2023 NDIA MICHIGAN CHAPTER
GROUND VEHICLE SYSTEMS ENGINEERING
AND TECHNOLOGY SYMPOSIUM
AUTONOMY, ARTIFICIAL INTELLIGENCE, AND ROBOTICS TECHNICAL SESSION
AUGUST 15-17, 2023 - NOVI, MICHIGAN

Application of the Autonomous Ground Vehicle Reference Architecture to MBSE

Calvin Cheung[1], Shannon Griffith[1], Larisa Wells[2], Douglas Gregory[3], Michael Moore[4], Mark Johannes[5], David Hetherington[6], Joshua Walters[2], Sean Kang[2]

[1] U.S. Army DEVCOM Ground Vehicle Systems Center, Warren, MI
[2] DCS Corporation, Alexandria, VA
[3] Douglas Gregory Consulting, Minneapolis, MN
[4] Moore Integrity Engineering, San Antonio, TX
[5] OAR Corporation, Huntsville, AL
[6] System Strategy Inc., Detroit, MI

ABSTRACT

The utilization of model-based systems engineering (MBSE) is a key enabler for high quality system design and application of Modular Open Systems Approach (MOSA) principles. The Autonomous Ground Vehicle Reference Architecture (AGVRA) provides meta-models, architectural guidelines, best practices, and a library of reusable model content for the Army Robotics and Autonomous Systems (RAS) community to facilitate the MBSE development of autonomous systems. This paper provides a summary of AGVRA's models, detailing the categories of model elements along with their overall utility, and describes key applications of AGVRA currently being utilized across the DoD. The applications of the AGVRA MBSE work products are contributing to high quality outcomes in RAS systems, providing new and improved functional and operational autonomous ground vehicle capability.

Citation: C. Cheung, S. Griffith, L. Wells, D. Gregory, M. Moore, M. Johannes, D. Hetherington, J. Walters, S. Kang, "Application of the Autonomous Ground Vehicle Reference Architecture to MBSE," In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 15-17, 2023.

1. INTRODUCTION

Per the "DoD Digital Engineering Strategy [1]" and "DoD Instruction 5000.88 Engineering of Defense Systems [2]", utilizing a model-based systems engineering (MBSE) approach to systems design, program planning, and mission engineering is necessary for agile development of military systems with high quality outcomes. Furthermore, Program Executive Office

---

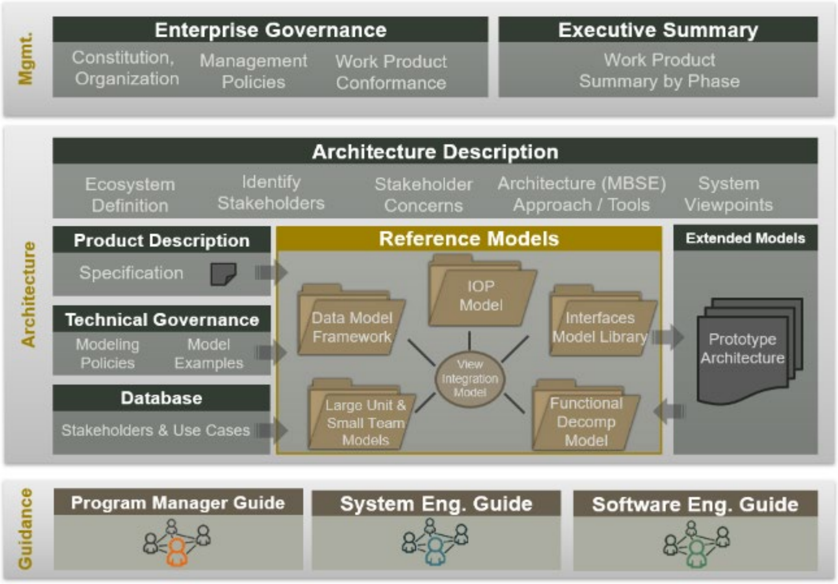


Figure 1. AGVRA work products.

(PEO) and Program Manager (PM) activities are focused on defining and evolving autonomous ground vehicles (AGV) in line with a Modular Open Systems Approach (MOSA) acquisition strategy, which has the following five key principles [3]:

1. Establish an Enabling Environment
2. Employ Modular Design
3. Designate Key Interfaces
4. Use Open Standards
5. Certify Conformance

The utilization of MBSE is a key enabler in ensuring that MOSA principles are properly adhered to through the entire lifecycle on an AGV program for maximum benefit.

