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IMPLEMENTING A COMMON ARCHITECTURE FOR EOD ROBOTIC SYSTEMS

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ABSTRACT

The Advanced Explosive Ordnance Disposal Robotic System (AEODRS) is a Navy-sponsored acquisition program developing a new generation of open, modular EOD robotic systems. In a previous paper, we described a common architecture for the AEODRS family of systems. The foundation of that architecture is the careful partitioning of an EOD robotic system into Capability Modules, and the definition of inter-module interfaces based on recognized and accepted open standards.

In this paper, we describe an implementation approach selected to demonstrate the architecture's contribution to subsystem and payload interoperability. We further describe an approach to incremental integration of independently developed subsystems and payloads into a mixed simulation System Testbed, allowing independent assessment of each integrand's compliance with the defined interfaces of the architecture. We also illustrate how this incremental approach enables the integration process to proceed with reduced dependence on the order in which the independently developed subsystems and payloads are delivered.

INTRODUCTION

The military services have successfully used ground robots in the fight against terror over the past decade. In addition, US and international law enforcement agencies have experienced the benefit of these systems in conducting dangerous and life threatening tasks. The use of ground robots is saving lives throughout the world. However, the lack of interoperability between Unmanned Ground Vehicle (UGV) subsystems imposes limitations on development and deployment, complicating the integration of advanced technologies and control schemes. The Advanced Explosive Ordnance Disposal Robotic System (AEODRS) is a Joint Service Explosive Ordnance Disposal (JSEOD) program, executed through the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) via the Navy Program Management Office for Explosive Ordnance Disposal/Counter Remote Controlled Improvised Explosive Device Electronic Warfare (PMS 408). The primary goal of the AEODRS program is to develop a new generation of open, modular EOD robotic systems that will provide the desired interoperability. The AEODRS approach to achieving interoperability hinges on the definition of a common architecture that partitions the system into modules possessing common physical, electrical, and logical interfaces. This enables the creation of a family of UGV systems providing interoperability and interchangeability at the module level. In turn, the high degree of module-level interoperability and interchangeability enables rapid incremental integration of new technologies and approaches into the AEODRS system.

The AEODRS Family of Systems (FoS)

The AEODRS Family of Systems (FoS) will consist of three UGVs and two Operator Control Units (OCU). These systems correspond to the three classes of EOD missions identified by EOD users.

The first AEODRS system to be fielded is the Dismounted Operations System. This system is intended to focus on reconnaissance tasks, but is also capable of supporting the placement of counter-charges to disrupt a device. The Dismounted System must be fully backpackable, which places a premium on size and weight. The system includes a compact, lightweight UGV and a lightweight handheld controller (OCU). A conceptual sketch of the Dismounted UGV is shown in Figure 1.

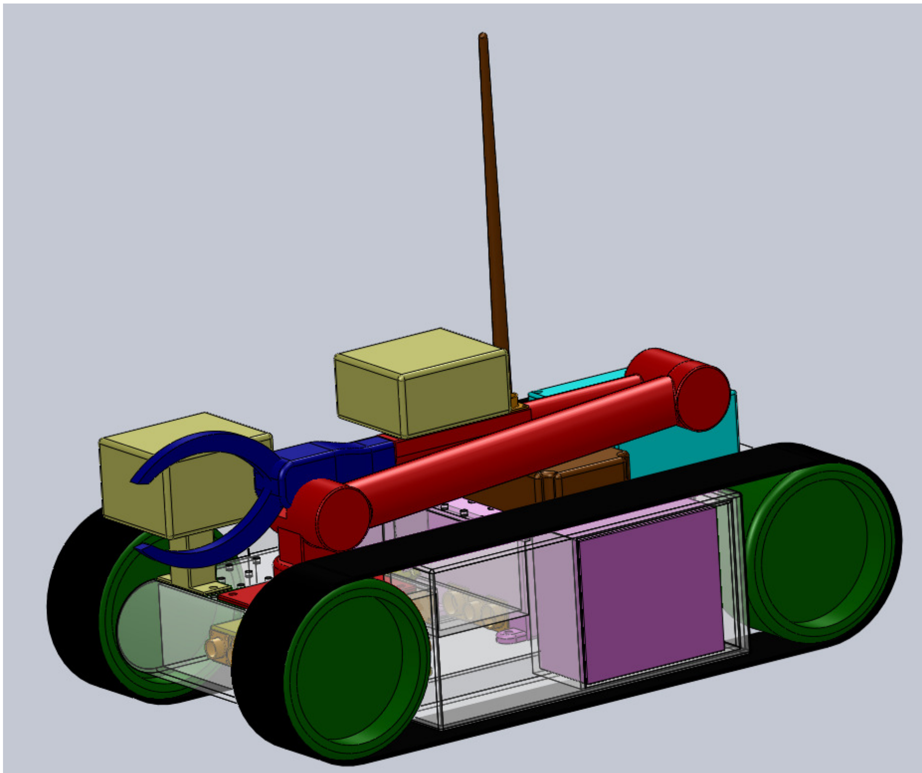

Figure 1: Dismounted Operations UGV Concept

The second AEODRS system is referred to as the Tactical Operations System. The primary mission focus of this variant is on in-depth reconnaissance and wide-range item prosecution. The Tactical Operations System is a medium sized system that must be able to be transported in a vehicle, and be capable of being carried by two technicians over a moderate distance. This system includes a larger, portable OCU that fully supports the increased functionality of the Tactical Operations and Base / Infrastructure Systems. In addition, the basic functionality of the Tactical Operations UGV can be controlled by the handheld OCU of the Dismounted System.

