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CONCEPTS FOR MANNED UNMANNED TEAMING BEHAVIORS IN MODEL BASED SYSTEMS ENGINEERING

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ABSTRACT

Manned Unmanned Teaming (MUMT) is fast becoming a critical capability for maintaining operational superiority and overmatch against near peer competitors. However, there is presently no concept of MUMT behaviors in Model Based Systems Engineering (MBSE) analyses. Such a concept is needed in order to capture and understand the increasingly complex interactions between humans and machines that will govern system behavior on the battlefield. This manuscript describes an effort that sought to identify and roadmap the development of the MUMT requirements necessary to build into the next generation of functional MBSE models that lead to sustainable autonomous (semi or full with MUMT) military operations. Three scenarios spanning the unmanned systems domain incorporating current state of practice and envisioning increased autonomy were used as the basis for developing a generalizable MBSE expression of MUMT behavior.

1. INTRODUCTION

The U.S. Military relies heavily on the use of unmanned vehicles for a variety of tasks, including surveillance and reconnaissance, explosive ordnance disposal, and strike operations. More and more, human operators are tasked with the direct supervision and control of semi-autonomous and autonomous assets to effectively carry out missions. This manned-unmanned teaming (MUMT) is fast becoming a critical capability for maintaining operational superiority and overmatch against near peer competitors. However, there is presently no concept of MUMT behaviors in Model Based Systems Engineering (MBSE) analyses. Such a concept is needed in order to capture and understand the increasingly complex interactions between humans and machines that will govern system behavior. A failure to consider appropriate workload and situational awareness demands for future MUMT CONOPS and their impacts on dynamic function allocations for complex missions will result in suboptimal outcomes and mission failures.

As system autonomy and therefore system complexity increases, the System Engineering (SE) community recognizes an increased need to move away from traditional document-driven SE processes for system development and adopt modeling and simulation (M&S) tools and techniques to enhance collaboration, communication, and traceability throughout the SE process. This results in a MBSE approach, which is defined as “the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases" [1].

While there has been much attention on the use of M&S tools to support the functional, logical and physical representation of a system, the emphasis is primarily on the non-human components of a system. As a result, there is a strong demand for incorporating MUMT behaviors in MBSE analyses to enable the representation of a complete system. Research is needed to understand and define best practices for analyzing various teaming arrangements between human operators and unmanned systems with various levels of autonomy. This should be done in concert with (and could inform) the Army's Robotic and Autonomous Systems Strategy and should be seen as a critical component for consideration for programs such as the Next Generation Combat Vehicle (NGCV).

The motivation for exploring MUMT and human relationships with MBSE for military contexts should be high. Manpower continues to be one of the highest cost drivers in the Department of Defense (DoD) budget and therefore how that factor changes in future operations involving battlefield robotics should be of prime importance. The advent of robotics does not mean that humans will no longer have a major impact on system safety, performance, and cost. It is critical that all human operators are considered upfront in the initial requirements and applicable human modeling and simulation tools, manifesting through MBSE, are considered early in acquisition. Doing so ensures that human performance requirements are realistic and provides a means of controlling total ownership costs for new systems.

Developing new methods that bring the human element into the MBSE formalism early in the design stages will not only expand the relevance of best practices to current and future systems, but also ensure this vital aspect is addressed early in the life cycle of a robotics program. Human considerations must be more thoroughly integrated into the modeling process to develop a more robust set of requirements, use cases, and balancing of resources that exist between the human operators and the system of interest. Doing this successfully is inherent to the future success of MUMT operations on the battlefield. This is crucial in understanding the impact of system architecture and design decisions from the human perspective. Without this, it is difficult to make informed trade-offs and decisions regarding the system safety, performance, and cost. Embracing standard human task modeling processes that are fully integrated with existing MBSE processes will strengthen the effectiveness of systems engineering processes and they represent a sensible path forward for the quantification of human-machine relationships and set the basis for requirements generation in this area.