Development of autonomous systems and autonomy-enabled missions, however, is a highly specialized field with modeling needs that are typically not met with available MBSE tools. Given the importance of MBSE and the lack of baseline tooling, autonomy specific modeling elements and processes need to be developed and utilized for DoD AGV efforts to comply with requirements and realize the benefits of MBSE. The Autonomous Ground Vehicle Reference Architecture (AGVRA), developed by U.S. Army DEVCOM Ground Vehicle Systems Center (GVSC), aims to provide the elements needed for successful AGV MBSE efforts. AGVRA provides SysML model libraries and a framework within which Government and Industry defense robotics partners can readily and uniformly meet their objectives, and in turn realize the benefits of MOSA principles.

2. AUTONOMOUS GROUND VEHICLE REFERENCE ARCHITECTURE

AGVRA is a reference architecture for AGVs that provides architectural guidelines and best practices, as well as a breadth of representative models to apply, for the Army Robotics and Autonomous Systems (RAS) community. As defined by the “DoD Reference Architecture Description [4],” a Reference Architecture is “an authoritative source of information about a specific subject area that guides and constrains the instantiations of multiple architectures and solutions.” A Reference Architecture provides:

- Common language for the various stakeholders
- Consistency of implementation of technology to solve problems

- Support for the validation of solutions against proven Reference Architectures
- Encouragement towards adherence to common standards, specifications, and patterns

AGVRA provides these things by offering a suite of SysML reference models, framework, and guidelines that facilitate development of an integrated MBSE system architecture with a comprehensive set of views that includes mission segments, data, interfaces, standards, and functional decomposition. Leveraging AGVRA allows the RAS community to better understand, inform, and bound the state of autonomy within MBSE and ways which these capabilities and architectures can be leveraged together or separately to support the RAS community.

At the foundation of AGVRA are multiple work products that are continually refined via government and industry feedback. The work products are developed in phases, with each phase defined by the overarching goals. The specific tasks to achieve these goals are validated by feedback mechanism appropriate for each progressive development sprint:

1. Initial concept document review
2. Integration into model framework
3. Development of model libraries and profile examples
4. Utilization by third-party stakeholders
5. Application to existing programs.

The long-term mission of AGVRA consists of successful application and instantiation of its work products to satisfy stakeholder concerns and program development and life cycle activities. Figure 1 shows all the AGVRA work products and their interrelations. While AGVRA contains a variety of guides and documents that help with the application of MOSA and MBSE for AGVs, the remainder of this paper focuses on the modeling work products. This narrowed scope allows a deeper dive of the benefits of each AGVRA model, along with examples of how they have been applied across the DoD.

3. MODELS

AGVRA's libraries of reference models and reusable model patterns provide resources to aid in the definition of the specific technical architecture of acquisition programs by leveraging open architectures and shared information models through a common framework, domain specific models, standards profiles, reference architectures, and guidance. The AGVRA models include the Mission Models, the Data Model Framework (DMF), the Interoperability Profile (IOP) Model, the Interfaces Model Libraries (IML), the Functional Decomposition Model (FDM), and the View Integration Model (VIM). AGVRA formalizes a set of common patterns and components across the AGV portfolio and constrains the design space of system or product line development in order to establish compatible best practices for AGV system design.

The objectives of the AGVRA models are:

1. Provide a minimum but essential set of model-based enablers required to support effective AGV system life cycle management.
2. Enable rapid generation of high-quality Physical System Architectures (PSA) by leveraging architecture knowledge and artifacts over the entire AGV domain, where a PSA is defined as the "as implemented" architecture of a system.
3. Support product line plug and play into open and compatible target architectures.

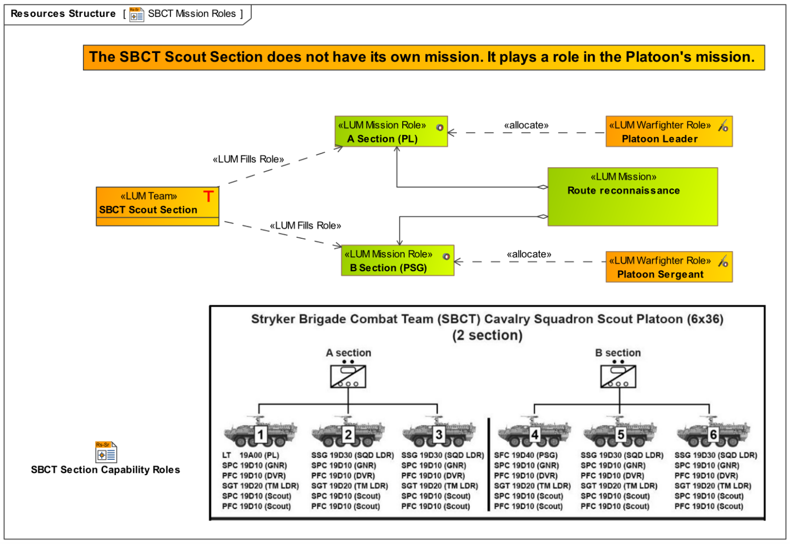


Figure 2. Large Unit Mission model example showing a Scout Platoon.