The third AEODRS system is referred to as the Base / Infrastructure System. This is the largest variant and requires transportation via a large response vehicle or trailer. The primary mission focus of this variant provides maximum load and lift capabilities and the widest-range of neutralization, render-safe, and other special capabilities. This system employs the larger portable OCU mentioned above. In addition, the basic functionality of the Base / Infrastructure System can be controlled by the handheld OCU of the Dismounted System.

The three vehicle classifications effectively address the needs of the EOD technicians in a variety of frequently encountered operational scenarios. Use of the common architecture enables use of some capability modules across all three platforms of the FoS. Other capability modules can be developed in an incremental fashion built upon the foundations of units developed for earlier increments.

Architecture Goals and Motivations

The EOD community desires to reduce the logistics footprint, and reduce the personnel and training footprint associated with field deployment of EOD robotics systems. The past environment of stovepiped proprietary systems results in an inability to share capabilities – even modular capabilities – between systems. The AEODRS program seeks, by adopting shared module definitions and standard module interfaces, to increase module commonality between members of the AEODRS Family of Systems, thereby reducing the spares and stocking requirements for the maintenance and configuration of a suite of fielded systems. Further, increasing module commonality also reduces the number of functionally similar (but non-interchangeable) modules that maintenance personnel must be trained to support. The use of common OCUs reduces operator cognitive load and training requirements for operators by presenting operators with consistent user interface appearance and behavior across the family. These goals can be reached by adopting a modular architecture that provides both interoperability of defined modules, and interchangeability of like modules. To restate and focus the overall goals, those goals include:

- Reduce the overall logistical footprint of the FoS
- Develop and adopt a common controller module to be used across the FoS
- Segregate and develop mission specific payloads
- Increase mission flexibility through the adoption of new capability modules as part of a continual technical development cycle

In order to address these goals, the AEODRS Family is characterized by the *interoperability* of its capability modules (subsystems) via Government defined and controlled logical, electrical, and physical interfaces and the commonality of its OCU. The Family is also characterized by the *interchangeability* of its capability modules with future capability modules that can be integrated in a plug and play fashion without proprietary issues. More formal definitions of *interoperability* and *interchangeability* are as follows[1]:

Interoperability – *The ability of systems to provide data, information, materiel, and services and accept the same from other systems, and to use the data, information, materiel, and services so exchanged to enable them to operate effectively together.*

Interchangeability – *A condition that exists when two or more items possess such functional and physical characteristics as to be equivalent in performance and durability, are capable of being exchanged one for the other without alteration on the items themselves or of adjoining items, except for adjustment, and without selection for fit and performance.*

In summary, interfaces between two functional components on an electric-drive UGV system can be defined in terms of their physical, electrical, and logical interfaces. This requires partitioning the system into a set of intercommunicating modules, each implementing specific, well-defined, cohesive subsets of the functionality of the overall system.

AEODRS Common Architecture Overview

Key capabilities identified by the EOD community as important for AEODRS UGVs can be decomposed into a few crude categories:

- *Mobility* of the platform,
- *Manipulation*: the ability to reach and manipulate or grasp objects in the UGV's environment,
- *Vision*: the ability to see the UGV's surroundings and to see objects to be manipulated,
- *Auditory*: the ability to hear and project sound,
- *Power*: a power system adequate to enable the activities and capabilities of the UGV,

Adopting these categories as identifiers of basic UGV capabilities leads to a crude identification of potential Capability Modules for the AEODRS system. These modules are illustrated in Figure 2, and briefly discussed in the paragraphs that follow.

