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THESIS

VALIDATION OF ARCHITECTURE MODELS FOR COORDINATION OF UNMANNED AIR AND GROUND VEHICLES VIA EXPERIMENTATION

by

Wyatt T. Middleton

June 2018

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13. ABSTRACT (maximum 200 words)

This thesis presents a model-based systems engineering methodology for employing architecture in system analysis (MBSE MEASA) for the cooperation of cross-domain unmanned vehicles conducting humanitarian assistance and disaster relief (HA/DR). The comprehensive architecture description developed in this paper uses Systems Modeling Language (SysML), which supports the assessment of system requirements for systems engineering. It also uses the Department of Defense Architectural Framework (DoDAF) to expand on the utility of the MEASA methodology, providing an additional level of detail for analyzing collaborative cross-domain unmanned systems performance. The architecture models focus on the interaction between unmanned air vehicles (UAVs) and unmanned ground vehicles (UGVs) and use the relationship of system architecture products and model-based systems engineering analysis to quantify system performance. The applied methodology highlights the feasibility of a UAV-UGV team collaboratively conducting structured, rudimentary tasks in a mission scenario. The result of this research is a validated and executable system architecture for cross-domain collaborative unmanned vehicles. The architecture serves as the conceptual template to guide future research and development of unmanned vehicles.

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Submitted in partial fulfillment of the
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ABSTRACT

This thesis presents a model-based systems engineering methodology for employing architecture in system analysis (MBSE MEASA) for the cooperation of cross-domain unmanned vehicles conducting humanitarian assistance and disaster relief (HA/DR). The comprehensive architecture description developed in this paper uses Systems Modeling Language (SysML), which supports the assessment of system requirements for systems engineering. It also uses the Department of Defense Architectural Framework (DoDAF) to expand on the utility of the MEASA methodology, providing an additional level of detail for analyzing collaborative cross-domain unmanned systems performance. The architecture models focus on the interaction between unmanned air vehicles (UAVs) and unmanned ground vehicles (UGVs) and use the relationship of system architecture products and model-based systems engineering analysis to quantify system performance. The applied methodology highlights the feasibility of a UAV-UGV team collaboratively conducting structured, rudimentary tasks in a mission scenario. The result of this research is a validated and executable system architecture for cross-domain collaborative unmanned vehicles. The architecture serves as the conceptual template to guide future research and development of unmanned vehicles.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF ACRONYMS AND ABBREVIATIONS

CEP	circular error probable
CT	counter-terrorist
C2	command and control
COTS	commercial-off-the-shelf
DoDAF	Department of Defense Architectural Framework
FLiR	forward looking infrared
GLONASS	global navigation satellite system
GPS	global positioning system
HA/DR	Humanitarian Assistance and Disaster Relief
IMU	inertial measurement unit
INS	inertial navigation system
JTF	Joint Task Force
LiDAR	light detection and ranging
LF	landing force
MBSE	model-based systems engineering
MCT	Marine Corps Tactical Task
MEASA	methodology for employing architectures in system analysis
MOOTW	Military Operations other than War
NEO	Non-combatant Evacuation Operations
OPNAV	Chief of Naval Operations Instruction
PID	persons in distress
SASO	Security and Stability Operations
SV	Systems View
SysML	Systems Modeling Language
UAV	unmanned air vehicle
UGV	unmanned ground vehicle

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EXECUTIVE SUMMARY

The role of unmanned systems continues to be defined and refined within the scope of military operations. Currently, unmanned systems are most often associated with operations in a single domain such as air, land, sea. However, the future of the military is progressing towards cross-domain operations. The U.S. military's "ability to integrate land, sea, air, space, and cyberspace military capabilities is unmatched" (Odom and Hayes 2014, 2), but in order to maintain technological superiority, the U.S. military must continue to integrate these domains across the services. The employment of unmanned systems conducting military operations must be a cross-domain, collaborative effort. This research used a model-based systems engineering methodology for employing architecture in system analysis (MBSE MEASA) for cross-domain unmanned systems conducting humanitarian assistance and disaster relief (HA/DR) operations.

This thesis applies the MBSE MEASA methodology to unmanned vehicles conducting HA/DR. The MEASA process integrates the architecture domain and analysis domain, creating "unique opportunity for iteration of the methodology, where the results of detailed system analysis can be integrated directly into subsequent iterations of the methodology" (Beery 2016, 23). Several components of the system were identified of areas of improvement in order to make the system more efficient and optimize the system's components. The identified requirements, functions, and physical components, that required adjustments were corrected with improvements and then implemented back into the system's architecture with the updated functions and system requirements. This led to a more advance system solution with refined system operational requirements and updated functional and physical components. Future work is required to construct and test the refined system in the validation exercise generated in Stage Four in order to analyze system performance. This work demonstrated the usability of the MBSE MEASA methodology by employing the process to a cross-domain unmanned vehicle system conducting HA/DR, resulting in a refined cross-domain collaborative system solution capable of satisfying the stakeholder's need.

Specifically, this research uses the MBSE MEASA to design and analyze architectures for cross-domain collaborative unmanned systems conducting the fundamental tasks necessary to find a person in distress (PID). The MBSE MEASA is a methodology that "integrates system architecture and the system analysis domains and maintains traceability, both forwards and backwards, from the system requirements to the system performance results" (Beery 2016, 21). The MBSE MEASA is a five-stage process that identifies the connection between the system's architecture and the system's analysis. The system architecture domain composition consists of the following stages: Requirement Analysis (Stage One), Functional Architecture (Stage Two), and Physical Architecture (Stage Three). The requirement analysis (Stage One) defined what conditions must be met in order to deem the system operational. The system requirements for conducting humanitarian assistance and disaster relief (HA/DR) were determined by the Chief of Naval Operations instruction (OPNAV) 3500.38B. This instruction served as the stakeholder inputs and provided the conditions of how the system must operate in order to comply with international and civil laws pertaining to humanitarian assistance. The requirements of the system defined the functions of the system, which led to the development of the functional architecture (Stage Two). The top-level functions of the cross-domain collaborative system was sense, navigate, communicate, and move and control. The unmanned vehicles must have capability to navigate the area of operation autonomously in order to search the environment and locate the PID. The functional architectures identified all the system's functions and how the function will operate together in order to meet the system's requirements. Once the system's functions were clearly stated, the physical components capable of executing such tasks were generated. The physical architecture (Stage Three) identifies the physical elements of the system that will conduct the functions depicted in the functional architecture. The physical components of this system consisted of one unmanned ground vehicle (UGV) and one unmanned aerial vehicle (UAV). The UGV and UAV were equipped with sensors capable of performing the functions listed in the functional architecture. These three stages make up the system architecture domain.

The system analysis domain consists of the following stages: Model Definition (Stage Four) and Model Analysis (Stage Five). Within the system analysis domain, a model for the system is constructed and then analyzed resulting in the assessments of technical feasibility and operational effectiveness of the system being highlighted. The model definition (Stage Four) was a validation exercise which consisted of the unmanned vehicles conducting a collaborative task of HA/DR. In this study, the original computer-based modeling of Stage Four was replaced with a validation exercise. The cross-domain vehicles worked together autonomously to identify, locate, and provide assistance to a PID. Both unmanned vehicles used their onboard sensors to navigate and locate the PID in a post-disaster environment. Stage Four provided the traceability of the system's architecture to the system's analysis. After the validation exercise was executed, the system's architecture and requirements were analyzed (Stage Five). The functions and physical components were analyzed to ensure the operational activities of the system were efficiently met. This qualitative analysis resulted in a refined functional and physical architecture being generated. It also produced specified operational requirements that enabled the system with better capabilities than before.

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I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

To date, there has been much research conducted concerning the military application of unmanned vehicles operating in a specific domain. Many of the military projects for unmanned vehicles have focused on unmanned aerial vehicle swarms, multiple unmanned ground vehicles, or several unmanned underwater vehicles executing various operations. The introduction to unmanned systems in the battlefield has been transformational. However, much like the military itself, the future of robotics within the military does not lie within one domain of operation, but in multiple domains. Marine Corps Commandant, General Robert B. Neller stated that in order to compete with other governments and foreign peers, the U.S. military requires “a ‘fifth-generation Marine Corps’ capable of competing in technological domains, as well as the traditional air, sea and land kinetic arenas” (Kreisher 2017, 1). Unmanned vehicles conducting military operations must obtain the capability to operate in land, sea, air, space domains. Throughout the armed forces, the term “cross-domain synergy” has been adapted when referencing the development of the employment of unmanned vehicle systems operating in multiple domains. Cross-domain synergy is defined as “the use of two or more domains to achieve a military advantage” (Odom and Hayes 2014, 125). For cross-domain unmanned systems, interoperability is defined as “the ability of robots to operate in synergy to the execution of assigned missions and the capability of diverse systems and organizations to work together, sharing data, intelligence and resources” (Marques 2012, 3). Obtaining the technological ability to operate unmanned vehicles in multiple domains will allow the U.S. military to maintain technological superiority. This thesis concentrated on developing a comprehensive architecture for cross-domain unmanned ground and aerial vehicles conducting expeditionary operations. Model-based systems engineering analysis enable the assessment of system feasibility and system performance.

B. MBSE MEASA METHODOLOGY

Model-based system engineering (MBSE) offers various methodologies that can be used to design and analyze a system. The methodology selected for this research is the model-based systems engineering methodology for employing architecture in system analysis (MBSE MEASA). The MBSE MEASA is a five-stage process that creates and analyzes the system’s architecture and then implements the revised architecture back into the process, creating an updated system with new capabilities. In order to do this, the MBSE MEASA develops “a comprehensive linkage between the system architecture domain and the system analysis domain” (Beery 2016, 197). This distinct linkage is created by utilizing system modeling language (SysML) products. The SysML products are generated during the five-stage process of the MBSE MEASA and directly support the validation exercise formulated to analyze the system’s architecture. In this thesis, a validation exercise replaces Beery’s computer-based modeling and simulation. One advantage of using the MBSE MEASA process is that it uses an iteration process to refine the system whereas other MBSE methodologies do not (Beery 2016). By using an iterative process, each version of the system encompasses the characteristics of the previous version and adds new capabilities to the updating product (SeBok 2015). A key aspect of the methodology is the traceability of system requirements to the architecture descriptions and validation exercise which assess the requirements and the design to specification parameters.

C. MBSE MEASA METHODOLOGY FOR CONDUCTING HUMANITARIAN ASSISTANCE AND DISASTER RELIEF

The thesis demonstrates the utility of the MBSE MEASA using humanitarian assistance and disaster relief (HA/DR) as a framing scenario. Using unmanned systems in support of this expeditionary warfare operation calls for cross-domain synergy. Currently, when a disaster strikes, civilian forces provide humanitarian aid. However, when a large-scale natural disaster strikes, the military will mobilize its expeditionary forces to provide support, which “often includes Marines on the ground within hours or days of a calamity to clear supply routes and airports, then a larger force, led by the Navy and one of its carrier groups” (Tritten 2013, 1). In addition to Marines on the ground, helicopters are often used for search and rescue efforts and to provide assistance to those in hazardous areas.

However, when providing humanitarian aid in environments that have experienced natural disasters, it can be difficult for Marines to safely carry out services and maintain situational awareness of the unstable environment in which they are operating. Cross-domain unmanned vehicle capabilities will enable the military to provide assistance in an efficient, timely manner, with an emphasis on safety for the operators. As land and air domains are key components of delivering emergency relief, HA/DR provides a great opportunity to explore the use of cross-domain unmanned vehicles and in this case, this work uses the MBSE MEASA to design and analyze the system architecture.