The following sections detail what each model provides.

3.1. Mission Models

The Mission Model components assist in mission engineering activities to decompose and/or relate mission segment models in support of system design. It is comprised of three separate models: the Large Unit Mission (LUM) profile, the Small Team Model (STM) profile, and the Doctrine Reference (REF) profile.

The LUM profile provides support for modeling the top-level mission execution of Army doctrine to establish the context for a system being developed using AGVRA. The LUM profile is based on the Unified Architecture Framework (UAF) which is used in procurement to describe the goals and context of an organization. In combination with UAF, the LUM profile can be used at the platoon and higher echelons to model:

- The goals of the organization.
- The capabilities required by the organization.
- The operational activities of the organization.
- The services provided and consumed by the organization.
- The personnel structure and roles within the organization.

An example of the LUM model can be seen in Figure 2, showing LUM mission roles and LUM team members when describing a Scout Platoon.

The LUM profile is intended to model down to a small team, a section of 2-3 vehicles or a platoon of 4 vehicles that perform tasks and maneuvers in a tightly synchronized manner. Below this level of detail, modeling hands off to the STM profile.

The STM profile provides support for modeling short tasks and maneuvers executed by a small team of vehicles. The STM profile is built around "Tasks". Tasks can be defined for the entire team or defined for individual vehicles. Examples of tasks and movements include:

- Bounding overwatch
- Formation transitions
- Positioning the vehicle for firing angle
- Observing the context

The current working assumption for AGVRA is that autonomy software works within a single vehicle. The purpose of models built using the STM profile is to clarify the coordination between vehicles.

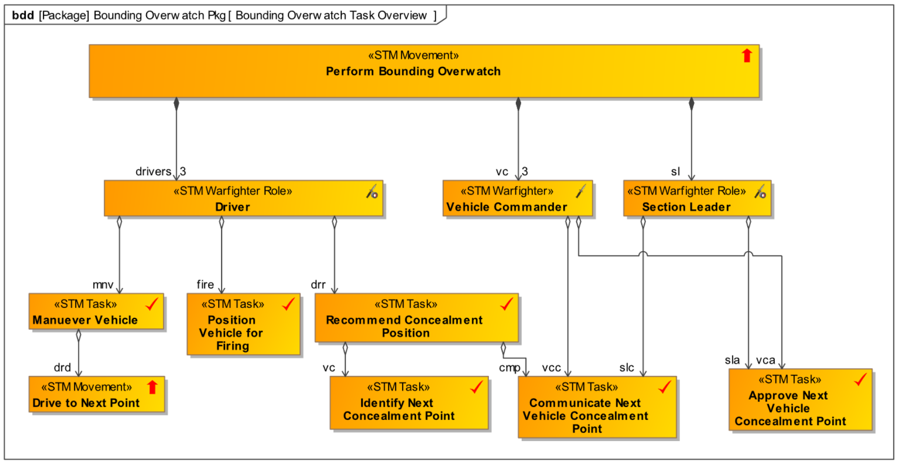


Figure 3. Small Team Model example for a bounding overwatch.

STM models flesh out required capabilities such as:

- Pretrained knowledge of standard maneuvers that must be stored in the vehicle.
- Coordination communication which could be radio, but also visual or other signals
- Sensing requirements such as visual alignment between vehicles

The STM profile is built directly on SysML (not UAF) to allow for convenient linking of lower-level engineering models built using the other AGVRA components and SysML-based system models. STM models are intended to hand off to FDM models for functional decomposition inside a single vehicle down to sensing, mobility, and other packages. Figure 3 provides an example of an STM model Stryker Brigade Combat Team Scout Section with roles, tasks, and movements for a bounding overwatch.

The REF profile provides support for modeling explicit and clear traceability to specific content in Army Doctrine, international standards, and other publications. The REF profile contains one stereotype, which is an extension of a SysML modeling element, for each of three types of traceability links:

- Traceability to paragraph numbers and text in formal Army Doctrine publications
- Traceability to international standards
- Traceability to other publications

The REF profile is built directly on SysML and can be used in either UAF or SysML models. The three stereotypes contain attributes to identify the title of the publication, source, publication date, and so on. These attributes are aligned with the Dublin Core standard for publication metadata now in use by leading libraries worldwide.

