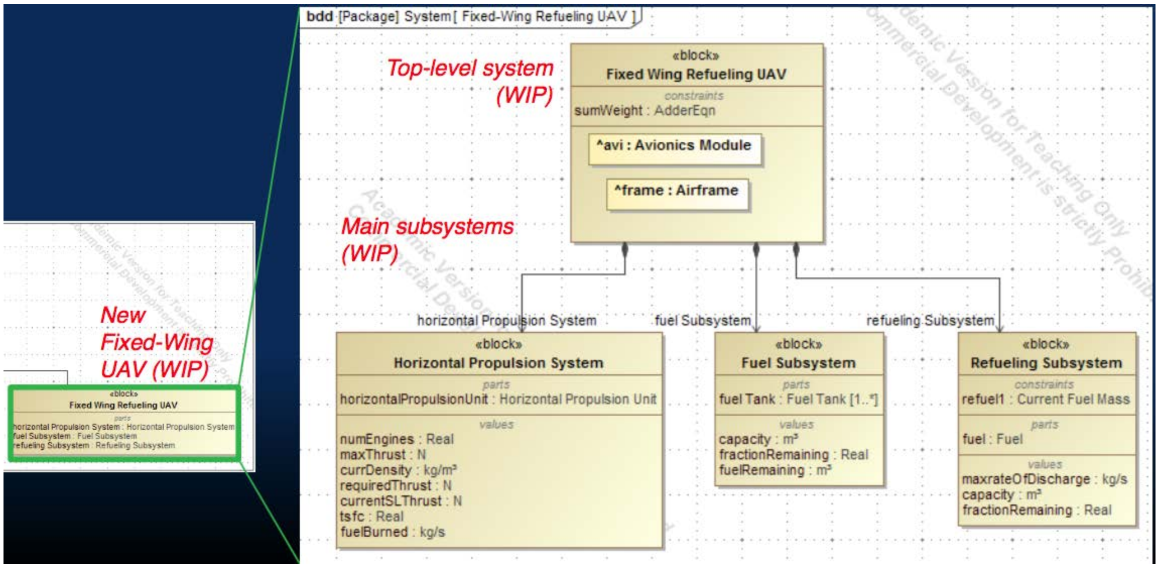


Figure 45. Fixed-Wing Refueling UAV Extension to UAV Portfolio

There are elaboration on some parameters of the fuel system as shown in Figure 46 to do some analysis on the First-Order Physics using SysML Parametrics. A parametrics diagram provides a way to describe constraints between parameters. Add-on analysis tools can then be used to verify that the constraints are satisfiable (i.e., not contradictory). This model is developed in MagicDraw [126], and uses some automation provided by a MagicDraw plugin called the Cameo Simulation Toolkit for requirement verification as shown in Figure 47. For example, the result of pass/fail on a constraint can be traced directly back to specific requirement object in the model.

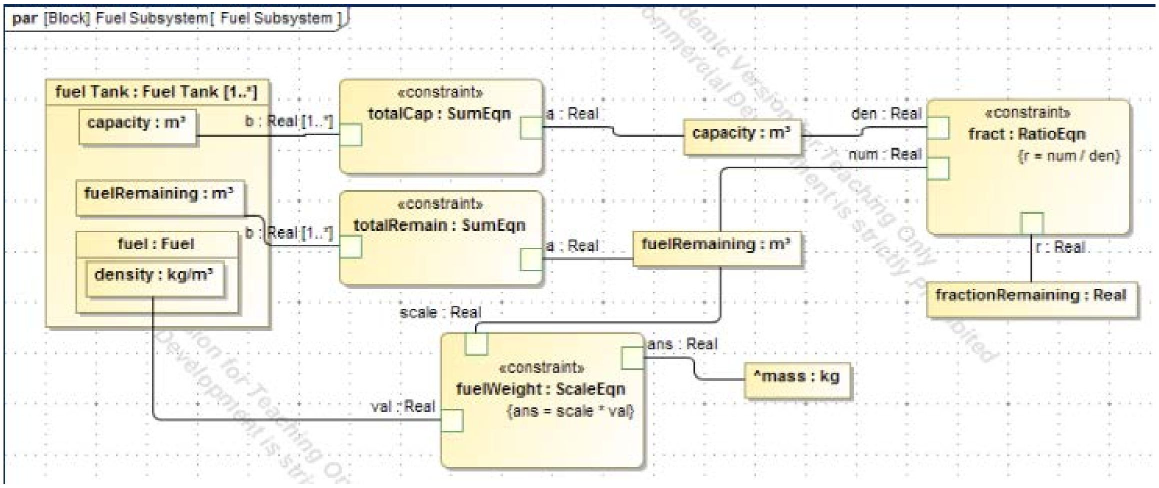
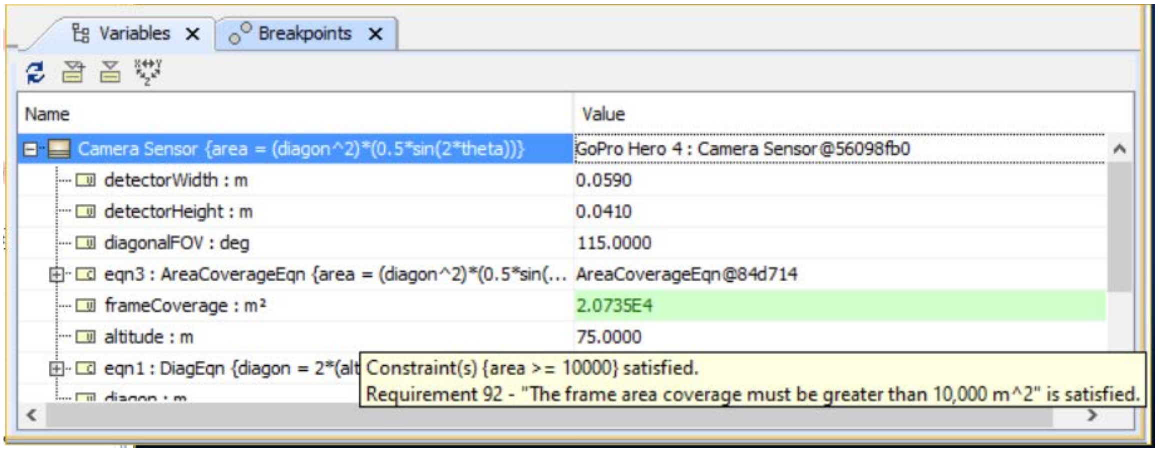


Figure 46. Parametric Diagram of Fuel System



Name	Value
Camera Sensor {area = (diagon^2)*(0.5*sin(2*theta))}	GoPro Hero 4 : Camera Sensor@56098fb0
detectorWidth : m	0.0590
detectorHeight : m	0.0410
diagonalFOV : deg	115.0000
eqn3 : AreaCoverageEqn {area = (diagon^2)*(0.5*sin(…	AreaCoverageEqn@84d714
frameCoverage : m²	2.0735E4
altitude : m	75.0000
eqn1 : DiagEqn {diagon = 2*(alt	
diagon : m	

Constraint(s) {area >= 10000} satisfied.
Requirement 92 - "The frame area coverage must be greater than 10,000 m^2" is satisfied.

Figure 47. Cameo Simulation Toolkit Verifies Constraints Representing Numeric Requirements

We will elaborate on these model to map to UC01, UC02, UC03, and also are investigating the integration of other modeling capabilities such as Mathworks [104] Simulink and Matlab for UC05.

8 COUNTER UAS IN THE CONTEXT OF MODEL BASED ENGINEERING (UC05)

This use case develops both the Model-Based Engineering (MBE) methods, the counter Unmanned Air Systems (UAS) scenarios and evolving approaches to Automated Concurrent Engineering, specifically related to MBE and manufacturability. This use case may be split in the future. In the context of working with the physical representation of various elements that are characterize abstractly in the system model, in the mechanical and electrical space, we are infested in how MBE can improve the physical reliability through manufacturing. Therefore, Kishore Pochiraju has discussed:

- Representation Methods, Model Frameworks and Verification Tools for Cyber Physical Design, which are discussed more in Sections 8.2 and 8.3
- Automated Concurrent Design as discussed in Section 8.4

8.1 MODEL-BASED ENGINEERING

We distinguish MBE from Model-Based System Engineering (MBSE). Typically, MBE involves modeling and simulation capabilities related to specific disciplines, electrical, mechanical, software, and the potential use of domain-specific modeling tools. Most importantly, we are interested in how these modeling tools for a specific, some of which have analysis and simulation capabilities, can be integrated with mission and system-level modeling and simulation (e.g., UC01 and UC02), MBSE (UC04), and MDAO (UC03). These various type of modeling capabilities are fundamentally important for a new class of systems that are generally referred to as Cyber Physical System (CPS).

8.2 MBE AND CYBER PHYSICAL SYSTEMS (CPS)

The phrase “cyber-physical systems”, coined by Helen Gills [72] defines “physical, biological, and engineered systems whose operations are integrated, monitored, and/or controlled by a computational core. Components are networked at every scale. Computing is embedded into every physical component, possibly even into materials. The computational core is an embedded system, usually demands real-time response, and is most often distributed.” Based on a 2015 National Academy of Science preliminary report [119] “Cyber-physical systems (CPS) are increasingly relied on to provide functionality and value to products, systems, and infrastructure in sectors including transportation (aviation, automotive, rail, and marine), health care, manufacturing, and electrical power generation and distribution. CPS are smart, networked systems with embedded sensors, computer processors, and actuators that sense and interact with the physical world (including people), support real-time, guaranteed performance and are often found in critical applications. Clearly, the types of UAS that are of interest to ARDEC are CPS.

Kishore Pochiraju presented his research entitled: *Representation Methods, Model Frameworks and Verification Tools for CPS Design* in a bi-weekly session. Some of the challenges discussed involve uncertain computation and network delays/latencies that can disrupt control performance and plant stability. Such control performance is critical to maintain system compositionality across these vary disciplines of a CPS. The integration of MBE tools with MBSE tools is of particular interest.

Another important aspect is CPS applications involve components that interact through a complex physical environment. Reliability, security, trustworthiness poses particular challenges in this context. These CPS need to be highly dependable, reconfigurable, and in many applications, certifiable. Trustworthiness must also extend to the system level.

Andrew Dawson joined the team in January 2017, and is working with Kishore on UAS capabilities using Simulink to look at the integration with SysML using MagicDraw and the integration with MDAO. We plan to integrate the concepts discussed by Kishore with this effort.

8.3 COUNTER UAS

We have included the counter UAS use case in this section, because Kishore has other related research in his area of expertise. To summarize the key objective for this counter UAS problem:

- Given a counter UAS system that identifies and restricts the flight of a UAV in a specified space
  - Represent the system using a compositional framework and appropriate models, much of which has been summarized in Section 8.2
  - Validate
    - For example, analyze the abstraction for a requirements satisfaction
  - Predict
    - Performance degradation due to timings and time-delays in implementation

        - Analyze the composability of the components and dependence on the system performance
        - Analyze the compositionality of the entire system
- Basic premise:
    - Watches the space for a UAS (Sensor Component)
    - Locates the UAS dynamically (Localization component)
    - Defeats the UAS (Act component)

To put the magnitude of this challenge is perspective, Business Insider magazine [37] reports that the global aerial drone market will reach nearly $13 Billion USD within the next 10 years. Nearly 75 percent of this market is projected to be defense-related. The commercial marketspace is also expected to develop into a $3 Billion market in the very near future. UAS will surely be ubiquitous enough to be perceived as annoyances or worse, threats, in many spaces [54]. The counter UAS technologies address the need for defense against unwanted UAS in military and public spaces and for the enforcement of various regulations against drone flight.

The current counter unmanned air systems, depending upon the context, integrate various "*Watch, Match and Catch*" methodologies [58]. These systems include area surveillance to detect the presence and location of a signal (watch phase), match (associate) to a UAV signature, and deploy a catch or defeat technique such as jamming. The watch phase can be based on passive detection of electromagnetic, thermal (IR), acoustic signatures or active use of RADAR [114], LIDAR, acoustic beamforming [145], and optical tracking methods. Match phase entails the use of library of signatures, machine learning methods, and physics-based models to identify the presence of a UAV in the surveilled space and also detect its type. Catch or defeat [15] requires jamming control signals or physically affecting the flight of the UAV with nets, projectiles or other UAS. Use of a particular method for the catch phase may be rendered infeasible due to safety requirements and the risk for collateral damage.

Modeling is central to all three phases. Watch phase technologies employ modeling not only for enhancing the signal to noise ratios, extracting localization information and constructing 3D representations of the tracked target, but also for numerous other purposes. Matching is typically conducted based on pattern identification models with the support of datasets. Catch methods employ modeling for interception path planning and directing transmission antennae for directional and selective propagation of jamming signals.

Due to the real-time nature of all the three problems, most accurate models that have the necessary computational efficiency are generally preferred. Accuracy versus time for the computation of a model-based solution is the general trade-off while deciding on the best algorithm to implement in each phase. The three phases are typically distributed among heterogeneous sub-systems with some pipelining of the tasks. However, the total time for response (detect-to-defeat) will be the sum of watch, match and catch phase times.

The objective of this sub-task is to investigate the role of modeling in both in terms of the effectiveness (i.e. accurately watching, matching and catching) and the performance (i.e. total response time and availability times).

Three activities are proposed for this use case:

1. Analysis of models used in counter-UAS methodologies: This activity entails analyzing open-military grade or a commercial counter UAS system and mapping role and performance of the models in the system. The expected deliverable is a broad state-of-the-art and gaps analysis report.
2. Assessment of watch-match phase models: The sub-task team will consider LIDAR and acoustic-based detection technologies and the effectiveness and performance of the models in the watch and match phases of the counter UAS problem.
3. Limited field experimentation: This sub-task team will collaborate in the design and conduct of preliminary experimentation of an idealized counter UAS system. The objectives for the experiments will be:
    - Measure the performance of selected signal detection and UAV localization models used in watch/match phases.
    - Investigate models that enable selective defeat (jamming) of one UAV flying in homogeneous or heterogeneous swarms.

