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USMC VERTICAL TAKEOFF AND LANDING AIRCRAFT: HUMANMACHINE TEAMING FOR CONTROLLING UNMANNED AERIAL SYSTEMS

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SYSTEMS ENGINEERING CAPSTONE REPORT

USMC VERTICAL TAKEOFF AND LANDING AIRCRAFT: HUMAN–MACHINE TEAMING FOR CONTROLLING UNMANNED AERIAL SYSTEMS

by

Scott A. Drake, Andre K. Gatlin, Bryan H. Harrison, David A. Ray, and Calvin W. Taylor III

June 2022

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13. ABSTRACT (maximum 200 words)

The United States Marine Corps (USMC) is investing in aviation technologies through its Vertical Takeoff and Landing (VTOL) aircraft program that will enhance mission superiority and warfare dominance against both conventional and asymmetric threats. One of the USMC program initiatives is to launch unmanned aerial systems (UAS) from future human-piloted VTOL aircraft for collaborative hybrid (manned and unmanned) missions. This hybrid VTOL-UAS capability will support USMC intelligence, surveillance, and reconnaissance (ISR), electronic warfare (EW), communications relay, and kinetic strike air to ground missions. This capstone project studied the complex human-machine interactions involved in the future hybrid VTOL-UAS capability through model-based systems engineering analysis, coactive design interdependence analysis, and modeling and simulation experimentation. The capstone focused on a strike coordination and reconnaissance (SCAR) mission involving a manned VTOL platform, a VTOL-launched UAS, and a ground control station (GCS). The project produced system requirements, a system architecture, a conceptual design, and insights into the human-machine teaming aspects of this future VTOL capability.

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USMC VERTICAL TAKEOFF AND LANDING AIRCRAFT: HUMAN–MACHINE TEAMING FOR CONTROLLING UNMANNED AERIAL SYSTEMS

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ABSTRACT

The United States Marine Corps (USMC) is investing in aviation technologies through its Vertical Takeoff and Landing (VTOL) aircraft program that will enhance mission superiority and warfare dominance against both conventional and asymmetric threats. One of the USMC program initiatives is to launch unmanned aerial systems (UAS) from future human-piloted VTOL aircraft for collaborative hybrid (manned and unmanned) missions. This hybrid VTOL-UAS capability will support USMC intelligence, surveillance, and reconnaissance (ISR), electronic warfare (EW), communications relay, and kinetic strike air to ground missions. This capstone project studied the complex human-machine interactions involved in the future hybrid VTOL-UAS capability through model-based systems engineering analysis, coactive design interdependence analysis, and modeling and simulation experimentation. The capstone focused on a strike coordination and reconnaissance (SCAR) mission involving a manned VTOL platform, a VTOL-launched UAS, and a ground control station (GCS). The project produced system requirements, a system architecture, a conceptual design, and insights into the human-machine teaming aspects of this future VTOL capability.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFRL	Air Force Research Laboratory
AI	artificial intelligence
AI-AMD	artificial intelligence-enabled air and missile defense
ALFUS	autonomy levels for unmanned systems
BDA	battle damage assessment
C2	command and control
COA	course-of-action
CONOP	concept of operations
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DoDAF	Department of Defense Architecture Framework
EW	electronic warfare
GCS	ground control station
HMI	human-machine interaction
HMT	human–machine teaming
IA	interdependence analysis
IC	intelligence collection
IDEF	integrated definition for functional modeling
ISR	intelligence surveillance reconnaissance
ICOM	inputs-controls-outputs-mechanisms
JP	joint publication
MPAAS	Marine Planning and After-Action System
MBSE	model-based systems engineering
MCWP	Marine Corps Warfighting Publications
MOVES	Modeling Virtual Environments and Simulation
MUM-T	manned-unmanned teaming
MWCL	Marine Corps Warfighting Laboratory
NAI	named area of interest

NASA	National Aeronautics and Space Administration
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
OPD	observability predictability directability
OPFOR	opposing forces
PIR	priority intelligence requirements
SA	situational awareness
SAE	Society of Automation Engineers
SCAR	strike coordination and reconnaissance
SME	subject matter expert
SML	Systems Modeling Language
TAI	targeted area of interest
TTPs	training, tactics, and procedures
UAS	unmanned aerial system
U.S.	United States
USMC	United States Marine Corps
VTOL	vertical takeoff and landing
VUCA	volatile, uncertain, complex, and ambiguous

EXECUTIVE SUMMARY

The United States Marine Corps is exploring the use of human-machine teaming to control unmanned aerial systems (UAS) in forward-deployed environments across a wide array of mission sets to include intelligence, surveillance, and reconnaissance (ISR), electronic warfare (EW), communication relays, and kinetic kill. The USMC envisions the use of future Vertical Takeoff and Landing platforms (VTOL) to support hybrid warfare missions and achieve military superiority. For USMC hybrid warfare applications to achieve mission superiority and warfare dominance, the USMC needs to understand the intricate human-machine interactions and relationships between a VTOL crew and UAS to gain battlespace situational awareness and effectively plan and execute rotary-wing operations against conventional and asymmetric threats. The focus of this research involves a USMC strike coordination and reconnaissance (SCAR) mission in a maritime environment that facilitates Expeditionary Base Advanced Operations (EABO) within the littorals. There are multiple complex functions that must be considered and assessed to support human-machine teaming interactions to enhance mission effectiveness: mission planning, movement and infiltration, area reconnaissance, reconnaissance battle handover, and transition.

This capstone report explored human-machine teaming between three systems during a SCAR mission: UAS, VTOL, and Ground Control Station (GCS). The study began with a literature review of the VTOL program and examined the USMC SCAR mission tactics and doctrinal concepts used to facilitate EABO. In addition, it included a study of autonomy and automation, artificial intelligence, and machine learning. By using the coactive design model to explore human-machine teaming interactions and processes for the three systems, the literature review explored how to determine interdependencies between the human performer and machine team member using the interdependence analysis (IA) framework based on three factors: observability, predictability, and directability.

Systems analysis was used to support the coactive design method by decomposing the high-level functions of a SCAR mission, through Model-Based Systems Engineering

(MBSE) tools, into hierarchal tasks and subtasks. According to Johnson (2014), the coactive design method examines the concept of interdependence and uses the IA framework as a design tool. The IA framework captured the interaction between primary performers and supporting team members to develop required capacities supporting each primary task and hierarchal sub-task to generate HMT requirements. This capstone report analyzed two alternatives. The first alternative considered the UAS as the primary performer with the VTOL and GCS serving as supporting team members. The second alternative considered the VTOL as the primary performer with the UAS and GCS as supporting team members. Based on the two alternatives, the IA framework assessed 17 primary tasks, 33 hierarchical sub-tasks, and 85 required capacities to conduct a SCAR mission.

Furthermore, the research discovered the need for a robust digital mission planning system like an upgraded Marine Planning and After-Action System (MPAAS) that facilitates machine learning by storing data from previous missions and lessons learned. The USMC will face challenges in processing power and storage of information on the UAS. All efforts should be made to add to the processing power of the UAS. A validated primary, alternate, contingency, and emergency (PACE) communication plan must be implemented to ensure redundancy across all communication platforms between the UAS, VTOL, and GCS. The USMC must implement interfaces that support trust, provide rapid feedback, and are simple to operate.

Lastly, to accurately assess the HMT requirements between a VTOL, UAS, and GCS, the capstone report enabled the development of an exploratory experiment to be used in the Naval Postgraduate School (NPS) Modeling Virtual Environments and Simulation (MOVES) laboratory to facilitate future research. Operational requirements and measurements were developed to determine the effectiveness of the HMT requirements.

This capstone provides unambiguous evidence for the complexity and intricacy of HMT interactions to execute VTOL/UAS hybrid operations during a SCAR mission. The capstone identifies the use of systems analysis and coactive design as an effective approach to facilitate the development of human-machine teaming requirements through the IA framework. Furthermore, the research identifies the need for sophisticated levels of autonomy and technology readiness that may not be currently available. The capstone recommends the USMC continue to study human-machine teaming and use the SCAR mission exploratory experiment to further refine and examine VTOL/UAS high-level system requirements in support of hybrid operations with a forward-deployed UAS, with an emphasis on achieving Level 4 autonomy.

Reference

Johnson, Matthew. 2014. "Coactive Design: Designing Support For Interdependence In Human-Robot Teamwork." PhD diss., Delft University of Technology, Mekelweg, Netherlands. https://www.researchgate.net/publication/267393898_Coactive_Design_Designing_Support_for_Interdependence_in_Human-Robot_Teamwork.

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I. INTRODUCTION

The future of hybrid military operations involving the cooperation of autonomous vehicles and piloted (or manned) vehicles continues to grow across the Department of Defense (DOD). The Office of Naval Research (ONR) is interested in researching future United States Marine Corps (USMC) hybrid operations involving vertical takeoff and landing (VTOL) aircraft and unmanned aerial systems (UAS). As the complexity of human-machine interactions and the intricacies between the two interdependencies evolve, the required analytical tools and decomposition of collaborative versus independent tasks invokes systems engineering processes in conjunction with other analysis tools. This capstone project studied human–machine interactions and interdependencies across manned and unmanned system platforms and categorized those relationships to understand and develop system requirements for future VTOL/UAS hybrid operations.

A. BACKGROUND

This section introduces three background topics for this capstone project. The first topic is the VTOL program, which is a DOD multi-service initiative to develop future aircraft systems. The second topic is human-machine teaming (HMT) and its application to missions involving human-piloted helicopters deploying and collaborating with UASs. The third background topic is a specific USMC mission, strike coordination and reconnaissance (SCAR), that was the focus of this capstone study.

1. Vertical Takeoff and Landing Aircraft Program

The VTOL is a U.S. "Army-led multi-service initiative focused on enhancing vertical lift dominance through the development of next generation capabilities" (Department of the Army [DA] 2018). The future aircraft developed through the VTOL program will increase "reach, protection, lethality, agility, and mission flexibility to successfully dominate in highly contested and complex airspace against known and emerging threats" (Department of the Army [DA] 2018). To achieve this dominance, the Army has led the VTOL initiative across the services to achieve "technologies that improve maneuverability, range, speed, payload, survivability, reliability, and a reduced logistical footprint" (Gertler 2021, 1). According to

Mason (2020), the DOD has recognized that VTOL technologies and initiatives will enable commanders to execute decisive aviation mission sets across the future battlespace and will bring significant modernization efforts across: Future Attack Reconnaissance Aircraft (FARA), Future Long- Range Assault Aircraft (FLRAA), Air Launched Effects and Future Tactical Unmanned Aircraft Systems (TUAS). The USMC and United States Navy (USN) plan to use VTOL-derived technologies in their next generation rotary aircraft systems. According to Vice Admiral James Kilby:

> The Navy is refining specific maritime requirements as part of the VTOL Maritime Strike (MS) Family of Systems to recapitalize the rotary and remotely operated platforms across the Joint Force. These requirements encompass a broad spectrum of warfighting and support capabilities to include logistics and intelligence, surveillance, and reconnaissance. (Shelbourne 2020, 1)

Kilby noted the Navy and Marine Corps are assessing how the services could create a "common, remotely operated aerial solution that could embark and operate from the Arleigh Burke-class destroyers" (Shelbourne 2020, 1). VTOL aircrafts are expected to be operational in the early 2030s (Gertler 2021).

2. Human–Machine Teaming for Hybrid Operations

The USMC is planning for a future piloted aircraft that can interact and control UAS through effective HMT to maintain military superiority (Johnson and Miller 2021). HMT is commonly known as the interaction and interdependencies of humans and machines. There is growing interest in researching HMT methods to address increasing complexity in the interactions between human operators and machines, with the rise in automated systems and advances in artificial intelligence (AI) and autonomy. However, there are inherent challenges involved in the advancement of HMT methods. In 2019, the Defense Advanced Research Projects (DARPA), stated the following:

> The inability of artificial intelligence (AI) to represent and model human partners is the single biggest challenge preventing effective human-machine teaming today. Current AI agents can respond to commands and follow through on instructions that are within their training, but are unable to understand intentions, expectations, emotions, and other aspects of social intelligence that are inherent to their human counterparts. This lack of

understanding stymies efforts to create safe, efficient, and productive human-machine teaming (Defense Advanced Research Projects [DARPA] 2019).