1 DAU Glossary of Defense Acquisition Acronyms and Terms, 12th edition, July 2005

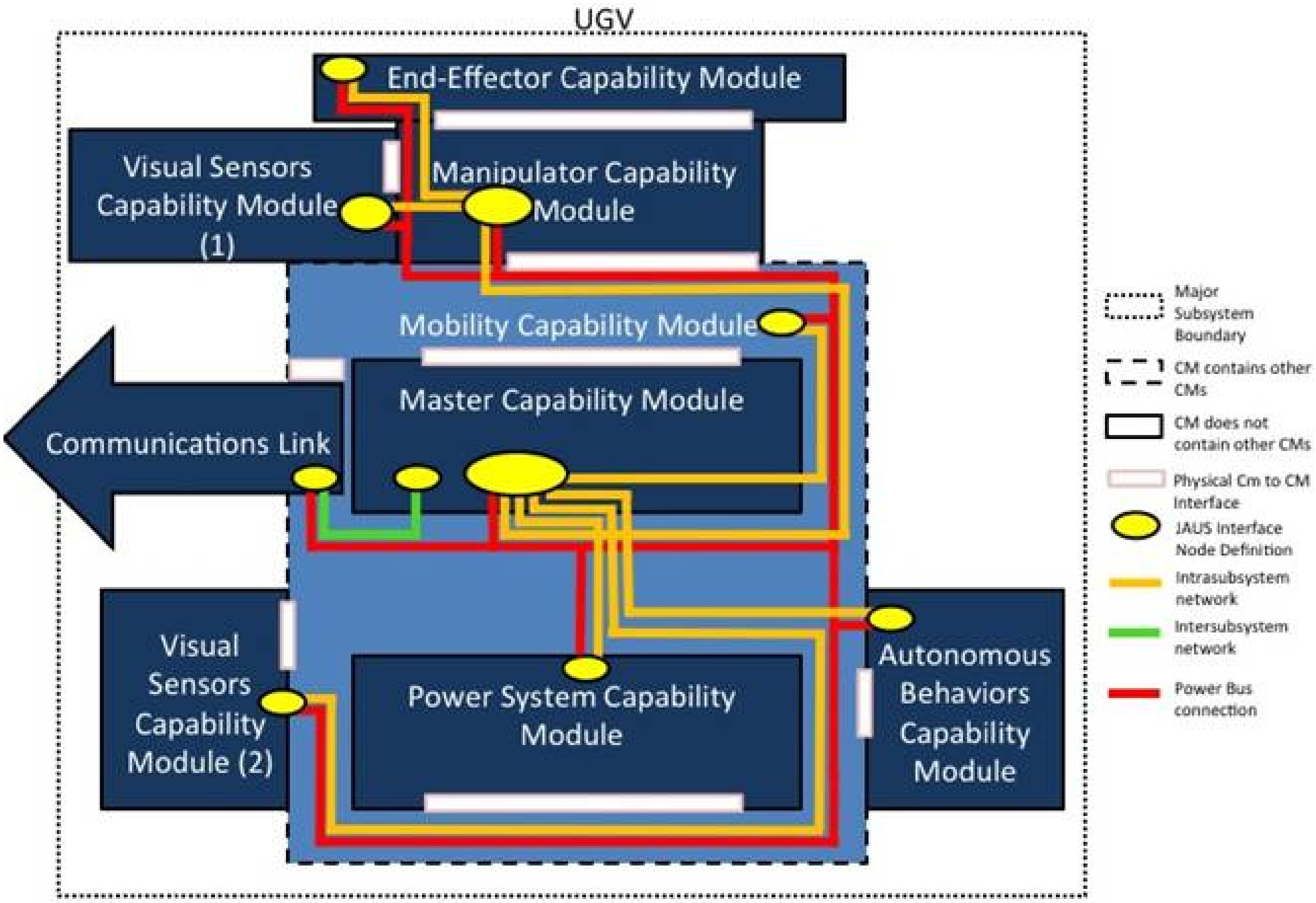

Figure 2: Partition into Modules

Figure 2 uses the aforementioned categorization of UGV capabilities to identify candidate Capability Modules; it further illustrates interfaces required between the modules in order to construct a functioning system. The Capability Modules identified are:

- Mobility
  The Mobility module provides the propulsion system for the UGV, and includes the UGV chassis/body.
- Power
  The Power module provides electrical power for all other UGV modules.
- Master
  The Master module provides common system level services, including support for configuration (detection, registration, publication and subscription to services provided by the UGV modules) and communications management.
- Communications
  The Communications module provides a data link between the UGV and the OCU.
- Visual Sensors
  Each Visual Sensors module may support multiple sensors (for example, full-light cameras and thermal imagers), and provides for management and control of those sensors, and formatting and transmission of each sensor's data.
- Manipulator
  A Manipulator module provides the UGV with means to reach to or towards objects of interest. This is typically implemented with a multi-segment jointed arm; the module provides for control and operation of the arm.

- End-Effector
  This module attaches to the distal end of the Manipulator arm, and provides means to grasp or otherwise manipulate an object of interest.
- Autonomous Behaviors
  This module implements autonomous navigation, high-level manipulation behaviors, and other autonomous and semi-autonomous control behaviors.

As suggested by the module partitioning, the AEODRS Common Architecture is a distributed architecture. Its logical architecture builds on the Joint Architecture for Unmanned Systems (JAUS) standard. The JAUS standard, which specifies transport, protocols and messages to be used in the control of unmanned systems, has evolved over the course of several years. Now an SAE standard supported by a suite of SAE specification and guidelines documents, JAUS has matured considerably in the last four years.

The current SAE-JAUS specifications derive from the JAUS Reference Architecture version 3.3 (JAUS-RA3.3); many of the service-sets of the SAE-JAUS specifications derive directly from JAUS-RA3.3. JAUS-RA3.3 has been successfully demonstrated in multiple advanced prototypes tested in operational scenarios, and under realistic operational conditions. Neither the choice of a distributed architecture nor the decision to employ JAUS transport, protocols and messages to provide inter-module communications represent novel or untested approaches.

Implementation Approach

In the current phase of the AEODRS program, a documentation set has been developed that provides architectural description, performance specifications for each of the identified modules, and interface specifications for the physical, electrical, and logical interfaces of each module.

There is, however, always risk attendant to the implementation of architecture for a new system. The remainder of this paper discusses implementation strategy adopted to detect, mitigate and manage those risks.

The implementation of standards-based systems is dependent on the quality of the standards, and on practitioners' knowledge of those standards. Incompleteness ("holes") and ambiguities in standards and specifications based upon those standards are clear risks in any standards-based development.

The AEODRS program attempts to mitigate those risks by providing additional interface definition in the program specifications; the program also attempts to document standards community best practices where applicable.