The research objective for this effort was to identify and roadmap the development of the MUMT requirements necessary to build into the next generation of functional models that facilitate sustainable, highly autonomous military operations. The research objective was explored through the analysis of MUMT scenarios across three unmanned systems domains spanning air and ground vehicles. A goal of the research was provide broad requirements that can be conceptualized in a MBSE analysis by helping to address the following questions:

- What degree of autonomy should be applied to the operational scenario to maximize the benefits of MUMT?
- Where should automation efforts focus for the most effective gains in MUMT operational scenarios?
- Which functions are critical for autonomous mission success versus mission enhancement due to autonomy?

The research objective was carried via the application of a structured approach for developing an implementation-agnostic decomposition of mission functions from the scenarios. An overview of this process is shown in Figure 1. The use of this functional decomposition process allows for tradeoffs in the different levels of autonomy that can be applied for various mission functions. This is critical to assessing what to automate within a workflow and when doing so is most impactful. Next, a resource tracking methodology was developed that extends the modeling of "atomic" mission functions derived from the application of the functional decomposition process. The resource tracking methodology categorized the impact and benefits of autonomy by specifying changes within the scenario narrative such as situational awareness, operator workload, process interrupts, bandwidth, capacity, etc. These metrics were tracked in order to aid in the comparison of various MUMT mission architectures that differ in the application of different levels of autonomy to accomplish various tasks.

Figure 1: MBSE for MUMT Process Overview (platforms depicted are notional)

2. VALIDATED SCENARIO GENERATION

The basis for the MBSE expressions of MUMT behaviors was a series of scenarios that spanned three unmanned systems domains: an explosive ordnance disposal (EOD) scenario, a cross platform teaming scenario, and a high altitude UAS scenario. For comparative analyses, two versions of each scenario were generated. One capturing the current state of practice and another emphasizing robotic behavior of a more highly autonomous nature that reflected how the same mission might be performed in the future.

These scenarios were envisioned to incorporate an expansive range of human-machine interactions spanning multiple control mediums. In this way, the goal was to generate a representation of MUMT behaviors that could be broadly ordered into categories that were applicable across unmanned system platforms. These categories included navigation, communications, and sensor interactions and housed specific tasks within each.

The approach for scenario generation began with the identification of mission elements. A mission element for this purpose was defined as some attribute of the MUMT mission that had an impact on human performance requirements and/or posed a hazard to personnel that required appropriate safeguards to be put in place. Mission elements included attributes such as mission type, environmental/situational factors, targets/threats, and possible system malfunctions.

Generally, mission elements are derived from system requirements documents, operational situations, or comparable/legacy systems. Once identified, the mission elements were compiled into a mission element matrix. The purpose of the matrix was to ensure that the scenarios incorporated each desired element into the scenarios

As opposed to creating a set of scenarios for each of the MUMT situations selected that reflected a spread of mission elements across multiple scenarios, the elements were generally repeated for both versions of the scenarios for each domain.

Ultimately, the purpose of the scenarios was to provide a basis for framing the tasks and functions to be expounded upon in the MBSE model that was (to the degree possible) validated by subject matter experts. The following is a brief description of each of the scenarios.

2.1. Scenario 1: EOD Operations

EOD robotics is a particularly relevant area for considering when and how to incorporate autonomy in current operations as a considerable amount of human judgement is required to identify suspicious/dangerous objects. These sorts of objects are not easy for machines to identify visually let alone render safe due to unpredictable and inconsistent nature of improvised explosive device (IED) threats.

The narrative for the EOD scenarios included coalition forces engaged in counterinsurgency operations in the fictitious People's Republic of Postrea operating at the invitation of a unitary provisional government. Insurgents were placing IEDs along major convoy routes that supply remote outposts. Coalition route clearance teams routinely patrolled these routes, which at certain points passed through populous villages with tall buildings positioned at blind turns. EOD teams were augmented by unmanned ground and aerial assets as they responded to calls for support

Human-machine interactions for this scenario were focused on remote piloting of an unmanned ground vehicle (UGV) with a limited field of view. Elements incorporated into this scenario were validated by EOD subject matter experts from Georgia’s National Guard Joint Task Force. Feedback on pain points from this community served as the basis for where automation was envisioned for the second more autonomous version of this mission. The scenario envisioning future operations relied heavily on augmenting a human operator’s field of view with assistive unmanned aerial vehicles (UAVs) and teleoperation.