With the intent of isolating and measuring the role and impact of the models, the experimentation will be planned in uncluttered physical spaces and with known dynamical behaviors of the UAVs.

8.4 AUTOMATED CONCURRENT DESIGN

Kishore provide two talks extending the first talk on CPS to reflect back on how the formalism and semantically rich information can contribute to automated concurrent design. The two talks included:

- Knowledge-Based Product Design and Manufacturing in the context of Automated Concurrent Engineering System (ACES) Technologies to provide significant reduction in product development time and cost while optimizing the design and its manufacturing
    - This was prior research, but there is a type of metaphor, where this work in the more mechanical space represented design knowledge to ensure manufacturability; we are attempting to do somethings similar in the system, system of system, and mission space
- Design Automation also related to Automated Concurrent Engineering Approaches
    - This particular research extended the prior work by investigating the feasibility of formalizing the design process to “provide a robot with a set of ‘specification’ to provide a design automatically”
    - This specifically formalizes a system as a network of dependencies from requirement to design controls
    - Provided early approach to MDAO for tradespace exploration
    - Networks of formalized design information allow design automation to proceed through a search process that can now be enhanced by Machine Learning and Deep Learning techniques and algorithm

8.5 ARCHITECTURE AND PROTOTYPING OF SYSTEM SIMULATION WITH SEMANTIC DATA EXCHANGE

The concept of a network of design dependencies can be characterize in SWT. The RDF which represent specific model instances, and are aligned with an ontology, is a graph (network of dependences). The concept is to create "gate keeper" tools that create/manage semantics and provide semantic data services to simulation tools. These gate keeper tools (two of them to be prototyped) differentiate data store/retrieve tasks into concurrent add/edit/modify operations on knowledge and data stores. The operations are divided into knowledge-dependent (may require negotiations with Human/AI experts), policy dependent (require reasoners - from heuristics, policy statements), and simply tedious tasks (i.e., automated out - e.g. use of a dictionary/thesaurus to check typos). The tools then create appropriate workflows. We also use the concept of "regularized operations" meaning all operations on knowledge/data stores complete if the integrities of the stores are maintained.

Kishore is aligning some of his research for semantic data exchange with our IoIF, with the objectives to:

- Create a “simulation-as-a-Service” framework with multi-physics, concurrent and concurrent execution of simulations during system architecture and design process.
- “On demand” and “As Appropriate” trade simulations during various phases of large complex systems design/integration
- Enable service-discovery, data-curation and tool interoperability
- Generalized abstraction for spatial, temporal and stochastic fields *with mapped semantics*
- Framework requirements:
    - Generalized abstraction for embedding simulation tools
    - Simulation concurrency and pipelining
    - Data_interoperability
    - Model abstractions enabling substitution
    - Indexed simulation inputs, outputs, storage
    - Abstraction to capture model use in design
    - Dynamic data flow tracking
    - Data model capable of large (2GB) data segments, access control, storage and transport.
    - Agnostic to OS and computational hardware
    - Open Application Programming Interface (API)
    - Support for real-time systems – Real-Time Controller API

8.6 MBE ANALYSIS FOR UAS ENERGY ANALYSIS

In order to accurately evaluate system performance as well as design choice consequences, two areas of battery system modeling have been explored by Andrew Dawson in support of added realistic performance in the quadcopter UAS elements in the graphical CONOPS (UC01). The two analyses include:

8.6.1 MASS TO ENERGY CAPACITY:

Based on the general architecture of common battery systems, system mass was anticipated to vary linearly with energy capacity. Battery parameters were compiled for the catalog of systems available from Gensace and Tattu, which are widely utilized in small-scale UAVs. For these batteries, the expected relationship was confirmed and can be expressed as follows:

```
mass [g] = 5.472 (capacity [Ah] * voltage [V]) + 61.87
```

The linear regression performed had an R-squared value of 0.991. This relationship allows battery mass to be easily incorporated into a variety of performance and flight models.

8.6.2 VOLTAGE VARIABILITY DURING DISCHARGE:

This analysis examined the relationship between discharge levels and maximum available power. Common battery systems specify a C-value, which is the maximum current that the system can safely produce. It is typically expressed as the ratio of maximum current to the current produced when discharging over one hour (the Ah rating). Therefore, a 10Ah battery with a C-value of 10 could produce a maximum of 100A.

During discharge, battery systems experience reducing voltage as charge level decreases. Therefore, for a specified C-value, the maximum power that the battery can produce will decrease along the discharge cycle. This is critical for UAV performance, because certain flight or performance characteristics may degrade over the mission cycle.

An empirical relationship between normalized discharge level (% of capacity) and voltage level (% of rated) was determined based on typical discharge curve literature. This is only intended to demonstrate the relationship and is not fully representative of all battery systems. Two variants were considered:

1. Increasing C-values impact the amount of voltage sag during discharge
2. Increasing C-values impact both the voltage sag and overall discharge capacity

The equations developed to describe these relationships can be utilized in performance models to determine the maximum available power at any point in the discharge cycle.

9 DECISION FRAMEWORK (UC06)

ARDEC uses the Integrated Systems Engineering Decision Management (ISEDM) Process to improve defense acquisition decision-making. The ISEDM process addresses the pressing issues targeted by the Department of Defense’s Efficiency and Better Buying Power Initiative and the 7-January-2015 DoDI 5000.02. A central issue confronted by both the initiative and the instruction was that systems engineering trade-offs made between capability requirements and lifecycle costs early in the acquisition process were rarely conducted and consequently realistic program baselines were not established such that associated lifecycle costs of a contemplated system are affordable within future budgets. Through the use the ISEDM Process and the family of synthesized data visualization techniques, systems engineers are able to assess a large number of system alternatives across a robust set of competing objectives in the presence of uncertainty and quickly recognize important trends across cost, schedule, and performance dimensions. While the ISEDM process has been applied with success to a number of defense research and development projects, there are several opportunities for enhancement and extension.

There are several objectives within this use case. We want to explore potential enhancements and extensions to the ISEDM process and the related decision support tool, AAMODAT. This use case has been associated with a new challenge area #5 that has expanded the objective to include considering how to integrate cross domain models with decision support models while executing ISEDM. In addition, as shown in Figure 1, the plan is to extract information across the various domain models in the underlying information model leveraging SWT as described in UC00. Specifically, we are looking to demonstrate the ability to a create domain ontology that align with AAMODAT views (i.e., the underlying metamodel for AAMODAT). This concept is notionally represented in Figure 1. We believe this capability to be applicable to ARDEC, but generally applicable to acquisition organizations such as NAVAIR.

9.1 DECISION FRAMEWORK OBJECTIVES

More specific objectives include:

- Generate a library of fundamental objectives hierarchies: A fundamental objectives hierarchy (and its associated measures) describes the criteria by which the goodness of each alternative is assessed. Studies show that the formulation of an objectives hierarchy is a difficult task and is often done incorrectly – significantly impacting decision quality in a negative way. The purpose of this sub-objective is to generate a library of thoughtfully prepared and well vetted objectives hierarchies for a set of common weapon system types such that a systems engineer can use a hierarchy from the library as a starting point that can be easily tailored for the particular decision at hand.
- Develop a Decision Risk Tracker: Cilli [41] identified 40 potential pitfalls associated with systems engineering trade-off analyses and through the use of practitioner surveys measured the perceived likelihood of encountering each pitfall and the consequence to decision quality given a particular pitfall was indeed encountered. The purpose of this sub-task is to develop a methodology to instantaneously assess the overall risk of a systems engineering trade-off analysis project and to update the risk assessment as known pitfalls are avoided through the use of best-practices through the execution of the study.
- Incorporate a Decision Adviser Feature into AAMODAT: Create a context sensitive pop-up decision advisor to alert AAMODAT users of best practices associated with the current process step.
- Add context sensitive best practices pop-up wizard to AAMODAT (avoid common pitfalls)
- Create Objectives Hierarchy Library within AAMODAT
- Enable Assessment Flow Diagram (AFD) Auto-generation in AAMODAT

- Improve GUI for AAMODAT
- Integrate Data Visualization COTS capabilities (i.e. Tableau) with AAMODAT
- Integrate Value Scheme Elicitation Tools with AAMODAT
- Develop improved automated Swing Weight Matrix Generator
- Integrate Conjoint Analysis tool into AAMODAT
- Integrate DOE capability in AAMODAT to generate run matrix for agent based models.
- Enable automated Design Structure Matrix (DSM) generation within AAMODAT and link to IRL portion of schedule estimator module
- Use unclassified, public releasable, but plausible and data rich problem (sUAV case study developed under ERS effort) to demonstrate ISEDM best practices with new upgrades listed above.
- Solve same problem but purposely trip on identified pitfall to illustrate why ISEDM process that avoids pitfall is superior.

9.1.1 DECISION FRAMEWORK METHODS

Research methods to achieve stated objectives will focus on the use of new product development case studies approved for public release, which is represented in a book chapter created by Matt Cilli [42].

In response to a request from the Engineered Resilient Systems (ERS) program, ARDEC is generating a hypothetical yet plausible case study that can be used to stimulate and focus academic discussion regarding systems engineering tradeoff analyses in the context of new product development efforts. The case study will possess elements of story such as setting, characters, plot, conflict, and point of view (Omniscient Limited), and theme. It will also provide detailed narrative incorporating many viewpoints; involve ambiguity, uncertainty, and un-structured presentation of initial information; give rich description of potentially useful data at multiple levels of fidelity; allow for multiple outcomes; and be publically releasable.

9.1.2 INTEGRATIONS WITH RELATED TASKS

The white text within the outer green ring of Figure 48 identifies systems engineering processes and methods while the ten blue arrows represent the ten steps of the analytical decision process. Interaction between the systems engineering processes and the decision process are represented by the small, dotted green or blue arrows.

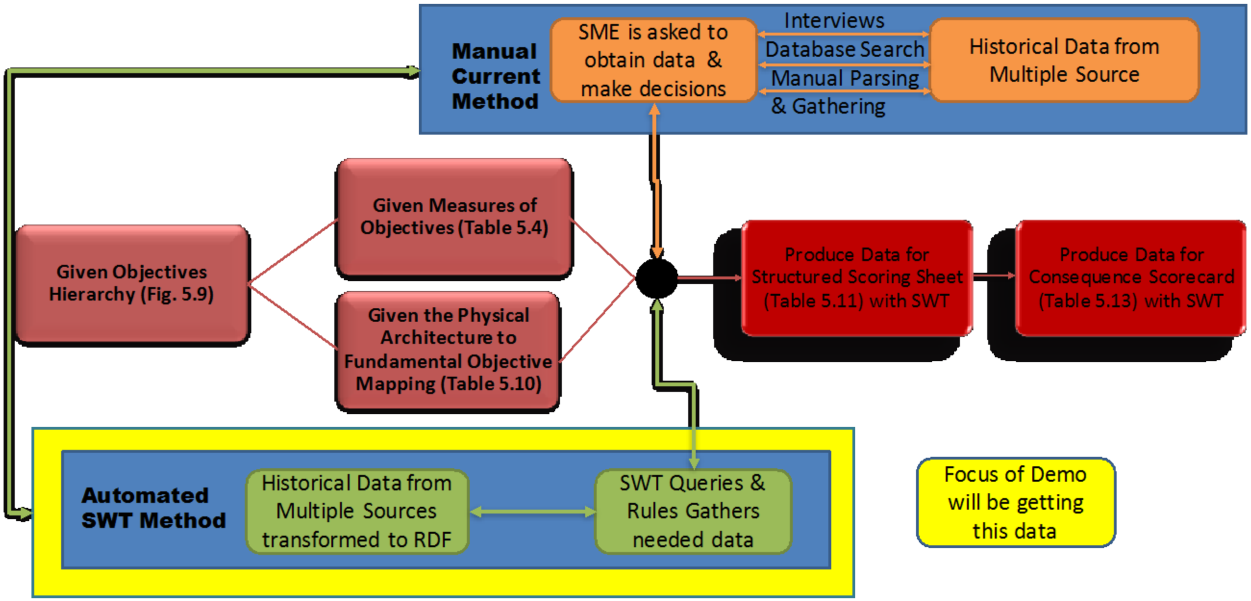
Figure 48. ISEDM Process Summary

9.2 USING SEMANTIC WEB TECHNOLOGIES TO FORMALIZE DECISION FRAMEWORK FOR AAMODAT

Fundamentally, if were able to formalize the concept discussed in the context of challenge area #5 by using underlying information model UC00 to populate AAMODAT, we would need for formalize all of the information and trace linkages through the Information model back to all other related perspectives on the system (UC01, UC02, UC03, UC04, UC05). These elements would include:

- Objective hierarchies
- Value functions
- Assessment Flow Diagrams (AFDs) trace the relationships between physical means, intermediate measures, and fundamental objectives, as discussed in Section 6.7
- Uncertainties

Figure 49 shows the use case refinement that has been discussed by the team. Mary Bone has provided an extended session at the third working session on a concept to show how SWT could support this effort to populate AAMODAT.



"Wiley: Trade-off Analytics: Creating and Exploring the System Tradespace - Gregory S. Parnell." [Online]. Available: http://www.wiley.com/WileyCDA/WileyTitle/productCd-111923753X.html. [Accessed: 27-Mar-2017].