The AEODRS systems engineering team recognizes that good intentions and hard work on the part of systems engineers and document authors is not sufficient to assure the completeness and correctness of the program's specifications. The use of the Architecture Testbed described below (Mitigation through Early Simulation) to perform initial, early testing of concepts is one element in a strategy of risk mitigation, as are Mitigation Through Architecture and Mitigation Through Exposure. The following sections provide brief overviews of these and other integration risk mitigations of the AEODRS program.

Mitigation Through Architecture

The AEODRS architecture provides several means to minimize integration risk to suppliers and integrator.

First, new or revised functionality is encapsulated in separate modules to facilitate testability.

Second, since the inter-module interfaces adhere to the JAUS standard, the exposed messages have known and parseable formats, and are therefore amenable to capture, inspection and analysis on the intra-subsystem and inter-subsystem communication links, again facilitating test and evaluation.

Third, the development approach facilitates risk mitigation by iterative integration of functionality, as illustrated in Figure 3:

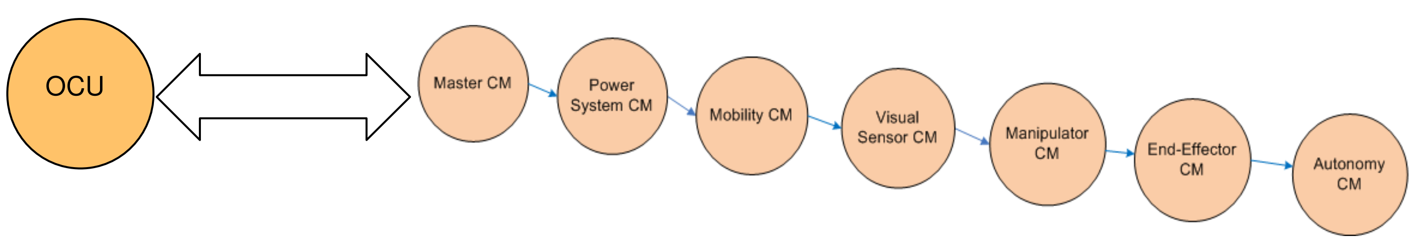

Figure 3: Incremental Integration Concept

The implementation of these approaches is expanded upon in the paragraphs that follow.

Mitigation Through Exposure

The AEODRS documentation set has been provided to members of industry to support the development, design, and construction of prototype modules for a proof of concept prototype UGV system satisfying the requirements of the Dismounted Operations System. Allocating all modules to a single vendor weakens the architectural demonstration, in that it is more likely that a single performer will make consistent assumptions when ambiguities exist within the document set than that multiple unrelated organizations will do so; allocating modules to different vendors increases the potential for identifying and resolving ambiguous, incomplete, or conflicting specifications.

Integration of these modules into a functioning Dismounted Operations System pre-prototype will be performed by the Applied Physics Laboratory, which has been designated the lead system integrator for this phase. The integration exercise will provide feedback and refinement for the architecture, its interface definitions, and the associated documentation.

Mitigation through Early Simulation

A simplified simulation of the system was constructed. This simulation testbed, referred to as the "Architecture Testbed," utilized an existing EOD UGV training simulator modified to support a standards-compliant façade referred to in AEODRS documentation as an *AEODRS Adaptor*. An AEODRS Adaptor supports the AEODRS system interface, and maps the system-level operations of that interface to the those required by the supported payload, device or subsystem. This is primarily intended to enable integration of existing payloads into an AEODRS system without the burden of redeveloping the payload.

The Architecture Testbed initially implemented a single adaptor for the simulated UGV subsystem; it was later modified, and supported a physical Visual Sensor CM in addition to the simulation of the UGV subsystem. A choice was deliberately made to implement the independent Visual Sensor CM using an independently developed JAUS framework in an attempt to identify ambiguities in the standard, and in early AEODRS documentation.

Incremental Integration and Test

An incremental integration strategy will be used, taking advantage of the well-defined, standards-based system interfaces of each CM. This strategy employs simulations of each of the Capability Modules within a System Testbed environment that allows replacement of each CM simulation with its corresponding Capability Module implementation at any time during the integration phase. The use of this mixed-simulation environment for integration relaxes program dependence on a given fixed sequence of module delivery, and reduces the number of unknown interactions in the initial testing of a given integrand. As a result, the lead integrator will be able to pursue incremental (stepwise) module integration, controlling each increment's scope and maintaining a controlled integration environment.

The iterative integration approach may be explained by examination of several test increments.