D. THESIS ORGANIZATION

The thesis consists of four chapters. The first chapter introduces the topic and provides the background and motivation for the research. It also introduces the MBSE methodology selected to conduct the research. The second chapter, a conference paper presented at the 16th Annual Conference of Systems Engineering, highlights the first three stages of the MBSE MEASA methodology. The third chapter, a conference paper presented at the Military Operations Research Society 86th Symposium, illustrates the final two stages of the MBSE MEASA methodology, providing context for the methodology and a system analysis. Finally, the fourth chapter discusses the lessons learned while employing the MBSE MEASA methodology and some of the future work that can be derived from this research.

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II. ARCHITECTURE MODELS FOR COORDINATION OF UNMANNED AIR AND GROUND VEHICLES CONDUCTING HUMANITARIAN ASSISTANCE AND DISASTER RELIEF

This chapter was previously published as: Wyatt T. Middleton, Gregory Miller, and Anthony Pollman, "Architecture Models for Coordination of Unmanned Air and Ground Vehicles Conducting Humanitarian Assistance and Disaster Relief." *Systems Engineering in Context – Proceedings of the 16th Annual Conference on Systems Engineering Research,* CSER Conference, May 8–9, 2018, Charlottesville, VA.

A. [CHAPTER] ABSTRACT

This paper presents a model-based systems engineering methodology for employing architecture in system analysis (MBSE MEASA) for the cooperation of cross-domain unmanned vehicles conducting humanitarian assistance and disaster relief (HA/DR). The comprehensive framework developed in this paper uses Systems Modeling Language (SysML), which supports the assessment of system requirements for systems engineering. The research develops architecture to analyze collaborative cross-domain unmanned systems performance. The architecture models focus on the interaction between UAVs and UGVs and use the relationship of system architecture products and model-based systems engineering analysis to quantify system performance. This methodology will also identify those design features which are most impactful to mission effectiveness. The MBSE MEASA incorporates the iterative process of systems engineering in determining the optimal solution for the architecture products. This research will demonstrate the usefulness of model-based systems engineering analysis in the design of UAV-UGV cooperation while conducting a mission scenario. The result of this research will be a validated and executable system architecture for cross-domain unmanned vehicle cooperation. The architecture will serve as the conceptual template to guide future research and development of unmanned vehicles.

B. INTRODUCTION

As the usability and accessibility of unmanned vehicles increases, it is highly likely the Department of Defense will use unmanned vehicles to be "first on the beach and first through the door on tomorrow's battlefield" (Cantelli 2013, 4). In recent studies, the exploration of a team of heterogeneous unmanned systems conducting collaborative autonomy in order to execute specific military operations has increased. This technological scenario is trending upward among various nations and will continue to redefine the future of unmanned systems missions. However, to date, few articles discuss the methods necessary to explore what is technologically feasible or discuss the operational utility of the collaborative unmanned systems. In addition, few studies quantifying changes in performance specifications for heterogeneous unmanned vehicle swarms with their impact on operations. The original motivation for this research comes directly from the Commandant of the Marine Corps, who stated the U.S. military "ha[s] to focus on the capabilities required for near-peer competitors, including cyber, information warfare, electronic warfare, unmanned air and ground systems and robots" (Kreisher 2017). A key step to creating a collaborative autonomous system is the development of the system architecture for the cross-domain system.

This paper contributes a comprehensive architecture for cross-domain UGV and UAV conducting expeditionary operations, which uses the relationship of system architecture products and model-based systems engineering analysis to analyze system feasibility and system performance. For the purpose of this study, a cross-domain system is defined as an unmanned system that can operate autonomously or remotely, alone or in a swarm, in at least two of the six defined domains: land, sea, air, space, cyberspace, and electromagnetic spectrum. However, this research will focus specifically on the operation of unmanned vehicles in the land and air domain. This report will process the system's operational requirements into preferred system configurations using a detailed experiment. The experiments will inform operational effectiveness metrics for a pairing of heterogeneous unmanned systems. The MBSE MEASA methodology also highlights the feasibility of the utilization of a UAV-UGV team collaboratively conducting structured, rudimentary tasks that may be present in a given mission scenario.

C. MODEL-BASED SYSTEMS ENGINEERING METHODOLOGY FOR EMPLOYING ARCHITECTURE IN SYSTEMS ANALYSIS

The Model-Based Systems Engineering Methodology for Employing Architecture in System Analysis (MBSE MEASA) is a baseline analysis method following the development of SysML products. SysML is defined as "a general-purpose graphical modeling language that supports the analysis, specification, design, verification, and validation for complex systems" (Friedenthal et al. 2015). Use of the MBSE MEASA approach is only appropriate when the stakeholder analysis has been conducted and the system's operational requirements have been defined. The MBSE MEASA has the capability to conduct a system analysis, determining the system's technical feasibility and examining the operational effectiveness of the system. The results of the analysis can then be implemented back into the system architecture based on the general system's engineering iteration process, leading to the optimal system solution. This method "defines the use of architecture to support analysis (and vice versa) to ensure that behaviors represented in the models and simulation created in the System Analysis Domain can be traced to functions prescribed in the System Architecture Domain" (Beery 2016, 11). By using this analysis, the system's comprehensive framework is traceable to the physical and functional components of the system. The MEASA methodology "provides a comprehensive framework for the creation of system architecture products, the creation of external simulation models, and the iteration of the systems engineering process beyond the capabilities of any existing systems engineering approach (Beery 2016, 11).

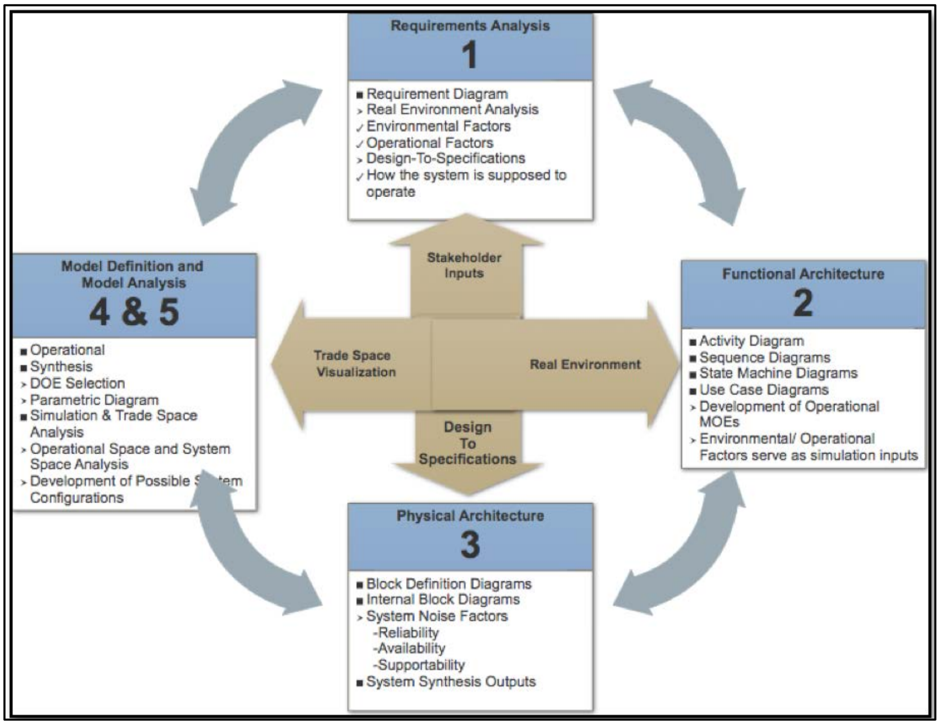


Figure 1. MBSE MEASA Methodology. Adapted from Beery (2016).

Figure 1 is a graphical representation of the stages of the MBSE MEASA. The MBSE MEASA is divided into five stages: Requirements Analysis, Functional Architecture, Physical Architecture, Model Definition (Operational)-Model Definition (Synthesis), and Model Analysis. Figure 1 also includes some of the SysML products of the system under research that will be generated. The first stage of MBSE MEASA is to conduct a requirements analysis, a very important stage of the iterative process that must be done efficiently. INCOSE (2010) states that the "system requirements are the foundation of the system definition and form the basis for the architectural design, integration, and verification" (Walden et al. 2015). This paper provides the MEASA SysML product generation for the collaborative autonomy of the unmanned vehicle systems conducting search and rescue efforts which decompose amphibious operations. Following the requirements analysis and the functional architecture for the system, the system design is developed. During this phase, the system is decomposed and partitioned into various critical functions that meet the system requirements. These critical functions in the system's decomposition will capture its complexity (Walden et al. 2015). Once the system's functional architecture is generated, the physical components of the system can be applied to the architecture, resulting in the physical architecture products. Finally, a system model can be developed. A unique function of the MBSE MEASA is that the analysis "utilizes the combined functional and physical architecture products as a basis for the development of external models and simulations" (Beery 2016, 120). This process allows for the model to be generated based on the system's architecture. This enables the model to focus on the system's operational effectiveness by evaluating physical and functional components of the system. As stated earlier, this paper focuses on the development of the system's architecture for the unmanned vehicle systems and the iterative process of implementing SysML products in order to help determine the system's technical feasibility and operational effectiveness.

D. INTRODUCTION TO HUMANITARIAN ASSISTANCE AND DISASTER RELIEF OPERATIONS

This research used humanitarian assistance and disaster relief (HA/DR) as the context for exploring the utilization of MBSE MEASA. The MBSE MEASA allows for the analysis of various levels of collaborative autonomy while conducting HA/DR amphibious operations. Figure 2 illustrates expeditionary operations with emphasis on amphibious operations. It also identifies amphibious operations of interest to MBSE MEASA.

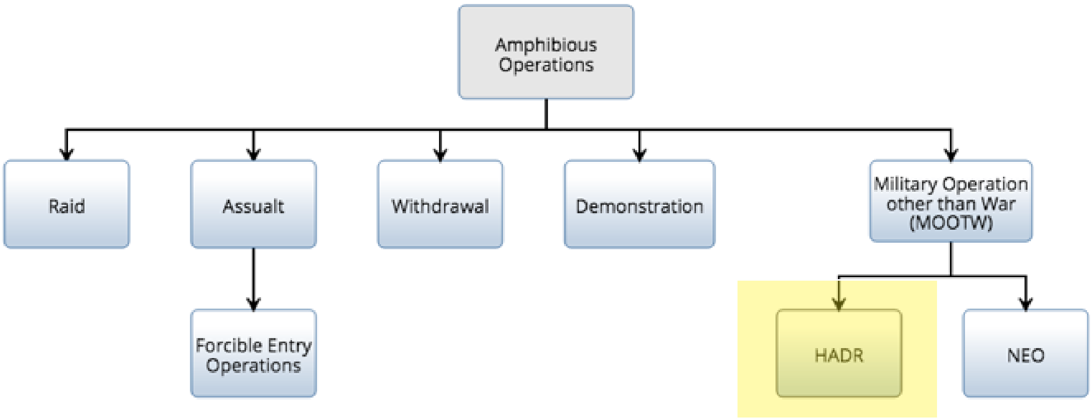


Figure 2. Amphibious Operations Activities. Adapted from Joint Chiefs of Staff (2009).