Figure 49. Decision Framework Use Case Refinement

There have been other developments toward that:

- Robin Dillon-Merrill is working on templates for different type of objective hierarchies (e.g., portfolio, product)
- Matt Cilli has an update to the UAV case study [42]
- Mary Bone walked through the use case using example to show how to use SWT (UC10) to produce score sheet and consequence score card for objective: reach areas of interest quickly
  - For demo purposes, Mary used SWT to get example data from DBpedia (which is a crowd-source effort to extract structured information from Wikipedia and make this information available on the Web)
  - Created a simple Aircraft Ontology & Properties for demo to show semantically rich data extracted from DBpedia using SWT tools (Protégé, OWL Viz, RDF)
  - More details in UC10

As discussed in Section 6.7, we also noted that the AFD is probably the single view that best describes how the specific design choices are made across the product structure, and are transformed into consequences across the fundamental objectives through an array of interrelated models. Because of the similarity in the AFD to MDAO workflows. We are researching ways to model the AFD as an MDAO workflow, because those workflows would most likely be related to Key Performance Parameter (KPP). We had noted in the past that the Decision Framework would potentially support a method for deciding on the KPPs. The AFD might prioritize the needed workflows to defined using MDAO (e.g., ModelCenter).

9.3 INTEGRATED MODELS OF THE ASSESSMENT FLOW DIAGRAM

See Section 6.7 which discusses the concept for using MDAO workflows to represent the AFD in a formal way that could be automatically extracted from models to populate SWT for automating the population of AAMODAT. An AFD can be used by the lead Systems Engineer to organize, manage, and track assessment activities especially when used in conjunction with the consequence scorecard.

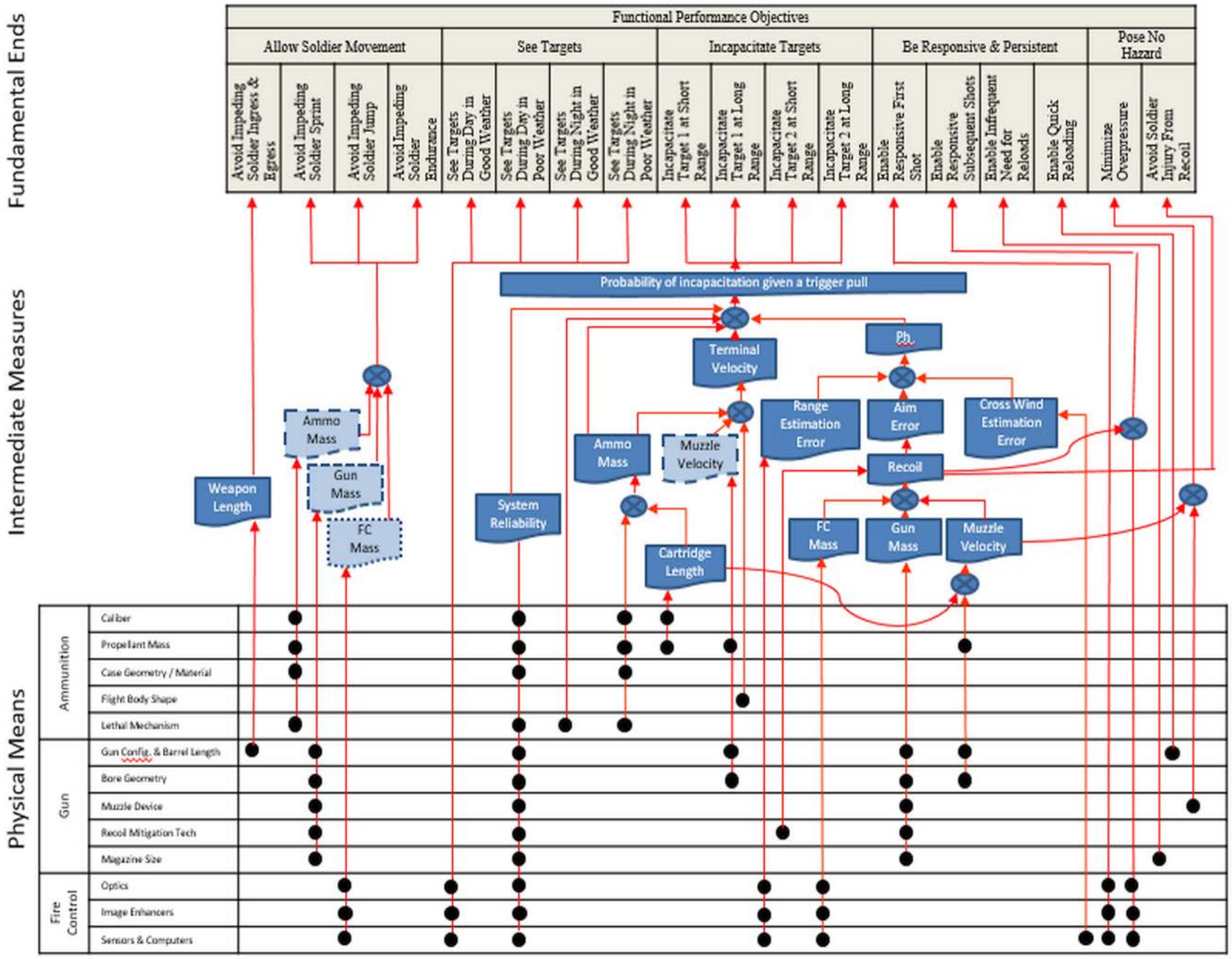


Figure 50. Assessment Flow Diagram

10 MCE IMPACTS ON VERIFICATION AND VALIDATION (UC07)

There was no explicit task to support Verification and Validation (V&V), however MCE can inherently produce information in a more formal way that can enable early and continuous V&V. Rigorously defined models can directly support V&V, and this could both subsume cost and risks. This use case can likely identify candidate requirements for AVCE. Therefore, we added this use case as a place holder, and are considering a potential task that relates to both UC05 and UC03. However, there are a number of possible contribution to various types of V&V. For example, the effort to use SERC RT-176 effort of Monterey Phoenix for V&V of requirements may support some of this effort. The model created by Georgia Tech for RT-170 has other examples illustrating some V&V. If we are able to use the IMCE ontologies for systems engineering from NASA/JPL, then this would provide another avenue to support V&V.

11 ACCESS AS CHIEF ENGINEERING ROLE (UC08)

This use case is created so that one of our researchers, experienced in systems engineering can provide some level of assessment of our overarching approach and contribute to the requirements for AVCE. We too want to bring as many technologies as possible into our lab at Stevens in order to assess the gaps, but are also interesting in bring in Masters students to use methods derived from this research.

This use cases focuses on the requirements and assessment for integrating the tools and methodologies that will constitute the integrated modeling environment based on IoIF, OpenMBEE, and other supporting tools as discussed in Section 12. Specifically, the effort focuses on the Systems Engineering and creation of a "Minimum Viable Demonstrator" at the Stevens. We have now assembled a lab with server machines that are being populated with tools and examples. We are also planning to investigate the use of UC03 using MDAO methods and tools in a Stevens course in the Fall of 2017. Another possibility we are considering for phase two as a stretch goal, is to recruit a student team to do their two-semester capstone design project (aka Senior Design) with the goal of participating in one of the many UAS related design competitions such as http://www.auvsi-suas.org.

12 TRADEOFF ANALYSIS OF TECHNOLOGIES FOR INTEGRATION OR INTEROPERABILITY (UC09)

This use case seeks to support the requirements analysis for AVCE iMBE and demonstrate new concepts for using interoperability to achieve tool-to-tool integration. Specifically, we are looking at the technologies and tools used by ARDEC, as well as other organizations who are creating and evolving their integrated modeling environments. We have a laboratory to support research on the tradeoff analysis of technologies for integration or interoperability in order to further study the technologies and provide demonstrations. Most importantly, the IoIF framework is evolving, and we have provided several demonstrations for both integration and interoperability through SWT (UC00, UC01, UC02, and UC04).

This tasks revisits some of the most advanced tool integrations that have been developed by NASA/JPL [59] [10], the DARPA META projects [8] [7], Engineered Resilient Systems [81], Airbus [76], and generalization of commercial and industry integrated modeling environments.

We have joined Open Collaboration Group for MBSE and OpenMBEE [132] and look to take advantages of the OpenMBEE open source tools. Jeff McDonald performed PTC Windchill [176] analysis for the Army under the SERC RT-152 [106]. We expanded on the Windchill research in support of identifying capabilities for the AVCE iMBE concept. We recently learned of Syndeia by Intercax [167], attended a demonstration on March 7th, 2017 with our ARDEC sponsor. We will look for another plan to continue this research on Syndeia.

12.1 ANALYZING TOOL INTEGRATIONS

We initially started this task looking at the application of a multitude of tools used in modern product development, aligning mostly with MCE. Complexity arises as the volume of the needed tool set and their inter-dependencies increase. The design structure matrix (DSM) has been demonstrated to be very helpful for representing and analyzing the architecture of an individual system, such as a product, a process, and an organization [51]. A DSM is often a two-dimensional matrix representation of the structural or functional interrelationships of objects, tasks or teams. Synonyms for DSM can be N2-Diagram (“N-squared”), and Dependency Structure Matrix. Types of DSM found in use include object-based, team-based, parameter-based, task-based, software module-based, and tool-based.

In this use case, we initially planned to explore the potential of DSM in addressing challenges associated with integrating various tools in product development. However, our researcher did not have detailed insights into many of these tools, several of which have been created by ARDEC to serve very special purposes in their analysis and designs. Rich Swanson in the second working session discussed some of these integrations, but we are not including those details in this report due to the labeling on the presentation material; we are not distributing this material either. Therefore, we have concluded that in order to attempt to do the DSM analysis, we would have need significant support from ARDEC or other experts that can discuss how they use the tools. Therefore, this section describes why and how we would attempt to perform this type of analysis.

12.2 THE DYNAMIC NATURE OF TOOL INTEGRATION

Tool integrations are dynamic consequences of customer requirements. Tool integration are not simply statically putting a certain set of tools together. Depending on the varying needs of tasks from particular stakeholders, the types of tools needed, their execution sequences, the interdependencies of data flow among them vary from case to case. In addition, the problem often gets worse when attempting to maintain an integration for different versions of tools. Figure 51 illustrates the dynamic nature of tool integration [157].

How do you solve this?

- Lack of integration
- Lack of management

March 22, 2015 | CSER 2016, Huntsville

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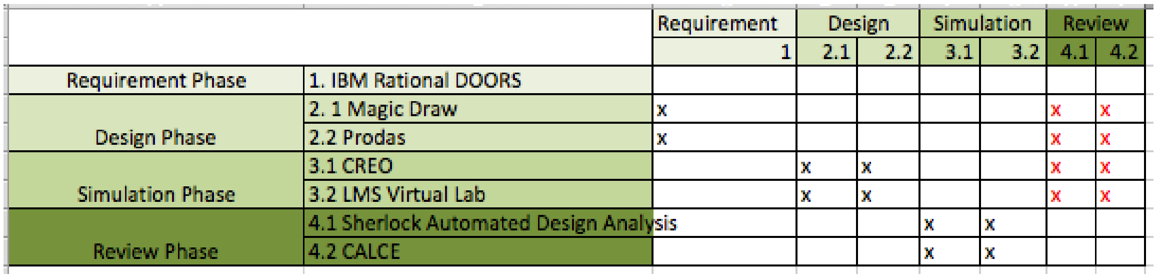
Figure 51. Coordination Across Tools Based on User Story

Given a particular user story, i.e. a requirement, the set of tools needed to be integrated, together with the interwoven relations among them should be computed, represented, and analyzed separately.

12.2.1 THE OVERALL DSM FOR TOOL INTEGRATION

Given a comprehensive set of available tools that may be potentially used in different phases of product development. We can construct a DSM to represent their relationships. As a toy example shown in Figure 52, the rows and columns can represent available tools, ranked in layers following the temporal order that tools can be used in various phases of product development. Each cell in the matrix can represent the dependency between the tool on the row and the tool on the column. For example, CREO (a 3D CAD software) may use the design blueprint created by the Prodas tool (weapon design tool) for 3D visualization, hence, there exist a dependency from the CREO to Prodas.



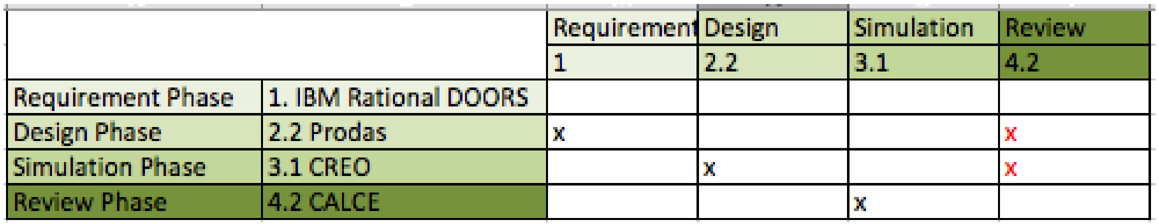
		Requirement	Design		Simulation		Review	
		1	2.1	2.2	3.1	3.2	4.1	4.2
Requirement Phase	1. IBM Rational DOORS							
Design Phase	2. 1 Magic Draw	x					x	x
	2.2 Prodas	x					x	x
Simulation Phase	3.1 CREO		x	x			x	x
	3.2 LMS Virtual Lab		x	x			x	x
Review Phase	4.1 Sherlock Automated Design Analysis				x	x		
	4.2 CALCE				x	x		

Figure 52. Overall DSM for Tool Integration

In general, the dependencies among tools form a hierarchy, where the later phase tools depend on the prior phase tools. However, there are exceptions, where the design and simulation phase tools can depend on the review phase tools. This is because the review phase tools can generate feedback information, which can lead the product development life cycle to iterate back to re-design and re-simulation.

12.2.2 SPLITTING OUT A SUB DSM FOR A USER STORY

For a particular user requirement, i.e. a user story, a sub DSM can be split out from the overall DSM to represent tool integration pertinent to the task at hand. This sub DSM focuses on the necessary tools and their relationship relevant to the particular user story. For example, for a task "X" in a certain problem domain, a sub DSM shown in Figure 53 can be split out from Figure 52 for a more focused view.