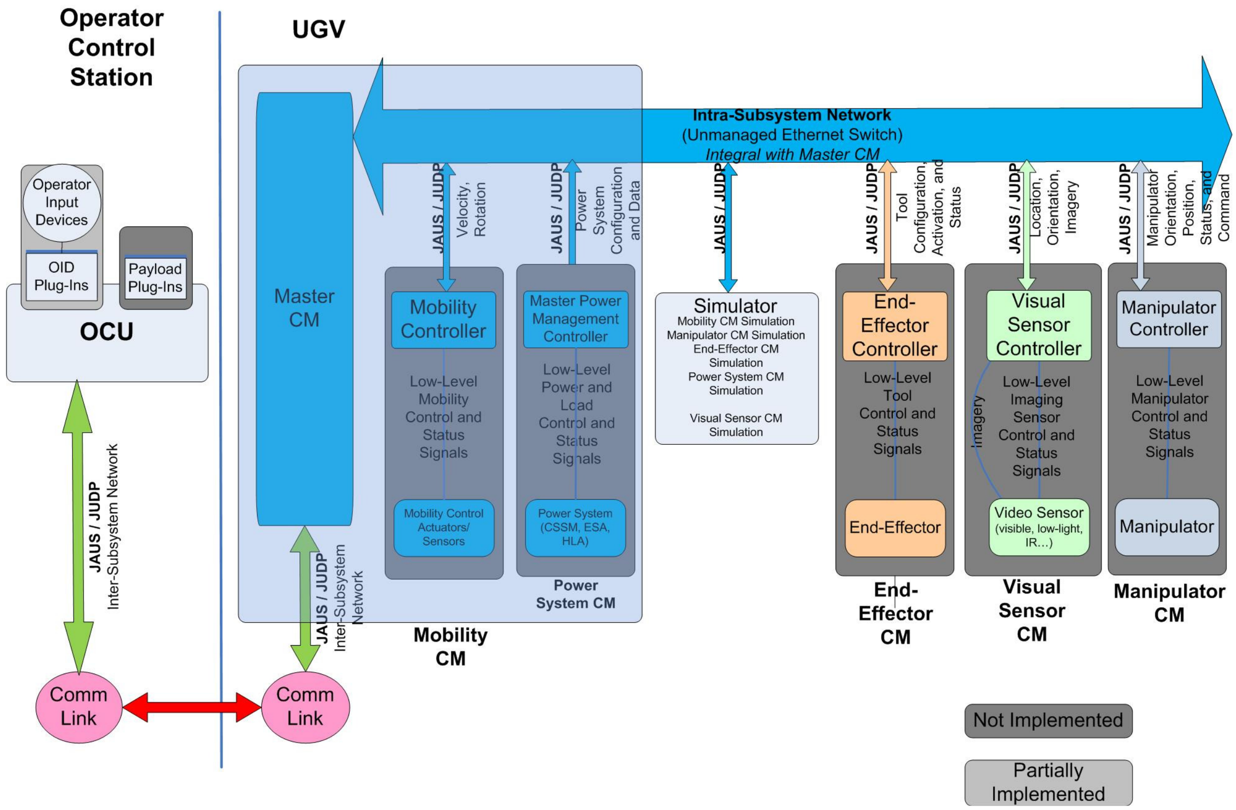

Figure 4: Incremental Integration - Full Simulation

In the first phase of the integration effort, the Master Module functionality is implemented, before other modules are available for integration. The Master Module is exercised by integration with the OCU and with a simulation of the Mobility Module, Manipulator Module, and Visual Sensor Module. This permits early exercise and testing of key Master Module capabilities including the Discovery process, and both Inter-Subsystem and Intra-Subsystem network communications.