An amphibious operation is defined as “a military operation launched from the sea by an amphibious force, embarked in ships or craft with the primary purpose of introducing a landing force (LF) ashore to accomplish the assigned mission” (Joint Chiefs of Staff 2009). Conducting amphibious operations allows the U.S. military to strategically mobilize their military forces, giving the military the capacity to strike at a position of choice and assert a strong projection of power for ground forces. The majority of amphibious operations are carried out by Navy and Marine Corps forces. Amphibious vessels such as amphibious assault ships, amphibious transport docks, and amphibious command ships were specifically designed to support the Marine Corps doctrine to operate from sea to land. These ships may support assaults, raids, withdrawals, demonstrations and humanitarian assistance and disaster relief operations. As natural disasters strike, the U.S. military has proven to be a key member of the relief support system. Within the scope of the recent natural disasters, for which the U.S. military has provided support, there has been a focused effort to avoid placing service members in life-threatening environments while conducting humanitarian assistance and disaster relief operations. Operationally, unmanned air vehicles and unmanned ground vehicles should keep service members out of harm’s way by performing some or all HA/DR missions.

E. MEASA SYSML PRODUCT GENERATION FOR CROSS-DOMAIN UNMANNED VEHICLES CONDUCTING HA/DR

This paper conducts a requirements analysis (Stage one), develops the functional hierarchy (Stage two), and develops the physical hierarchy (Stage three) for a cross-domain unmanned vehicle system conducting HA/DR operations and implementing the following stages into the system analysis. Stages one to three develop the comprehensive framework for the system which can then be related to an external model, simulations, or field experiment to determine operational effectiveness and technical feasibility. Stages four and five represent the model, simulations, and or field experiment used to complete the MEASA. This paper does not present the results of Stages four and five of the MBSE MEASA. It highlights only the first three stages of MBSE MEASA by identifying system requirements and developing the system’s architectures. Future work will fully implement the entire methodology of MBSE MEASA.

1. Requirements Analysis

The purpose of the requirements analysis is to take the inputs of the stakeholders and transform that stakeholder-centric view into a technical view that can provide a system that fulfils those primary activities. The foreign and domestic policies such as the Chief of Naval Operations Instruction (OPNAV) 3500.38B guide U.S. military forces on how to efficiently conduct HA/DR without violating humanitarian or operational laws. The instructions included in OPNAV 3500.38B define the system's operational requirements. The requirement analysis for HA/DR is represented by the governing policies currently in place:

Expeditionary Operations

- Amphibious Operations
- Amphibious Raid (Marine Corps Tactical Task (MCT) 1.3.2.2)
- Amphibious Assault (MCT 1.3.2.3)
- Amphibious Withdrawal (MCT 1.3.2.7)
- Amphibious Demonstrations (MCT 1.3.2.1)
- Military Operations other than War (MOOTW) (MCT 1.6.6)
- Provide Humanitarian Support [Assistance] (Navy Tactical task (NTA) 4.7.8)
- Provide Disaster Relief Support (NTA 4.7.9)
- Conduct Non-combatant Evacuation Operations (NEO)-(MCT 1.6.6.6)
- Conduct Anti-Terrorism Operations-(MCT 1.6.6.1)
- Conduct Anti-Terrorism Enabling/Support Operations-(MCT 1.6.6.2)
- Conduct Counter-Terrorist (CT) Operations-(MCT 1.6.6.3)
- Implement Anti-Terrorism Measures-(MCT 1.6.6.4)

- Support Anti-Terrorism Measures -(MCT 1.6.6.5)
- Conduct Peace Operations-(MCT 1.6.6.8)
- Conduct Security and Stability Operations (SASO) -(MCT 1.6.6.9)

Another way to graphically represent what the system must accomplish is to generate a SysML requirement diagram. The requirement diagram highlights the functionality of the system as well as its capabilities, operational requirements, and performance conditions as shown in Figure 3. The collaborative autonomy of the unmanned vehicle system will take place while providing search and rescue efforts.

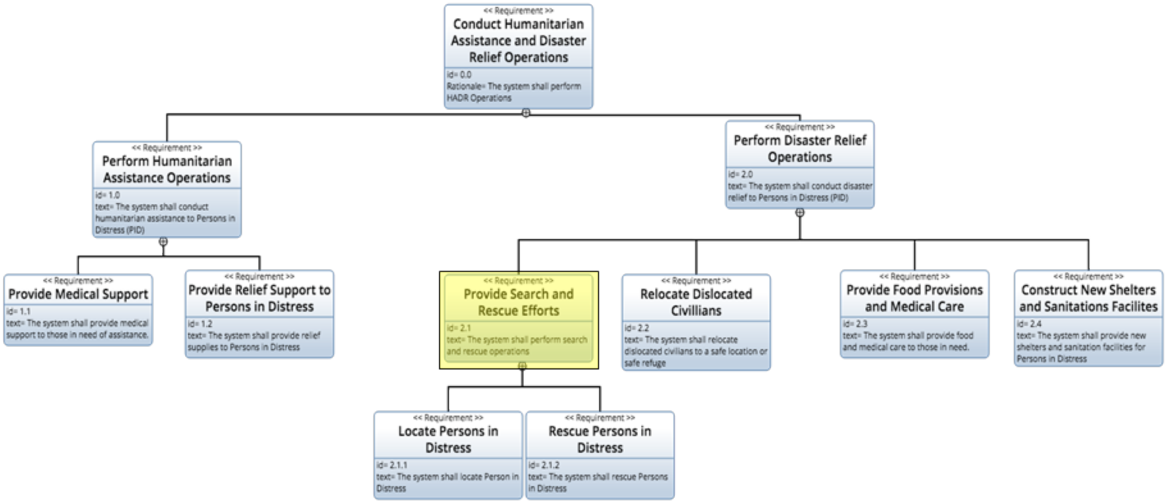


Figure 3. Requirements Diagram

2. Functional Architecture Products

After the problem is clearly stated, the system must be designed. System design is composed of functional architecture, physical architecture, design configurations, and modeling and simulation. Functional architecture is defined as “an arrangement of functions and their sub-functions and interfaces (internal and external) that defines the execution sequencing, conditions for control or data flow, and the performance requirements to satisfy the requirements baseline” (IEEE 2005). The functional architecture describes the operations or functions that will be carried out in order to meet mission objectives. It also breaks down the capabilities of the system to ensure unnecessary operational activities are reduced. Reducing unnecessary activities results in fluent system updates and a cost-effective system. Figure 4 depicts the functional decomposition of a team of unmanned vehicles conducting search and rescue operations autonomously.

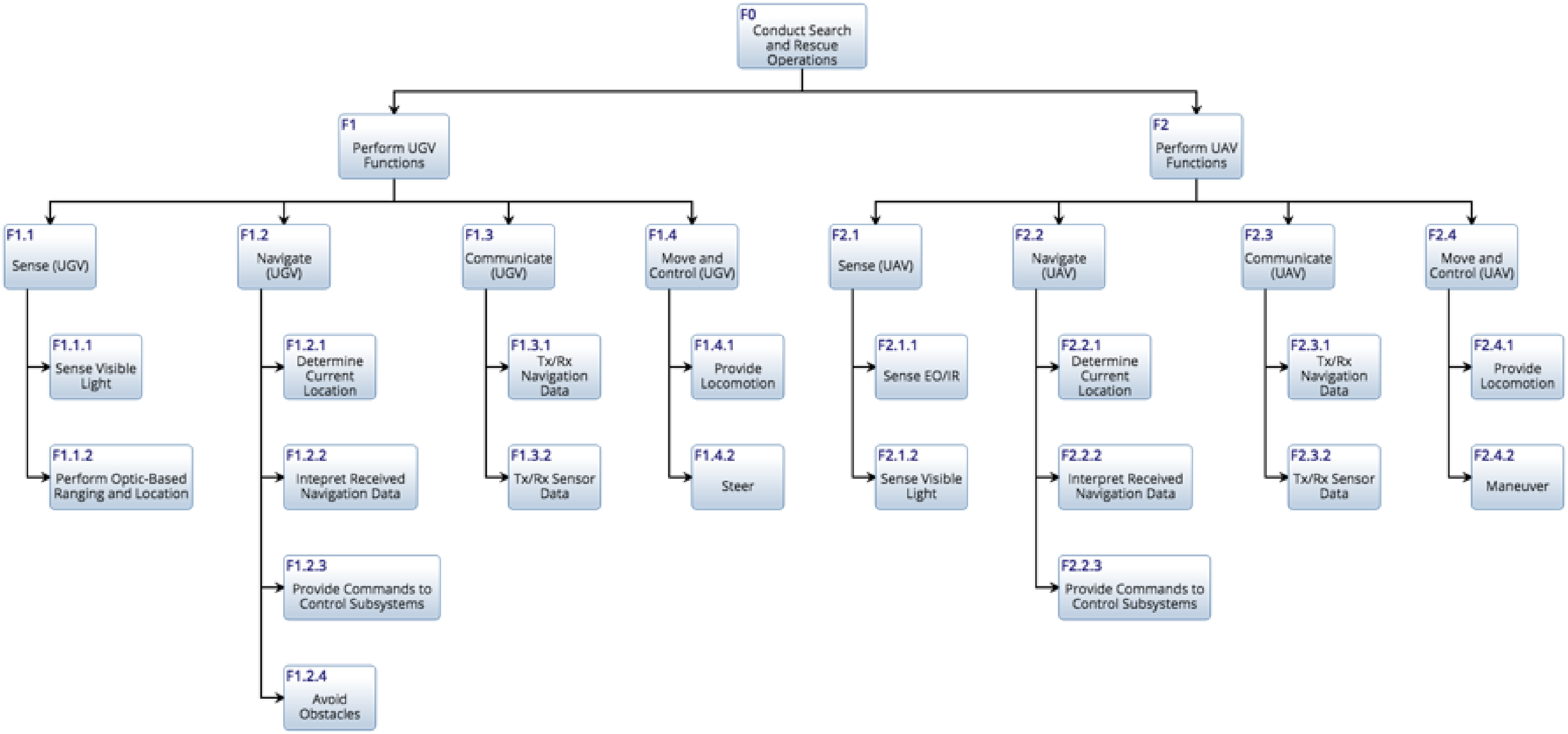


Figure 4. Functional Architecture for HA/DR Operations

The UGV and UAV collaborate with one another in order to locate the persons in distress and provide assistance. The high-level functions for the UGV and UAV include: sense, navigate, communicate, and move and control. Each vehicle will be equipped with similar electro-optic capabilities. Ideally, the UAV will locate the Persons in Distress (PID) and then command and control (C2) will launch the UGV to rendezvous with the PID to provide relief support and rescue assistance. In order to keep the human interface in the communication loop, all data gathered from the UAV and UGV will be transmitted back to C2, where the Joint Task Force (JTF) commander will make the operational decisions.

The MBSE MEASA functional architecture also consists of developing any of the following diagrams: activity diagrams, sequence diagrams, state machine diagrams, and use case diagrams. The use case diagram depicts all personnel involved in the operation and can be used as a tool to help identify issues in system control or system implementation. All of the components in the SysML use case diagram illustrate what functional components of the system must be completed in order to meet the primary activity.