		Requirement	Design	Simulation	Review
		1	2.2	3.1	4.2
Requirement Phase	1. IBM Rational DOORS				
Design Phase	2.2 Prodas	x			x
Simulation Phase	3.1 CREO		x		x
Review Phase	4.2 CALCE			x	

Figure 53. Tool Integration Sub-DSM for a User Story

In summary, using the DSM representation, we can represent: 1) the comprehensive inter-dependencies among available tools, and 2) the dynamic integration of any subset of tools for a particular task. Table 2 provides a list of some of the more than 80 tools that are considered for integration or interoperability.

Table 2. ARDEC Tools List

Tool Name	Description
IBM Rational DOORS	Requirements management application
Magic Draw	Business process, architecture, software and system modeling tool with teamwork support MBSE. Also has integration with ModelCenter and OpenMBEE.

AAMODAT	Excel-based spreadsheet tool that supports the decision framework concept as discussed in Section 9
ERS	NA
IMPRINT	NA
D/S ABAQUS/CFD	Provides advanced computational fluid dynamics capabilities with extensive support for preprocessing and post processing provided in Abaqus/CAE.
ANSYS FLUENT	ANSYS Fluent is the most-powerful computational fluid dynamics (CFD) software tool available, empowering you to go further and faster as you optimize your product's performance.
ANSYS FEA/CFD	NA
ANSYS Ansoft (EE/RF)	Design flow that for modeling and simulate complex analog, RF, and mixed-signal applications and perform signal-integrity analysis and system verification of high-performance IC/package/board designs.
LabVIEW	LabVIEW is an integrated development environment designed specifically for engineers and scientists. Native to LabVIEW is a graphical programming language (G) that uses a dataflow model instead of sequential lines of text code, empowering you to write functional code using a visual layout that resembles your thought process.
MSC Suite	NA
LMS Virtual Lab	an integrated suite of 3D FE and multi-body simulation software which simulates and optimizes the performance of mechanical systems for structural integrity, noise and vibration, system dynamics and durability.
MS TFS	The collaboration platform at the core of Microsoft's application lifecycle management solution. TFS automates the software delivery process and gives you the tools you need to effectively manage software development projects throughout the IT lifecycle
Mathworks	Matlab, Simulink, Stateflow
Prediction Probe	Data prediction
JMP PRO	Predictive modeling and cross-validation techniques.
CALCE	A CALCE methodology that uses physics-of-failure based principles and software to assess whether a part/system can meet defined life cycle requirements based on its materials, geometry, and operating characteristics.

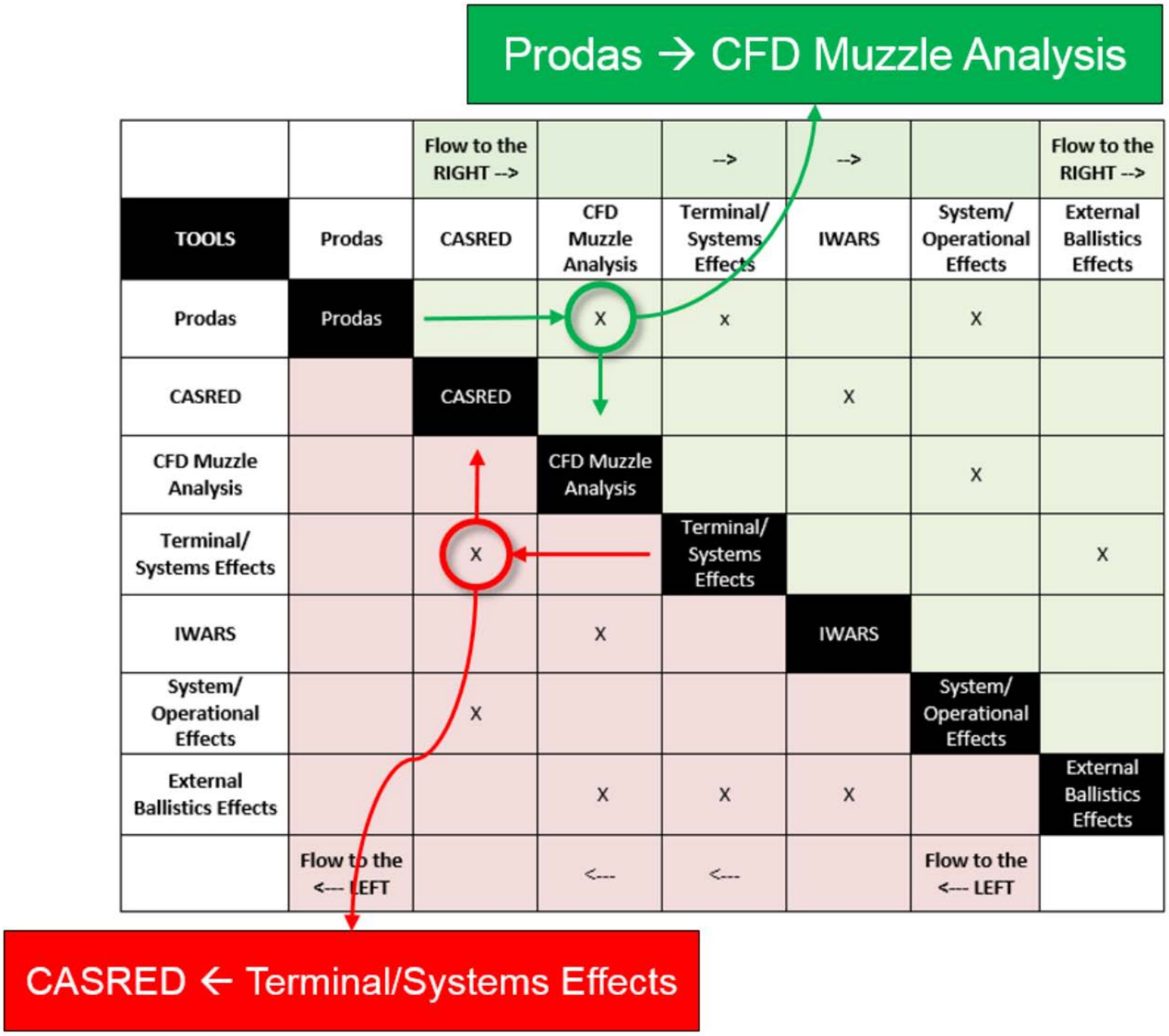
Sherlock Automated Design Analysis	A software tool developed by DfR Solutions[1][2] for analyzing, grading, and certifying the expected reliability of products at the circuit card assembly level.
Erosion	NA
Prodas	Weapon design tool
AutoDesk	An American multinational software corporation that makes software for the architecture, engineering, construction, manufacturing, media, and entertainment industries.
CREO	3D CAD Software

*NA means we didn’t find related information

12.2.3 CAPTURING WORKFLOW INFORMATION USING DESIGN STRUCTURE MATRIX

ARDEC has identified about 85 tools that should be considered as part of various workflows, which cover the entire lifecycle. As shown in Figure 54, they are investigating the use of the DSM concept for capturing information about the numerous workflows that exist at ARDEC.

- Basic question: what tools provide information used by other tools?
- Upper/right portion (Green) - identify sequence from left to right.
- Lower/Left portion (Red) - Identify sequence from right to left.
- Example. Output from Prodas is used as input to CFD Muzzle Analysis.



		Flow to the RIGHT -->		-->	-->		Flow to the RIGHT -->
TOOLS	Prodas	CASRED	CFD Muzzle Analysis	Terminal/ Systems Effects	IWARS	System/ Operational Effects	External Ballistics Effects
Prodas	Prodas		X	x		X	
CASRED		CASRED			X		
CFD Muzzle Analysis			CFD Muzzle Analysis			X	
Terminal/ Systems Effects		X		Terminal/ Systems Effects			X
IWARS			X		IWARS		
System/ Operational Effects		X				System/ Operational Effects	
External Ballistics Effects			X	X	X		External Ballistics Effects
	Flow to the <--- LEFT		<---	<---		Flow to the <--- LEFT	

Figure 54. Example: Output from Terminal/Systems Effects is used as input to CASRED.

12.3 CANONICAL REFERENCE ARCHITECTURE OF AN INTEGRATED MCE ENVIRONMENT

Recalling that a critical element of the first year of this research is to understand the requirements for AVCE iMBE, we believe that the RT-141 final report [22] generalized capabilities heard by many organizations [7] [8] [10] [43] [59] [81] [90] [139] and characterizes a canonical reference architecture of an Integrated MCE Environment, as shown in Figure 55. The following sub-sections discuss various elements from the canonical reference architecture for an integrated MCE environment. The following provides some perspectives and capabilities of this vision concept:

- Provides appropriate views for the various stakeholder
- Stakeholders have views into the Single Source of Truth (SST)
- Using rich modeling interfaces for those with expertise in modeling

- Using rich "web" interface, which today provides support for graphics, integrated with structure inputs, generated textual views and 3D model viewing [144]
- MDAO layer provides for problem and design space exploration of
  - Physics-based models
  - Integrity-based models
  - Cost and scheduling models
  - Risk models
  - Various "illities" models
  - Including surrogates and components
- Enabled by High Performance Computing (HPC)
- Semantically rich linkages between data and information in the SST provides for continuous workflow orchestration – enabled by HPC
- Document generation is enabled by
  - Semantically rich links to information in the SST
  - Templates that formalize patterns for requirements, contracts, etc.
- Enabling technologies such as machine learning provides a virtual knowledge librarian that assist users guided by embedding knowledge and training
- Contractor and collaborators have a secure means to plugin to view or share digital information as a new paradigm for interactions
- This view of the Designing System provides links downstream to fully link Product Lifecycle Management (PLM)

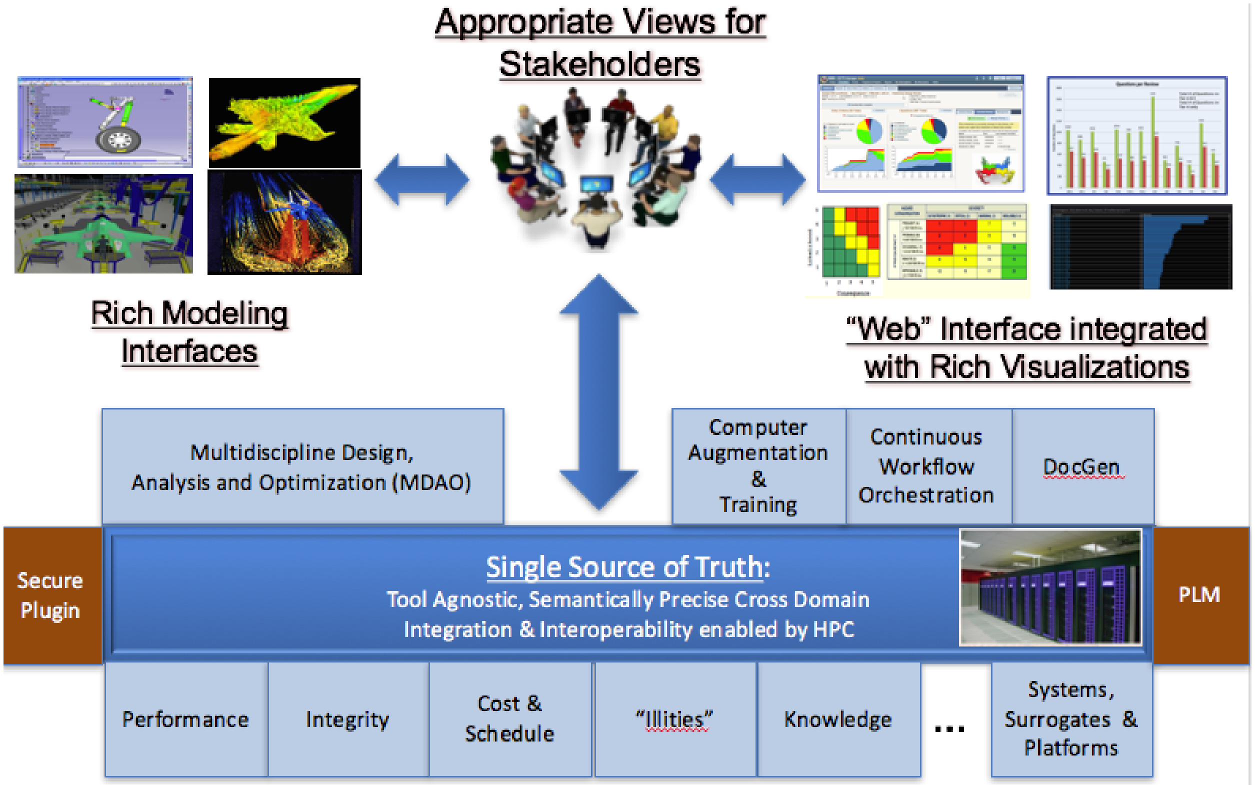


Figure 55. Integrated Environment for Iterative Tradespace Analysis of Problem and Design Space

Therefore, the elaboration of the subtasks as described in Section 12 come from insights gained in discussions from over thirty organizations, related SERC analyses, and new research findings.

12.4 WINDCHILL ANALYSIS

ARDEC is interested in how Windchill can support the AVCE. The RT-152 [106] technical report indicates that PTC Windchill [176] is a capable engineering design data management tool, but it has shortcomings in terms of integration with simulation tools and lifecycle data management. Additionally, Windchill fails to provide the "real-time" linkages to allow data comparison and migration amongst various toolsets. The RT-152 report provides the following summary (non-exhaustive):

- Windchill implementation requires a detailed plan that includes architecture, work process revisions, testing, training, and deployment requirements
- Windchill should only be configured
- Avoid customizations to minimize impact on data migration, support costs, use of third party software, and ability to upgrade versions
- Windchill is an engineering tool that is used by non-engineers
- Windchill is not user friendly and detailed training is required
- Training should be tailored to each class of users

This task has additional research objectives and questions (non-exhaustive):

- Can the current capabilities of Windchill support the AVCE vision?

- How will Windchill data support the concept of the underlying information model?
- What is the interoperability of Windchill with other systems to support the concept of Single Source of Truth (STT)?
- What are the pros and cons of Windchill vs. the concept of domain ontologies using SWT?
- What are the pros and cons of Windchill vs. other potential COTS solutions (i.e. Syndeia) for achieving the AVCE vision?