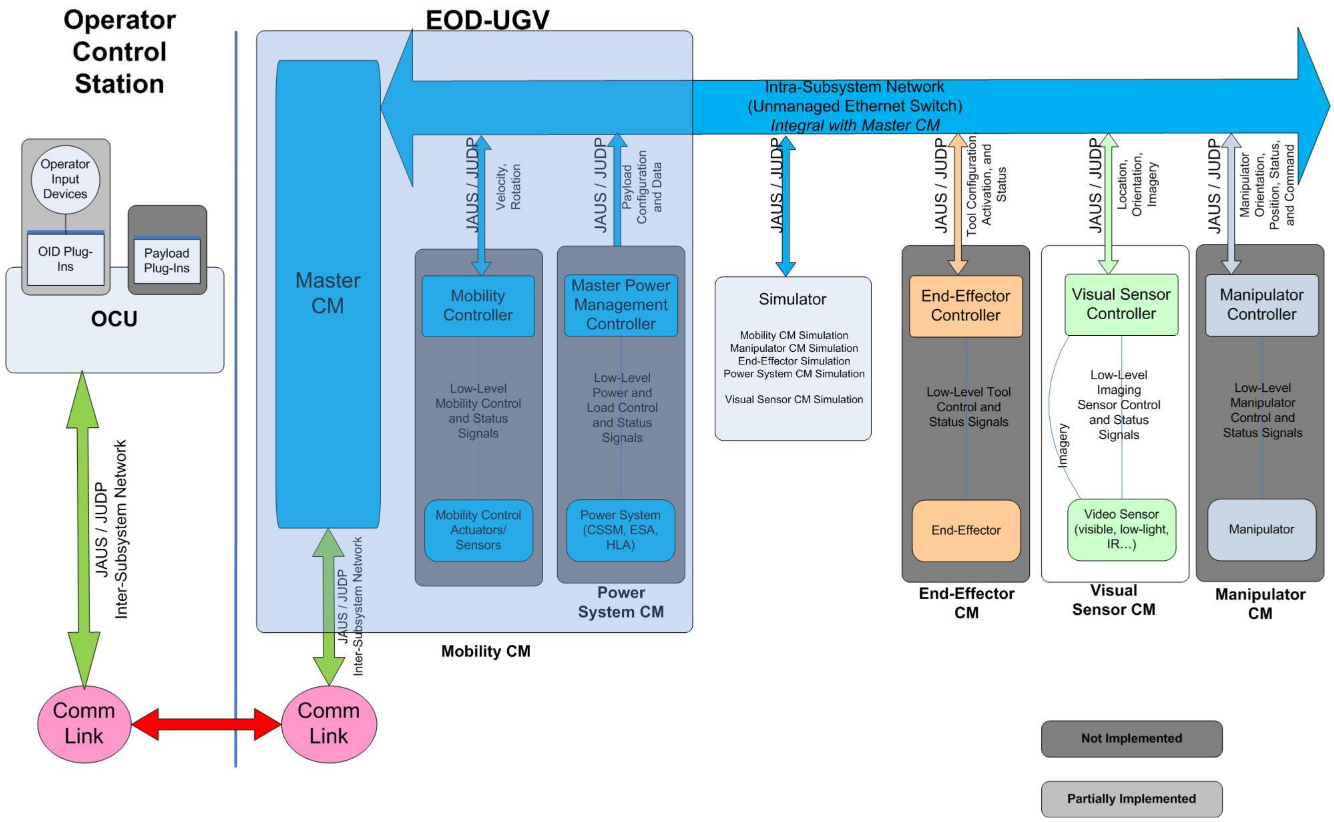

Figure 5: Incremental Integration - Visual Sensor CM

A second phase of the integration and test effort adds the Visual Sensor Module integrand to the system, in addition to the simulator's video. This enables testing not only of the integration of the Visual Sensor Module, but of the handling and display of two concurrent video streams. Again, functionality and interfaces are added in manageable steps, and the integration process is both incremental and iterative.

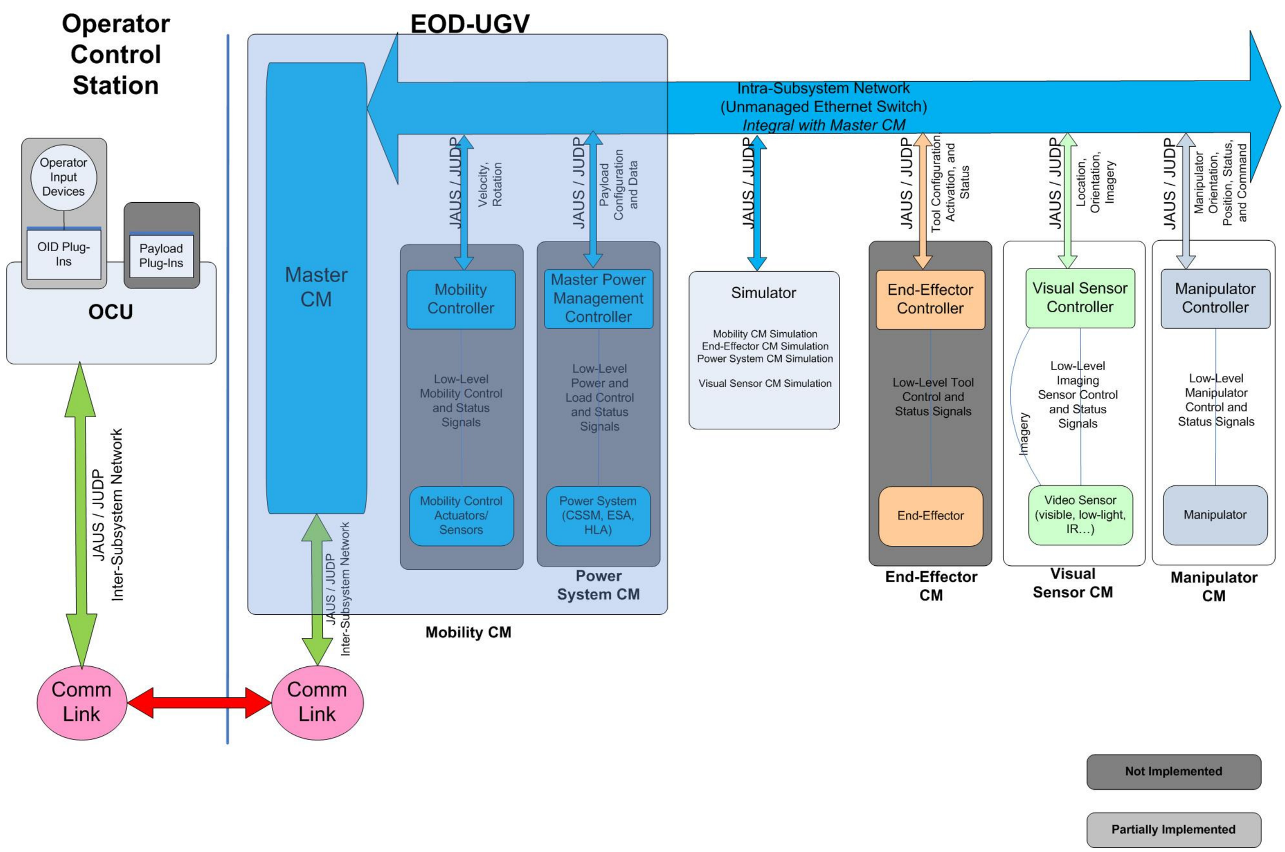

Figure 6: Incremental Integration - Manipulator CM

A third phase of the effort extends the system by integration of the Manipulator Module. The Manipulator functionality and interfaces will be added in two phases; the phase shown here introduces basic, low-level joint control. A later integration phase adds end-effector control modes; additional integration phases replace simulations of the platform, and power system modules with physical modules.