The USMC is studying future warfare capabilities involving complex HMT operations. One example involves the launching of a UAS from future human-piloted VTOL aircrafts (while airborne) for collaborative manned/unmanned missions. Specific mission sets for the proposed UAS/piloted-helicopter team include intelligence, surveillance, and reconnaissance (ISR), electronic warfare (EW), communications relay, and air-to-ground engagements. Paramount to all the mission sets is the ability to achieve effective HMT which will depend on sufficient observability, predictability and directability (OPD) between the Marine VTOL pilots and the UASs.

3. Strike Coordination and Reconnaissance Mission

Joint Publication 3-03 defines SCAR as a "mission flown for the purpose of detecting targets and coordinating or performing interdiction or reconnaissance on those targets" (Department of the Army [DA] 2016, 11). SCAR missions normally focus on a specific geographic area either a Named Area of Interest (NAI) or a Target Area of Interest (TAI) where possible or known targets are located. A critical difference between a reconnaissance mission and a SCAR mission is that in addition to target location, a SCAR mission "coordinates target destruction and will typically be armed with munitions and systems that better enhance target designations" (United States Marine Corps [USMC] 2001, 1–7). This capstone project investigated a SCAR mission involving coordination between a piloted VTOL helicopter, UAS deployed from the VTOL, and a ground control station (GCS). This project studied the complex HMT interactions of this mission involving UAS deployment and control, target detection, communication of target location and identification, dynamic coordination during operations, and support for enabling timely decision-making for the USMC battlespace commander.

B. PROBLEM STATEMENT

The USMC seeks to maintain mission superiority and warfare dominance. One pathway toward this goal is through technology advances and the ability to effectively provide innovations to warfighters. The USMC is studying the combination of two innovations (future

VTOL helicopters and UASs with different capabilities) to significantly increase mission performance and mission capabilities. However, the collaboration of future human-piloted helicopters and UASs introduces new complexities for HMT. The USMC needs to better understand the complex HMT interactions among future piloted helicopters that launch and coordinate with future UASs for operational missions, such as the SCAR mission. The USMC needs to determine what mission planning factors must be considered and needs a set of human-machine functional requirements to support future USMC VTOL missions.

C. PROJECT OBJECTIVE AND RESEARCH QUESTIONS

The objective of this capstone project was to study HMT challenges and needs for future USMC VTOL/UAS hybrid operations. The capstone team addressed the following research questions as part of the project:

1. What capacities need to be analyzed between a VTOL, UAS, and GCS in accordance with the functional tasks required to conduct a SCAR mission?
2. How do the following interdependency factors of observability, predictability, and directability influence the HMT relationships between the VTOL, UAS, and GCS?
3. What are the decision-making abilities of an autonomous UAS and what decisions can it make on its own as part of the HMT system?
4. What are the HMT requirements in support of VTOL/UAS hybrid operations for a SCAR mission?

D. TEAM ORGANIZATION

The capstone team comprises five systems engineering graduate students. Table 1 lists the team members and their roles and responsibilities. Team roles were assigned based on the strengths and skills of each member. Calvin Taylor served as the Team Leader for this capstone. Bryan Harrison served as the Lead Editor due to his writing ability and organizational skills. David Ray, as a former civilian fixed wing pilot, served as the VTOL subject matter expert. Andre Gatlin’s background in Army reconnaissance and UAS mission operations led to his role as a subject matter expert in several project areas. Scott Drake and

Calvin Taylor provided in-depth research on the Coactive Design process and interdependency analysis to display HMT relationships between the GCS, VTOL, and UAS. The team has a strong background in systems engineering and provided input on all model-based system engineering MBSE tools to support the capstone project.

Table 1. Team Roles and Responsibilities

Name	Professional Background	Project Roles	Responsibilities
David Ray	Prior Army Adjutant General Officer with five years serving as a contracting officer. Provided insight froma private pilot's perspective.	-Interdepedence Analysis Manager -VTOL SME -Alternate Lead Editor -Systems Engineering SME	-CH I: Introduction -CH II: Literature Review -CH III: Systems Analysis -CH IV: Interdependence Analysis
Bryan Harrison	Prior Militay Police Officer with extensive experience utilizng UAS's at the tactical and operational level.	-Dashboard Manager -IRB Submission Manager -Lead Editor -Systems Engineering SME	-CH I: Introduction -CH II: Literature Review -CH III: Systems Analysis -CH V: Explaratory Experiment
Andre Gatlin	Prior Armor Officers with in-depth experience utilizing UAS's, aerial, and ground assets to provide effects on enemy targets.	- Coactive Design SME -USMC Area Recon SME -Scenario Simulation Development SME	-CH II: Literature Review -CH III: Systems Analysis -CH IV: Interdependence Analysis -CH V: Explaratory Experiment
Scott Drake	Prior Armor and Signal Officer with experience in coordinating effects in a multi-domain environment.	-Coactive Design SME -Assistant Manager -Systems Engineering SME	-CH II: Literature Review -CH IV: Interdependence Analysis -CH V: Conclusion
Calvin Taylor	Prior Armor and Signal Officer with experience using UAS's at the tactical level as well as synchronizing aerial and ground assets to provide desired effects.	-Team Leader -Independence Analsysis SME -Automation and Autonomy SME	-CH II: Literature Review -CH IV: Interdependence Analysis -CH V: Conclusion

E. PROJECT APPROACH

This capstone project was conducted in three phases as shown in Figure 1. The project began in Phase I with a needs analysis to provide a foundation of understanding and background knowledge to support the analysis in later phases. During Phase I, the team researched key areas of the capstone project including interdependence analysis, HMT characteristics, USMC mission essential tasks (MET), and capacity requirements. The team identified stakeholders and studied stakeholder needs and desires related to the project and mission. During Phase II (Coactive Design Model), the team developed an operational view (OV-1) to display the mission scenario and hybrid operational concepts between a VTOL, UAS, and GCS for a SCAR mission. The team performed systems analysis and used the coactive design approach to develop functional tasks and HMT requirements in the form of OPD to display the interdependency relationships between the three systems. The team's interdependency analysis and MBSE artifacts were used to develop a roadmap to drive HMT system requirements using a specific SCAR mission scenario while receiving stakeholder feedback. During Phase III (Results), the team produced analysis results by utilizing the interdependency analysis table of HMT characteristics. The team assessed the results and finalized the project by reporting all results and recommendations obtained using the coactive design and MBSE approaches which will lead to future living lab experiments.

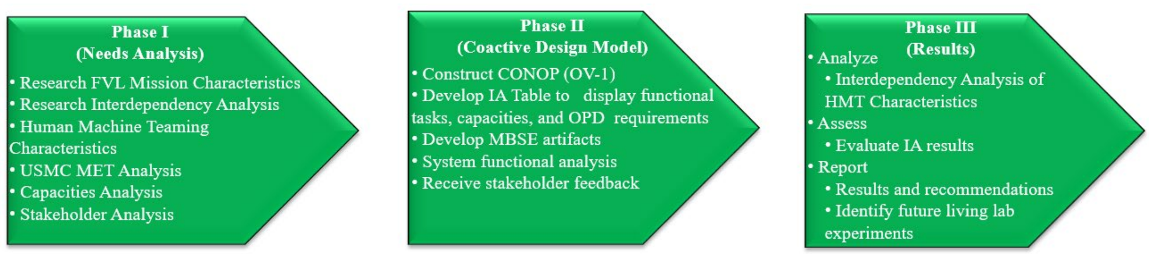


Figure 1. Project Approach Diagram

F. CAPSTONE REPORT OVERVIEW

Chapter I provided background information on the VTOL and SCAR mission, problem statement, and research objectives and questions for this capstone. Chapter II introduces literature that applies to the problem statement and its framework. Chapter III illustrates the research method utilizing systems analysis to support the Coactive Design approach. Chapter IV describes the Coactive Design Model and interdependency analysis table methodology to develop HMT requirements applied to the SCAR mission vignette. Chapter V presents an exploratory experiment that will be analyzed for follow-on research. Lastly, Chapter VI summarizes the capstone results and provides recommendations for follow-on research.

II. LITERATURE REVIEW

This chapter contains an in-depth review of the literature relevant to understanding the stakeholder problem statement and its context. In the previous chapter, we discussed the current USMC aerial reconnaissance for Expeditionary Advanced Base Operations (EABO) concepts and tasks, giving particular attention to USMC use of unmanned aerial systems in support of reconnaissance activities to facilitate future combat operations. We developed a vignette from our USMC stakeholders' input that incorporated aerial reconnaissance capabilities and human-machine teaming activities between the VTOL, UAS, and GCS. Second, we presented coactive design as a method to analyze the interdependencies between humans and machines in a human-machine team. The coactive design process enabled the team to develop HMT requirements between a VTOL, UAS, and GCS. Third, we explained autonomy and automation to delineate the key distinctions between the two in relation to unmanned aerial systems. Lastly, we explained the importance of HMT and its benefits and challenges to improve performance between a human and machine.

A. AERIAL RECONNAISSANCE IN EXPEDITIONARY ADVANCED BASE OPERATIONS

Our stakeholder, the USMC, directed our team to pursue EABO because it supports the new force design structure in the USMC 38th Commandant's Planning Guidance. It enables U.S. Naval forces "to persist forward within the arc of an adversary's long-range precision fires to support allies with combat credible forces in the littorals" (Department of the Navy [DON] 2019, 2). To support the stakeholder's EABO requirements, the team chose to model the SCAR mission because this allowed us to optimize identification of HMT requirements in VTOL/UAS hybrid operations.

1. Marine Expeditionary Advanced Base Operations

Published in February 2021, the Tentative Manual for Marine EABO serves as the Marine Corps' vision for supporting the Concept for Expeditionary Advanced Base operations signed in March 2019 (DON 2021, iii). EABO is "a form of expeditionary warfare that involves the employment of mobile, low-signature, persistent, and relatively easy to maintain and sustain naval expeditionary forces from a series of austere, temporary locations ashore or inshore within a contested or potentially contested maritime area to conduct sea denial, support sea control, or enable fleet sustainment" (DON 2021, 1–3). EABO employs various missions and for this capstone the team evaluated the following: "Provide forward command, control, communications, computers, combat systems, intelligence, surveillance, reconnaissance, targeting (C5ISRT), and counter C-5ISRT capability" (DON 2021, 4–5).

The Navy's EABO optimizes the littorals as the Marines' operating environment. The littorals are part of the Joint Maritime operation, which includes seaward and landward areas. The seaward segment spans from the open ocean to the shore. Seaward segment must be controlled by littoral forces to allow successful support operations on the shore. The landward segment incorporates all inland areas. Littoral forces will conduct ground operations on landward while being supported and defended from the sea (DON, 2021, 4–5). Figure 2 illustrates the littorals in which an operating force would operate.

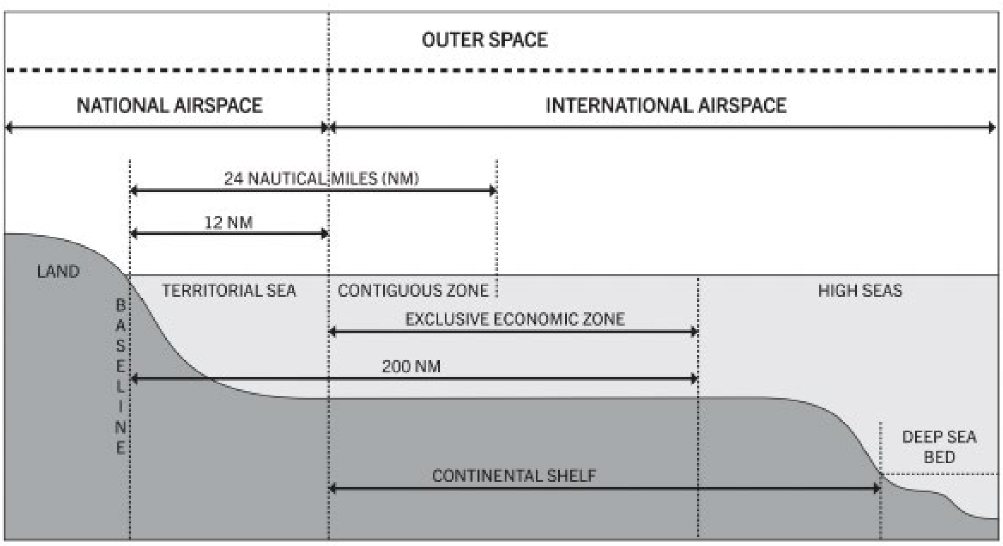


Figure 2. EABO Littoral Diagram. Source: DON (2021, 4–6).