Preliminary analysis to these questions suggests that:

- Windchill can address some aspect of the AVCE Vision
- Windchill is a powerful PDM tool that provides the backbone for PLM
- Windchill integrates many design tools (mechanical CAD, electrical CAD, enterprise resource planning [ERP], and MS Office)
    - The user defined relationships allow linking artifacts to create an integrated database
- Windchill has partnered with many leading software designers to offer adaptors to link data to third party software (IBM Doors, Solidworks, ThingWorx)
- If no partnership exists, Windchill supports importing and exporting of engineering data in multiple formats to support use in third party or custom software
    - This relationship is not linked to source data
- Windchill has complicated user interface that requires extensive training
    - One user termed it, "An engineering tool that must be used by non-engineers."
- Windchill cannot achieve SST as a stand-alone product
- PTC offers complimentary software that when combine may support a SST within the Windchill environment (e.g., PTC Integrity Modeler, PTC Windchill Project Link, PTC Windchill Parts Link)
- PTC Navigate (compatible with Windchill v10.1 and later) offers a user friendly html based interface for viewing and accessing part and document data stored within Windchill
- PTC has recently developed multiple partnerships to leverage advances in Internet of Things (IoT) software to integrate disparate data sources

Our early assessment suggests that Windchill can provide support of the underlying information model:

- Windchill currently integrates the product information from multiple software tools and can export this data in its native form or as metadata
- Windchill could potentially be used as one of the main sources for data/metadata for the information model
    - Non-integrated software data could be fed to the information model separately
- A hybrid solution could use Windchill as a software source for the data acquisition and aggregation layer to support the High Level Framework Concept

Table 3 provides a summary of the current analysis:

Table 3. Comparison of Approaches Related to Windchill

	Windchill	PTC Software Suite	Ontologies	Syndeia
Achieves SST	Poor	Good	?	?
Supports Information Model	Excellent	Excellent	?	?
Supports Decision Framework	?	?	?	?
Tool Integration	Good	Excellent	?	?
User Interface	Poor	Good	?	?
Expertise to Setup/ Maintain	Good	Fair	?	?
Commercial Availability	Excellent	Excellent	Poor	Good

🟦	**Excellent**
🟩	**Good**
🟨	**Fair**
🟥	**Poor**
?	**Under Evaluation**

This section also includes a description of Syndeia in Section 12.5, which has relationships to Windchill and other tool integrations. Section 12.7 discusses another example using the Airbus Space's Digital Environment that includes Windchill. We will look at other approaches such as data interoperability, and specifically investigating if Windchill can support the SWT approach or can operate using a publish/subscribe approach flowing data to Windchill for the information model via proxies as discussed in Section 12.8.

12.5 SYNDEIA

Syndeia is a software platform for MCE. It seeks to enable engineering teams to collaboratively develop and manage a system model. It provides a means to combine a system architecture model defined in languages such as SysML with models in other MBE domain, including PLM (e.g. Teamcenter, Windchill), CAD (e.g. NX, Creo), Application Lifecycle Management (ALM) (e.g. GitHub), Project Management (e.g. JIRA), Requirements Management (e.g. DOORS-NG), Simulations (e.g. Mathematica and MATLAB/Simulink), Databases (e.g. MySQL), and other data sources (e.g. Excel).

This subtask looks to assess the comprehensiveness of this approach in the context of ARDEC's needs, and researching viable commercial alternatives to a SWT approach. Specifically, we are looking into PTC software toolsets (PTC Link) and Interval Syndeia. Early paper analysis on Syndeia suggests this may offer a potential solution or partial solution based upon its ability to integrate other third party software. Specifically, we are interested if proprietary simulation tools can be integrated into Syndeia. The demonstration of Syndeia to ARDEC and the RT-168 team was held on March 7th, 2017. We have requested academic licenses for further analysis. We do know that organizations like NASA/JPL are using Syndeia in the context of OpenMBEE, which is described in Section 12.6.

The concept of a federated set of software tools allows for repositories that are optimized for the type of data that each specific tool can store and the workflows that create and manage that type of data. A tool like Syndeia can facilitate the mining of relationships across these domain specific repositories that allows one to build system level models to facilitate the design and analysis at the system level. Because this can be done in "real time," with what is going on at the engineering design level, it opens up for new ways of doing system engineering to better link across domains. Instead of a traditional "top down" approach, which prescribes the "specification" of the components due to (a mostly unreliable) step by step process of transforming user needs into lower level specifications, it now be a much more fluent and adaptive process of guidance and facilitation using existing assets, modified assets and new assets as needed. Our research team need to see how this paper analysis aligns with the realities of how this type of integration can support a different operational paradigm for systems engineering. However, creating a laboratory with some of the kinds of tools that integrate through Syndeia may be challenging in the university environment.

12.6 OPENMBEE AND OPEN COLLABORATION GROUP FOR MBSE

We recently joined the Open Collaboration Group for MBSE that is providing support for adopting and contributing to OpenMBEE [132]. We are planning to use OpenMBEE in our lab. OpenMBEE, as shown in Figure 56, is an open source platform for modeling that utilizes the Model Management System (MMS) that can be accessed from rich SysML desktop clients like MagicDraw, and light-weight web-based client like View Editor. It provides infrastructure for fine-grained versioning (i.e., at the object level, not the file level), workflow management, and access control. OpenMBEE facilitates multi-tool and multi-repository integration across engineering, computing, and management disciplines. OpenMBEE provides the core allowing tracking relations between heterogeneous data sources in a linked data architecture. System models are constructed, queried and rendered following the view and viewpoint paradigm. OpenMBEE was started by NASA/JPL, but is open sourced and there is growing community that includes industry users and contributors (e.g., Boeing, Lockheed Martin).

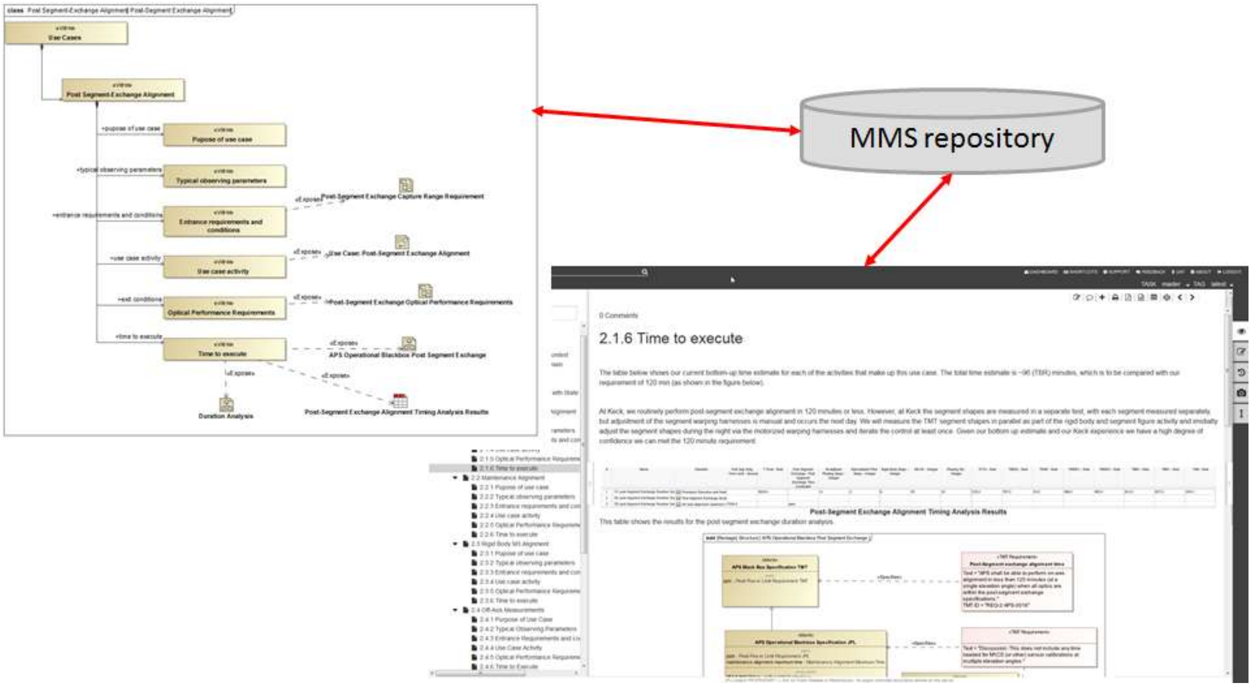


Figure 56. Conceptual Elements of OpenMBEE

We will highlight a few parts of an instantiation of OpenMBEE as shown in Figure 57. ModelCenter, supporting MDAO is part of the environment. They formalize the System Engineering modeling methodology through model patterns [40] [109] that are captured through ontologies using SWT. The approach is associated a SysML-profiled modeling tool approach that not only guides development, but provides model analysis to ensure compliance with the patterns (e.g., models are well-formed, consistent, etc.) [90]. There is a video training module [91] that provides details about this concept and tooling.

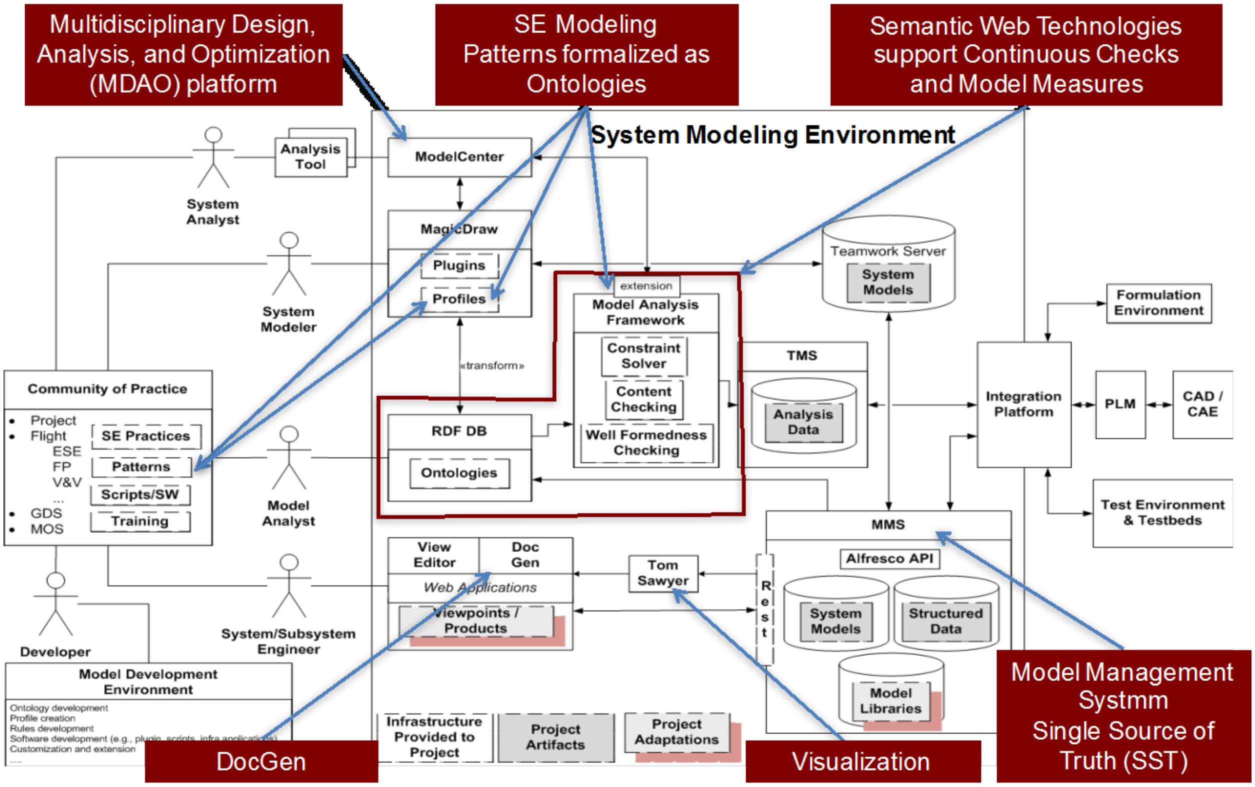


Figure 57. OpenMBEE Instantiation (2014)[118]

They formalize at least 25 modeling patterns applicable to systems engineering in ontologies using the standard Web Ontology Language (OWL) [179] to provide a way of defining a set of concepts and properties applicable to the domain of discourse of Systems Engineering such as: component, function, requirement, and work package, data properties like mass and cost, and object properties (relationships) like performs, specifies, and supplies. This provides for a controlled vocabulary and enforcing rules for well-formedness, which permits, among other things, interdisciplinary information integration, and automated analysis and product generation. Because the SE ontologies are expressed in OWL, they are amenable to formal validation (syntactic and semantic) with formal reasoning tools. The approach embedded in SysML and the OWL ontologies is created by transformations from SysML models [90]. Once a model is completed other transformations are performed to the model, such as checking properties of well-formedness and consistency of the model. They currently have about 60,000 test cases for checking these types of properties. The approach is illustrated in several case studies [109]. Finally, we are also interested in the approach for automatically generating a specification from a model, and will experiment with using the MDK plugin [111] with DocGen through MagicDraw.

12.7 DIGITAL ENVIRONMENT AT AIRBUS SPACE

We have discussed the importance of an underlying information model to enable the cross-domain integration of information in a single source of truth [22]. Ralf Hartmann, the Vice President of Enterprise Digitization gave a technically detailed and highly relevant presentation at the NASA/JPL Symposium and Workshop in Jan 2017 [76]. While there were many points, of particular interest was a historical perspective on how they have been assembling a system design engineering environment to cover the entire lifecycle. The representation of the environment as shown in Figure 58 was particularly interesting as it relates to the concept of a semantically rich information; this pertains to the box in the middle call RangeDB Data Management. This is a relatively recent development where they replaced a commercial product with their own infrastructure functionality (i.e., “secret sauce”) that provides a Semantic Data Model for multi-disciplinary Integration as shown in Figure 59. We did discuss this with a person from Airbus at the event, and asked about the strange name (i.e., RangeDB), and he said it was “historical.” This effort confirms why we believe SWT will play a key role to characterize the underlying information model for both ARDEC and NAVAIR, and again reflects positively on the NASA/JPL use of SWT as discussed in Section 12.6.