In addition to the three primary models, AGVRA also includes a Mission Data Model (DM) that can be used in data exchanges to support the concept of operations from the LUM, STM, and REF. These data exchanges can be conceptual or logical. For conceptual models, the data exchanges are not concerned with how machines represent information – only with defining the innate information itself. In contrast, logical models convey the values of a properties.

3.2. Functional Decomposition Model

AGVRA provides the FDM, which is a decomposition of abstracted autonomous system functions that can be used to build a system in satisfaction of a particular mission.

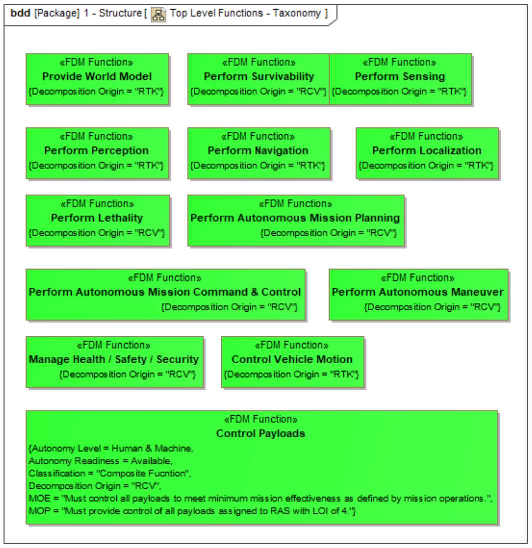


Figure 4. Top level functions of the Functional Decomposition Model.

It can be used to model a mission, helping to identify smaller sets of modular autonomous systems functions needed to accomplish mission goals. The FDM provides metadata for each function including pedigree, maturity, measures of effectiveness, measures of performance, and responsible parties. This helps to apply MOSA principles by providing a modular viewpoint into the functions that are typically found in RAS that can be procured separately and provided by various suppliers and then integrated into the system, establishing a robust product line for RAS programs.

The FDM helps to manage obsolescence of system components by providing insight into where the hierarchy of functions are vulnerable to new technologies and how to mitigate and replace these small modular components over time. Also, this viewpoint offers insights into potential gaps in technology that must be developed under R&D or other means to complete an acquisition strategy by exposing common functions performed in critical or dangerous mission segments. Figure 4 shows the top-level functions provided by the FDM.

3.3. Interoperability Profile Model

The Robotic and Autonomous Systems Ground (RAS-G) IOPs are a set of documents that profile standards to define the logical, physical, and electrical interfaces between major subsystems on robotic ground vehicles. The IOP model is offered as an AGVRA model to enable the representation of IOP concepts including attributes, requirements, parameters, and instantiations, which a Project Manager (PM) may use for acquisition and risk mitigation. In IOP, "Instantiations" specific to a program may be provided as part of the "Request for Proposal" process. The IOP Instantiation becomes an additional type of Interface Control Document that the vendor must adhere to. As part of risk mitigation, the IOP Instantiation can be viewed as a set of requirements to evaluate competing solutions against each other. As part of the acquisition process, a vendor utilizes an IOP Instantiation as a set of requirements that their product's interfaces must fulfill in order to be interoperable with other products within the system under development.

The IOP Model libraries allow modeling of PM Force Projection interoperability concepts within the AGVRA ecosystem. The profile library contains two profiles: Source

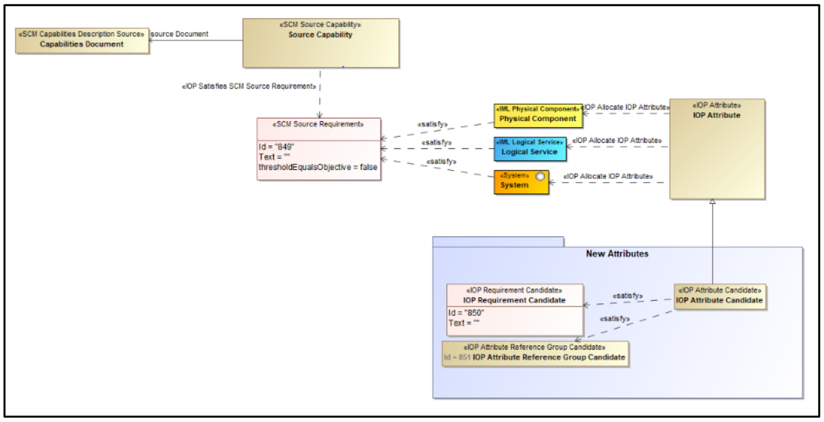


Figure 5. IOP model example.

Capture and IOP. The Source Capture profile is how a user creates traceability back to a program's "source" capabilities descriptions and requirements. The IOP profile contains the stereotypes for the core IOP constructs, which are attributes, requirements, and parameters. In addition, it contains candidate specializations for attribute and requirement are provided.