An MBSE expression of the relationships between machines and soldiers in this context can help establish baseline requirements for the design of future systems and CONOPS that support the building of common operating pictures (COPs) and mitigate the uncertainty and limitations of robots struggling to overcome information sharing challenges. For this domain, these challenges include robotics assisting warfighters in the identification of potential threats, and advanced artificial intelligence (AI) learning over time what emerging threats might be. In the end, this sort of clarity in an operationally unfamiliar and contested environment littered with concealed threats enhances the survivability and lethality of the warfighter, and enhances mission effectiveness. Further, designers of next generation unmanned systems for this domain can rely on MBSE to help them assess measures of effectiveness (MOEs) and measures of performance (MOPs) as well as support Analysis of Alternatives (AOA) activities. These sorts of analyses are necessary to ensure that the next generation of robotics are designed to incorporate appropriately quantified MUMT relationships as opposed to relying on what is technically possible to drive future requirements.

2.2. Scenario 2: Cross Platform Teaming

The narrative for the cross platform teaming scenarios included groups of coalition AH-64 Apache helicopters that were part of an attack reconnaissance battalion supporting security forces in the fictitious desert country of Vollwuste as they reclaimed townships from insurgent forces. Insurgents were known to move rapidly from town to town in convoys of lightly armored vehicles, so coalition forces had been assisting the much slower security forces with ISR and kinetic action when necessary. The mountainous regions of Vollwuste had advanced EW and missile systems supplied by near peer competitor nations that were now in insurgent hands. The Apache missions were supported by numerous MQ-1C Gray Eagle and RQ-7 Shadow unmanned aerial assets.

Human machine interactions for this scenario were focused on negotiating weather related challenges for safety critical ISR data, and UAVs being used as communication relays.

An MBSE expression of the relationships between machines and pilots in this context can help set the basis for requirements for communication, human workload in the cockpit, and dynamic information sharing from robotic battlefield assets. It is insufficient to augment human pilots with unmanned assets if those assets require an unrealistic level of human intervention or command and control (C2) to maintain relevance. Further, a disparate team of cross platform unmanned assets can quickly overwhelm the humans with information and data that is not mission-relevant.

Important challenges that MBSE expressions of this MUMT scenario can assist in meeting have to do with a robot's understanding of (1) what information is relevant and when, (2) how and when to share that information with respect to an understanding of the human teammate's current level of workload, communication in denied environments, and (3) what user interfaces are appropriate for respecting pilot's finite cognitive capabilities while flying a helicopter and managing unmanned teammates.

2.3. Scenario 3: High Altitude UAS

The narrative for the high altitude UAS scenarios was a mission occurring during peacetime in friendly airspace. No specific threats were identified but there were indications of possible attacks on United States and allied vessels. A carrier strike group deployed to the region required long-range surveillance. A littoral country had granted permission for the UAS to fly over its airspace but only through specified transit corridors. The only surveillance permitted during flight in the overland corridors was open ocean targets. The friendly country would not allow overland imagery. While transiting through the corridor, the UAS was required to communicate with friendly nation's airspace managers.

This scenario was validated by Navy subject matter experts and was adapted from a workload analysis part of a larger mission task analysis for a high altitude persistent UAV. Due to this, the scenario had certain supporting artifacts that the other scenarios did not have. These included scenario vignettes, an initial functional breakout, and performance requirements. Scenario vignettes are variations of segments of missions reflected in a scenario in which all of the other elements within the stay the same. For this scenario, these included a catastrophic malfunction and an emergency landing related to weather conditions. The performance requirements were derived with the intent to find the best performance against time, money, and technical capability for the candidate system.

Of the three scenarios generated, the high altitude UAS scenario was selected for MBSE functional decomposition first because the level of detail associated with it was thought to generate models of a more salient nature. The following sections describe the functional decomposition process and the outputs it yielded.