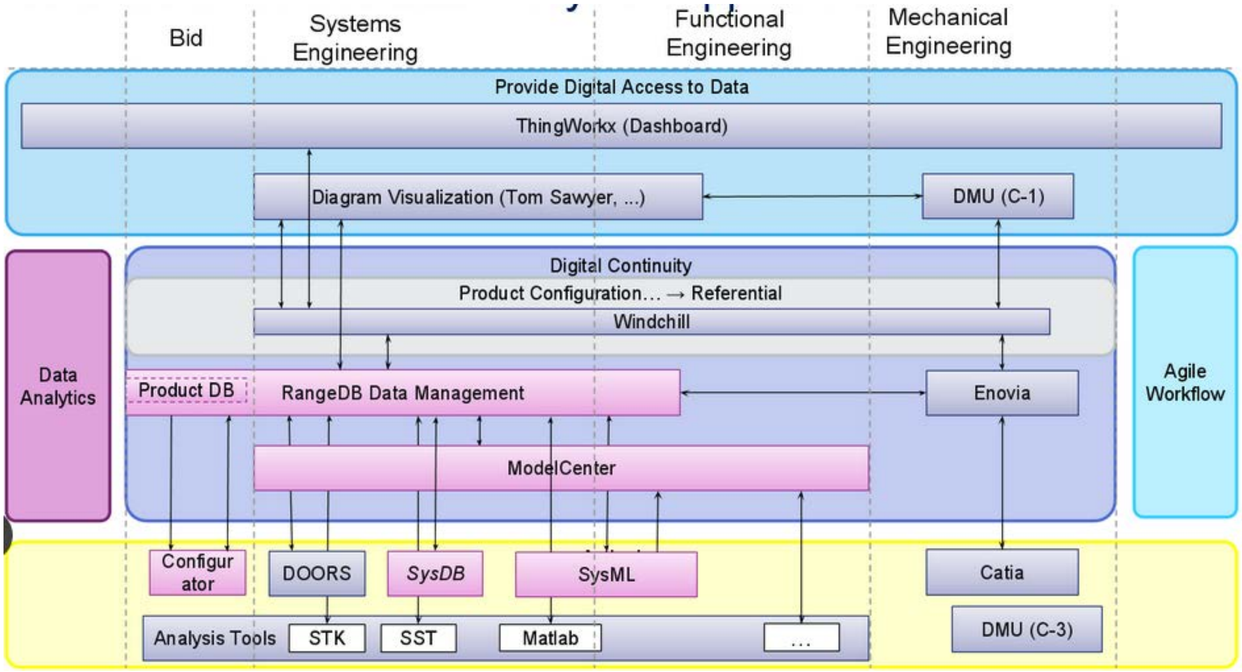


Figure 58. Airbus Digital End-to-End (System & Product) Engineering

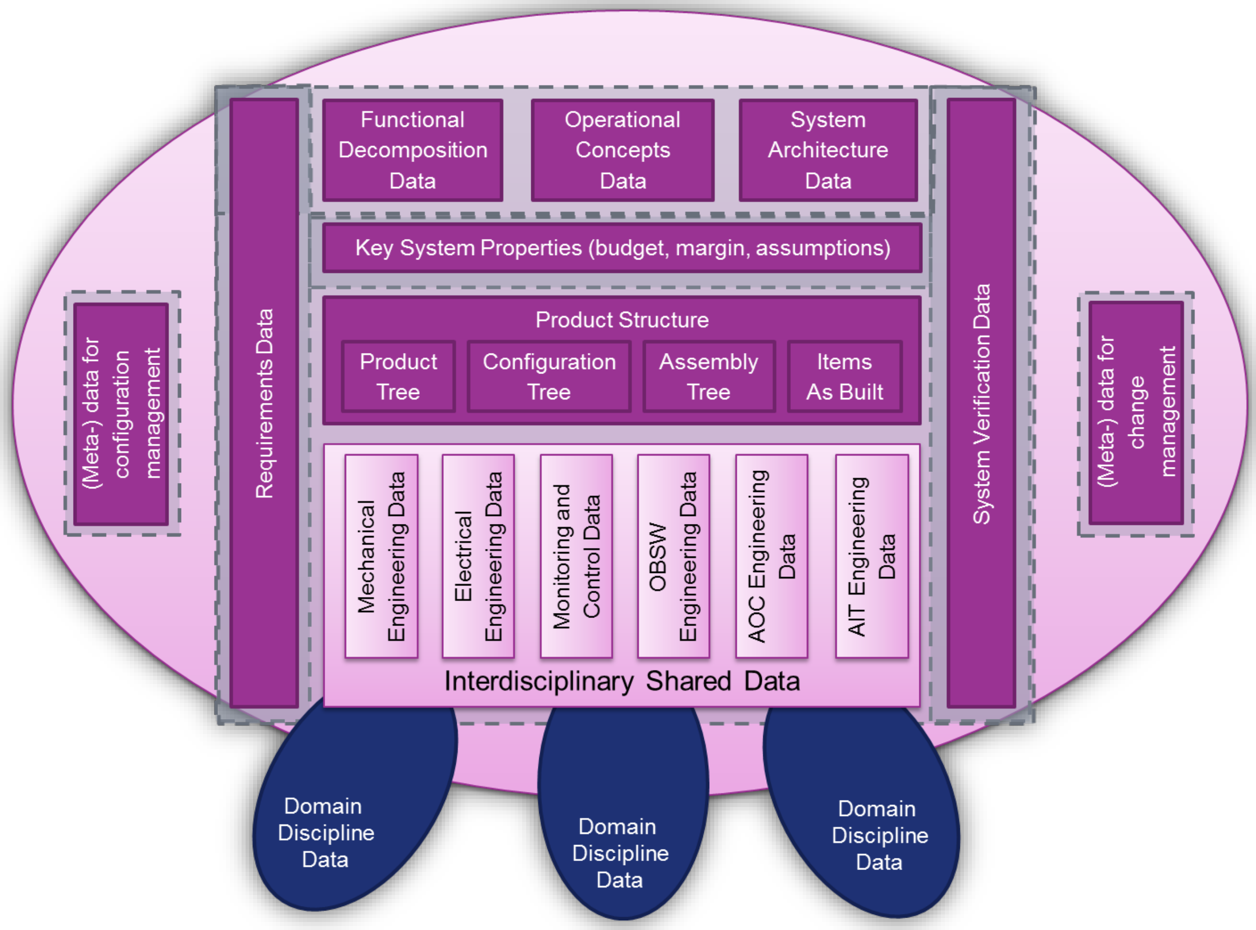


Figure 59. Semantic Data Model for Multi-Disciplinary Integration

Finally, the Hartmann briefing also included an associated roadmap as shown in Figure 60 that was structured in two dimensions:

- Technology clusters
  - Requirement engineering & V&V
  - MBSE and design
  - Engineering data lifecycle management
  - Collaborative engineering
- System engineering technology integration levels
  - Data integration (just connecting data)
  - Semantic integration (identifies rules how to connect and understand data)
  - End-to-end (knowledge management)

The key reflection on this roadmap is acknowledging the increased need to formalize the underlying information model as we move to the right (i.e., future), which can exploit more computational automation enabled by high performance computing.

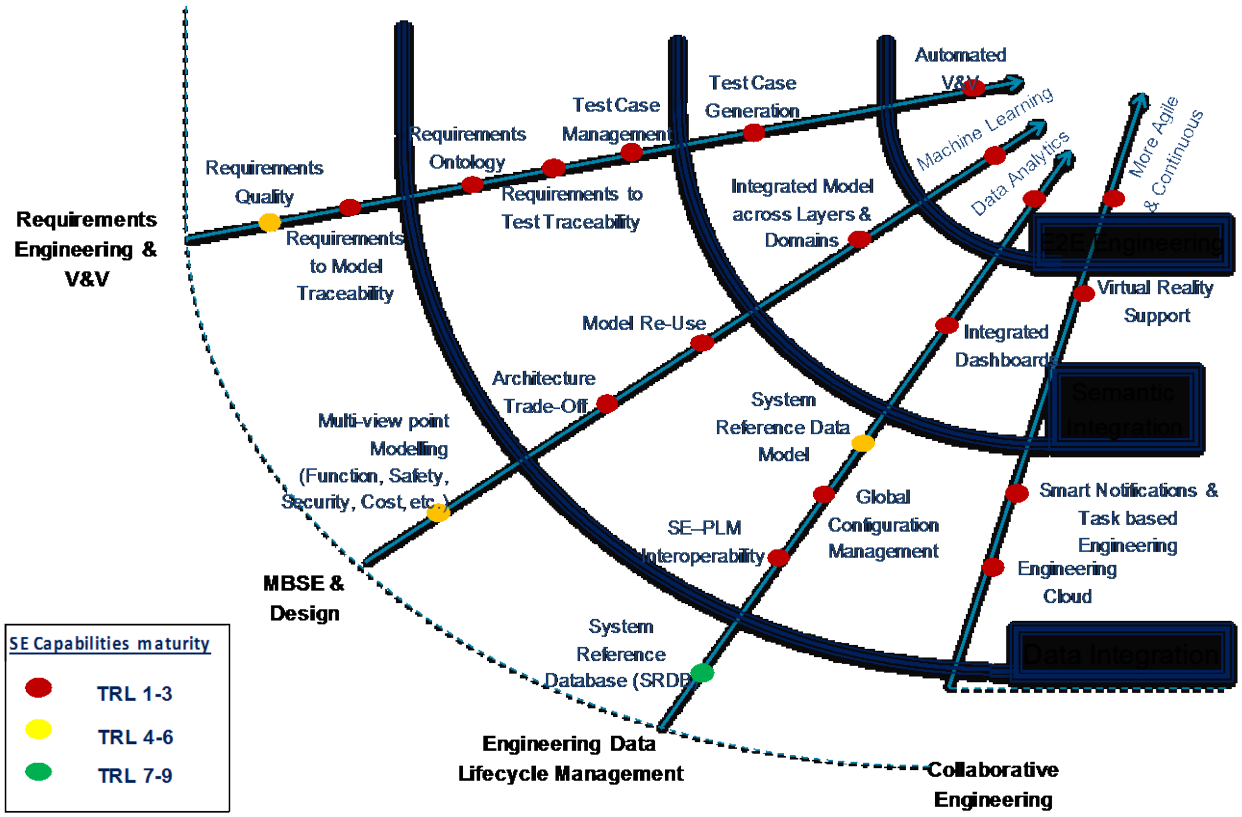


Figure 60. Airbus Roadmap Shown Bands of Digital Engineering Integration

12.8 RT-168 TOOL-TO-TOOL INTEGRATING AND INTEROPERABILITY FRAMEWORK

Given the context about integrated modeling environments, we have been able to assemble some relevant tools. Our researcher Roger Blake also runs a laboratory and can provide the resources to experiment with both tool-to-tool integration, as well as operational models. This section discusses the evolving state of those integrations by providing an overview of Tool-to-Tool Integrating and Interoperability Framework (IoIF).

The IoIF under UC01, UC02, UC3 and UC04 provides some software tool(s) and data acquisition functionality, but we will need to coordinate the ideas of what their software tools are calculating so that we have consistency from the data output of the software tools and into the VR-Forces Simulation Model [103]. This framework is being designed to be used with various software tools and various simulation environments. As reflected in Figure 61, the immediate goals are:

- Abstracts away from the software client tools as much knowledge and dependencies of the tool-to-tool data integration architecture as possible
- Allows for tool-to-tool data integration on computer systems that are physically remote from each other
- Uses an ontology framework (i.e., SWT) that implements an automated decision process regarding tool/data relationships

- Uses a Publish / Subscribe framework that implements an automated data transport layer between various software client tools
- Creates a storyboard regarding the prototypes purpose
- We need to understand how we can leverage OpenMBEE