Based on the two segments, the EABO tentative manual describes the littorals as having five dimensions within the maritime domain (DN 2021). The Department of the Navy states, "five dimensions: seaward (both surface and subsurface), landward (both surface and subterranean), the airspace above, cyberspace, and the electromagnetic spectrum" (DON 2021, 1–2). The five dimensions illustrated in Figure 3, provides the framework for littoral forces to assess competition containment from friendly, enemy, and neutral activities to enable the understanding of the impacts of EABO activities (DON 2021, 4–5). To provide battlespace awareness across the five dimensions of littorals, for the USMC, reconnaissance and surveillance are required in the littoral area.

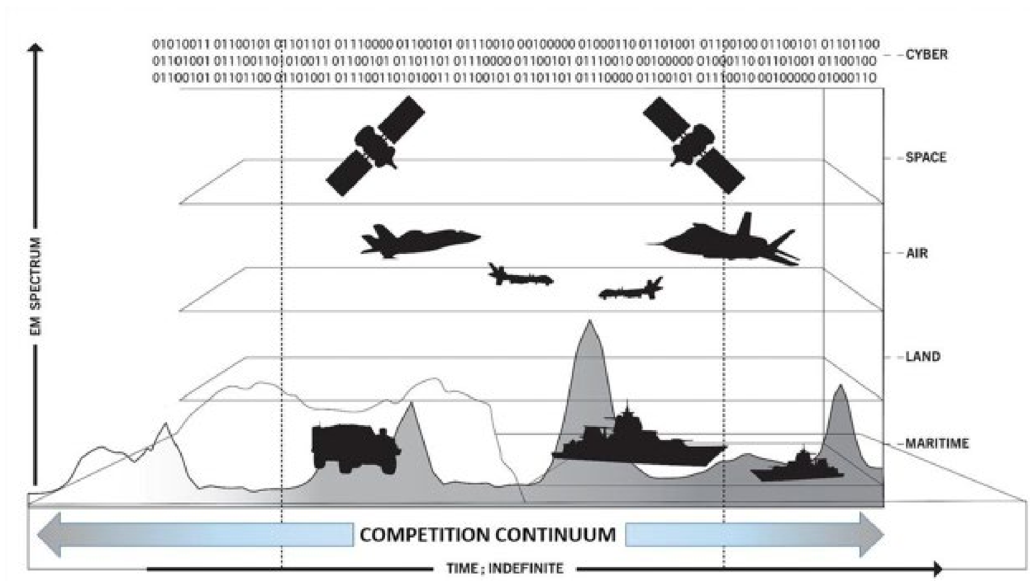


Figure 3. Littoral Dimensions. Source: DON (2021, 4–5).

2. Strike Coordination and Reconnaissance Mission

SCAR missions in EABO acquire targets and report and coordinate the destruction of targets. SCAR missions are broken down into two fundamental parts: Strike Coordination and Reconnaissance. During a SCAR mission an "aircraft may discover enemy targets and provide a target mark or talk-on for other Attack Reconnaissance missions or locate targets for Air Interdiction Missions" (USMC - Warfighting Publication

2001, 2–3). SCAR missions can be flown by any manned or unmanned aircraft that has been assigned an area for future Strike Coordination.

a. The Purpose of Strike Coordination

The purpose of strike coordination is to provide the commander marked targets that can be engaged with multiple effects to include fire effects during littoral operations (DON 2001). An aircraft conducting a SCAR mission may carry its own munitions. It can also coordinate the use of other munitions and effects as needed.

b. The Purpose of Reconnaissance

The purpose of reconnaissance actions is to provide the commander with a current and accurate picture of potential enemy threats, activities, positions, and resources. At the tactical level, the objective of Marine Aerial Reconnaissance is to conduct "tactical threat warning, mission planning, targeting, combat assessment, threat assessment, target imagery, artillery and naval gunfire adjustment, and observation of ground battle areas, targets, or sections of airspace" (USMC 2018, 1–3). The most relevant category of air reconnaissance for this capstone is visual reconnaissance. Visual reconnaissance is conducted to support the Littoral Commander's Priority Information Requirements (PIRs) utilizing fixed - or rotary-wing (VTOL) aircraft and unmanned aerial vehicles.

c. Intelligence, Surveillance, and Reconnaissance Management

Reconnaissance operations utilize multiple Intelligence, Surveillance, and Reconnaissance (ISRs) platforms to acquire the Littoral Commander's PIRs, thereby driving current and future operations. Prior to any mission execution, a list of available assets such as the VTOL/UAS are generated and placed onto the Intelligence Collection (IC) Matrix. These assets are then assigned to a Named Area of Interest (NAI) or a Targeted Area of Interest (TAI). Each NAI and TAI is given one or more PIRs, which triggers intelligence generation or an effect to be placed in the NAI or TAI; effects may include kinetic, fire, obstacles, or signal effects. Effective commanders will use a layering of collection assets to achieve effective Reconnaissance Management. There are three methods to accomplish collection layering: cueing, mixing, and redundancy (DA 2016). See Figure 4 for examples.

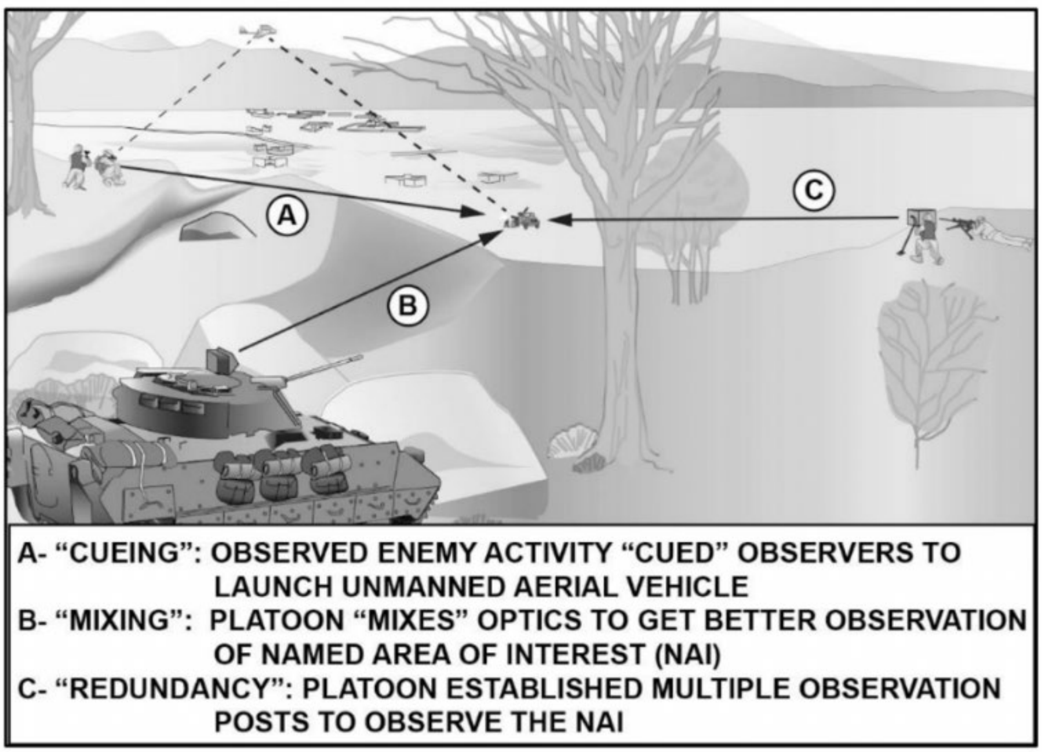


Figure 4. Reconnaissance Management. Source: DA (2019, 3–14).

B. COACTIVE DESIGN METHOD

This capstone project focuses on identifying the interdependence relationships of human-machine teams consisting of the VTOL, UAS, and GCS during a SCAR mission so the USMC can incorporate the draft requirements into their planning considerations for the VTOL/UAS hybrid operations. To that end, the researchers used coactive design to explore human-machine design by identifying value for autonomous users and potential impacts on performance. Matthew Johnson developed Coactive Design at Florida Institute of Human and Machine Cognition (IHMC) in 2010 "to address the increasingly sophisticated roles that robots and people play as the use of robots expands into new, complex domains. Coactive Design's goal is to help designers identify interdependence relationships in a joint activity so they can design systems that support these relationships, thus enabling designers to achieve the objectives of coordination, collaboration, and teamwork" (Johnson et al. 2014, 390). Johnson states that using Coactive Design can be a "useful approach for developers trying to understand how to translate high-level teamwork concepts into reusable control algorithms, interface elements, and behaviors that enable robots to fulfill their envisioned role as teammates" (Johnson et al. 2014). The concepts of Coactive Design most relevant to this research are interdependence, coactive system model, and OPD.

1. Interdependence

To achieve the desired end state for VTOL and UAS as successful system, we must understand interdependence. Johnson defines interdependence as the "dependence of two or more people or things on each other" (Wilcox and Chenoweth 2017, 12). In the case of a UAS and a human, both of which are actors, understanding the nature of the interdependencies between the two will determine how they can work together and contribute to mission success.

In addition, maximizing a system's capability requires a balance of autonomy. Both self-sufficiency and self-directedness are required in any activity involving a human and a machine. Johnson also states that "while awareness of interdependence may not be critical to the initial stages of system development, it becomes an essential factor in the realization of a system's full potential" (Johnson 2014, 47).

2. Coactive System Model

When developing interdependence requirements for human-machine teaming, engineers use the coactive system model. This model uses the OPD framework to analyze interdependence. The coactive system model is depicted in Figure 5. For the purposes of our research, the blue column on the left represents the UAS and the VTOL is represented in the red box on the right. In the middle are the interface requirements of OPD.

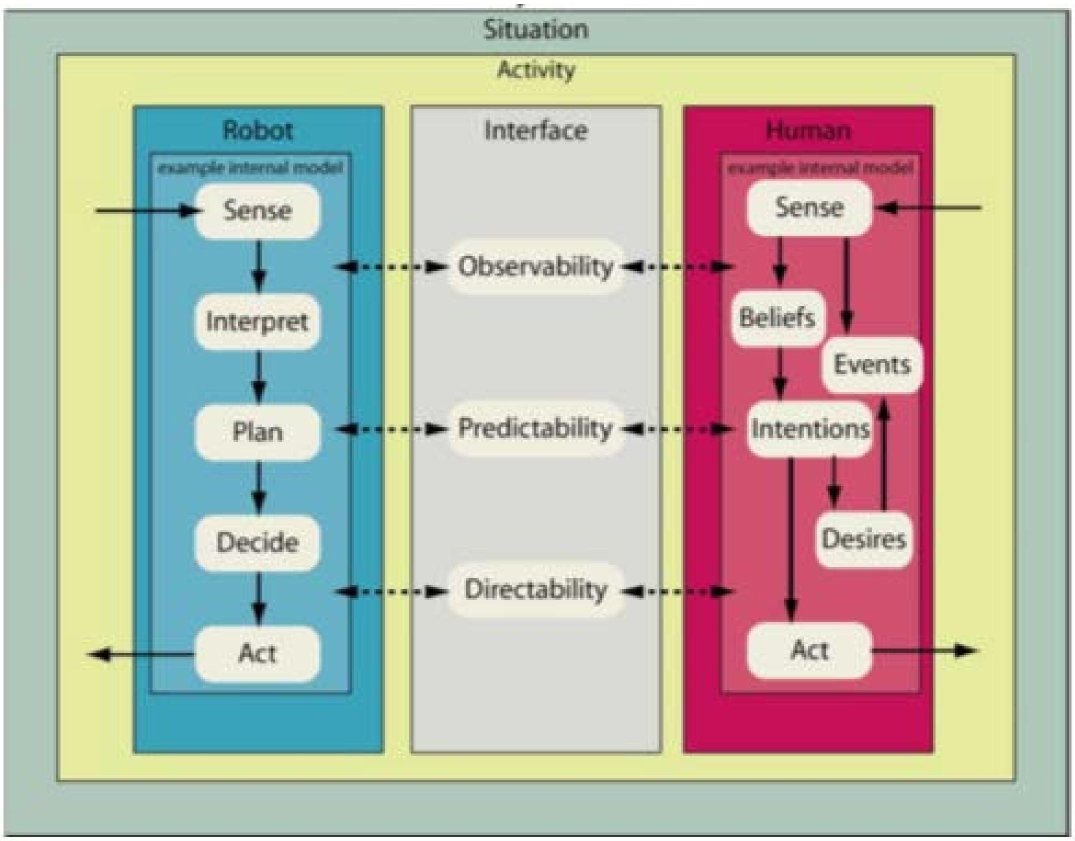


Figure 5. Coactive System Model. Source: Johnson (2014).