AGVRA also provides library content from each of the released versions of the IOP from Version 2 to Version 5. Said models contain all of the IOP attributes, requirements and parameters in a version and can be used to build an IOP instantiation within the modeling environment. Figure 5 shows how the IOP model can be used.

3.4. Interfaces Model Library

The IML describes interfaces that are either defined by standards or used in software frameworks commonly applied to ground vehicle robotics systems. The interfaces are modeled at logical and physical levels of abstraction. The logical level interface definitions relate the data used in the interfaces to the semantic datatypes defined by the DMF. The physical level interface definitions define the storage type, encoding, and the implementation details of the interfaces.

The IML profile defines stereotypes for describing physical and logical aspects of design elements. Physical model types include message, interface, port, and component models. Logical model types include dataset, interface, port, and service models. Mapping models are used to show how the logical level data interfaces are realized to physical level message interface realizations.

The IML includes example models of the SAE's Joint Architecture for Unmanned Systems (JAUS) services and Robot Technology Kernel (RTK) Robot Operating System (ROS) nodes that are all related to mobility and localization functions. The intent of concentrating on these functions was to maximize the chance of identifying commonality in the data types, messages, and interfaces of these otherwise disparate interfaces.

Figure 6 shows the rules of construction when mapping IML physical interfaces to logical interfaces.

3.5. Data Model Framework

The DMF is a metamodel comprising two parts: the Family of Dictionaries (FOD) and the Value Property Metamodel.

The first part is the FOD, which establishes stereotypes for various kinds of definition elements. A FOD defines concepts necessary to understand meaning of observable phenomena in the physical world and how they are measured. It provides a set of

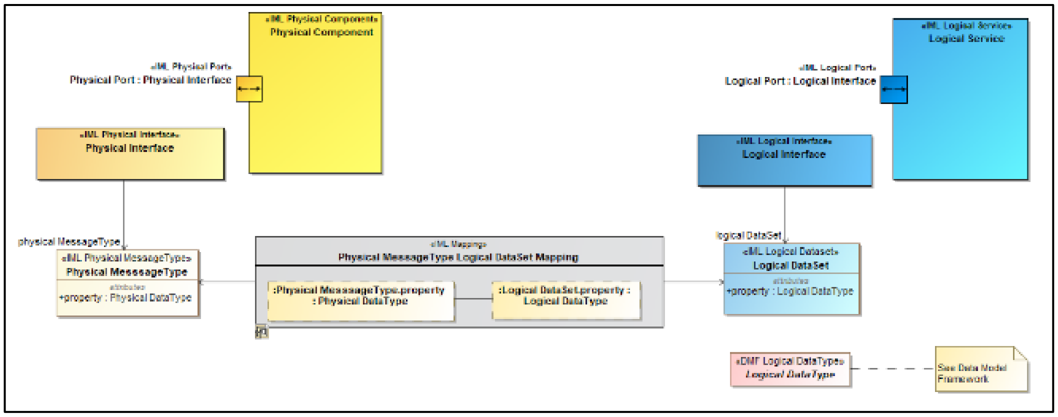


Figure 6. IML Physical to Logical mapping.

mathematical definitions for state quantities and measurements used in the command and control of manned and unmanned vehicles, weapons, sensors and other cyber physical devices. This provides the means to equate the semantics of a named element in one model with the semantics of a named element in another via their unique identifier, thus saving time and reducing errors in model-to-model integration. A sampling of available dictionaries in the FOD includes "Standard International Units", "Global Time Reference Systems", and "Space and Time", along with many more.

The second part is the Value Property Metamodel. This metamodel establishes stereotypes for various kinds of datatypes and various kinds of properties that can be typed by those datatypes. This metamodel is also based on the FOD ontology and references the FOD metamodel. The Value Property Metamodel is used to create the Joint Common DataType Library (JCDL). The JCDL derives datatypes from the FODs to be used in conceptual and logical data models. Categories of possible datatypes that can be created from the JCDL include things such as coordinate operations and statistical quantities. Figure 7 shows an example of JCDL datatypes used to describe commonly used vehicle body orientations.

3.6. View Integration Model

The VIM is an example of how all AGVRA model work products can be used to model a system in a mission context. Although each individual model within AGVRA can be used independently, the VIM provides a view of how it is possible to link them all together. It provides summary and overview diagrams as an illustrative target system architecture model called the Bounding Overwatch Model. The purpose of the Bounding Overwatch Model is to fully exercise the profiles, patterns and type libraries provided in the AGVRA models within a single, unified example model. The model is based on an operational vignette for a Scout Platoon with Robotic Combat Vehicles (RCVs). The vignette results in an RCV maneuver to an Overwatch waypoint based on the AGVRA Mobility Task Agent concept and existing JAUS and RTK ROS interfaces and messages. Figure 8 shows all the AGVRA work products used by the VIM, along with groupings of tightly coupled models.