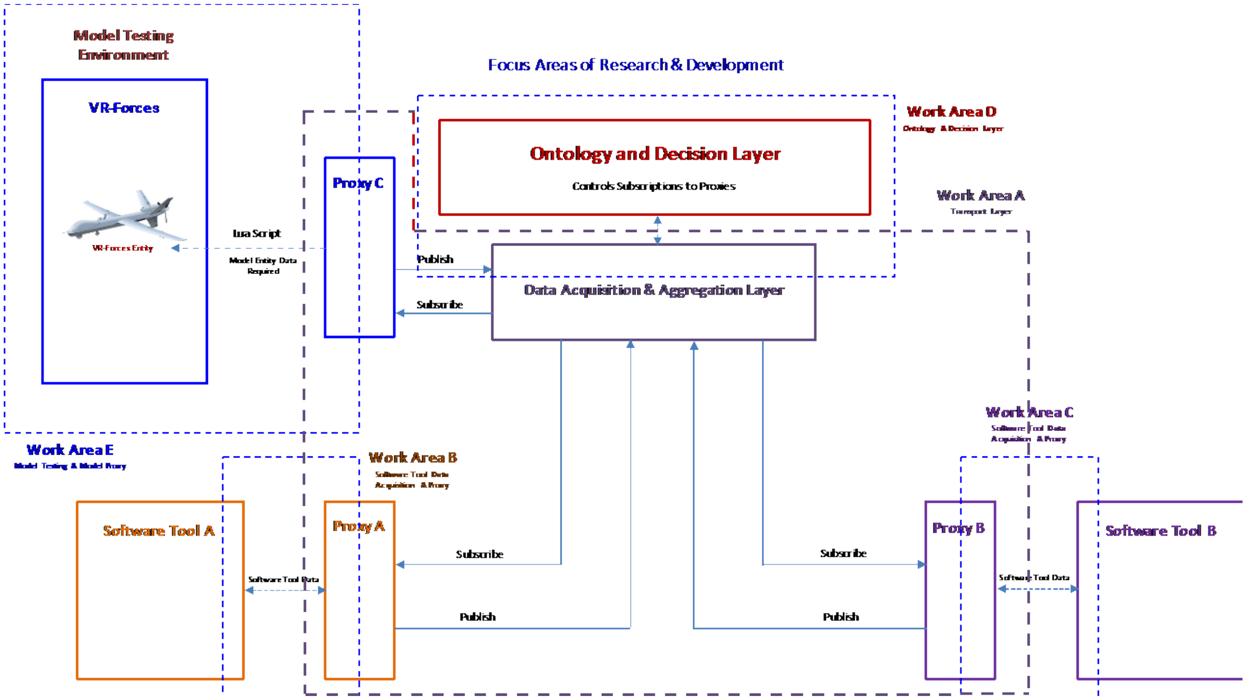


Figure 61. RT-168 Tool-to-Tool Integration and Interoperability Framework

13 RESEARCH SEMANTIC WEB TECHNOLOGIES APPLIED TO AAMODAT (UC10)

This use case relates to UC00 and UC06, and the new challenge area #5. The plan is to develop an initial ontology that will demonstrate the ability of ontology driven SWT to parse, infer, and restructure data for input into the AAMODAT excel file. The sUAV case developed my Matt Cilli created for the Engineering Resilient System (ERS) research may work well for the ontology demonstration. To develop an ontology, we need to understand the data that we need to parse (documents, data bases, standards, etc.) and then we need to understand how we need to put it back together (restructure) it for AAMODAT. These elements would include:

- Objective hierarchies
- Value functions
- Assessment Flow Diagrams (AFDs) trace the relationships between physical means, intermediate measures, and fundamental objectives
- Uncertainties

The demonstration and discussion at the third working session covered how AAMODAT is usually something that happens early on for ARDEC, and all over the project. It has helped to identify Key Performance Parameters (KPPs) at the mission level and the elements from the sub-domains that are relevant to those KPPs. 'All requirements are tradeable,' but looking at how much they contribute to the KPPs, is a different way of thinking.

In the "old" process of AAMODAT – with the given objectives, Measure of Objectives, etc. we had to go to SMEs to populate data in AAMODAT. SMEs would look at historical data and tools to provide the information. Matt Cilli believes most of this can be automated, but still some SME augmentation is required to sign off or to choose an option (i.e., identifying the objective functions) as illustrated by Mary's demonstration.

The demonstration using SWT and DBpedia provided good support for this concept. DBpedia is a crowd-sourced community effort to extract structured information from Wikipedia, which make this information available on the Web in a SWT-compliant manner. Mary used a DBpedia database populated with aircraft data. DBpedia employs its ontology to go to Wikipedia (that has both structured and unstructured data), grabs data and bring it in to DBpedia as RDF data (base data format for SWT). Turtle, OWL are RDF formats. Once data is inside DBpedia, it is ready to be queried.

- Web Ontology Language (OWL) can be thought of as a type schema
- Resource Description Framework (RDF) is a standard model for data interchange on the Web; think about RDF as the data elements that should be compliant with an ontology defined using OWL
- Turtle (Terse RDF Triple Language) is a format for expressing data in RDF
- Examples were presented at the demo

The demonstration illustrated concretely with visualization using Protégé, the DBpedia ontology, which is a class structure. In DBpedia, 'aircraft' is a subclass of 'means of transportation' and so, it inherits all properties of the class above it. The demonstration used the Protégé tool, which is an open source ontology editing tool, and DBpedia, which does a lot of background checking to the data that it pulls is from Wikipedia.

14 ASSESS AVCE IMBE (UC11)

Mark Blackburn was requested by ARDEC to provide a peer review of the Requirements for AVCE iMBE. The material provided were traditional text-based requirements. Our first major comment was that if we are moving away from document-centric requirements, then we should develop a model for such requirement, much like the OpenMBEE model. Mark during the review added some packages to the RT-168 MagicDraw SysML model and started adding use cases implied by the textual requirement statement. We also added other use cases and some associated relationships derived from our knowledge of those environments, including OpenMBEE. We supplied the model to ARDEC, and have received their model of requirements for AVCE iMBE, but have not had an opportunity to thoroughly review the model.

While ARDEC has finished the SRR for AVCE iMBE, we asked Rick Dove to join RT-168 research team, because Rick has done some interesting work on the INCOSE's Agile Systems Engineering Life Cycle Model (ASELCM) project, and specifically, the ASELCM Pattern of Three Concurrent Systems. Agile systems engineering encompasses three nested concurrent systems, depicted in Figure 62 as an iconic pattern. The pattern is the work of Bill Schindel, a principle co-author in the ASELCM case studies. The ASELCM Pattern establishes a set of system reference boundaries. Whether the systems of interest are small or large, human or inanimate, flying through the air or performing business processes.

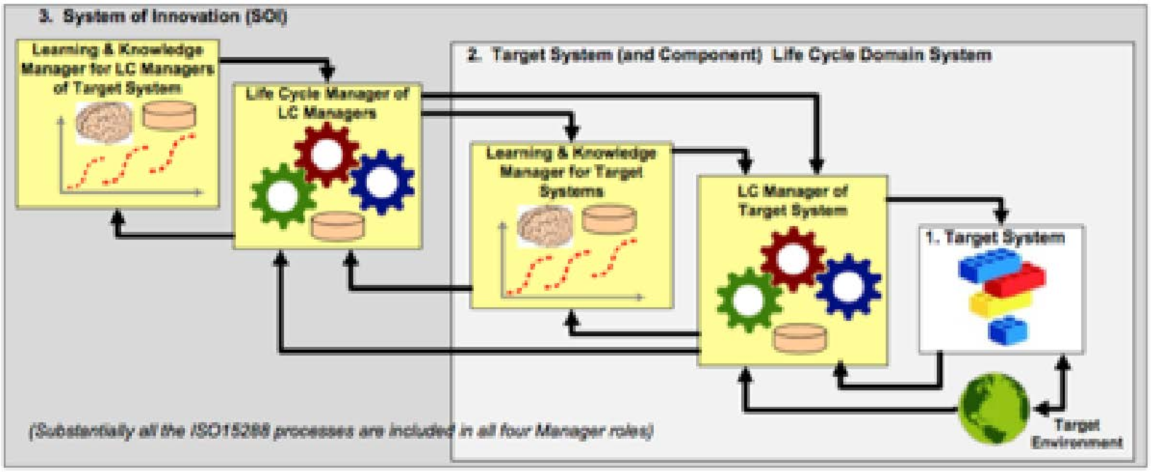


Figure 62. Notional Relationships of Systems 1, 2, and 3 [154]

This ASELCM Pattern particularly refers to three major system reference boundaries, and within those, six subsystem reference boundaries. These are all logical boundaries (defined by the behavior, not the identity, of systems):

- System 1: The Target System, the subject of innovation over managed life cycles of development, deployment, and support.
  - Normally, one would think about the target system as the one that ARDEC would deploy (e.g., fire control, munitions)
  - In this case, however, the target system is AVCE iMBE
- System 2: The Target System Life Cycle Domain System, including the entire external environment of the Target System—everything with which it directly interacts, particularly its operational environment and all systems that manage the life cycle of the Target System. This includes the external environment of the operational target system(s), as well as all the (agile or other) development, production, deployment, support, security, accounting, performance, and configuration management systems that manage System 1.
- System 3: The System of Innovation, which includes System 1 and 2 along with the systems managing (improving, deploying, supporting) the life cycle of System 2. This includes the systems that define, observe, analyze (as in agile software process retrospective), improve and support processes of development, deployment, service, or other managers of System 1. System 1 is contained in System 2, which is contained in System 3. All are (or at least should be) happening simultaneously, effectively an organic complex system motivated by self-preservation to evolve suitably in an uncontrolled operational environment. Think of the arrow-pointed pipes of Figure 62 as a circulatory system.

15 SERC RESEARCH SYNERGIES

An early request of ARDEC was for our research team to help them increase awareness and synergies with other organizations. This section discusses some synergies to the ongoing ARDEC research tasks that are briefly mentioned in this report to inform readers of the relationships to these other activities.

15.1 RT-170 NAVAIR SYSTEMS ENGINEERING TRANSFORMATION THROUGH MODEL CENTRIC ENGINEERING

There are many related research efforts between ARDEC and NAVAIR, as well as other government organization that are working towards and SE transformation using MCE. However, the domains and concern are different way, therefore, we are working with different and complementary researchers to cross-pollinate the results. This includes:

- Strategies related to MBSE supported by our Georgia Tech collaborators (Dr. Russell Peak, Steven Edwards)
- Approaches to use SWT investigating cross-domain integration, requirements ontologies, Natural Language Processing of requirements, supported by Mary Bone and our University of Maryland collaborators (Dr. Mark Austin, Dr. Leonard Petgna)
- MDAO examples of UAVs

15.2 RT-176 VERIFICATION AND VALIDATION (V&V) OF SYSTEM BEHAVIOR SPECIFICATIONS

Our NAVAIR sponsor had requested that the SERC RT-176 research task being led by Dr. Kristin Giammarco be aligned with the ongoing research from RT-157 and RT-170. RT-176 aims to leverage and extend existing research in the area of methods, processes and tools for performing early Verification & Validation (V&V) of requirements and architecture models managed within its organization, and to educate its workforce in the use of automated tools for conducting early and continuous V&V across the entire lifecycle. We have shared our UAV system model and hope that this model will be developed as a surrogate to actual systems under development at NAVAIR for use as a case study to test new or improved methods, processes and tools that are developed based on those summarized in the background and as a result of this task, which are expected to apply to other systems in many domains throughout DoD.

15.3 AEROSPACE INDUSTRY ASSOCIATION CONOPS FOR MBSE COLLABORATION

This is a follow-up to the effort completed last year which developed a white paper on the Life Cycle Benefits of Collaborative MBSE Use for Early Requirements Development[3]. This white paper discusses the current state and benefits of MBSE across the entire life cycle and provides proposals for addressing such issues as MBSE Collaborative Framework, Government Data Rights, Intellectual Property, and Life Cycle Effectiveness with MBSE.

The effort for this year involves many of the industry contractors to NAVAIR and DoD. The results should produce a white paper describing a CONOPS for how industry and government can collaborate through MCE/MBSE.

15.4 OPENMBEE AND OPEN COLLABORATION GROUP FOR MBSE

We recently joined the Open Collaboration Group for MBSE that is providing support for adopting and contributing to OpenMBEE [132]. We are planning to use OpenMBEE in our lab, and contribute to the community effort in order to advance it with capabilities developed under RT-168, RT-170 and RT-176.

15.5 SEMANTIC TECHNOLOGIES FOUNDATION INITIATIVE FOR SYSTEMS ENGINEERING

The NASA/JPL Symposium and Workshop on MBSE had a keynote talk given by Steve Jenkins that was fundamentally based on SWT and a foundational ontology for Systems Engineering as discussed in Section 3.1. There were also two breakout session on the subject SWT. There was significant attendance at the break out session title: “Ontologies, Formalisms, & Reasoning” possibly due to the motivation given by Steve Jenkins. In general, there is progress being made in this area and there is significant interest. Dinesh Verma has initiated an effort with the support of Steve Jenkins and Mark Blackburn to bring a community of people together in an attempt to create and ecosystem on Semantic Technologies.

The working group has created a charter and mission:

- Charter
    - The Semantic Technologies Foundation Initiative for Systems Engineering is to promote and champion the development and utilization of ontologies and semantic technologies to support system engineering practice, education, and research.
- Mission
    - The mission of the initiative is to collect a suite of interoperable ontologies that are logically well-formed and accurate from both scientific and engineering points of view. The initiative will charter a collective of stakeholders that are committed to collaboration and adherence to shared semantic principles for the advancement of systems engineering. To achieve this, initiative working group participants will voluntarily adhere to and contribute to the development of an evolving set of principles including open use, collaborative development, and non-overlapping and appropriately-scoped content. They will capture and maintain metadata for each ontology to encourage implementation and reuse.

15.6 DIGITAL ENGINEERING WORKING GROUP

We are also participating in the Digital Engineering Working Group, in which both NAVAIR and ARDEC are participating. The Office of Deputy Assistant Secretary of Defense for Systems Engineering (ODASD(SE)) formalized the goals, which are:

- G1. Formalize the development, integration and use of models to inform enterprise and program decision making.
- G2. Provide an enduring authoritative source of truth.
- G3. Incorporate technological innovation to link digital models of the actual system with the physical system in the real world.
- G4. Establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders.
- G5. Transform a culture and workforce that adopts and supports Digital Engineering (DE) across the lifecycle.

These goals are working toward realizing the benefits that were found in Phase I and identified at a recent Government-Industry DE forum conducted by the SERC and the Office of the Deputy Assistant Secretary of Defense for Systems Engineering. The benefits of a DE transformation are [46]:

- Improved Acquisition – by accepting digital deliverables could improve the governments understanding of a projects status and risk along with allowing them to “validate” the contractor’s deliverables.
- Improved Efficiency and Effectiveness – reduce time and effort in the performance of existing tasks using a single source of truth for the system.
- Improved Communication; Better Trade-Space Exploration; Reduced Risk – using ontology-based information models to translate and extract useful information between a variety of models and model types could allow for improved communication among specialists. This enables the goal of the DoD to establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders.
- Improved Designs and resulting Systems and Solutions – being able to understand the impact of requirement and/or design decisions early could help improve the overall system design and identify adverse consequences of the design before committing to a design choice. This enables the DoD goal to formalize the development, integration and use of models to inform enterprise and program decision making through an authoritative source of truth.