3. Observability, Predictability, and Directability

Viewing the battlespace or operational environment is critical during any forward-deployed mission. The adaptability and expediency of effort is directly linked with the ability of the VTOL and the UAS to observe the mission area and its surrounding environment. As human-machine teaming becomes standard operating procedure for the USMC, the technical capability and operational capacity to observe and provide real-time reports of the operational environment between humans and machines is paramount. Observability in human-machine teaming is an interdependency that refers to how both the human and the system can determine each other's state based on outputs. It requires multi-directional and real-time communication between human-machine teams and their respective platforms (manned aircraft, autonomous aircraft, semi-autonomous aircraft). This type of collaboration will require diligent mission planning and coordination to facilitate the command and control of the battlespace, as well as authority over the machine in the human-machine team. This collaboration must be capable of providing real-time feedback to all systems within the operational area. In the case of human and UAS interaction, this collaboration may refer to the ability to see the current system state of the UAS, while from the UAS's perspective, observability might entail constantly monitoring the change in flight maneuvers executed by the human. Lastly, observability must enable the human and machine to coordinate complex movements, collect intelligence information from the battlefield, and facilitate safe collaboration across the battlespace for all personnel and equipment (Sanchez 2021).

In addition to observability, the predictability of action must be considered and planned to effectively implement a human-machine team. Understanding the complexity of operational environments, the fluidity of decision-making processes, and the dependency on task execution between the VTOL and UAS, requires a detailed understanding and analysis of predictability. Both systems must complement each other's tasks and actions using predictability. Predictability allows the synchronization of efforts between the systems, the coordination of action with a foundation of trust and understanding that enables short-term and long-term mission planning and execution. An example of predictability between the human and the UAS is the human anticipating any changes in flight path for the UAS due to weather. A second example are corrections in the input of human flight maneuvers for the UAS executed by the UAS itself. Predictability must be established and implemented throughout the mission planning process, as well as during execution. The human-machine teaming effort will require predictable and repeatable input, output, and action scenarios which establish predictive operational concepts. Control and understanding of human and machine behavior between the UAS and VTOL, when coordinated, will be vital to effective and safe human-machine operations (Johnson 2014).

Directability is another key interdependency of human-machine teaming. Directability is the ability of the human and machine to influence each other. An example of directability is the ability of the human to override the machine if required. When combined with observability and predictability, directability of the machine in the human-machine team enables rapid and ethical operational control over the autonomous system.

To execute successful directability, human-machine teams must be responsive to inputs from each other (Johnson 2014).

Using the elements of OPD will better enhance the VTOLs and UASs control of and reliance on effective human-machine teams. As unmanned aerial systems become more complex, it is the human factor in the human-machine team that will be critical when executing hybrid operations.

4. Coactive Design Method

The coactive design method is a framework tool that is used to assist engineers in identifying the interdependence relationships between humans and machines. Figure 6 depicts the flow of the coactive design process, starting with identification, the "selection and implementation process and evaluation of change process" (Wilcox and Chenowith 2016, 16). It includes the breakdown of inputs, processes, and outputs for the four main processes that make up Coactive Design. When the process is applied, the outputs show how "interdependent activity makes the coactive design process a responsive method" (Wilcox and Chenowith 2016, 16).

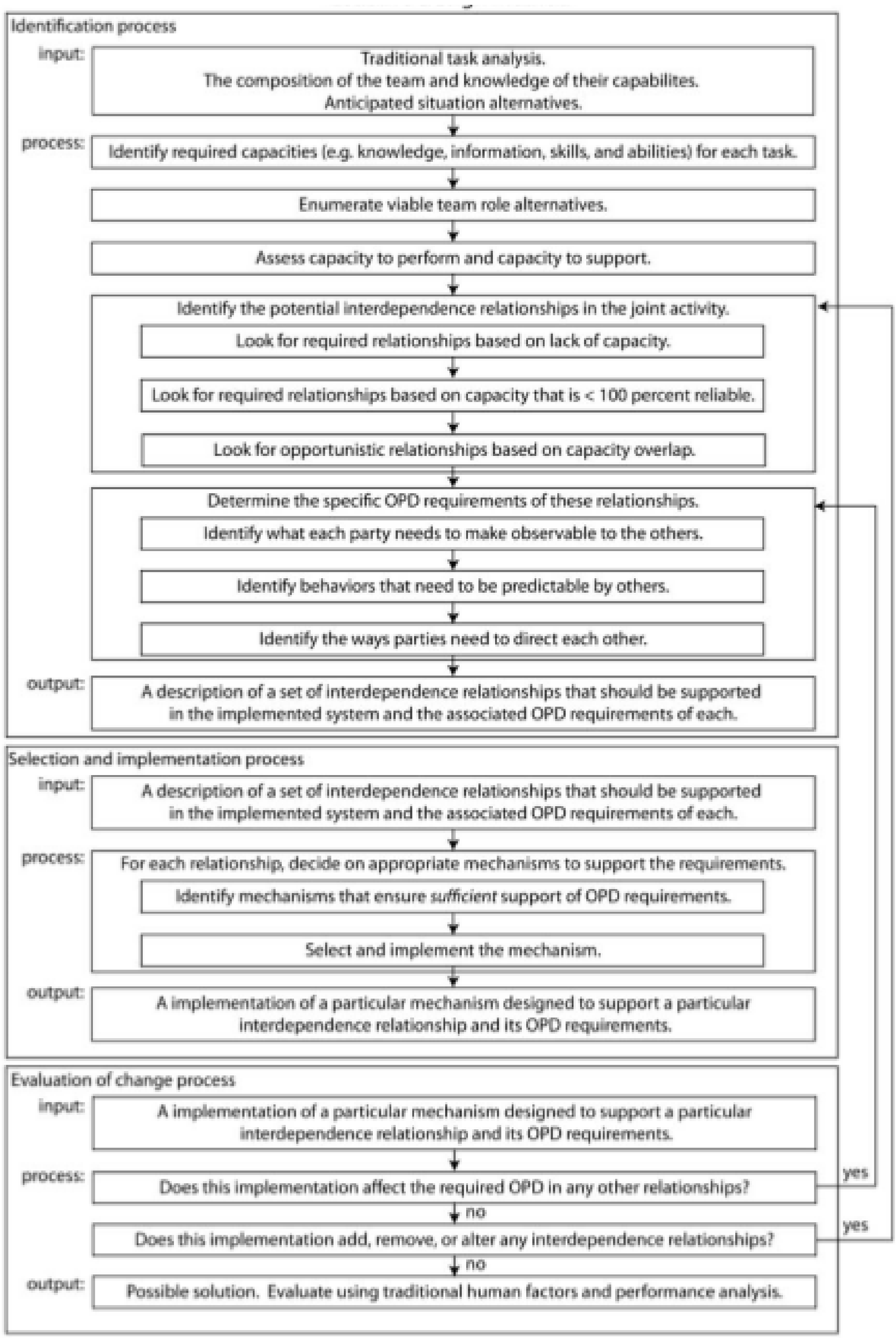


Figure 6. Coactive Design Process. Source: Johnson (2014).

In addition to the coactive design process, Johnson "proposed an analysis tool called the Interdependence Analysis (IA) Table, depicted in Table 2. This tool represents several ways of designing for interdependence such as:

- Allowing for soft or opportunistic constraints by a human or machine that will improve team performance
- Allowing for more types of interdependence than just task dependency
- Representing other participants in the activity by name or by role
- Allowing for assessment of capacity to perform
- Allowing for assessment of capacity to support
- Allowing for consideration of role permutations (Johnson 2014, 74)

Table 2. Interdependence Analysis Table. Source: Johnson 2014

Tasks	Hierarchical Sub-tasks	Required Capacities	Team Member Role Alternatives								OPD requirements
			Alternative 1				Alternative 2				
			Performer	Supporting Team Members			Performer	Supporting Team Members			
			A	B	C	D	B	C	D	A	
task	subtask	capacity									
task	subtask	capacity									
		capacity									
		capacity									
	subtask	capacity									
task	subtask	capacity									
		capacity									
	subtask	capacity									
		capacity									

Traditional hierarchical task analysis

Enumeration of viable team role alternatives

OPD requirements specification

Identification of required capacities including situation awareness information, knowledge, skills, and abilities

Assessment of capacity to perform and capacity to support, as well as identification of potential interdependence relationships in the joint activity

The first step in the IA process for the SCAR mission is analyzing and identifying the order of tasks and subtasks. Step two requires the capacities for each subtask to be listed. Capacities are knowledge, skill, or abilities the operator leverages to perform the tasks, hierarchal sub-tasks and required capacities. The Team Member Role Alternatives in the table notates the different teaming combinations. The table is further broken down into two sections that assess the human and machine's capacity to perform, support, and identify potential interdependence relationships involved in the human-machine teaming interaction. The IA Coloring Scheme, shown in Table 3, further defines the role alternatives for both the performer and the supporting team members. The ability of the team member, or performer, to execute a listed task is color coded and notates the level of assistance required by the performer o complete that task. The supporting team members column shows the possible levels of assistance provided by supporting members to the performer in that specific task. The supporting team member column describes how assistance can improve efficiency, improve reliability, assistance is required or if no assistance can be provided (Johnson 2014).

Table 3. Team Member Role Alternatives Table. Source: Johnson (2014).

Team Member Role Alternatives	
Performer	Supporting Team Members
I can do it all	My assistance could improve efficiency
I can do it all but my reliability is < 100%	My assistance could improve reliability
I can contribute but need assistance	My assistance is required
I cannot do it	I cannot provide assistance

Zach (2016) provides an example of the IA color scheme implemented in Table 3. He states,

> the robot may be able to search a room while looking for an object all on its own. However, introduce a tall table into the room and place the object on it, out of view of the robot, and the robot is unable to complete the task with 100 percent reliability. Using a human to inspect the table would improve that overall reliability. As a result, both the performer column supporting column would be represented in yellow (26).

Designers analyze these color combinations to determine interdependence requirements of the relationships being supported. Table 4 shows different color combinations and their definitions (Johnson 2014).

Table 4. Interdependence Analysis Table Color Combinations with Interpretations. Source: Johnson (2014).

Team Member Role Alternatives		Interpretation
Performer	Supporting Team Members	
A	B	
Reliable	Soft Interdependency	Independent operation by performer is a viable option, but assistance could improve efficiency.
Reliable	Soft Interdependency	Independent operation by performer is a viable option, but assistance could improve reliability.
Reliable	Must be independent	Independent operation by performer is necessary.
Potential Brittleness	Soft Interdependency	Performer is < 100 percent reliable, but assistance could improve efficiency.
Potential Brittleness	Soft Interdependency	Performer is < 100 percent reliable, but assistance could improve reliability.
Potential Brittleness	Must be independent	Performer is < 100 percent reliable, and no assistance is possible from this team member.
Missing Some Capacity	Soft Interdependency	Performer requires assistance, team member can provide it, and assistance can improve efficiency.
Missing Some Capacity	Soft Interdependency	Performer requires assistance, team member can provide it, and assistance can improve reliability.
Missing Some Capacity	Hard interdependency	Performer requires assistance, and team member can provide it.
Unachievable		Performer requires assistance, but none is possible.
Unachievable		Performer cannot do task.