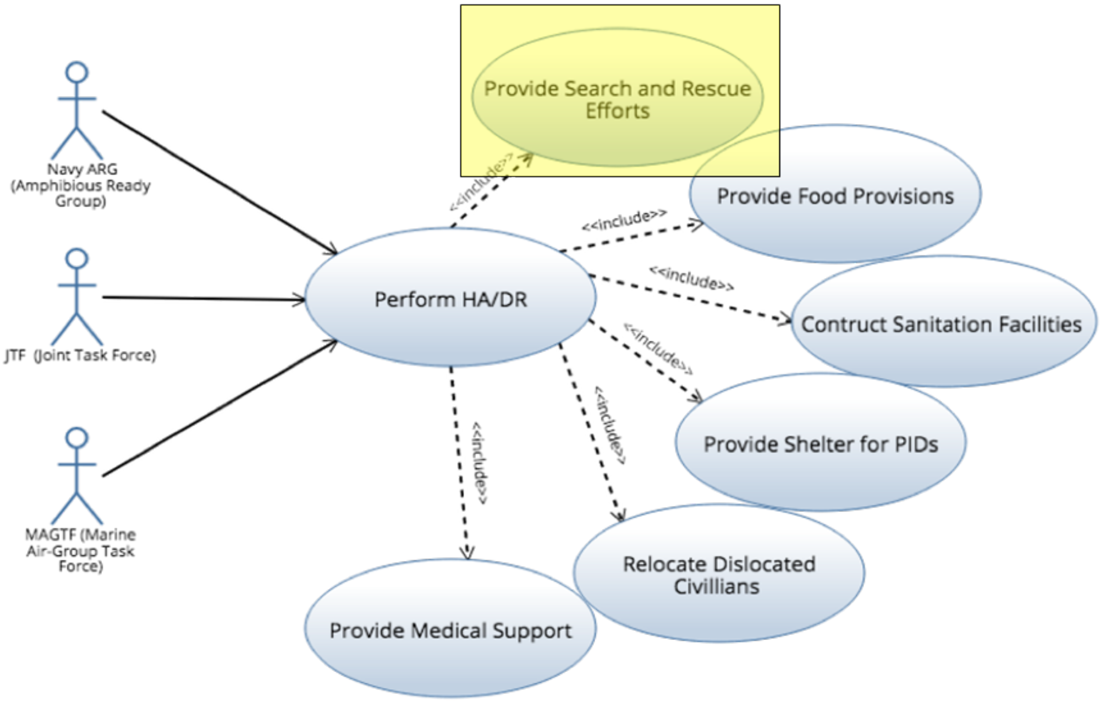


Figure 5. Use Case Diagram for HA/DR

Figure 5 identifies all U.S. military forces involved in HA/DR. The combination of these two diagrams depict what functions the system must execute and the key members of the system. The products generated in this phase capture how the system will satisfy the system requirements outlined earlier. The SysML diagrams generated in this section help portray traceability which highlights the expected utilization of each diagram. Both diagrams presented will help ensure the technical feasibility of the design.

3. Physical Architecture Products

Once the system has been divided into functions and sub-functions, the physical architecture can be developed. The physical architecture provides the baseline for all the required component resources. These architectures are often graphically represented by block definition diagrams. Block definition diagrams provide a graphical representation of the system's components. Once one has defined the high-level components, then a decomposition of those components can be conducted which will examine the physical makeup of the system more in depth. There are several benefits of using the SysML block definition diagrams. One benefit is how the relationship of each component is shown in the diagram. This allows the architect to know the decompositional relationship of all the components in the system.

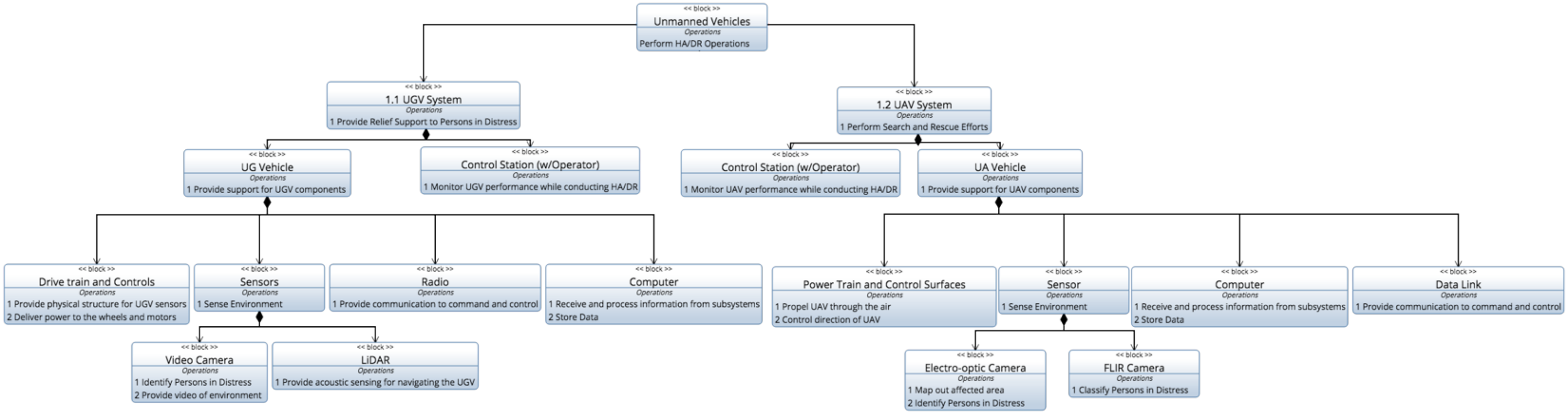


Figure 6. Block Definition Diagram for Unmanned Vehicle Systems

The UGV system physical components are the UG vehicle and the control station with an operator. The UG vehicle is broken down into the following components: drive train and controls, sensors (LiDAR and video camera), radio, and computer. The LiDAR’s optical sensing ability enables the UGV with the capability of obstacle avoidance. The UAV system is composed of the UA vehicle and the control station with an operator. The UA vehicle is broken down into the following components: power train and control surfaces, sensors (electro-optic camera and FLIR camera), data link, and computer. The FLIR camera allows the mission to be conducted during low visibility and also help to the identify and classify a PID. Both operators are included in the physical loop to monitor the vehicle’s performance and to help identify PIDs.

F. CONCLUSION

The MEASA methodology develops an iterative and systematic approach to developing a solution for the collaborative system. By focusing on stages one, two, and three, the operational requirements were clarified and the functional and physical architectures were developed. This allows those inquiring about collaborative autonomous systems conducting HA/DR missions to have the critical functions and physical components of the system identified, organized, and analyzed. Multiple designs for potential cross-domain unmanned vehicle systems maybe generated and analyzed using this methodology. Future work will consist of developing a field experiment using the SysML products generated in this paper to determine the operations effectiveness of the system based on the architecture and provide a cost-effective option of constructing a collaborative autonomous system that has military utility and technical feasibility. This paper presented the functional and physical architecture required to execute amphibious missions such as HA/DR, which will catalyze further development for the use of robotics within expeditionary operations.

III. COOPERATIVE UNMANNED AIR-GROUND VEHICLE SEARCH AND RESCUE EXERCISE

This chapter was previously published as: Wyatt T. Middleton, Gregory Miller, and Anthony Pollman, "Cooperative unmanned, Air-Ground Vehicle Search and Rescue Exercise." *Military Operational Research Society – The 86th MORS Symposium,* MORS Conference, June 18–21, 2018, Monterey, CA.

A. [CHAPTER] ABSTRACT

This paper describes the application of a modified model-based systems engineering methodology for employing architecture in system analysis (MBSE MEASA) to create and validate a cross-domain collaborative autonomous system. Results from the early stages of the MEASA methodology are presented, specifically, the architecture descriptions of Unmanned Air Vehicle (UAV)-Unmanned Ground Vehicle (UGV) team collaboration while conducting humanitarian assistance and disaster relief operations. This study replaces computer-based modeling and simulation inherent to the original MEASA methodology with a field exercise that validated the architecture descriptions. The applied methodology highlights the feasibility of a UAV-UGV team collaboratively conducting structured, rudimentary tasks in a mission scenario. The result of this paper, validated the model for cross-domain unmanned vehicles conducting expeditionary warfare and an analyzed assessment of the system design. This research serves as a model-based systems engineering analysis method for the future development of employing collaborative autonomous systems with military utility.

B. BACKGROUND AND MOTIVATION

Throughout recent conflicts, the U.S. military has increasingly avoided placing human soldiers in a life-threatening environment while conducting dangerous operations. In order to continue executing expeditionary military operations in a safe manner, without placing human lives at risk, military robotics such as unmanned air vehicles (UAVs) and unmanned ground vehicles (UGVs) must be incorporated into military standard operating procedures. Developing the operational framework required to accomplish the mission will catalyze further development for the use of robotics within expeditionary warfare. This study highlights the technical and non-technical challenges that must be overcome to bring an unmanned air-ground task force for humanitarian assistance and disaster relief (HA/DR) to fruition. The result of this research is a validated and executable system architecture for cross-domain unmanned vehicle cooperation. “For the purpose of this study, a cross-domain system is defined as an unmanned system that can operate autonomously or remotely, alone or in a swarm, in at least two of the six defined domains: land, sea, air, space, cyberspace, and electromagnetic spectrum” (Middleton, Miller, Pollman 2018, 1). The architecture will serve as the conceptual template to guide future research and development of unmanned vehicles.

This research processed the system’s operational requirements into preferred system configurations using the Model-Based Systems Engineering Methodology for Employing Architecture in System Analysis (MBSE MEASA) methodology in the context of a detailed validation exercise. It also highlighted the feasibility of cross-domain autonomous systems collaboratively conducting military operations.

The MBSE MEASA methodology is a five-stage process that enables a designer to go from a system’s concept to its final design using model-based techniques. Stages One to Three generated in Middleton, Miller, and Pollman (2018), developed the architectural models for the system. Stages Four and Five use the architecture description developed in Stages One to Three to form the exercise and conduct a model analysis. This paper presents the result of completing Stages Four to Five.

C. THE MBSE MEASA APPROACH

The MBSE MEASA is a way to analyze a system by connecting the system’s architecture to the system analysis spectrum by models and simulations. This research replaces computer-based simulation with a validation exercise. An interested reader can find the original MBSE MEASA in Beery (2016). The first three stages of the MBSE MEASA are used to formulate a model to examine the system’s architecture and design which are simulated in Stage Four and analyzed in Stage Five.