4. APPLICATIONS OF AGVRA

Given the importance of MBSE [1] [2], there is a vital need to leverage reusable and vetted modeling elements in the development and acquisition of RAS systems. AGVRA provides a plethora of such modeling elements that can be used to build out or enhance existing MBSE designs. AGVRA has been utilized across the Army and DoD

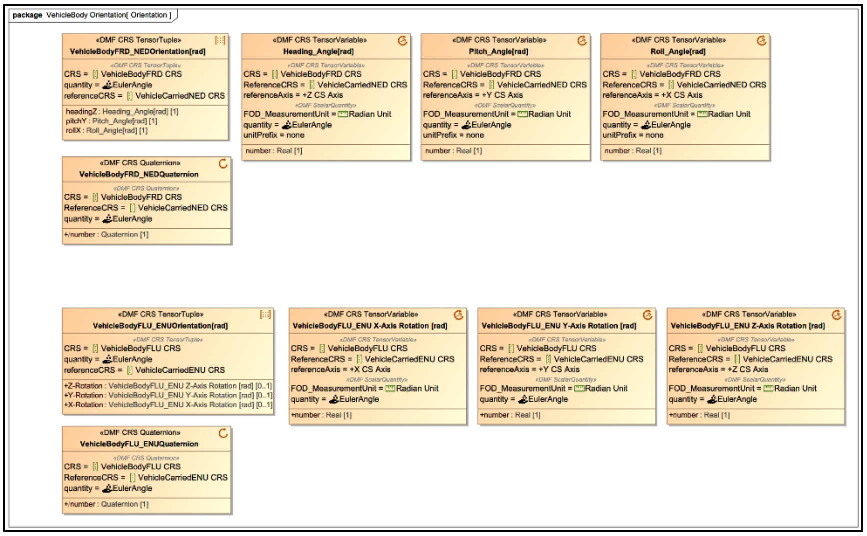


Figure 7. JCDL datatypes.

as a whole to meet the needs of the RAS community and allow for the development of models, enabling all the benefits of higher quality outcomes at lower costs and adherence to MOSA principles. This section details some key applications of AGVRA models in past and ongoing efforts.

4.1. GCIA Data Architecture

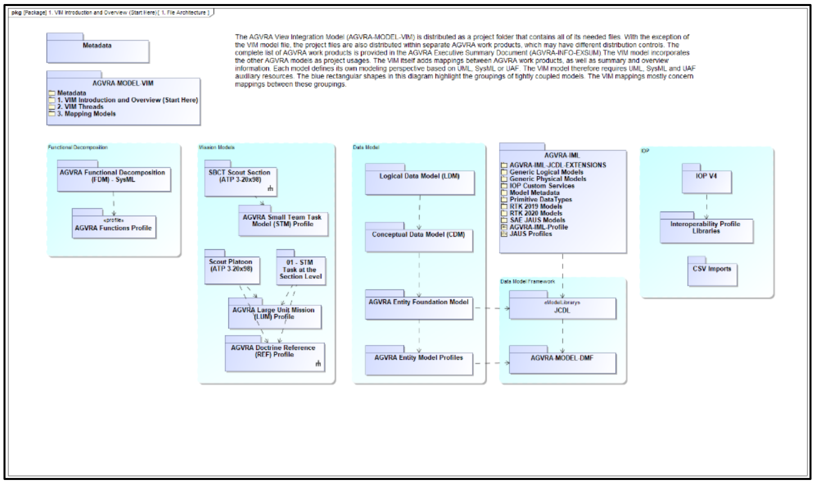
Ground Combat Systems (GCS) Common Infrastructure Architecture (GCIA) applies an MBSE approach to bridge the gap between existing standards and architectures and the acquisition and system design and development processes in GCIA ground vehicle programs. GCIA provides an objective architecture that defines the network and service infrastructure commonly required in these systems, and a data architecture that defines the MBSE languages, rules of construction, and reusable model libraries of existing standards and components to be used by programs and vendors when defining solution architectures and designs.

The GCIA Data Architecture (DA) includes Data Architecture Model Libraries (DAML) that define the services, behaviors, interfaces, and data defined by standards and frameworks commonly applied in RAS and vehicle programs (VICTORY 1.9, SAE J1939, the common GCIA infrastructure services, etc.). DAML libraries also define the same aspects of reusable components and subsystems.

GCIA DA models are defined using the AGVRA IML profile and extend the AGVRA IML libraries (SAE JAUS, IOP Services, ROS-M and RTK).