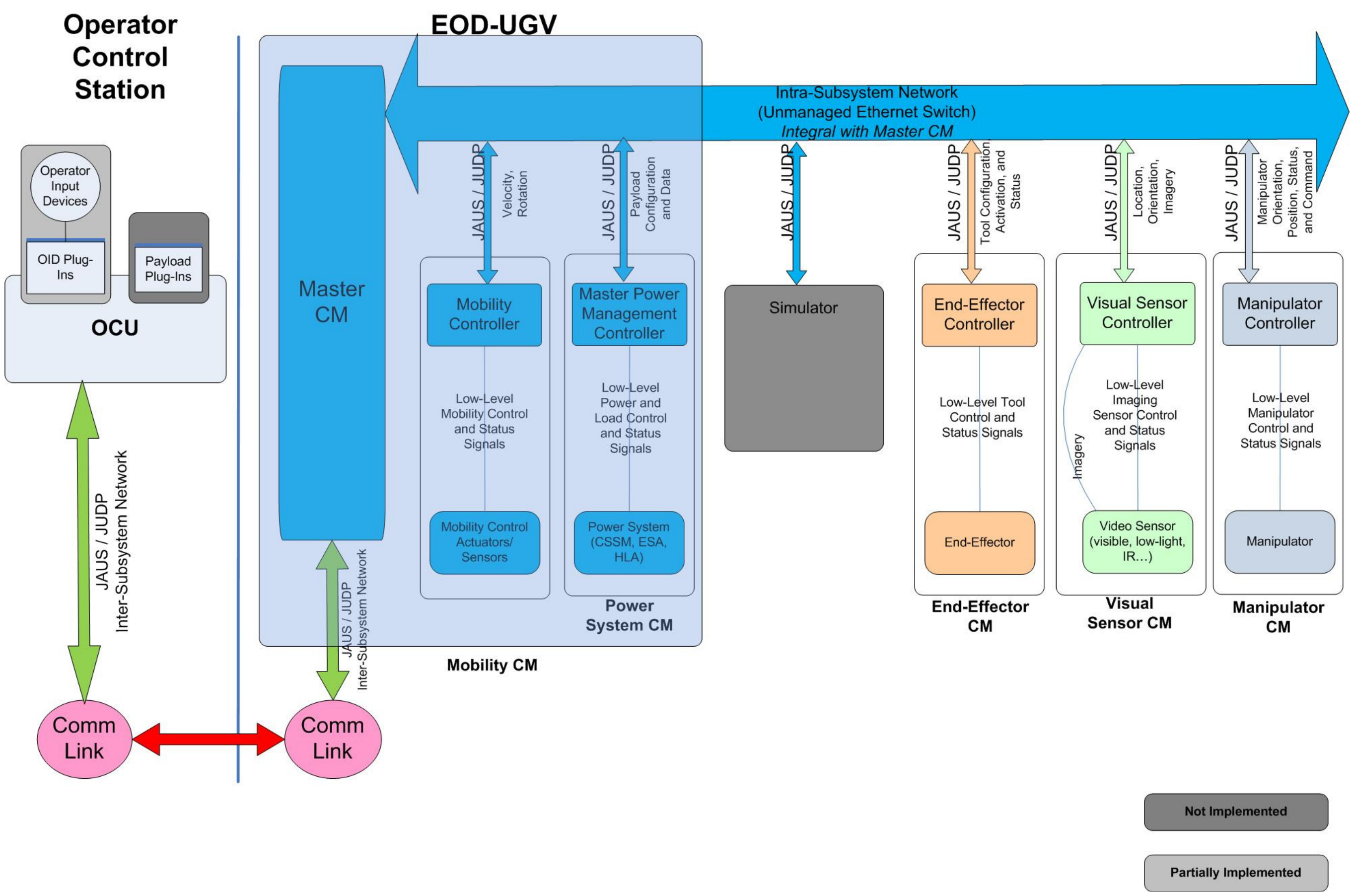

Figure 7: Incremental Integration - Physical Realization

System Testbed

The Incremental Integration and Test process is supported by a mixed-simulation System Testbed constructed to support UGV simulation, and the integration of individual prototype CMs. Initial testing of a prototype CM will be conducted against the known and tested simulations of the system's other CMs; once the prototype CM under test demonstrates implementation of conforming interfaces and basic expected operation, that CM will be integrated with other tested CMs, still within the System Testbed environment.