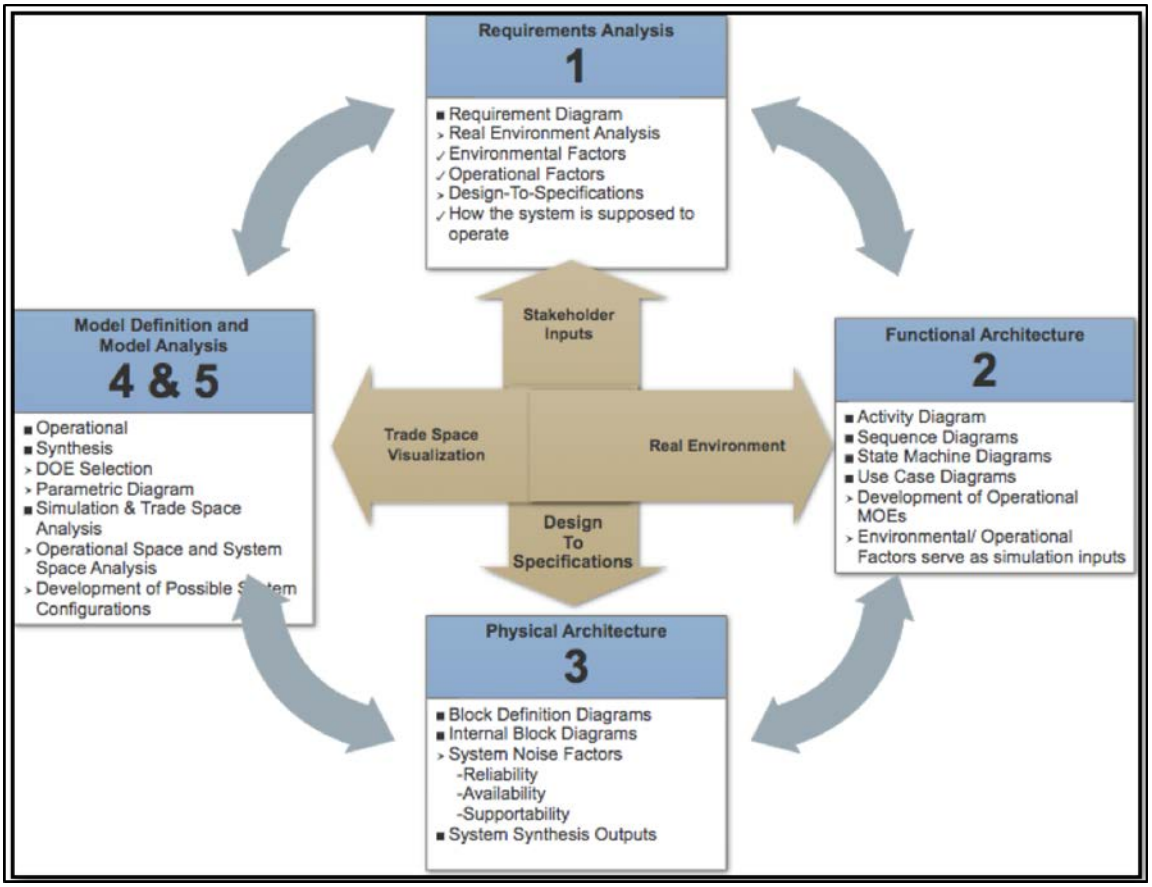


Figure 7. MBSE MEASA Methodology. Adapted from Beery (2016).

Figure 7 depicts the five-step methodology for the MBSE MEASA. In Stage One, the system's operational requirements are determined. Stage Two develops the functional architecture for the system based on the system's operational requirements. Stage Three develops the physical architecture for the system. Stage Four repurposes the developed functional and physical architectures in order to create an external model for the system (Beery 2016). Stage Five represents the system analysis used to determine the system's effectiveness and refine the products of Stages One to Three, completing the MBSE MEASA process.

A large contribution of the MBSE MEASA methodology is the connection between the architecture domain and the analysis domain illustrated in Figure 8.

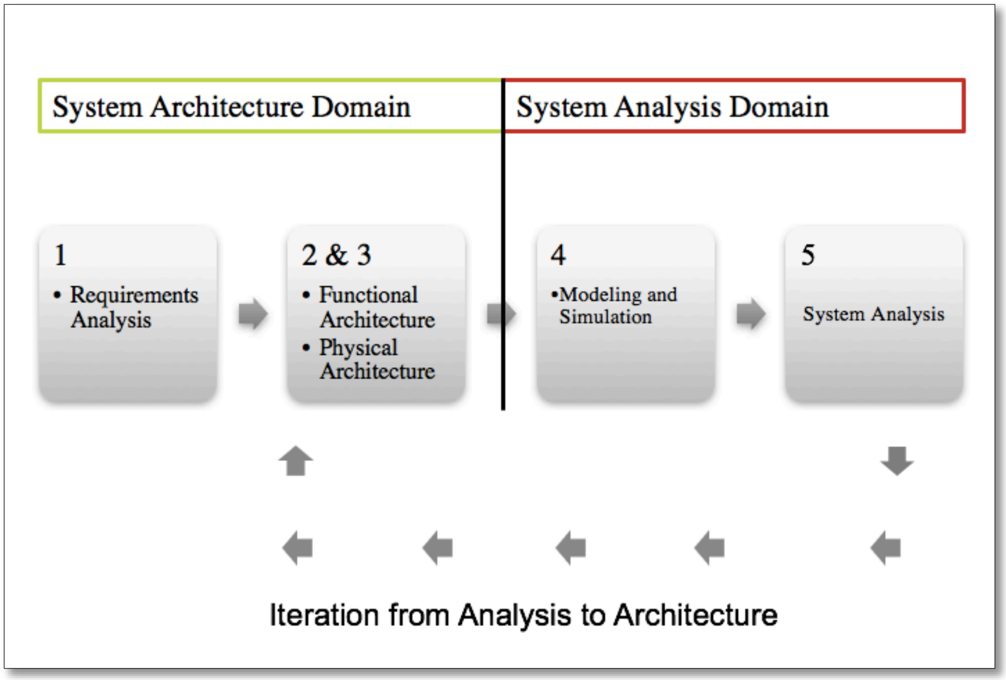


Figure 8. MBSE MEASA Architecture and Analysis Domain.
Adapted from Beery (2016).

The MBSE MEASA explicitly uses the results of the modeling and simulations and feeds them back into the requirements and the architecture design in order to refine the system. In this research, the results from the validation exercise are implemented back into the requirements and architecture design for a refined system with new capabilities.

D. THE MBSE MEASA FOR HUMANITARIAN ASSISTANCE AND DISASTER RELIEF

Stages One to Three in Middleton, Miller, and Pollman (2018) developed the architectural description for the system which was used to create an external model that took the form of a validation exercise in this study, to determine operational effectiveness and technical feasibility. The last two stages in the MBSE MEASA process are highlighted in this paper by defining the model and analyzing the results, completing the five-step methodology of the MEASA.

1. Requirements Analysis

The requirements analysis section (Stage One) takes stakeholder inputs and develops a "set of system requirements that capture both the intended operational environment and design specifications for the system" (Beery 2016, 120). For Humanitarian Assistance and Disaster Relief (HA/DR) operations, the system's operational requirements can be found in the Chief of Naval Operations Instruction (OPNAV) 3500.38B.

2. Functional Architecture Products

After the requirements analysis is complete, the system's functional architecture (Stage Two) can be generated. The functional architecture is "a set of functions and their sub-functions that defines the transformations of input flows into output flows performed by the system to achieve its mission" (SEbok 2017). The requirements developed in Stage One are the "basis for functional Architecture development, which defines the system in terms of the functions that the system must perform as well as the ordering and dependencies of those functions" (Beery 2016, 26). Figure 9 illustrates the functions that must be completed by the collaborative autonomous system.

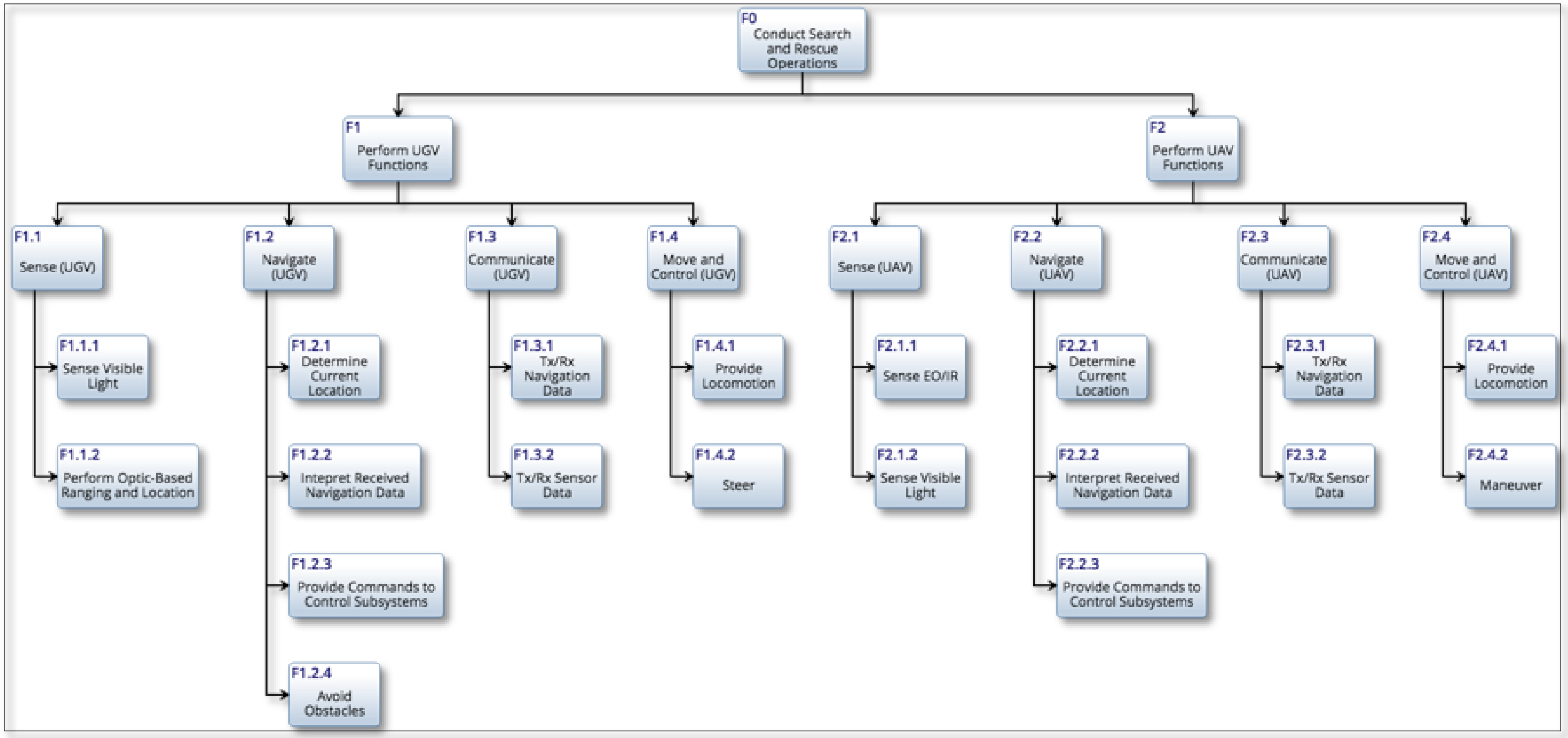


Figure 9. Functional Architecture for HA/DR Operations. Source: Middleton, Miller, and Pollman (2018).

3. Physical Architecture Products

Once the functional architecture is generated, the physical architecture (Stage Three), also known as the physical components of the system, can be identified. The physical architecture provides the baseline for all the required component resources. These architectures are often graphically represented by block definition diagrams, as shown in Figure 10.