Johnson (2014) explains how to analyze the color associations which provides understanding into the interdependence of a system. The first column represents the performer, and the colors measure the performer's capacity to execute the task. Limitations of the performer are depicted in yellow, orange, and red. An example might be an issue with reliability like brittleness (yellow), a lack of capacity due to a hard interdependency (orange), or an absolute lack of capacity (red).

The type of interdependence relationships that support the performer are represented by the supporting team member column. No chance for assistance is indicated by a red shaded block in the column. In this case, the performer acts as a single point of failure. A brittle system is represented by a score of less than 100 percent reliable.

> However, if you can provide support for interdependence then you can avoid the single point of failure. Colors other than red in the supporting team member column indicate potential required (orange) or opportunistic (yellow and green) interdependence relationships between team members. The hard interdependencies are easy to identify because you cannot complete the task without it. Soft interdependencies tend to be more subtle but provide valuable opportunities for teamwork and alternative pathways to a solution (Johnson 2014, 77).

Johnson states "The accurate analysis of color combinations can identify repeatable patterns within the listed teaming and support relationships. It now becomes increasingly simple to identify the below items assisting in the design process and resource allocation. OPD requirements are then derived from the identified interdependencies as well as how the system responds to these questions:

- Who needs to observe what, from whom?
- Who needs to be able to predict what?
- How do members need to be able to direct each other?" (Johnson 2014, 57)

Once the identification process has been successfully completed, the selection and implementation phase are executed. The selection and implementation phase involves locating procedures that fulfill the requirements gathered during the identification process. Next, is the process of evaluating changes in interpretation to ensure that the procedures chosen to meet the requirements do not result in any unintended negative effects on other OPD relationships. According to Satzinger et al. (2012), continuous feedback loops are indicative of the spiral design process. In the process of evaluation, if new and/or different OPD relationships are revealed, they may need to be incorporated into the original identification process, requiring a repeat of the coactive design method.

C. AUTONOMY AND AUTOMATION

Understanding the difference between autonomy and automation, how it applies to a VTOL pilot and an UAS as part of a HMT, and how we assess it based on a specific model is critical to our application. The terms automation and autonomy are often presumed to be interchangeable (McNabb 2019). McNabb defines automation as "the use or introduction of automatic equipment in a manufacturing or other process or facility, while the term autonomy is defined as freedom from external control or influence; independence" (McNabb 2019). Looking at this definition from a UAS perspective, an automated drone executes its programming to follow the coordinates from one point to another without making decisions, while the autonomous UAS would make the decision on where to go and the path it takes to the destination. Table 5 illustrates a 10-level scale of degrees of automation.

Table 5. Parasuraman, Sheridan, and Wickens's Scale of Degrees of Automation. Source: Parasuraman, Sheridan, and Wickens (2000, 287).

LEVELS OF AUTOMATION OF DECISION AND ACTION SELECTION	
HIGH	10. The computer decides everything, acts autonomously, ignoring the human.
	9. informs the human only if it, the computer, decides to
	8. informs the human only if asked, or
	7. executes automatically, then necessarily informs the human, and
	6. allows the human a restricted time to veto before automatic execution, or
	5. executes that suggestion if the human approves, or
	4. suggests one alternative
	3. narrows the selection down to a few, or
	2. The computer offers a complete set of decision/action alternatives, or
LOW	1. The computer offers no assistance: human must take all decisions and actions.

The level of autonomy is described differently from multiple perspectives. The Society of Automation Engineers (SAE) utilize Table 6 as their standard for autonomous ground vehicles but can be applied to any vehicle capable of autonomy (Society of Automation Engineers 2018).

Table 6. SAE Level of autonomous drone navigation mapped by functional features. Source: Society of Automation Engineers (2018).

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

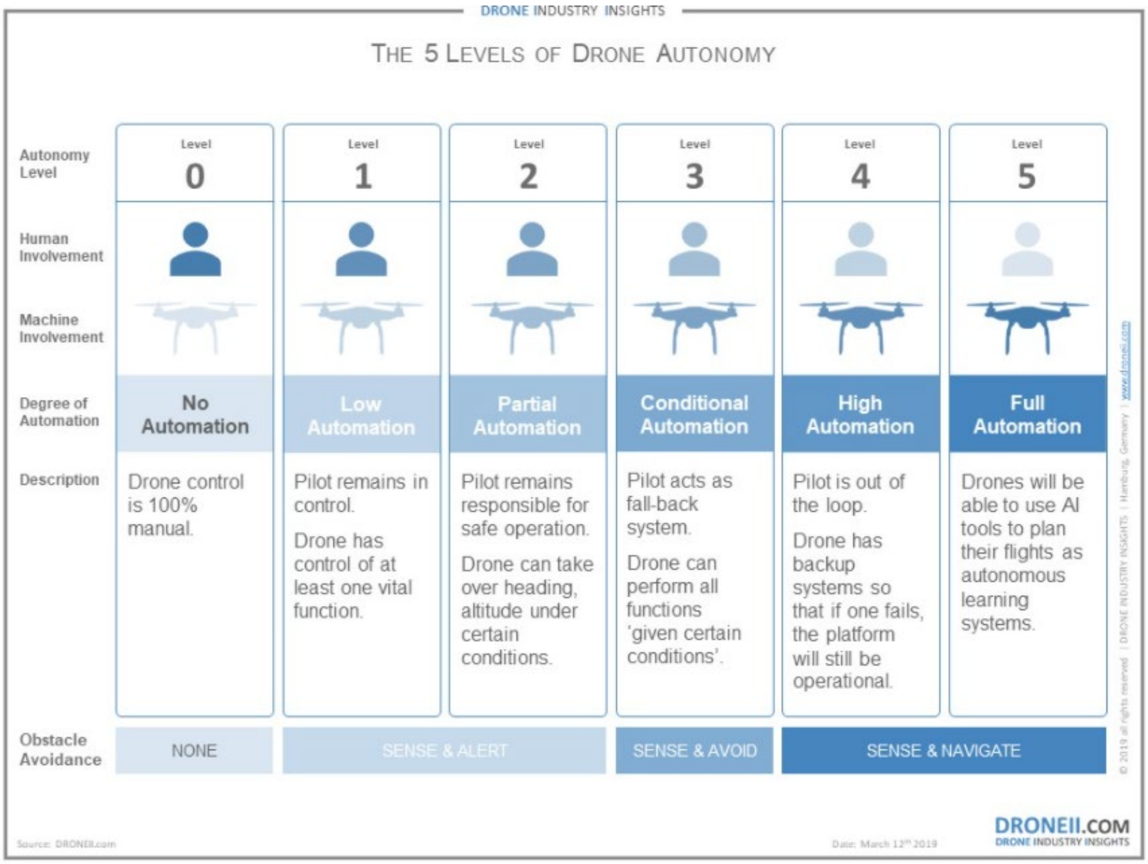
A NASA research team utilized a different table to determine the level of autonomy for a particular function as seen in Table 7 (Proud, Hart, and Mrozinski 2003).

Table 7. NASA's Level of Autonomy Assessment Scale. Source: Proud, Hart, and Mrozinski (2003).

Level	Observe	Orient	Decide	Act
8	The computer gathers, filters, and prioritizes data without displaying any information to the human.	The computer predicts, interprets, and integrates data into a result which is not displayed to the human.	The computer performs ranking tasks. The computer performs final ranking, but does not display results to the human.	Computer executes automatically and does not allow any human interaction.
7	The computer gathers, filters, and prioritizes data without displaying any information to the human. Though, a "program functioning" flag is displayed.	The computer anlayzes, predicts, interprets, and integrates data into a result which is only displayed to the human if result fits programmed context (context dependant summaries).	The computer performs ranking tasks. The computer performs final ranking and displays a reduced set of ranked options without displaying "why" decisions were made to the human.	Computer executes automatically and only informs the human if required by context. It allows for override ability after execution. Human is shadow for contingencies.
6	The computer gathers, filters, and prioritizes information displayed to the human.	The computer overlays predictions with analysis and interprets the data. The human is shown all results.	The computer performs ranking tasks and displays a reduced set of ranked options while displaying "why" decisions were made to the human.	Computer executes automatically, informs the human, and allows for override ability after execution. Human is shadow for contingencies.
5	The computer is responsible for gathering the information for the human, but it only displays non-prioritized, filtered information.	The computer overlays predictions with analysis and interprets the data. The human shadows the interpretation for contingencies.	The computer performs ranking tasks. All results, including "why" decisions were made, are displayed to the human.	Computer allows the human a context-dependant restricted time to veto before execution. Human shadows for contingencies.
4	The computer is responsible for gathering the information for the human and for displaying all information, but it highlights the non-prioritized, relevant information for the user.	The computer analyzes the data and makes predictions, though the human is responsible for interpretation of the data.	Both human and computer perform ranking tasks, the results from the computer are considered prime.	Computer allows the human a pre-programmed restricted time to veto before execution. Human shadows for contingencies.
3	The computer is responsible for gathering and displaying unfiltered, unprioritized information for the human. The human still is the prime monitor for all information.	Computer is the prime source of analysis and predictions, with human shadow for contingencies. The human is responsible for interpretation of the data.	Both human and computer perform ranking tasks, the results from the human are considered prime.	Computer executes decision after human approval. Human shadows for contingencies.
2	Human is the prime source for gathering and monitoring all data, with computer shadow for emergencies.	Human is the prime source of analysis and predictions, with computer shadow for contingencies. The human is responsible for interpretation of the data.	The human performs all ranking tasks, but the computer can be used as a tool for assistance.	Human is the prime source of execution, with computer shadow for contingencies.
1	Human is the only source for gathering and monitoring (defined as filtering, prioritizing and understanding) all data.	Human is responsible for analyzing all data, making predictions, and interpretation of the data.	The computer does not assist in or perform ranking tasks. Human must do it all.	Human alone can execute decision.

To further complicate how to determine the level of autonomy, of the drone industry uses a five-level drone autonomy scale as seen in Table 8 (McNabb 2019). Understanding the difference between autonomy and automation and how we assess it based on a specific model is critical to our application. Knowing how to assess the levels of autonomy and automation and how it applies to a VTOL pilot and an UAS as part of an HMT will provide clarity to a convoluted problem.

Table 8. Drone Industry 5 Level of Drone Autonomy. Source: McNabb (2019).



DRONE INDUSTRY INSIGHTS

THE 5 LEVELS OF DRONE AUTONOMY

Autonomy Level	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
Human Involvement						
Machine Involvement						
Degree of Automation	No Automation	Low Automation	Partial Automation	Conditional Automation	High Automation	Full Automation
Description	Drone control is 100% manual.	Pilot remains in control. Drone has control of at least one vital function.	Pilot remains responsible for safe operation. Drone can take over heading, altitude under certain conditions.	Pilot acts as fall-back system. Drone can perform all functions 'given certain conditions'.	Pilot is out of the loop. Drone has backup systems so that if one fails, the platform will still be operational.	Drones will be able to use AI tools to plan their flights as autonomous learning systems.
Obstacle Avoidance	NONE	SENSE & ALERT		SENSE & AVOID	SENSE & NAVIGATE	

Source: DRONEII.com

Date: March 12th 2019

DRONEII.COM DRONE INDUSTRY INSIGHTS

1. Industrial Definitions of Autonomy and Automation

The American Heritage Dictionary defines autonomy as "the condition or quality of being self-governing" (The American Heritage 1982). The Autonomy Levels for Unmanned Systems (ALFUS) workshop defines autonomy as "An unmanned system's own ability of sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/ executing to achieve its goals as assigned by its human operators through designed HRI or assigned through another system that the unmanned system interacts with" (Huang, 2008). Neema defines autonomy "as a system's ability to accomplish goals independently, or with minimal supervision from human operators in environments that are complex and unpredictable" (Neema 2017). Sheridan defines automation as "the automatically controlled operation of an apparatus, a process, or a system by mechanical or electronic devises that take the place of human organs of observation, decision, and effort" (Sheridan 1992, 3). The SAE International Standard J3016 clearly defines the six level of driving automation, from no automation to full automation, which the U.S. Department of Transportation included in the Automated Vehicles Comprehensive Plan (Department of Transportation 2021). SAE standard has six levels, the first three levels, a human has primary responsibility, while the last three the computer is in control.