3. FUNCTIONAL DECOMPOSITION

Ref. [2] "introduces a process for producing robust functional decompositions that provide full coverage of system functionality." This process enables consistency throughout the system architecture and promotes reusability of system functions. An overview of the functional decomposition process is shown in Figure 2.

The functional decomposition process consists of a total of 64 process steps that begins with identifying the project domain and ends with a collection of implementation-agnostic functions [2]. The functions for each scenario can range across mission and operational activities from sensing, communicating, and navigating/ maneuvering. The functional decomposition results

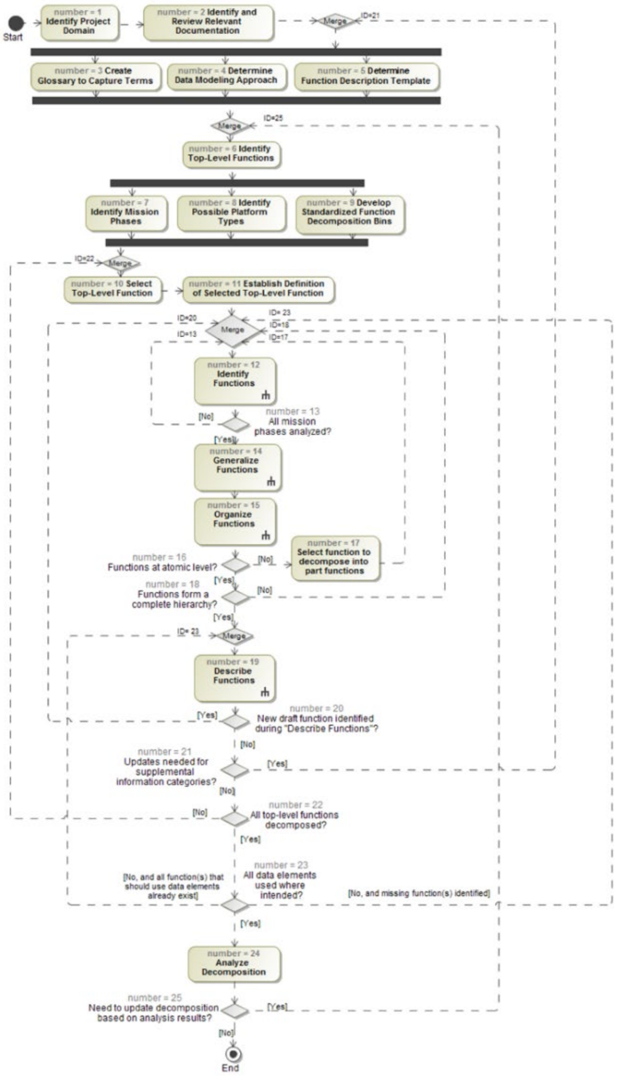


Figure 2: Functional Decomposition Process Overview

in a collection of "atomic level" functions that are implementation agnostic, though they may be specific to a particular domain such as aviation. For example, a functional decomposition of *Aviate*, *Navigate*, and *Communicate* activities yields over 40 functions for each activity. Each function is defined in terms of the following: inputs, outputs, controls, enablers (mechanisms), and narrative description. For example, the function "Sense & Track Objects" for the UAS scenario is shown in Figure 3.

The inputs to the sense and track objects function include "Raw External Measurements" as well as "Calculated Aircraft State". These inputs are resources that the function depends upon in order to execute the desired functionality. In terms of outputs, there are three: "Calculated External Object Properties", "Calculated External Object State", and "Calculated External Object Track". These outputs serve as inputs to another function "Update Flight Plan".

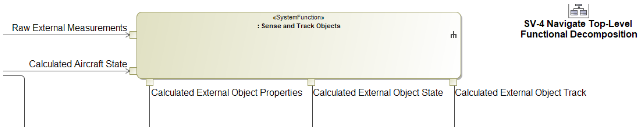


Figure 3. Sense & Track Objects Function Definition

Building a functional decomposition according to the process in Figure 2 can be accomplished using a variety of tools, including spreadsheets. The authors of Ref. [2] selected the Unified Modeling Language, or UML, which is "a general purpose visual modeling language for specifying, constructing and documenting the artifacts of systems that can be used with all major application domains and implementation platforms" [3]. UML provides the foundation for the Object Modeling Group Systems Modeling Language (OMG SysML) specification, which is an extension specifically developed for systems modeling and used extensively in MBSE.