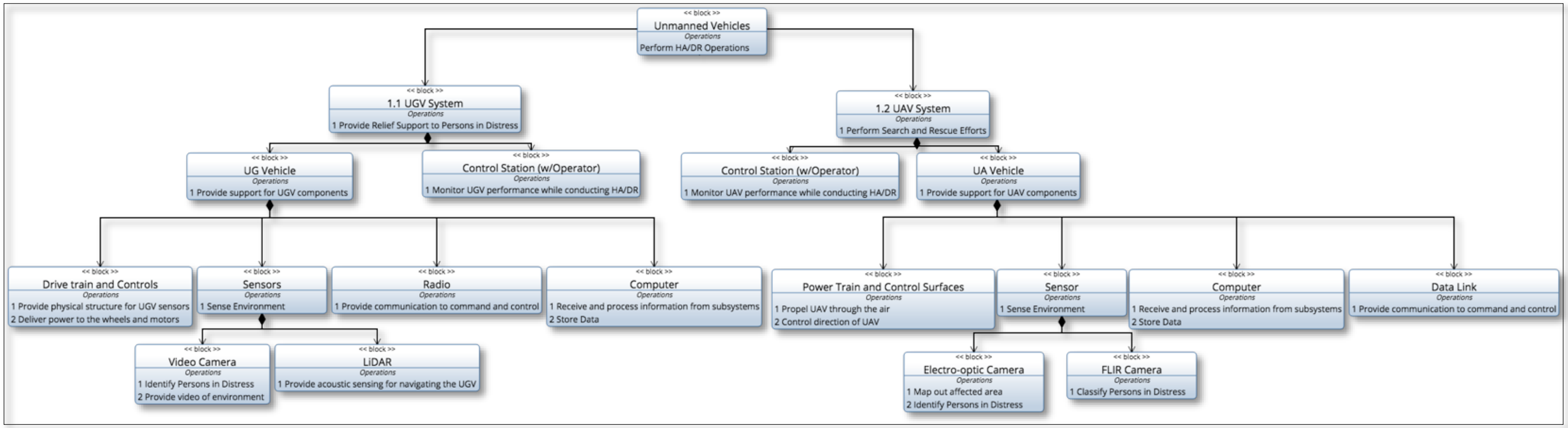


Figure 10. Block Definition Diagram for Unmanned Vehicle Systems. Source: Middleton, Miller, and Pollman (2018).

For a more detailed explanation of the Stages One, Two, and Three, please reference Middleton, Miller, and Pollman (2018).

E. MODEL DEFINITION FOR HA/DR VALIDATION EXERCISE

Stage Four represents the validation exercise. While Beery's (2016) work emphasizes computer-based simulations, this application replaces that with a field exercise. The system requirements and the system's architectures described above contributed to the generation of a system model (Stage Four) capable of analyzing the system's performance (Stage Five). The model consisted of collaborative cross-domain unmanned systems conducting a surveillance sweep to identify potential hazards and potential targets in distress and in need of assistance. Once distressed personnel are identified, the unmanned vehicles transmit the location of the persons in distress (PID) to the unit commander. This allows the human-interface to efficiently task their platoon to provide assistance in a safe and timely manner. The unmanned systems will also be used to provide emergency care packages to disaster relief victims in hazardous areas.

1. Validation Exercise

A lab-scale physical exercise was conducted to measure the operational impact of design variables identified in the system architectures. The validation exercise highlighted the feasibility of the utilization of a team of unmanned aerial vehicles and unmanned ground vehicles interoperating while conducting HA/DR operations.

a. Scenario

The High-Level Operational Concept Graphic (OV-1) presented in Figure 11 explains the environment in which the UAV and the UGV are operating.

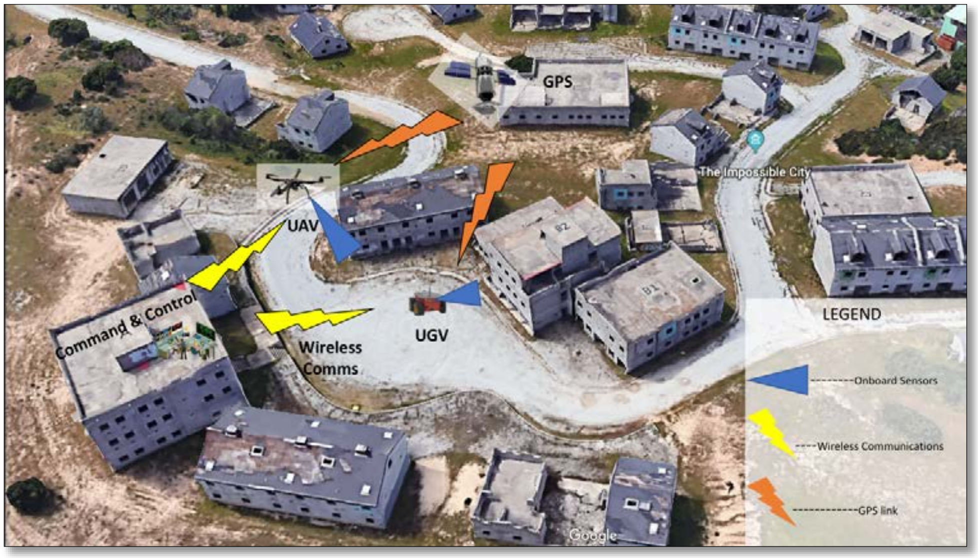


Figure 11. High-Level Operational Concept Graphic

The location is a post-disaster environment deemed too hazardous for human lives. The UAV conducted a scan of the environment using the onboard sensors, looking for persons-in-distress (PID). Once a PID was located, the UAV transmitted the information to command and control (C2). C2 launched the UGV to rendezvous with the PID in order to provide support. Throughout the exercise, the UAV and UGV communicated to C2 using the established wireless network.

b. Equipment

(1) UGV

The UGV used for the exercise was the Pioneer 3-AT, an aluminum powder-coated vehicle, capable of operating in rugged terrain, that can climb obstacles no higher than six inches as illustrated in Figure 12.

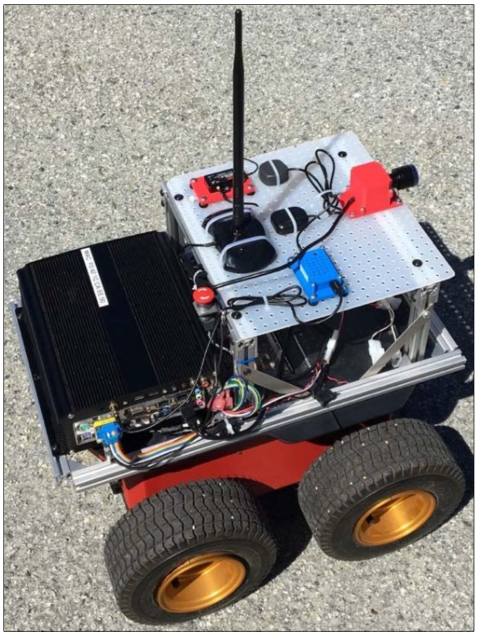


Figure 12. Pioneer 3-AT UGV

It is equipped with a split differential drive train which allows the vehicle to conduct zero-point turns. The sensors used to equip the UGV are illustrated in Figures 13 and 14.

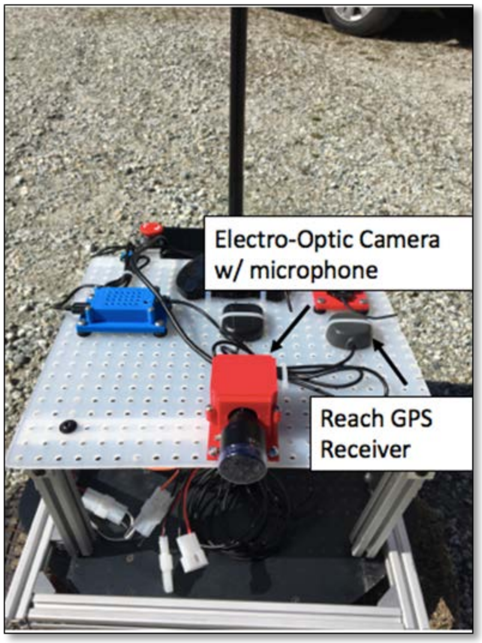


Figure 13. UGV Camera and Reach GPS Receiver

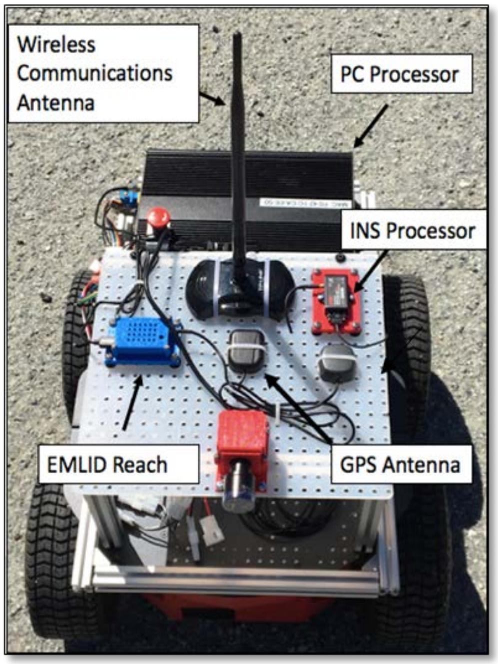


Figure 14. UGV Sensor

The electro-optic camera equips the vehicle with the ability to sense the area of operation. The wireless communications antenna enables the UGV to transmit and receive navigation and sensor data. The data is transmitted to C2 via the established wireless network. The inertial navigation system (INS) processor and the global positioning system (GPS) antenna determine the vehicle's location, interpret received navigation data from C2, and allow the vehicle to navigate via waypoint navigation. The EMLID Reach increases the GPS accuracy of the UGV, making waypoint navigation more accurate and precise. The PC processor interprets all the data received from the sensors and provides commands to the subsystems.

UGV Setup

- LiDAR—The UGV was equipped with a LiDAR in order to perform optic-based ranging and location for obstacle avoidance. (F1.1.2 and F1.2.4)

- EO Camera—The UGV was equipped with an electric-optic camera in order to provide the UGV operator with real-time feedback. (F1.1.1)

- GPS—The GPS provided the UGV with precise location. The GPS also provided the UGV with waypoint navigation capabilities. (F1.2.1 and F1.2.2)
- EMLID Real Time Kinematic (RTK) System—The EMLID system was incorporated into the system to increase the GPS accuracy of the UGV. (F1.2.1)
- Wireless Antenna—The wireless antenna mounted on the Pioneer enabled a communication system between the UGV and C2 via the wireless network established. (F1.3.1 and F1.3.2)
- Microphone—The UGV was equipped with a radio to provide the PID with the capability to communicate with C2. (F1.3)
- PC Processor—The PC processor is responsible for interpreting data and providing commands to control subsystems. (F1.2.3)

(2) UAV

The UAV used in the exercise is illustrated in Figure 15. The DJI Inspire is a multirotor aircraft capable of attaining a maximum flight time of approximately 18 minutes.

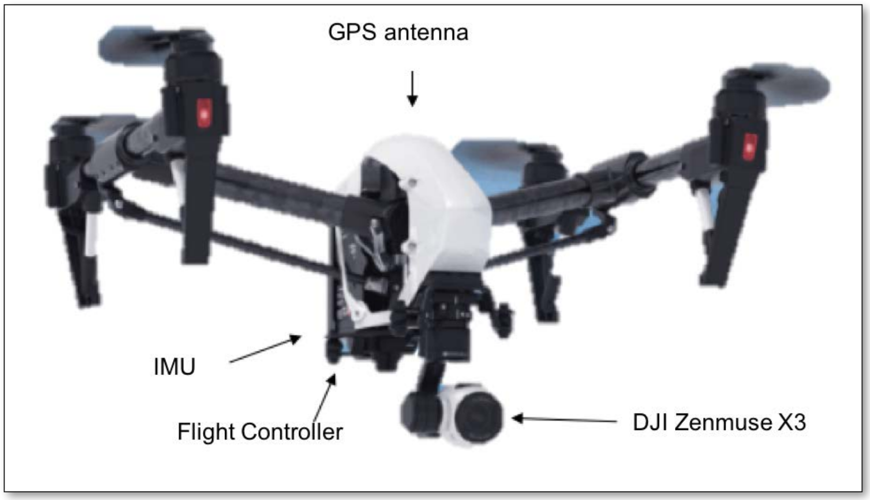


Figure 15. DJI Inspire 1 UAV. Adapted from DJI (n.d.).