The DAML models define the interface libraries and reusable components in a common MBSE-language, which significantly lowers the cost of learning the myriad of specifications that exist as thousands of pages of documents using greatly varying terminology, styles, and concepts.

A significant value that is a result of the DAML is that all the data elements used in the interface definitions of the standards and reusable components are tied to the same semantic datatype definitions provided by the AGVRA DMF and JCDL. Because all data is tied to the same underlying datatype definitions, the data defined in the standards are inherently related through the JCDL datatype referenced. The semantic similarities and differences between a dataset in VICTORY and the same concept defined in JAUS can be discovered by tracing the types in the DAML to their semantic



The AGVRA View Integration Model (AGVRA-MODEL-VIM) is distributed as a project folder that contains all of its needed files. With the exception of the VIM model file, the project files are also distributed within separate AGVRA work products, which may have different distribution controls. The complete list of AGVRA work products is provided in the AGVRA Executive Summary Document (AGVRA-INFO-EXSUM).The VIM model incorporates the other AGVRA models as project usages. The VIM itself adds mappings between AGVRA work products, as well as summary and overview information. Each model defines its own modeling perspective based on UML, SysML or UAF. The VIM model therefore requires UML, SysML and UAF auxiliary resources. The blue rectangular shapes in this diagram highlight the groupings of tightly coupled models. The VIM mappings mostly concern mappings between these groupings.

Figure 8. VIM models and couplings

datatypes and the underlying DMF. The need for transformations is automatically identified in the modeling tools. The mathematics of the transformations is defined by tracing to the underlying DMF libraries, and documentation is generated automatically. Nowhere else are the relationships between standard interfaces defined in a generalized and semantically complete fashion.

GCIA DA defines SysML-based modeling languages for defining system architectures as a composition of IML services, and system designs as a composition of IML components. Defining a system can be done by dragging the standard models into a system architecture model and connecting them together with application and infrastructure models.

The GCIA DA also includes a SysML-based modeling language for defining Domain Specific Data Models (DSDM), and a software tool called the FACE Data Architecture Model Translator, which translates DSDM and GCIA models into FACE data model and Unit of Portability models and exports them to FACE conformant UDDL files. This allows system architectures to be composed using existing standards, then transformed into FACE DA models automatically.

GCIA DA has been built upon AGVRA provided languages and model content, and would not have been possible without the work done to define the core languages and models. DA v1.0 baselines this capability and is being provided to programs for use. The GCIA DA can easily be generalized and extended to a wide range of other domains that include interface standards and an intent to apply MBSE.

4.2. CoVeR EET Mission Modeling

The GVSC Combat Vehicle Robotics (CoVeR) program is an Army Science and Technology effort focused on developing and maturing AGV technology to effectively maneuver and operate as part of the manned/unmanned team. Divided into individual increments, the CoVeR program conducts regular Engineering Evaluation Test (EET) events to assess investment using an independent third-party evaluator. Over the last few years, the CoVeR program and EET events have grown both in program partners and technologies being evaluated. To help manage this growth, an MBSE approach using AGVRA for the CoVeR program and EET events was leveraged for the agile development of military systems with high quality outcomes.

CoVeR EET mission models were developed by utilizing the AGVRA SysML reference models, frameworks, and guidelines. Figure 9 shows the structure of CoVeR mission models such as:

- Use case of a mission capability
- Proposed tests to evaluate the capability
- Proposed Operational Design Domain (ODD) for evaluations

The STM profile from the AGVRA Mission Models was used for modeling short tasks and maneuvers executed by a small team of vehicles. CoVeR EET mission models also include required capabilities inside a single vehicle down to sensing, mobility, and other packages. AGVRA models such as the FDM and the VIM will be used to understand, define, and decompose the skills, tasks, and scenarios of a particular mission. For future EET events, CoVeR mission models are being developed for dozens of internal and external partners and their proposed mission capabilities.

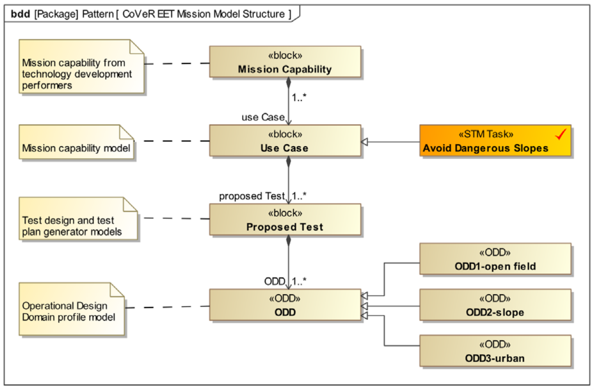


Figure 9. CoVeR EET Mission Model Pattern.