2. Department of Defense Definitions of Autonomy and Automation

According to the Defense Advanced Research Projects Agency, "autonomy refers to a system's ability to accomplish goals independently, or with minimal supervision from human operators in environments that are complex and unpredictable. Autonomous systems are increasingly critical to several current and future DOD mission needs" (DARPA 2022). A DOD community of interest defined autonomy as "the computational capability for intelligent behavior that can perform complex missions in challenging environments with greatly reduced need for human intervention, while promoting effective man-machine interaction" (Kearns 2014, 4). According to the DOD, automation is a system that "has a set of intelligence-based capabilities that allows it to respond to situations that were not pre-programmed or anticipated (i.e., decision-based responses) prior to system development. Autonomous systems have a degree of self-government and self-directed behavior (with human's proxy for decisions)" (DOD 2015, 13). Autonomy and automation are key components to enable human-machine teaming in hybrid operations.

3. Conclusion

As technology continues to advance, the demand of autonomous systems being used by the DOD will increase. A full autonomous system may be desired, but the practicality of this system and the complexities to achieve this is not feasible with current technology. An optimal balance between the HMT must be established. We incorporated autonomy and automation requirements into our IA analysis and demonstrated how it applied to OPD to develop HMT requirements for VTOL/UAS hybrid operations that can be used for future research.

D. HUMAN-MACHINE TEAMING

Common knowledge of human team collaboration focuses on clear communication that enables the team's overall effectiveness including transferring data and situational awareness to build a cohesive team. As we assess the tasks required for HMT, we determine there are some tasks that are set aside for the human aspect of the team, while others are pushed to the unmanned system for which we seek the system to fill a gap or increase the effectiveness of the team. However, humans and machines interpret data in different ways. Humans use verbal and non-verbal cues, while machines must use algorithms, programming languages via computer software and hardware. The Air Force Research Laboratory (AFRL) stated that for the "human–machine teaming aspect of autonomic research, it is imperative to focus design decisions on the explicit allocation of cognitive functions and responsibilities between the human and computer to achieve specific capabilities" (Defense Innovative Marketplace 2017). Figure 7 illustrates the technology challenges with HMT that the AFRL articulated. HMT provides a list of benefits including improved performance, better teamwork that leads to faster performance of tasks with minimal errors, communication improvements via interfaces and in the end reduces the total number of humans required, which reduces cost to the force.

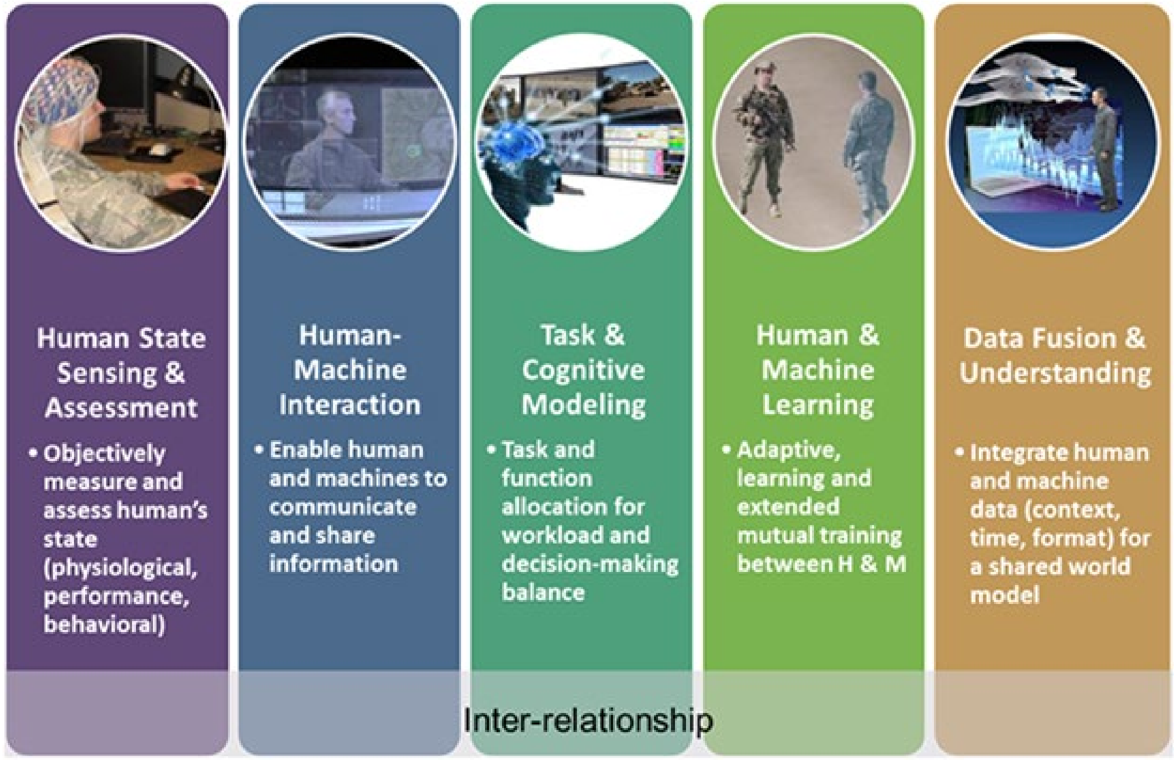


Figure 7. HMT Inter-Relationship. Source: Defense Innovative Marketplace (2017).

E. CHAPTER SUMMARY

This chapter reviewed existing literature and research to identify relevant material, methodologies, and historical data to capture and expound upon in this capstone project. Next, we used the Marine SCAR mission to facilitate EABO and serve as the operational concept for Johnson's (2014) Coactive Design Model to explore human-machine teaming between VTOL/UAS platforms and delineate areas of autonomy and automation in defining OPD requirements for hybrid operations. Lastly, we explored the various models and processes that support complex system decomposition.

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III. SYSTEMS ANALYSIS

This chapter elaborates on the use of systems analysis to understand and decompose the problem statement defined in Chapter I to support the coactive design model. Specifically, by using Department of Defense Architecture Framework (DoDAF) models, operational (OV) and systems (SV) level viewpoints were defined to satisfy stakeholder needs and present "an architecture consisting of multiple views or perspectives facilitating integration and promoting interoperability across capabilities and among integrated architectures" (Department of Defense [DOD] Deputy Chief Information Officer 2010).

A. SCOPE OF THE SYSTEM AND SYSTEMS ANALYSIS PROCESS

The SCAR scenario illustrates the integration of the coactive design model and the systems analysis process, focusing on the requirements and interdependencies that enable HMT across the family of systems. The integration of the systems analysis process aims to anticipate how a UAS, serving as the primary performer, will respond when conducting reconnaissance and surveillance within NAIs in a contested environment against enemy combatants in conjunction with a VTOL and GCS as supporting team members to enable hybrid operations.

The decomposition side of the systems engineering Vee model shown in Figure 8 was used to assist in developing and evaluating potential solutions. To better understand the austere environment and operational context of the mission, a design reference mission (DRM) framework was incorporated to define the operational situation. Based on the DRM, the identified capability need was decomposed based on the physical environment and proposed mission set. Lastly, the stakeholder needs were analyzed and cross referenced against the decomposition to ensure traceability across the HMT System.

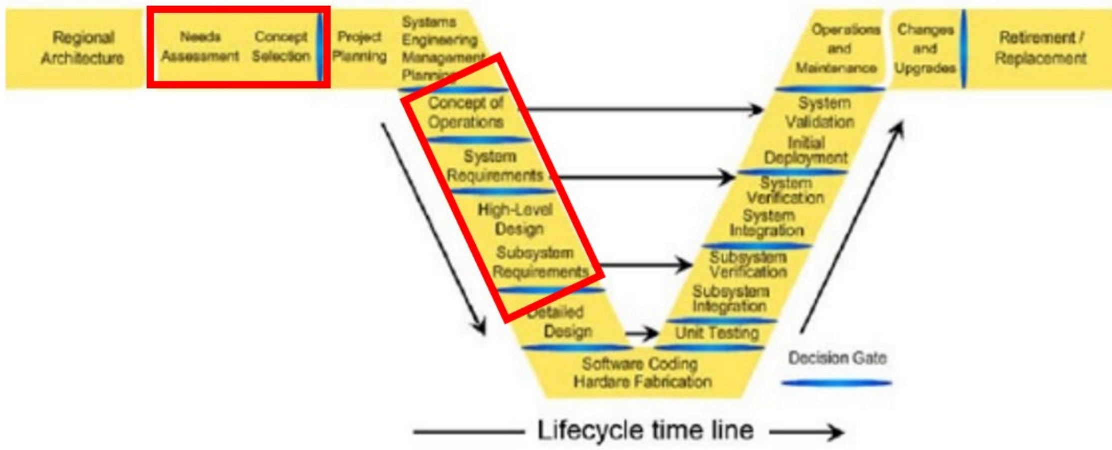

Figure 8. Systems Engineering Vee Model. Source: Langford (2009).

Given this operational situation, a concept of operations (CONOP) was utilized to display a phased approach by which the user would accomplish the mission, based on the system's capabilities. An OV-1, the first viewpoint in the Department of Defense Architecture Framework (DoDAF), shows a high-level view of the CONOP for the mission. The IA table represents the high level and sub-level functions in the Systems Requirements Phase of the Vee Model. The systems analysis process displays functional hierarchy and the Integration Definition for Functional Model (IDEF), illustrating model decisions, actions, and activities of the system. In addition, a Systems Interface Description (SV-1) and Operational Activity Model (OV-5) were used for graphical representations.

To build these products, the SysML framework for MBSE was applied using internal block, block definition, and activity diagrams. This concluded the decomposition phase of the Vee Model. Table 9 provides a summary of the phases and demonstration methods that were incorporated for the coactive design model and systems analysis process. Stages within the decomposition phase of the Vee model were omitted from this demonstration because this project is purely conceptual and will assist in future research.

Table 9. Systems Analysis Process (Vee model)

Vee Model Decomposition Phase	Demonstration Method
Needs Assessment	-Capability Need Statement -Stakeholder Needs -Projected Operational Environment -Input/Output (I/O) Model Analysis -Context Diagram -Functional Analysis
Concept Selection	-IA Table
Project Planning	-Omitted
SEMP	-Omitted
Concept of Operations	-Operational Viewpoint (OV-1)
System Requirements	-IA Table
High Level Design	-Systems Viewpoint (SV-1) -Inputs, Controls, Outputs, Mechanisms (ICOM) Model -Integration Definition for Functional (IDEF0) Model
Subsystem Requirements	-IA Table -Operational Activity Model (OV-5b)
Detailed Design	-Omitted

B. ASSUMPTIONS

Variability applies in all systems analysis scenarios. For the SCAR scenario the team created a non-exhaustive list of assumptions to minimize the amount of variability.

1. The VTOL deploys the UAS.
2. UAS and VTOL have the current TRLs and capabilities to conduct the mission.
3. The USMC MET will not change for this SCAR scenario.
4. Cognitive load was considered but not evaluated in determining HMT requirements.
5. The GCS is in the supply support area of the mission environment.
6. Other enemy combatants and noncombatants exist in addition to those at the NAIs.

7. The UAS is not lethally armed and has AI software that is capable of machine learning.

8. No hardware or software failures exist across any system.

C. NEEDS ASSESSMENT

The first phase of the systems analysis in the Vee Model is the Needs Assessment which is understanding the fundamental needs and interests of the stakeholders. The needs analysis should define the want of a stakeholder "into a more specific system-level requirement" (INCOSE 2007, 58). This process allowed the team to define the problem statement highlighted in Chapter I and develop a solution to address it. The team analyzed the HMT system based on the projected operational environment and system's boundary to dissect the operational and technical needs of the system. The following sections in this chapter facilitated the development of the IA table to create the HMT requirements depicted in Chapter IV.

1. Capability Need Statement and Projected Operational Environment

The identified capability need is for the team to develop HMT requirements for VTOL/UAS to conduct hybrid operations for a SCAR mission in a contested environment. The conceptual operational situation shown in Figure 9 guided the coactive design and systems analysis processes that were based on recent activity from the Democratic Republic of Centralia (DRC) and provocation across the region. Neighboring Centralia has seen a rise in rebel and DRC sympathizer activity, resulting in condemnation from the United States and its allied partners in Dakota. The government of Centralia appealed to the world for assistance and the United Nations condemned the recent DRC challenges to Centralia's sovereignty. U.S. forces were granted authority to conduct preemptive intelligence, surveillance and reconnaissance operations throughout the Republic of Centralia, littorals, and surrounding islands. Initial efforts focused on intelligence gathering and the identification of DRC assets and rebel activities in the assigned NAIs.