The Inspire comes equipped with a DJI Zenmuse X3 Camera, which provides the UAV with the ability to surveil the area. The inertial measurement unit (IMU) grants the UAV hovering capabilities in order to classify a PID. The GPS unit determines the UAV's position and provides the flight controller with navigation data in order to navigate. The flight controller allows the UAV to process the navigation and sensor data. It also provides commands to the UAV subsystems in order to maneuver.

UAV Setup

- IMU—The Inertial Measurement Unit (IMU) automatically keeps the UAV stable while flying. The IMU uses a 6-axis gyroscope and accelerometer to compensate for environmental conditions the vehicle may experience while in operation. (F2.4.2)

- Flight Controller—The Flight Controller is responsible for executing the commands given to the aircraft. The flight controller serves as the system processor, receiving data and translating that data to the system controls. (F2.2.3 and F2.4.1)

- GPS—The Inspire uses a Global Navigation Satellite System (GLONASS) and GPS system while operating. This combination provides the user with a more accurate and precise location than the standard GPS satellites. The dual GPS system also acquires satellites at a faster rate, allowing for a live map to be displayed on the remote controller. (F2.2.1 and F2.2.2)

- DJI Zenmuse X3—The Zenmuse X3 is a 4K, 3-axis gimbal camera with a rotating angle of 360°. The camera receives information such as angular velocity, height, momentum, and inertial force so that it can counteract the effects the vehicle experiences in order to keep the camera level at all times. (F2.1.1 and F2.1.2)

(3) Network Communications

This exercise used four 2.4 GHz wireless routers for the network system. All four wireless routers were configured as repeaters, creating one network for the UAV, UGV, and C2 communication.

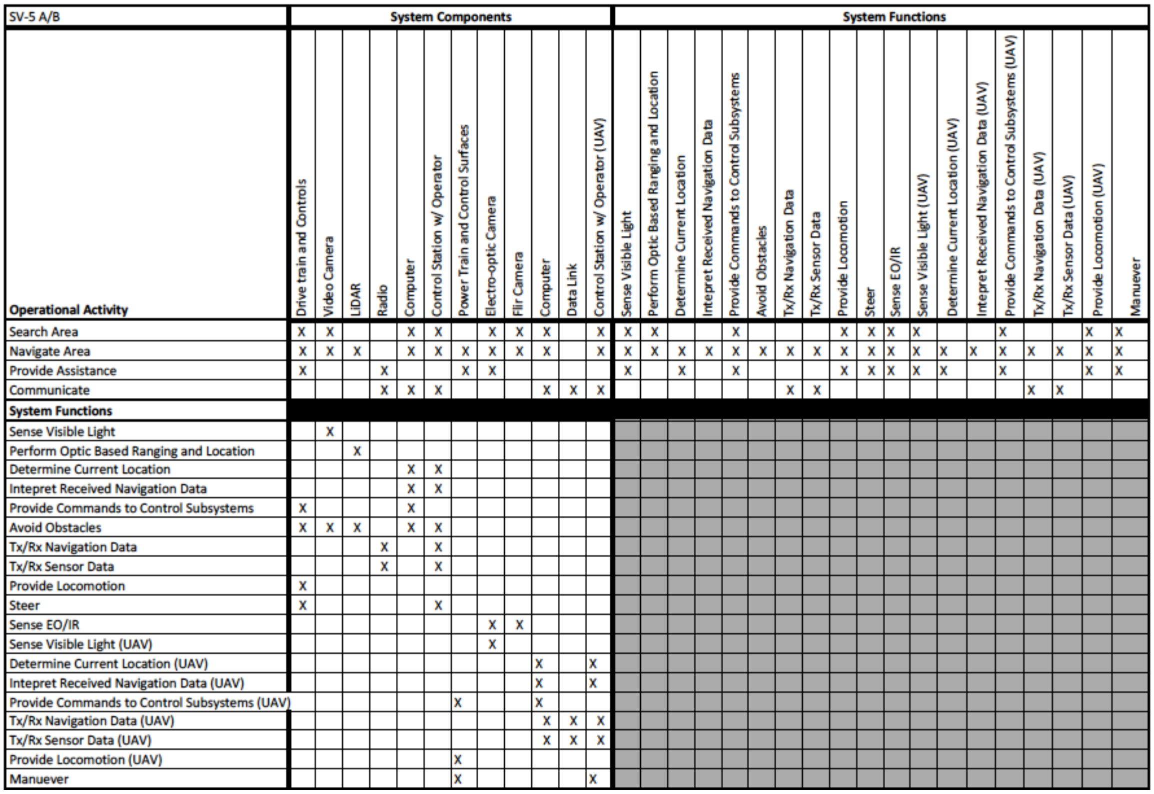
Figure 16. 2.4 GHz Wireless Router

The wireless network system was not included in the physical architecture displayed in Figure 16 because it is beyond the scope of the unmanned vehicle system. The MBSE MEASA methodology focused on the relationship of the unmanned vehicle's system architecture and system analysis.

F. MODEL ANALYSIS FOR HA/DR VALIDATION EXERCISE

1. Implementation of Architecture for Unmanned Systems

The MBSE MEASA uses various SysML products to portray the stages in the methodology. SysML's parametric diagram is a useful tool that "defines systems of equations that describe the behavior of a block (recall that a block is most often a physical element of a system)" (Beery 2016, 31). Though efficient, this diagram is not applicable when conducting an exercise instead of a simulation. It is most useful when conducing simulations that define specific constraints in the model. A useful tool capable of analyzing whether the system architecture is able to satisfy the systems operational requirements is the Department of Defense Architectural Framework (DoDAF) product, Operational Activity to Systems and to System Function Traceability Matrix (SV-5 a/b). The SV-5 a/b illustrates the traceability of the system components and functions to the operational activities. This allows for the qualitative assessments of the system to be conducted in order to determine a refined system solution architecture for the system. Figure 17 portrays the system's traceability.



SV-5 A/B	System Components												System Functions																		
Operational Activity	Drive train and Controls	Video Camera	LiDAR	Radio	Computer	Control Station w/ Operator	Power Train and Control Surfaces	Electro-optic Camera	Flir Camera	Computer	Data Link	Control Station w/ Operator (UAV)	Sense Visible Light	Perform Optic Based Ranging and Location	Determine Current Location	Intepret Received Navigation Data	Provide Commands to Control Subsystems	Avoid Obstacles	Tx/Rx Navigation Data	Tx/Rx Sensor Data	Provide Locomotion	Steer	Sense EO/IR	Sense Visible Light (UAV)	Determine Current Location (UAV)	Intepret Received Navigation Data (UAV)	Provide Commands to Control Subsystems (UAV)	Tx/Rx Navigation Data (UAV)	Tx/Rx Sensor Data (UAV)	Provide Locomotion (UAV)	Manuever
Search Area	X	X			X	X		X	X	X		X	X	X			X				X	X	X	X			X			X	X
Navigate Area	X	X	X		X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Provide Assistance	X			X			X	X					X		X		X				X	X	X	X	X		X			X	X
Communicate				X	X	X				X	X	X							X	X								X	X		
System Functions																															
Sense Visible Light		X																													
Perform Optic Based Ranging and Location			X																												
Determine Current Location					X	X																									
Intepret Received Navigation Data					X	X																									
Provide Commands to Control Subsystems	X				X																										
Avoid Obstacles	X	X	X		X	X																									
Tx/Rx Navigation Data				X		X																									
Tx/Rx Sensor Data				X		X																									
Provide Locomotion	X																														
Steer	X					X																									
Sense EO/IR								X	X																						
Sense Visible Light (UAV)								X																							
Determine Current Location (UAV)										X		X																			
Intepret Received Navigation Data (UAV)										X		X																			
Provide Commands to Control Subsystems (UAV)							X			X																					
Tx/Rx Navigation Data (UAV)										X	X	X																			
Tx/Rx Sensor Data (UAV)										X	X	X																			
Provide Locomotion (UAV)							X																								
Manuever							X					X																			

Figure 17. SV-5 A/B for Collaborative Cross-domain Unmanned Vehicles Conducting HA/DR Operations

Figure 17 depicts the mapping of operation activities to system functions and system components. The matrix has been broken up into the following sections: Operational Activity, System Components, and System Functions. The SV-5 a/b "identifies the transformation of an operational need into a purposeful action performed by [the] system" (Department of Defense Chief Information Officer 2010, 1). It also maps the system functions to the operational activities, ensuring traceability and consistency. For instance, the system function ‘Perform Optic-Based Ranging and Location’ can be traced back to the operational activities: Search Area and Navigate Area. The traceability analysis illustrates the connection of a network of interrelationships between components of a system and their functions. This matrix also determines if unspecified features have been introduced into the system, and provides documentation for all products with their designated predecessor specification. The high level of redundancy directly correlates to the structure of the functional and physical architectures.

2. Iteration of MBSE MEASA

When conducting a validation exercise, certain factors were experienced that gave the system a realistic experience in operating in a post-disaster environment. This observation was helpful in determining which operational requirements, system functions, and physical components needed to be refined. There were several functions that initially were going to be conducted, but could not be achieved. Those functions were: Provide Storage and Transport for First-Aid Supplies, Determine the UGV’s Current Location within Less than One Meter of Circular Error Probable (CEP), Provide an Automated PID Identifier on the UGV, and enable the UAV and UGV with the capability to exchange information with one another.

In order to improve the UAV-UGV system by implementing the system analysis into the system architecture, some of the initial system requirements must be changed or added to the system. Adding a new requirement results in new system functions being identified and new physical components of the system being generated. For instance, Provide for Storage and Transport of First-Aid Supplies is a new system requirement that must be identified. In doing so, a new system function is generated as illustrated in Figure 18.