4.3. RTK IOP Bridge Modeling

Usage of the IOP profiles promotes interoperability between payloads, controller, and robotic systems. The RTK autonomous software library leverages IOP to communicate with robotic controllers to take full advantage of the interoperability that IOP provides. RTK utilizes an IOP Bridge to facilitate communications between the robot and the robotic controllers. Recent updates to the IOPs have spurred efforts to update the RTK IOP Bridge to have greater maintainability and extensibility for all future IOP updates. To accomplish this goal, developers in RTK utilized both AGVRA IOP Models to leverage an MBSE approach for the RTK IOP Bridge updates. The Source Capture profile was used to capture RTK's requirements for the RTK IOP Bridge. This model, as seen in Figure 10, provided traceability in development efforts to an easily maintainable source of truth.

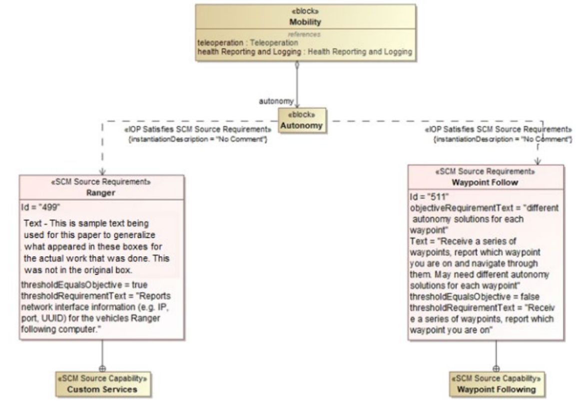


Figure 10. Excerpt of Source Capture Model for IOP Bridge.

With the Source Capture Model of the RTK IOP Bridge, the AGVRA IOP profile was used to model the IOP instantiation needed to meet requirements. The AGVRA IOP Profile contains stereotypes of IOP attributes, requirements, and parameters, allowing the creation of a model-based instantiation tied to the Source Capture Model, with greater maintainability and traceability when leveraged with an MBSE approach. By leveraging the AGVRA IOP Model, developers were able to generate a consistent and maintainable model of the RTK IOP Bridge to be used for current and future development efforts, providing a digital artifact for a consistent source of truth towards future updates and other efforts utilizing RTK.

4.4. SAE Standards with the DMF

SAE International, a globally active professional association focused on mobility solutions, releases consensus-based standards to improve the design of safety, productivity, dependability, and efficiency for the fields of aerospace, automotive, and commercial vehicles. The AGVRA DMF is utilized by multiple standards, such as “SAE AS6969 Data Dictionary for Quantities Used in Cyber Physical Systems” and “SAE AS6518B Unmanned Systems (UxS) Control Segment (UCS) Architecture: UCS Architecture Model” to provide a digital data model of conceptual datatypes, logical datatypes, and properties, allowing for improved clarity, quality, and consistency. These standards have been used across the DoD in various systems, such as the Army Universal Ground Control Station and Navy’s PMA-281 Unmanned System Common Control System, putting AGVRA on the forefront of cross-service commonality for unmanned systems.

5. CONCLUSION

The AGVRA serves as a set of models used to better understand, inform, and bound the state of the AGV domain and the manner in which capabilities and architectures can be leveraged to support the RAS community. In using the AGVRA models, RAS programs and R&D efforts are able to accelerate MBSE development. This is achieved by taking advantage of AGV specific reference architectures and model elements to build their models with key interfaces and open standards, allowing for the application and benefits of MOSA. In this paper, we provided details about the AGVRA models and illustrated their utility by providing key examples of AGVRA’s application across the DoD. It is AGVRA’s mission to publish and maintain the Army’s community-recognized RAS meta-architecture to facilitate MBSE in providing functional and operational autonomous ground vehicle capability. Through continual development and expansion of reference models, framework, and guidelines, AGVRA strives to meet its mission for Army AGV, providing higher quality systems at reduced cost and schedules for the entire RAS community.

6. REFERENCES

[1] Office of the Deputy Assistant Secretary of Defense for Systems Engineering, "Department of Defense Digital Engineering Strategy," Office of the Deputy Assistant Secretary, Washington, DC, 2018.

[2] Office of the Under Secretary of Defense for Research and Engineering, *DoD Instruction 5000.88 Engineering of Defense Systems,* Department of Defense: Washington, DC, 2020.

[3] T. Carlson, "About 'FACE'," *Army AL&T,* pp. 86-91, April-June 2015.

[4] Office of the Department of Defense Chief Information Officer, "DoD Reference Architecture Description," Department of Defense, Arlington, VA, 2010.