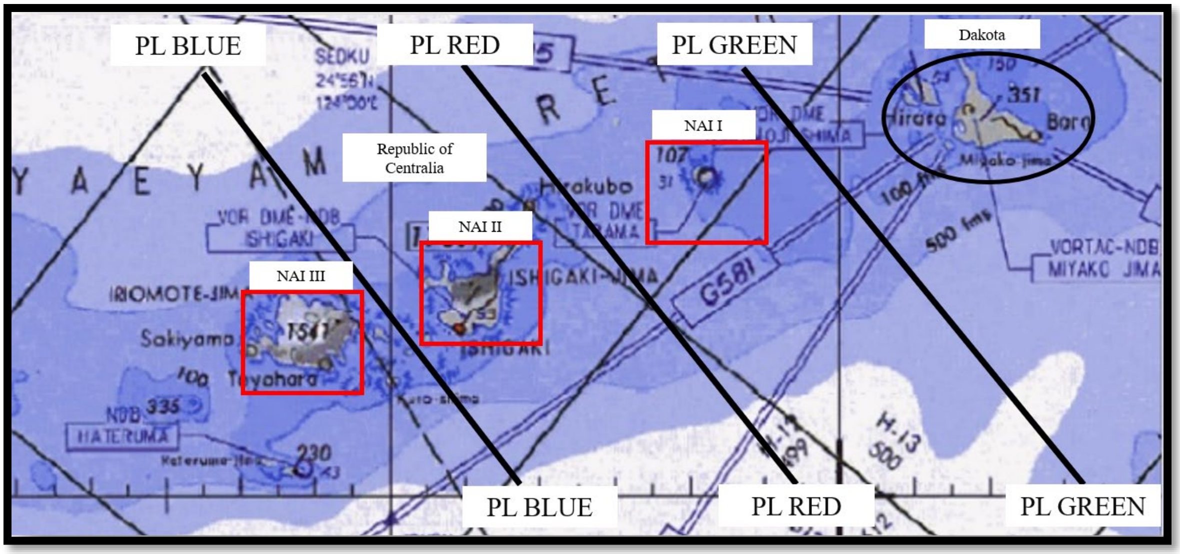

Figure 9. Operational Situation. Source: NPS MOVES Lab (2022).

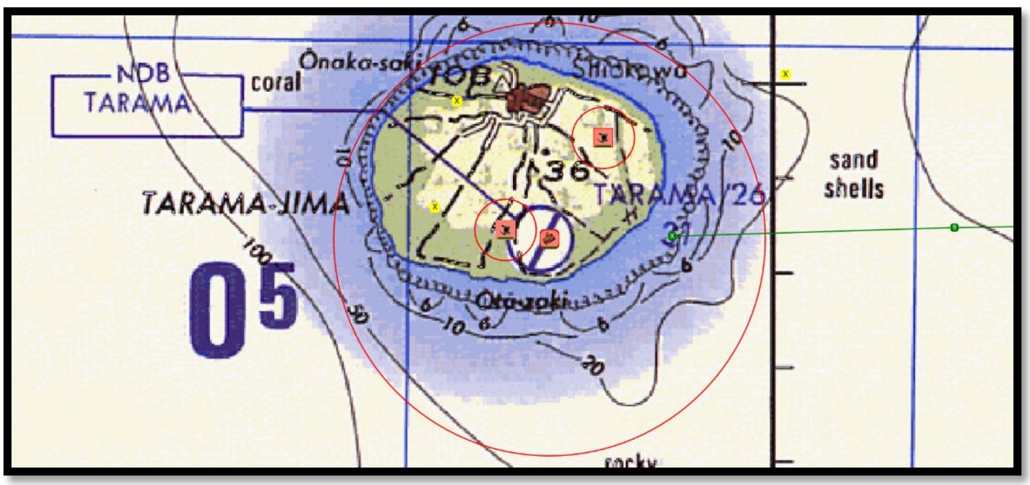

Figure 10. NAI I. Source: NPS MOVES Lab (2022).

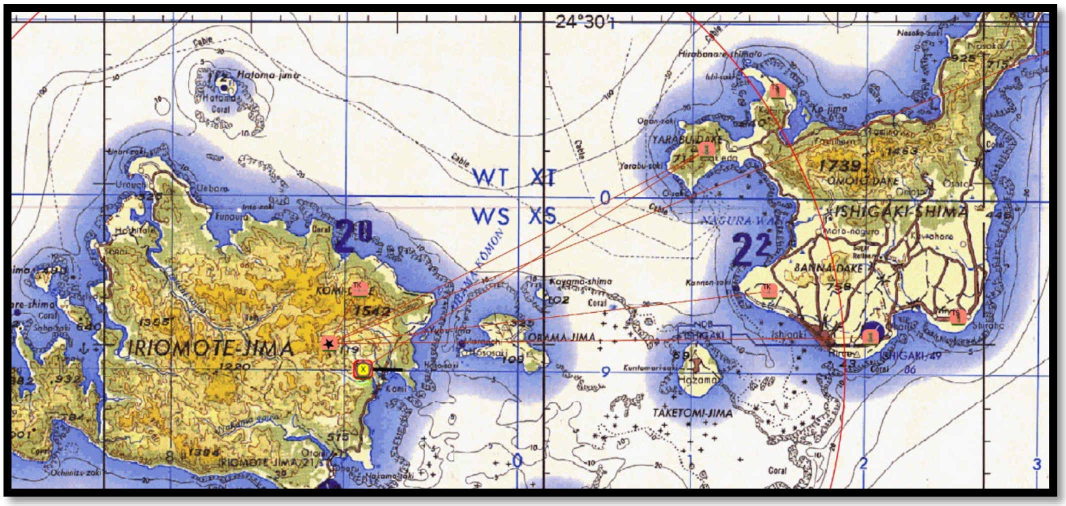

Figure 11. NAI II. Source: NPS MOVES Lab (2022).

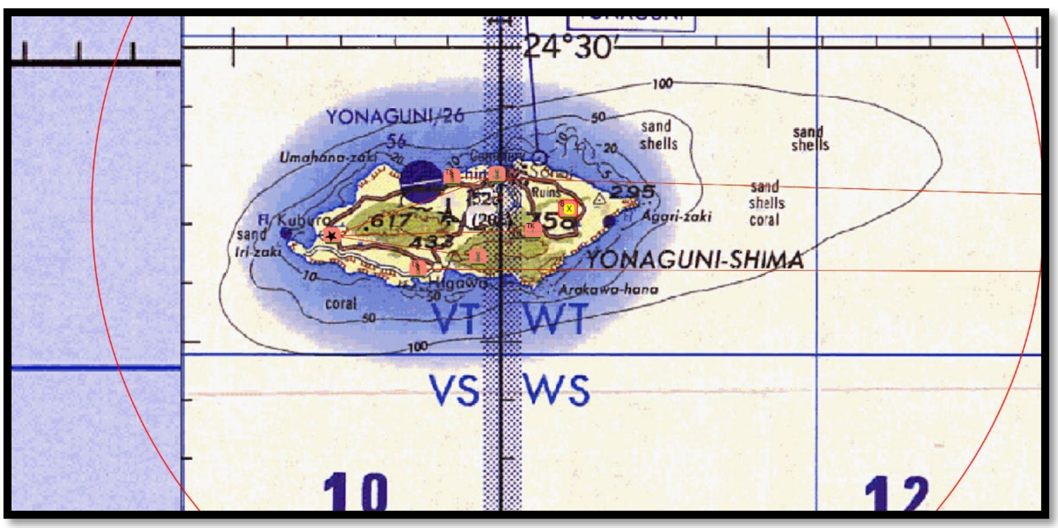

Figure 12. NAI III. Source: NPS MOVES Lab (2022).

2. Stakeholder Needs

According to INCOSE, stakeholders include any entity (individual or organization) with a legitimate interest in the system (INCOSE 2015). Each stakeholder identified in Table 10 represents a unique and specific interest in the HMT concept and will exercise differing levels of influence over the program. The team analyzed key concerns of the stakeholders to provide traceability of the high-level initial requirements for the HMT system to enable hybrid operations.

Table 10. Stakeholder Key Concerns

Stakeholder	Key Concerns
Department of Defense	-New technology to improve capability gap -Cost-effective
USMC HQs Aviation	-Cost-effective and reliable HMT system -Increased capability set -Interoperability with current systems -Trust in HMT concepts
System Developers	-Low manufacturing costs -Achievable technology readiness levels -Reliable systems
VTOL Users	-Trust of HMT -Reliability of data/inputs -Availability of HMT system -Ease of use in current mission sets
UAS Users	-Advances in technology and capabilities -New functions and mission requirements -Ease of use in current mission sets

3. Input/Output (I/O) Model Analysis

The I/O model in Figure 13 displays a black box, which is a system that produces useful information without revealing internal workings inside that system. It scoped and bounded the HMT system, and defined the system's functions, conditions, and boundaries by identifying controllable inputs required to create the intended outputs. The controllable inputs support the intended outputs which facilitate the USMC's objective to development and implement effective HMT interactions for VTOL/UAS hybrid operations. Recon of NAIs and enemy neutralized are intended outputs that enable the USMC to establish military superiority and warfare dominance. The uncontrollable inputs and unintended outputs identified are potential threats to the system and proper mitigation controls are required.

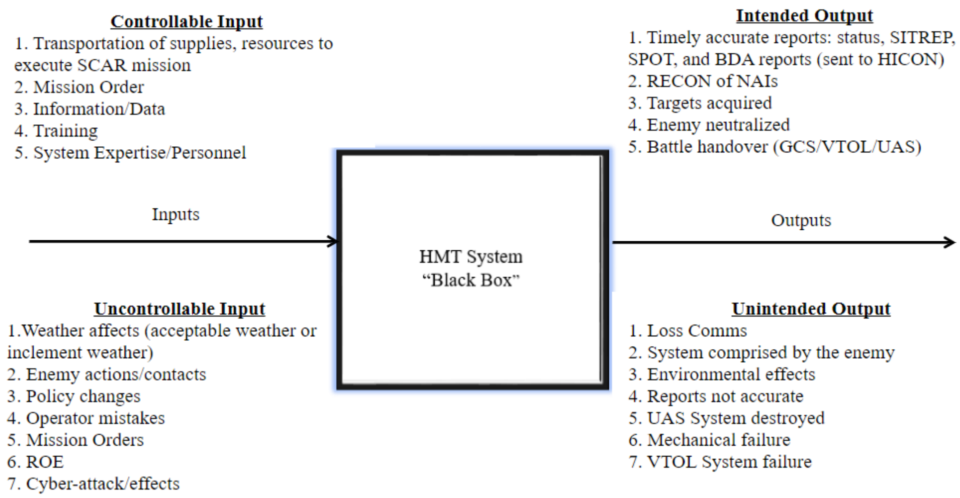

Figure 13. I/O Model

4. System Boundaries

A system boundary determines whether a component or subsystem belongs to a system (Input-Output). Everything outside of the defined boundaries is considered the environment (Input-Output). The I/O Model consumes controllable and uncontrollable variables from the environment, such as information, energy, and material, and produces intended and by-product outputs (Input-Output). This model is important for understanding the value of the environment the system operates within.

In 2011, Kossaikoff et al. stated when defining a system boundary, several criteria should be used when determining whether an entity should be defined as part of a system: developmental control, operational control, functional allocation, and unity of purpose.

- Developmental control answers the question, "Does the developer have control over the entity's development?"
- Operational control is about, "Will the entity be under the operational control of the organization that controls the system?"
- Functional allocation involves if the systems engineer is permitted to allocate functions to the entity.
- Unity of purpose addresses, "Is the entity dedicated to the system's success?"