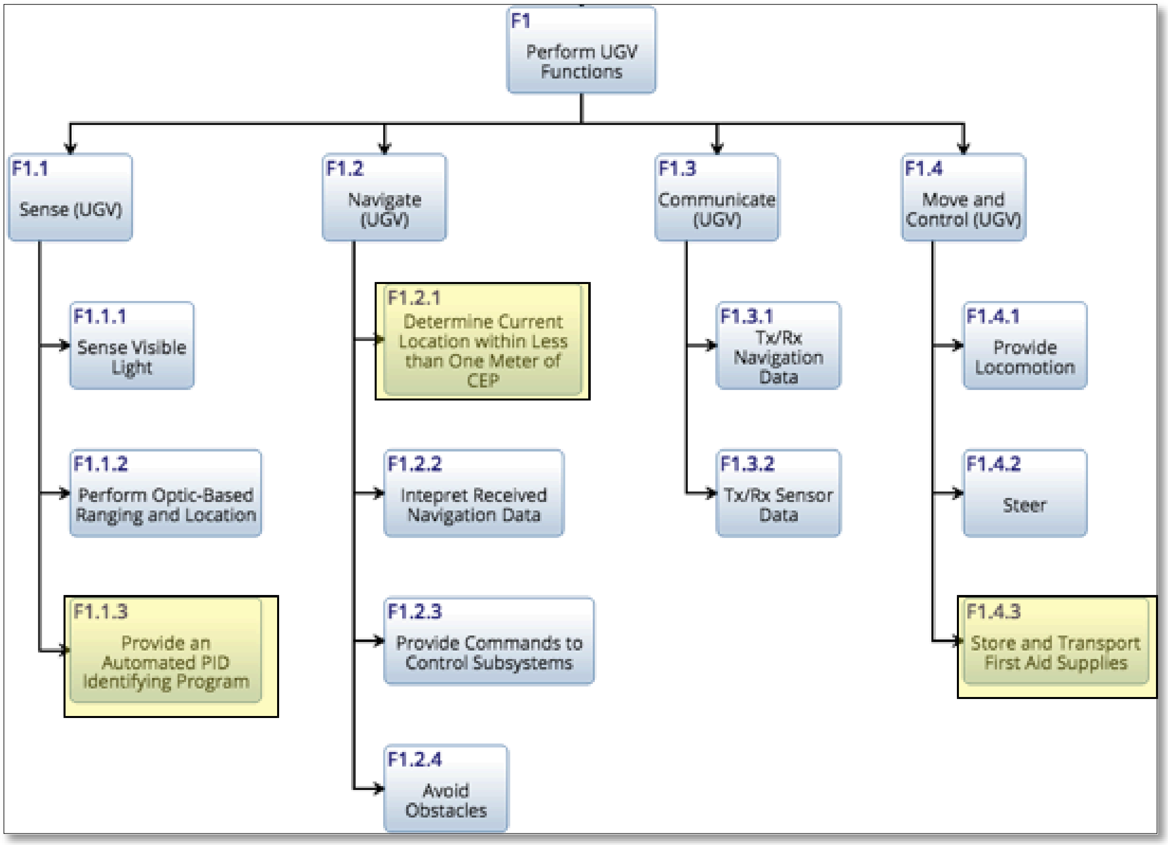


Figure 18. New System Function: Store and Transport First Aid Supplies

Figure 18 highlights the new items in the functional architecture based on implementing the system analysis into the system architecture for an updated system. The additional functions such as: Provide an Automated PID Identifying Program and Determine Current Location within Less than One Meter of CEP are also highlighted in Figure 18. The iterative process of using the analysis in the system architecture domain not only develops new functions and physical components of the system, but it also adds specificity to the functions based on the performance of the unmanned vehicles. During the validation exercise, the UGV would often have to correct itself while using waypoint navigation because the GPS location was not precise. By adding the CEP specification, waypoint navigation for the UGV will be more accurate and precise, decreasing the transit time to a PID. As previously stated, if the functional architecture has an additional function, then there must be a system component capable of executing such a task. Figure 19 illustrates the refinement of the physical architecture in order to develop a system capable of achieving all the functions of the system.

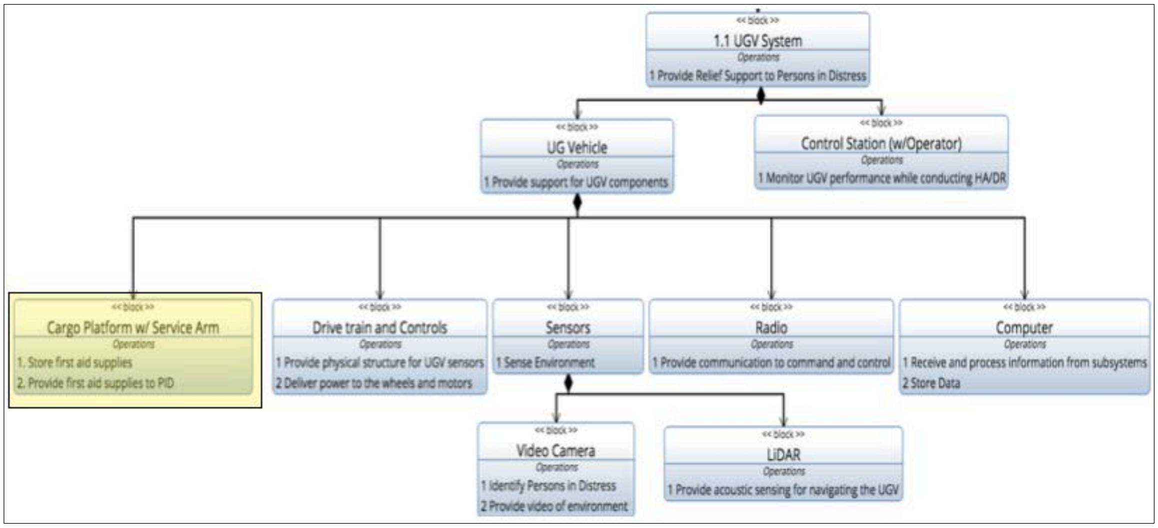


Figure 19. Refined Block Definition Diagram for Unmanned Ground Vehicle System

The UGV system’s additional physical component, Cargo Platform with Service Arm, was added to the physical architecture to ensure the UGV system with the capability to Provide Storage and Transport First-Aid Supplies to PIDs. Finally, Figure 20 illustrates the refined functional architecture for the collaborative unmanned system.

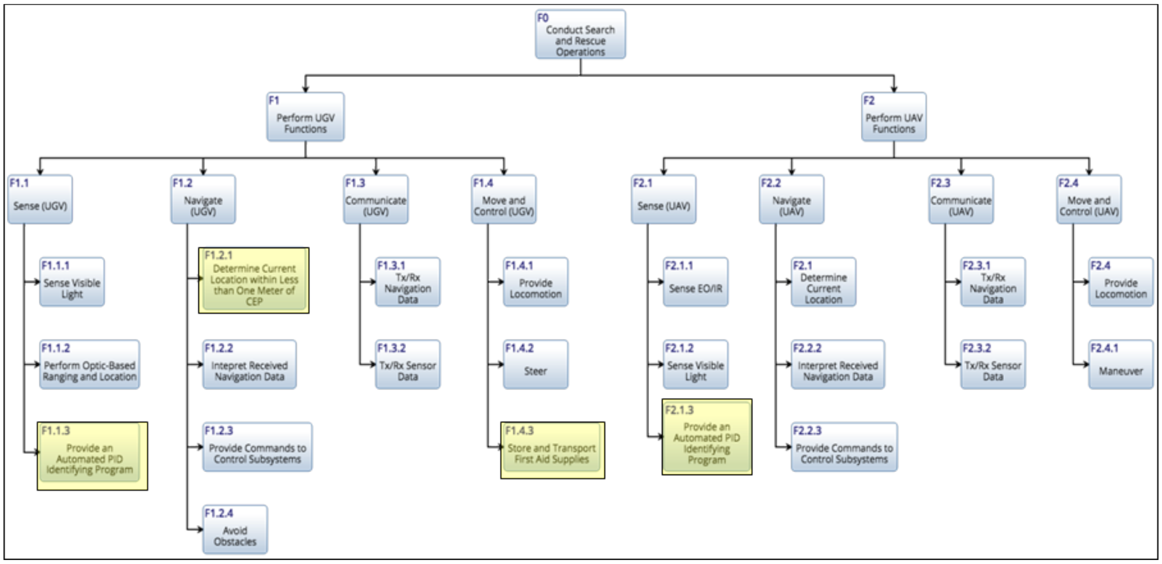


Figure 20. A Refined Functional Architecture for HA/DR Operations

Figure 20 includes the function, Provide an Automated PID Identifying Program, on the UAV. The UAV was the first unmanned vehicle conducting the surveillance sweep and should be equipped with the proper tools to identify a PID in a post-disaster environment. Figure 21 illustrates how the UAV will locate and identify the PID and transmit the PID location to the C2 and the UGV. Once the UGV has the location of the PID, it is launched to provide first-aid supplies.

Figure 21. UAV and UGV Locating the PID

The UAV and UGV must have the ability to differentiate between a PID and moving debris in order to accurately locate PIDs. By incorporating this function, the unmanned vehicles will have a redundant system capable of accurately identifying the PID regardless of environmental conditions.

G. CONCLUSION

The MBSE MEASA methodology generated the system's architecture to support the system analysis. This process ensures that the systematic behaviors illustrated in the validation exercise can be linked to the functions and physical components listed in the system's architecture. The system's traceability allows for the system solution to be continually improved based on the MBSE MEASA iterative process. This paper presented the validation model (Stage Four) required to determine the operational effectiveness and technical feasibility of cross-domain unmanned systems conducting HA/DR. It also presented an analysis of the system design (Stage Five) to identify which areas of the architecture could be improved to develop a more efficient system. The research presented in this paper helps establish model-based system engineering analysis modeling for cross-domain unmanned vehicles conducting expeditionary warfare, hence providing data to support future research and development of unmanned vehicles for military application.

IV. CONCLUSION

A. MBSE MEASA CLOSE-OUT

This thesis presented an MBSE MEASA methodology that developed an iterative process which used the system's descriptive architectural products, a validation exercise, and the system's analysis to create a refined version of the system with new capabilities. The MBSE MEASA consisted of explicitly defining the system requirements, developing the functional and physical architectures using SysML, and designing at validation exercise in order to analyze the system. This research ensured that the initial system requirements led to the development of a technically feasible and operationally effective system. The results highlighted in this thesis could serve as the foundation for using a model-based systems engineering analysis for the employment of cross-domain collaborative unmanned systems throughout the military.

B. LESSONS LEARNED

The MBSE MEASA has the ability to use multiple modeling languages to produce architectural products. It is a good practice to use one or two modeling languages in order to efficiently produce the architectural products of the MBSE MEASA.

While conducting the validation exercise in post-disaster terrain, the integrity of the wireless network was inconsistent. The network for a collaborative unmanned system must be a robust network with the ability to transmit data instantaneously. The network system was beyond the scope of the research presented in this thesis. However, future efforts should consider the network as part of the system to be architected in an integrated way. In addition to the network, it is imperative that the utilization of the GPS is precise and accurate. The GPS receivers on the unmanned systems had limited accuracy which made waypoint navigation difficult. Integrating more GPS receivers or using more accurate receivers could serve as feasible solutions to help mitigate the poor accuracy of the GPS. It would also improve the UGV's ability to avoid obstacles and maintain waypoint navigation.

C. FUTURE WORK

The MBSE MEASA process presented in this thesis resulted in refined architectural descriptions being generated as a result of the iteration from system analysis to system architecture. Further work would include modifying the UAV and UGV with the proposed sensors based on the revised system architecture. Once the unmanned vehicles are updated, they must execute the same validation exercise so the qualitative data can be gathered and analyzed. Also, this work focused on the interface of one UAV and one UGV. Additional research is needed to consider various configurations of the number of unmanned vehicles used in the exercise and the extension to cross-domain unmanned vehicle swarms.

Another area of the research requiring further work is developing fully autonomous unmanned vehicles. Enabling the unmanned vehicles with the capability to operate without human interaction is an area that presents vast potential. Full autonomy allows the vehicles to communicate directly with one another in order to execute the given tasks. It also decreases the reaction time by communicating directly with each other and not having to rely on C2 to receive information and transmit the information to the other unmanned vehicle. Continued vigorous work is required to reach full autonomy for the unmanned vehicles.

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