The special session on ***Systems Engineering Transformation through Model Centric Engineering Past-Why, Present-What, and Future-How*** held on July 31st at Stevens with our ARDEC and our Office of the Deputy Assistant Secretary of Defense for Systems Engineering sponsors, included some other special guest from Digital Warfare Office, Naval Surface Warfare Center, MITRE and Raytheon. We had a breakout session looking at the risk and priorities associated with the mapping future research areas to goals of digital engineering transformation strategy as shown in Figure 63.

Future Research Areas	G1. Formalize the development, integration and use of models to inform enterprise and program decision making.	G2. Provide an enduring authoritative source of truth.	G3. Incorporate technological innovation to link digital models of the actual system with the physical system in the real world.	G4. Establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders.	G5. Transform a culture and workforce that adopts and supports DE across the lifecycle.
Cross-discipline integration of models to address the heterogeneity of the various tools and environments using semantic technology	X	X	X	X	X
High Performance Computing (HPC) advancements such as; 1) supporting organizing and analyzing "Big Data" and 2) being able to program in parallel to take advantage of HPC capabilities, are needed to support the DE effort	X	X	X	X	
Model integrity to ensure trust in the model predictions by understanding and quantifying margins and uncertainty	X	X	X	X	X
Modeling methodologies that can embed demonstrated best practices and provide computational technologies for real-time training within digital engineering environments	X		X	X	X
Model composability to understand the possibilities, constraints and rulesets for composition of multiple models	X		X		
Human-model task allocation to understand what activities are best performed by human decision makers and what can effectively be automated or augmented with model intelligence					X
Workforce development to understand what is needed to educate model developers, users and decision makers to work in a DE environment					X
MCE acquisition to understand the needed changes to acquisition and security when developing in the new DE environment	X	X		X	X

Figure 63. Mapping Future Research Areas to Digital Engineering Transformation Goals

15.7 NATIONAL DEFENSE INDUSTRY ASSOCIATION MODELING AND SIMULATION

National Defense Industry Association (NDIA) Modeling and Simulation group is looking at approaches for using digital engineering for competitive down select. We are involved in all of these efforts to further the objectives of our sponsor in August of 2016 [120].

15.8 SYMPOSIA AND WORKING GROUPS

The RT-168 researchers have also attended a number of events, not necessarily funded under RT-168, however, these events do have relevance to informing our research, and we have delivered meeting notes related to these events which include:

- NASA/JPL Symposium and Workshop on Model Based System Engineering, January 25-27, 2017.
- MBSE-related Events at INCOSE International Workshop, January 28-31, 2017.

16 PART II SUMMARY

This final technical report summarizes the accomplishments for this Phase I research. The report also outlines the refinement of the tasks with a mapping to evolving use cases that associate the roles of the various researchers and ARDEC stakeholders to other linked use cases to show a non-exhaustive set of dependencies. These dependencies reflect on cross-domain concerns, where discipline-specific stakeholders will ultimately use different technologies, methods and associated analyses. We think this collective set of use cases that are being researched in the context of various related UAV/UAS operational scenarios and case studies are helping us understand both technology and socio-technical concerns that can provide inputs to operational scenarios and requirements for AVCE iMBE.

This report includes the updates characterizing demonstrations, deliverables, reports and research analyses presented during the bi-weekly status meeting, as well as the information presented at five working sessions, one special event, and 19 virtual meetings that include, but are not limited to:

- Demonstrations of concepts, technologies and framework to leverage integration and interoperability that provides computationally enabled systems engineering to address the challenges of cross-domain model integration of increasingly complex cyber physical systems
- Demonstrations of mission and system-of-system engineering analysis for new operational approaches such as graphical CONOPS through mission-level, system-level, and component-level model-centric engineering
- Bringing concepts developed by NASA/JPL OpenMBEE and specifically the Model Development Kit (MDK) DocGen component, where we have developed a number of View and Viewpoint hierarchies for using DocGen, including generation of the “specification” for AVCE iMBE
- Concept for integrating Graphical CONOPS gaming technology to expose functionality, interfaces, controls, and parametric details that are going to be analyzed using Multidisciplinary Design, Analysis and Optimization at the mission-level
- Characterizing metadata extracted from the Early Synthetic Prototyping (ESP) work to inform the information model that captures measures associated with human interaction of ESP and more generally concepts such as the graphical CONOPS
- SWT application to the Decision Framework and AAMODAT and formalization of a concept for using MDAO workflows to represent the Assessment Flow Diagrams in a formal way that could be automatically extracted from SysML models to populate SWT for automating the population of AAMODAT
- Provides methodological guidance for identifying Key Performance Parameters
- Facilitated several research synergies both SERC (e.g., NAVAIR and non-SERC (NASA/JPL, commercial) to increases ARDEC’s knowledge and leverage insights and foster synergies from other organizations we have been able to leverage
- Facilitate the acquisition and application of “high-end” MCE commercial technologies to ensure that the research questions are posed in the context of the most advanced technologies used by government and industry

- Align ARDEC and NAVAIR research with the DoD Digital Engineering Transformation Strategy

We are currently working with our ARDEC sponsors to define specific plans for RT-168 Phase II (August 2017 through August 2018) that still fundamentally align with the current set of use cases, but with more integration provided with and through the IoIF including the latest SWT, and an ARDEC-aligned set of ontologies.

17 ACRONYMS AND ABBREVIATION

This section provides a list of some of the terms used throughout the paper. The model lexicon should have all of these terms and many others.

2D	Two dimensions
3D	Three dimensions
AADL	Architecture Analysis & Design Language
ACAT	Acquisition Category
ACES	Automated Concurrent Engineering System
AFD	Assessment Flow Diagram
AFT	Architecture Framework Tool of NASA/JPL
AGI	Analytical Graphics, Inc.
AGM	Acquisition Guidance Model
AGS	Army Game Studio
ALM	Application Lifecycle Management
AMMODAT	Armament Analytics Multiple Objective Decision Analysis
ANSI	American National Standards Institute
AP233	Application Protocol 233
API	Application Programming Interface
AR	Augmented Reality
ARDEC	Armament Research, Development and Engineering Center
ASELCM	Agile Systems Engineering Life Cycle Model
ASR	Alternative System Review
ATL	ATLAS Transformation Language
AVCE	Armament Virtual Collaboratory Environment
AVSI	Aerospace Vehicle Systems Institute
BDD	SysML Block Definition Diagram
BN	Bayesian Network
BNF	Backus Naur Form
BOM	Bill of Material
BPML	Business Process Modeling Language
C-BML	Coalition Battle Management Language
CAD	Computer-Aided Design
CASE	Computer-Aided Software Engineering
CDR	Critical Design Review
CEO	Chief Executive Officer
CESUN	International Engineering Systems Symposium
CFD	Computational Fluid Dynamic
CGF	Computer Generated Forces
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
CONOPS	Concept of Operations
CORBA	Common Object Requesting Broker Architecture
COTS	Commercial Off The Shelf
CPS	Cyber Physical System
CREATE	Computational Research and Engineering for Acquisition Tools and Environments

cUAS	Counter UAS
CWM	Common Warehouse Metamodel
DAA	Data Acquisition and Aggregation layer
DASD	Deputy Assistant Secretary of Defense
dB	Decibel
DBMS	Database Management System
DAG	Defense Acquisition Guidebook
DARPA	Defense Advanced Research Project Agency
DAU	Defense Acquisition University
DCDR	Digital design from Critical Design Review (CDR)
DE	Digital Engineering
DIS	Distributed Interactive Simulation
DL	Descriptive Logic
DLR	
DoD	Department of Defense
DoDAF	Department of Defense Architectural Framework
DoE	Design of Experiments
DOORS	Requirement Management product
DOORS-NG	DOORS-Next Generation
DSEEP	Distributed Simulation Engineering and Execution Process
DSL	Domain Specific Languages
DSM	Domain Specific Modeling
DSM	Design Structure Matrix
DSML	Domain Specific Modeling Language
E/DRAP	Engineering Data Requirements Agreement Plan
ERP	Enterprise Resource Planning
ESP:HE	ESP: Higher Echelon
ERS	Engineered Resilient Systems
ESP	Early Synthetic Prototype
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis
FMI	Functional Mockup Interface
FMU	Functional Mockup Unit
FOM	Federation Object Model
GAO	Government Accounting Office
GUI	Graphical User Interface
HLA	High Level Architecture
HPC	High Performance Computing
HPCM	High Performance Computing Modernization
HW	Hardware
I&I	Integration and Interoperability
IBM	International Business Machines
IBD	Internal Block Diagram (SysML)
ICD	Interface Control Document
ICT	Institute for Creative Technologies
ICTB	Integrated Capability Technical Baseline
IDEF0	Icam DEFinition for Function Modeling

IEEE	Institute of Electrical and Electronics Engineers
iMBE	AVCE-Integrated Model-Based Engineering
INCOSE	International Council on Systems Engineering
IPR	Integration Problem Report
IoIF	Integration and Interoperability Framework
IRL	Integration Readiness Level
ISEDM	Integrated Systems Engineering Decision Management
ISEF	Integrated System Engineering Framework developed by Army's TARDEC
ISO	International Organization for Standardization
IT	Information Technology
IWC	Integrated Warfighter Capability
JCIDS	Joint Capabilities Integration and Development System
JEO	Jupiter Europa Orbiter project at NASA/JPL
JSF	Joint Strike Fighter
JPL	Jet Propulsion Laboratory (NASA)
JSON	JavaScript Object Notation
KPP	Key Performance Parameter
KSA	Key System Attributes
LIDAR	Light Detection and Ranging
LOC	Lines of Code
LSL	Lab Streaming Layer
M&S	Modeling and Simulation
MARTE	Modeling and Analysis of Real Time Embedded systems
MATRIXx	Product family for model-based control system design produced by National Instruments; Similar to Simulink
MBE	Model Based Engineering
MBEE	Model Based Engineering Environment
MBSE	Model Based System Engineering
MBT	Model Based Testing
MC/DC	Modified Condition/Decision
MCE	Model Centric engineering
MDA®	Model Driven Architecture®
MDAO	Multidisciplinary Design, Analysis and Optimization
MDD™	Model Driven Development
MDE	Model Driven Engineering
MDK	MagicDraw Model Development Kit
MDSD	Model Driven Software Development
MDSE	Model Driven Software Engineering
MIC	Model Integrated Computing
MMM	Modeling Maturity Model
MMS	Model Management System (part of OpenMBEE)
MoDAF	Ministry of Defence Architectural Framework (United Kingdom)
MOE	Measure of Effectiveness
MOF	Meta Object Facility
MOP	Measure of Performance
MRL	Mixed Reality Lab
MxRP	Mixed Reality Prototyping
MSDL	Military Scenario Definition Language

MVS	Multiple Virtual Storage
N2	N-squared diagram
NASA	National Aeronautics and Space Administration
NASA/JPL	NASA Jet Propulsion Laboratory
NAVAIR	U.S. Navy Naval Air Systems Command
NAVSEA	U.S. Naval Sea Systems Command
NDA	Non-disclosure Agreement
NDIA	National Defense Industrial Association
NEAR	Naval Enterprise Architecture Repository
NPS	Naval Postgraduate School
NSGA	Non-dominated Sorting Genetic Algorithm
OCL	Object Constraint Language
OMG	Object Management Group
OO	Object oriented
OpenMBEE	Open Model Based Engineering Environment
OpenVSP	Open Vehicle Sketch Pad
OSD	Office of the Secretary of Defense
OSLC	Open Services for Lifecycle Collaboration
OV1	Operational View 1 – type of DoDAF diagram
OWL	Web Ontology Language
PAR	Parametric Block in SysML
PDM	Product Data Management
PDR	Preliminary Design Review
PEA	Post Exercise Analysis
PES	Physical Exchange Specification
PIA	Proprietary Information Agreement
PIM	Platform Independent Model
PLM	Product Lifecycle Management
POR	Program of Record
PRR	Production Readiness Review
PSM	Platform Specific Model
QMU	Quantification of Margins and Uncertainty
RDEC	US Army Research Development and Engineering Center
RDF	Resource Description Framework
RDECOM	US Army Research, Development and Engineering Command
RT	Research Task
RTI	Runtime Infrastructure
RFP	Request for Proposal
RPM	Revolutions Per Minute
RPR FOM	Real-time Platform Reference Federation Object Model
ROI	Return On Investment
SAVI	System Architecture Virtual Integration
SE	System Engineering
SERC	Systems Engineering Research Center
SETR	System Engineering Technical Review
Simulink/Stateflow	Product family for model-based control system produced by The Mathworks
SCR	Software Cost Reduction
SDD	Software Design Document

SE	System Engineering
SFR	System Functional Review
SISO	Simulation Interoperability Standards Organization
SLOC	Software Lines of Code
SME	Subject Matter Expert
SOAP	A protocol for exchanging XML-based messages – originally stood for Simple Object Access Protocol
SoS	System of Systems
Software Factory	Term used by Microsoft
SPARQL	SPARQL Protocol and RDF Query Language
SRR	System Requirements Review
SRS	Software Requirement Specification
SST	Single Source of Truth
SSTT	Single Source of Technical Truth
STOVL	Short takeoff and vertical landing
SVR	System Verification Review
SW	Software
SWT	Semantic Web Technology
SysML	System Modeling Language
TARDEC	US Army Tank Automotive Research
TBD	To Be Determined
TRL	Technology Readiness Level
TRR	Test Readiness Review
Turtle	Terse RDF Triple Language
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aerial System
UC	Use Case
UCAV	Unmanned Combat Air Vehicles
UML	Unified Modeling Language
Unix	An operating system with trademark held by the Open Group
UQ	Uncertainty Quantification
US	United States
USD	US Dollars
USC	University of Southern California
VHDL	Verilog Hardware Description Language
VR	Virtual Reality
V&V	Verification and Validation
XMI	XML Metadata Interchange
XML	eXtensible Markup Language
XSLT	eXtensible Stylesheet Language family (XSL) Transformation
xUML	Executable UML

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