4. RESOURCE TRACKING USING MBSE

Once the functional decomposition was achieved, the next step was to identify functions where the application of autonomy is both feasible and either maintains or improves mission performance within the scenario. Candidate functions were identified based on the following criteria:

- Estimated reduction in operator workload
- Estimated increase in operator bandwidth/ capacity
- Difficulty in achieving autonomy

In order to estimate the difficulty in achieving autonomy for a given function, a resource tracking methodology was developed that extended the modeling of atomic-level mission functions derived from the application of the functional decomposition process. To accomplish this, the resource tracking methodology helped to specify whether a function could be automated or not by accounting for factors that would disrupt or make automation of certain tasks and functions more difficult. This is a "data centric" approach that focuses on the function inputs in order to determine whether a function is a good candidate to invest resources in order to automate. These factors include the following:

- Operating/Environmental Effects
- Situational Awareness/Context
- Sensitivity to Process Interrupts

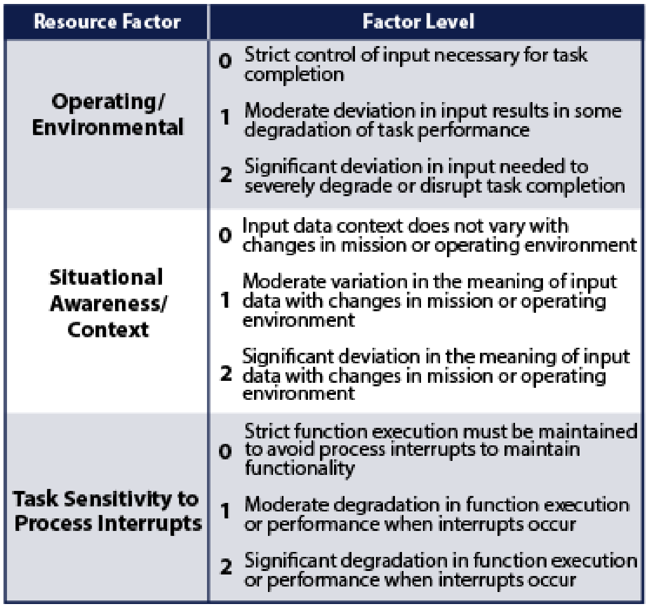
Operating/Environmental Effects: The resource tracking methodology looks at the effects the operating environment can have on each function input. The more sensitive the input is to environmental variables and conditions, the less likely the function itself can be automated without a high degree of difficulty. In the Sense & Track Objects function, for example, if the Raw External Measurements input can be reliably obtained in a variety of operating conditions and environments, then automating that function becomes a much easier task since the data is more reliable. In this case due there is reduced variability and uncertainty of the input data and operating conditions surrounding the data.

Situational Awareness/Context: Here, the resource tracking methodology seeks to define the level of situational awareness or context needed to correctly interpret the input data. The more situational awareness or context needed to make use of the data, the more difficult it will be to automate the task or perform the function to a satisfactory level. For example, if the input data (single or in combination) must be processed through numerous if/then conditions, the automated function may be too "brittle".

Sensitivity to Process Inputs: Real world operating environments introduce a great deal of nonlinearities and uncertainties. The methodology seeks to take into account sensitivities to process interrupts when attempting to execute functions. Functions that are more amenable to resuming after interrupts (e.g., if conditions or priorities change, for example) are better suited for automation. Conversely, if the interruption of the function requires extensive management to ensure successful completion, then the function is a poor candidate for automation.

Each of these factors are added to the UML-based description that includes the function input, output, control, etc. defined during the functional decomposition. Threshold values are then defined to indicate a value below which the functionality would be severely degraded or impaired, or that would have a negative impact on the human operator. Threshold values can be set using the level descriptions shown in Table 1.