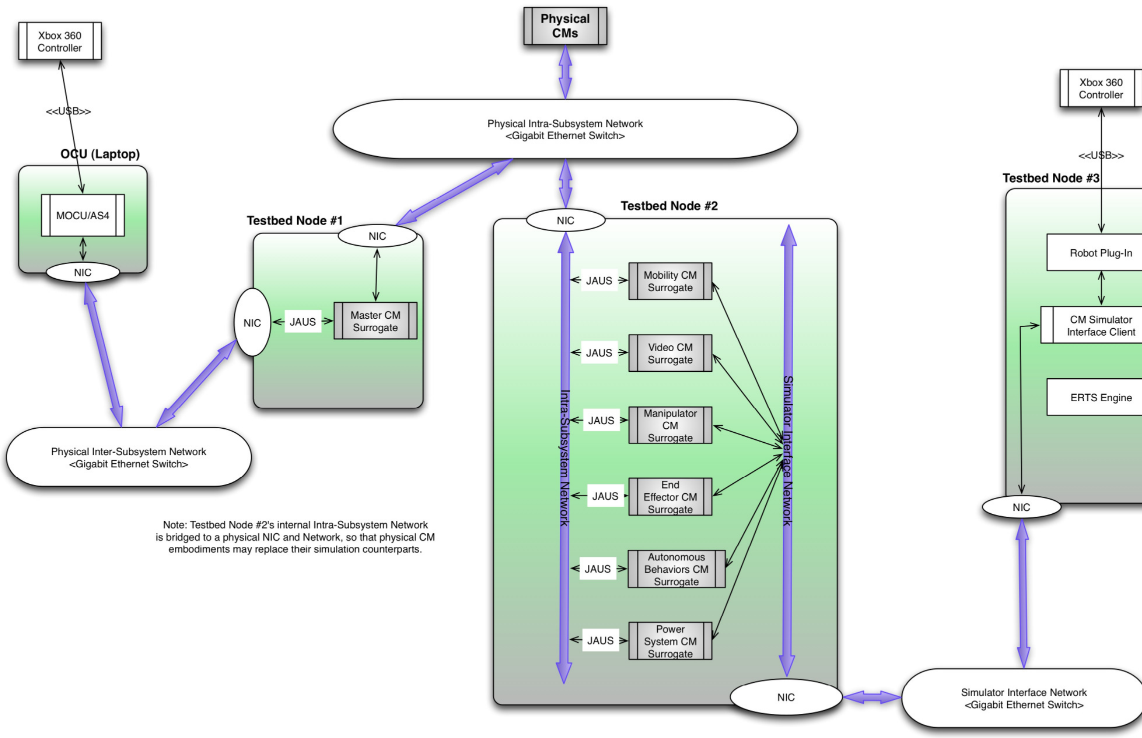

Figure 8: System Testbed Concept

The current System Testbed incarnation utilizes a single laptop computer as the Operator Control Unit subsystem. The OCU subsystem software is a variant of MOCU, developed by SPAWAR Systems Center. The OCU connects via the Inter-Subsystem Network to the Inter-Subsystem Network port of the Master CM; the Inter-Subsystem Network is presently represented in the Testbed by an Ethernet switch, as shown above. The switch provides a means by which an additional laptop (not shown in the illustration above) may be attached to perform packet capture and message stream analysis as part of compliance assessment and performance measurement.

The Testbed currently provides a functional surrogate for the final Master CM; the surrogate is implemented on an embedded PC supporting two network interfaces (for the OCU-facing Inter-Subsystem Network and the UGV-onboard Intra-Subsystem Network). The functionality provided by the surrogate is as described for the Master CM; the surrogate is also used as a convenient point at which to introduce communications delay to emulate communications latencies and data corruption that may be injected by the communications subsystem when used in EMI hostile environments. External connection to the Intra-

Subsystem Network, as the Inter-Subsystem Network, is implemented via an Ethernet switch.

The remaining CM surrogates serve as AEODRS adaptor front ends for the simulation engine; these surrogates run on a second embedded PC distinct from the computer running the Master CM surrogate. Each of these surrogates supports the AEODRS logical system interfaces specified for the CM they represent. As AEODRS adaptors, the surrogates provide interface to the simulation engine.

The simulation engine currently used provides a physics-based simulation of the UGV EOD system within environments representative of common EOD missions. The simulator engine is based on an operator training system (the EOD Robotics Training Simulator, ERTS) developed for NAVEODTECHDIV by a team at Battelle Memorial Institute. The simulator accepts and executes commands, updating status and representative video. The video simulation is provided via AEODRS messaging compliant with the Visual Sensor CM interfaces.

Each surrogate CM supports and participates in the AEODRS Discovery process (detection, identification, registration and publication of services). Thus, if a given CM surrogate is not started, it will not appear in the Discovery registration tables. This provides the flexibility the System Testbed requires in order to support substitution of simulated CMs for physical CM realizations (and vice versa), which enables the Testbed to support the AEODRS incremental integration and test approach.

Conclusion

While the development of modular open system architecture and the proof of that architecture through multi-team prototype implementation pose risks, the AEODRS program has identified and is using multiple strategies to mitigate those risks. The selected strategies take advantage of architecture properties, such as the encapsulation of module function and strong specification of module interfaces. These strategies, briefly outlined in this paper, include early identification of architecture shortcomings through system-level simulation, the ability to exercise both system interfaces and module functionality of a single module-under-test by means of a simulation-based testbed, the ability to perform those tests independent of the order of prototype module availability, and the ability to test controlled groupings of modules against simulations of the remaining modules within a system context.

The ability to perform scope-controlled integration and testing within a mixed-simulation environment requires the construction of a mixed-simulation testbed; this paper also provided an overview of the topology of the AEODRS System testbed.

Acknowledgment

The AEODRS program benefits from the participation of several organizations within the framework of the AEODRS Systems Development and Integration Team (SDIT). The SDIT members come from the following participating organizations:

- NAVEODTECHDIV, Indian Head, MD
- The Johns Hopkins University Applied Physics Laboratory
- The Penn State University Applied Research Laboratory
- Battelle Memorial Institute
- SPAWAR Systems Center Pacific, San Diego, CA

The development of the integration concepts and approaches briefly described in this paper could not have been possible without the collective innovation, active participation and full cooperation of all members of the SDIT.

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