Table 1. Resource Factor Levels



Resource Factor	Factor Level	
Operating/ Environmental	0	Strict control of input necessary for task completion
	1	Moderate deviation in input results in some degradation of task performance
	2	Significant deviation in input needed to severely degrade or disrupt task completion
Situational Awareness/ Context	0	Input data context does not vary with changes in mission or operating environment
	1	Moderate variation in the meaning of input data with changes in mission or operating environment
	2	Significant deviation in the meaning of input data with changes in mission or operating environment
Task Sensitivity to Process Interrupts	0	Strict function execution must be maintained to avoid process interrupts to maintain functionality
	1	Moderate degradation in function execution or performance when interrupts occur
	2	Significant degradation in function execution or performance when interrupts occur

The threshold value for each input varies for each function. Threshold values can be assigned based upon subject matter expertise, or through analysis of the SysML model. The Activity Diagram in particular can be executed or simulated with variations to the input of different functions to determine the effect on system operation. An Activity Diagram shows the relationship of different functions and can be used to analyze system behavior. An example Activity Diagram for the Control Communications activity, which is made up of many different functions, is shown in Figure 3.

The metrics for each function input are tracked in order to aid in the comparison of various MUMT mission architectures that differ in the application of different levels of autonomy to accomplish various tasks. Together, these factors define a sort of "resource container" that indicates the degree of difficulty that would be encountered in attempting to automate a particular task.

Using SysML, functionality can be executed and then analyzed to determine system behavior and performance. The resource tracking methodology seeks to quantify the benefits to system performance that would be achieved by automating certain functions. Benefits include enhanced system performance and reduced operator workload. This sets up a type of cost/benefit relationship that forms the basis of an analysis environment for comparing different combinations of MUMT.

In this way, tradeoffs in the different levels of autonomy can be applied for various mission functions and the impact analyzed with an eye towards optimizing resource utilization and system performance. SysML can also be used to capture different architecture alternatives, with each alternative specifying the allocation of different functions between manned and unmanned systems. For example, an activity partition, or swim lane can be used to help organize functions and sub-functions and represent the allocation of relationships [1].

For the three previously defined scenarios, a subset of mission functions for each scenario were analyzed to assess the use of the methodology. Preliminary application of the resource tracking methodology yielded the following results:

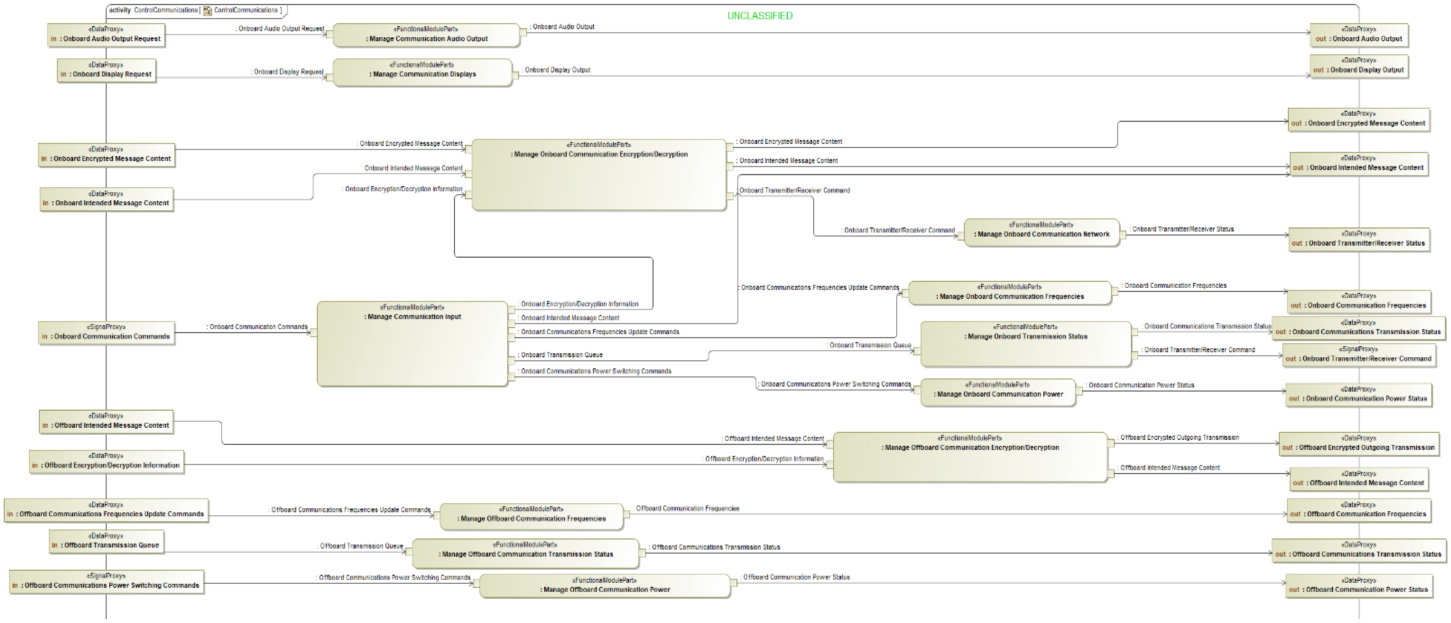


Figure 3: An Example of a Control Communication Activity Diagram

- Across all three of the scenarios, functions related to maneuvering, such as aviating, piloting, and steering/repositioning were rated as the most difficult to potentially achieve autonomy, but provided great benefit and reduction in operator workload.
- The automation of communication functions would be the most feasible path, but this depends greatly on the information that is being communicated, and the conditions under which communication must occur. For example, if communicating at certain times could lead to a compromise of the platform location or status.
- The EOD scenario in particular may prove to be the most difficult to apply MUMT, but would benefit greatly from automation due to the high operator workload requirements. This scenario in particular requires a high-level of situational awareness/context.

It should be noted that these results are preliminary and could change based on differences in the rating of function inputs across the three different factors. Also, due to the large number of functions associated with each scenario, not all functions were initially rated. A more detailed analysis would include all of the functions that compromise each scenario. However, the methodology seems to provide intuitive results at this stage.

5. CONCLUSION

A good teaming arrangement is one in which human limitations/capability are managed appropriately. This helps to address what degree of autonomy should be pursued, where efforts should be focused to increase autonomy, and which tasks are the most amenable to being automated.

The use of an implementation-agnostic functional decomposition process creates a collection of functions defined by their relevant inputs or resources. Once these functions and corresponding function inputs are defined, a data-centric MBSE approach is used to develop a resource tracking methodology that helps determine how difficult it would be to automate each function based on changes to the function input due to environmental factors, dependence upon situational awareness/ context, and sensitivity to process interrupts.

The result is an MBSE approach to defining and analyzing the impact of function automation on the execution of mission scenarios. A model-based tradeoff and execution environment is created that allows for more robust analysis of MUMT architectures. This also aids system designers and architects in evaluating where to invest resources to bolster autonomy in certain cases, and where the human operator may benefit from the application of autonomy. These benefits, as the product of human-centered analyses expressed via MBSE, can then influence the next generation of battlefield robotics system requirements to ensure that MUMT relationships are designed within the limitations and capabilities of human warfighters, planned for appropriately in acquisition, and executed in a manner that increases the lethality and survivability of warfighters. Additionally, extending this work in the future could lead to more automated methods of performing MUMT analysis and creating teaming profiles that would further describe MUMT system performance for different combinations of automated functions.

6. REFERENCES

[1] Friedenthal, Sanford, Alan Moore, and Rick Steiner. “A practical guide to SysML: the systems modeling language.” Morgan Kaufmann, 2014.

[2] Brimhall, Erika, et al. "A Systematic Process for Functional Decomposition in the Absence of Formal Requirements." INCOSE International Symposium. Vol. 26. No. 1. 2016.

[3] No Magic, Inc. 2013. “UML Profiling & DSL, Version 18.0, User Guide”. Allen, US-TX.