Based on these definitions, and from the stakeholder's perspective, our system will include a GCS, VTOL, UAS, and digital planning system such as an imagined Marine

Planning and After-Action System (MPAAS). The environment included enemy forces, friendly forces, and the Republic of Centralia government. These system boundaries assume a single HMT system. Figure 14 describes the HMT system's boundaries and the interactions between systems that are within its boundaries. The passage of energy, matter, material, and information are depicted to inform the presence of the HMT systems physical, behavioral, and environmental boundaries. All other system interactions that are outside the depicted illustration are outside the scope of this research.

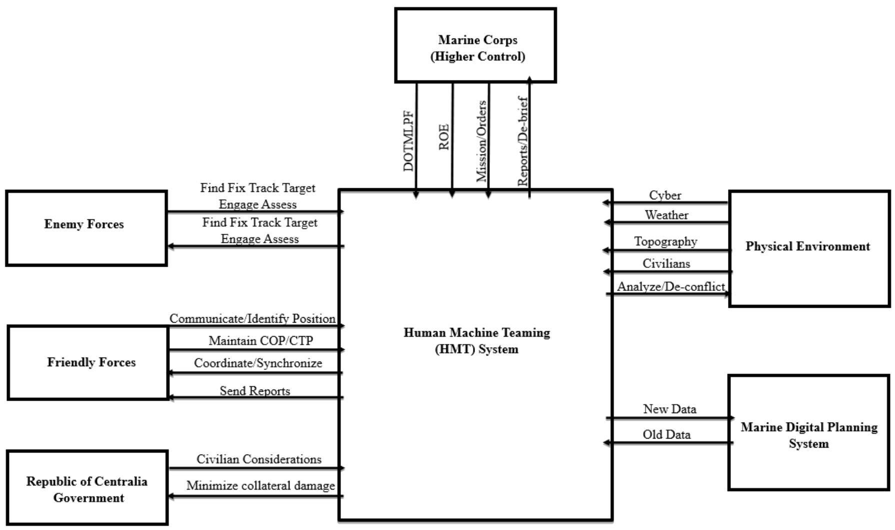

Figure 14. Operational Context Diagram

5. Functional Analysis

Figure 15 displays the functional hierarchy for the HMT system functions. The functional hierarchy decomposes the system functions three levels down. The overarching objective known as the mission essential task (MET) of the system is the function, Conduct SCAR Mission. There are five primary functions at the secondary level that must occur to facilitate the accomplishment of the MET. In addition, the tertiary level functions support the execution of the secondary level functions. The team used these system functions created through the systems analysis process to generate tasks and hierarchical sub-tasks for the Coactive Design Interdependency Analysis table for the HMT system to define HMT requirements for a SCAR mission illustrated in Chapter IV.

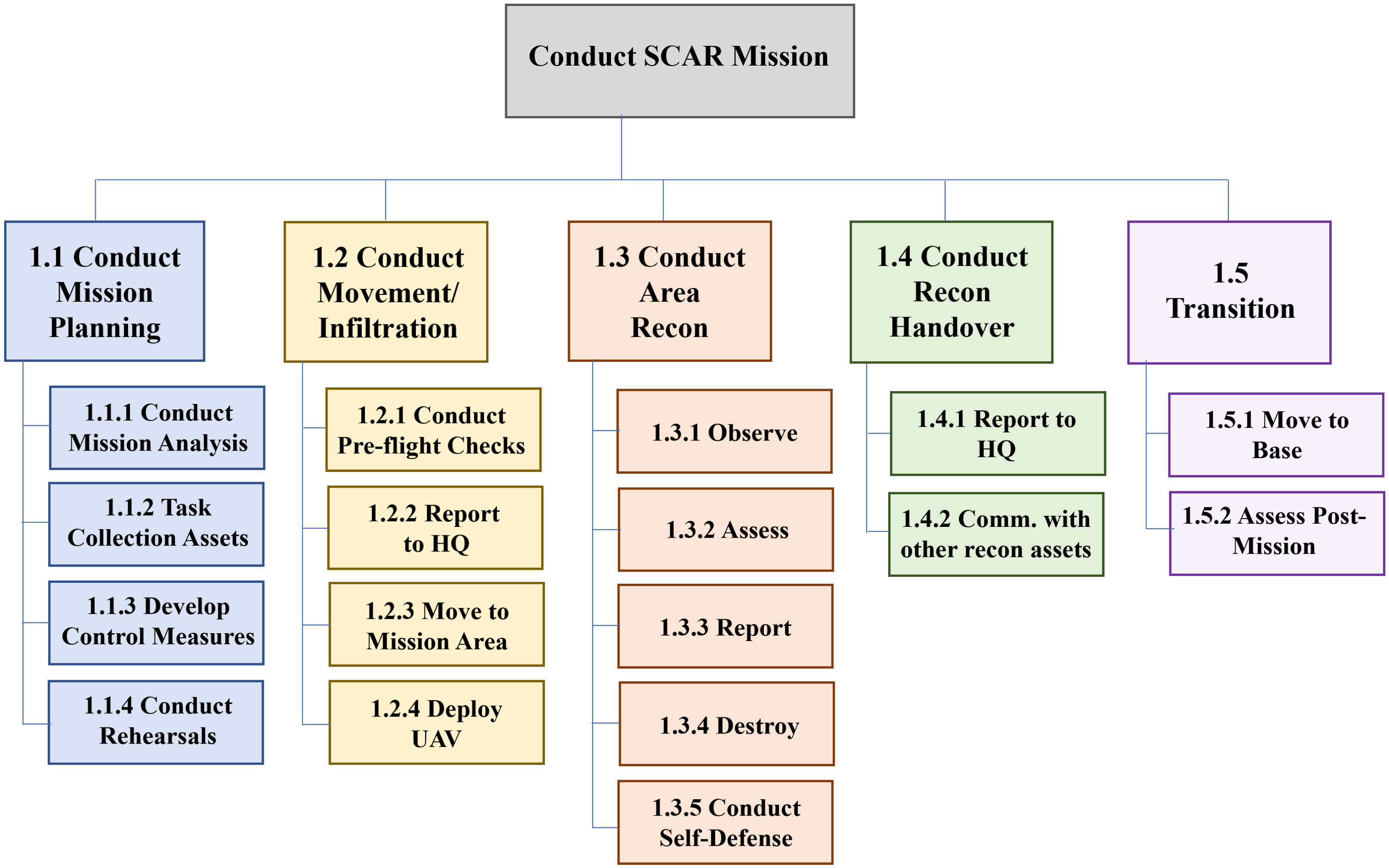

Figure 15. Functional Hierarchy Diagram

D. CONCEPT OF OPERATIONS (CONOP)

The first stage in the DoDAF Operational Viewpoint model (OV-1) is the concept of operations. Figure 16 is a visual representation of the operational concept of the HMT system executing a SCAR mission through interdependency using observability, predictability, and observability in support of the government of Centralia against the rise in rebel and DRC sympathizer activity across the region. The HMT system includes the VTOL deploying a UAS within the mission area from a release point (RP) to conduct reconnaissance and surveillance of the assigned NAIs within the DRC using a pre-assigned mission plan with the GCS providing command oversight.

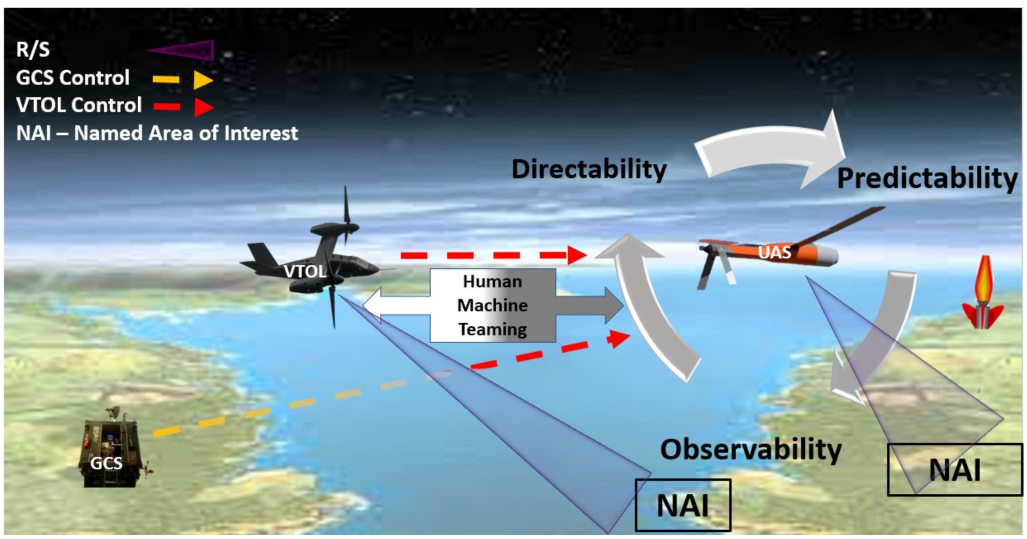

Figure 16. HMT System OV-1 Model

There are three NAIs in the assigned area of operations. The phase lines depicted in Figure 9 for the operational situation are used to control and coordinate the advance of the HMT system between each NAI. Once deployed at the RP, the UAV observes, assesses, and reports visual confirmation of enemy activity at each NAI through a SPOT report. The SPOT report contains the enemy size, activity, location, unit/uniform type, time observed, and equipment (SALUTE). The VTOL and GCS receive the SPOT report from the UAS and execute strike coordination to neutralize the enemy. Once VTOL uses lethal force to neutralize the enemy, the UAS conducts a battle damage assessment (BDA) report at each

NAI to confirm accurate and effective damage. The GCS maintains system visibility with the UAS during the hybrid operation. When the VTOL completes its mission, it conducts a battle turnover of UAS control to the GCS, since the VTOL endurance is less than the UAS.

Communication and control of the UAS is vital to mission success. To account for any degraded or loss of communications, a primary, alternate, contingency and emergency (PACE) plan is required. Figure 17 shows the (PACE) plan between the GCS, VTOL and UAS. For instance, if one form of communications is degraded and does not respond within 20 seconds of transmission the redundant communication link will be activated. Each level of the PACE plan will be allotted 20 seconds to establish connectivity. If the emergency SATCOM communication loses connectivity for 80 seconds the UAS will execute return to base (RTB) operations. The PACE plan can be altered based on capabilities and resources allocated to the mission.

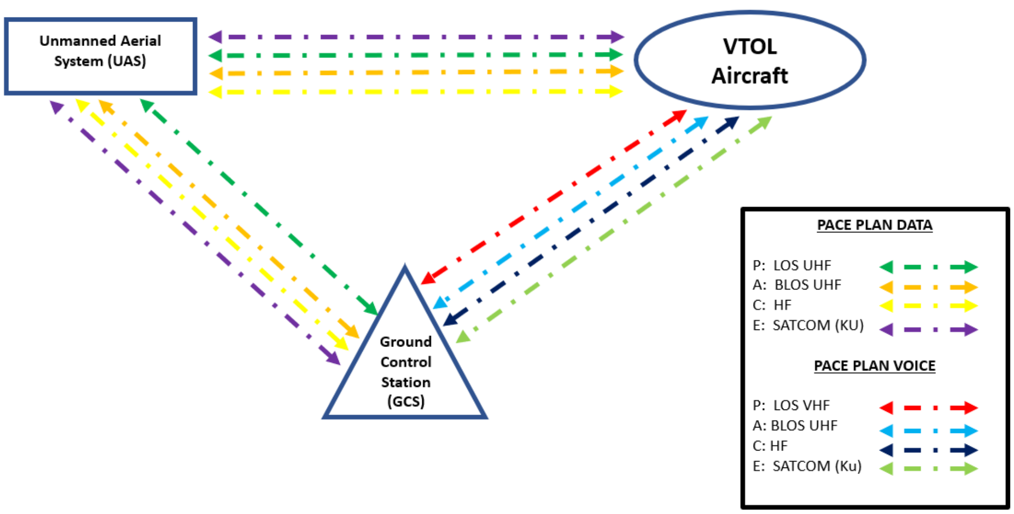

Figure 17. HMT System Information Flow

E. HIGH LEVEL DESIGN

1. System Interface Description-1

INCOSE states the System Interface Description identifies the system, system items, and their interconnections (INCOSE 2007). The "SV-1 serves to specify which interfaces correspond to which systems and contributes to the identification of other systems with which coordination must be established" (DoDAF.) Figure 18 illustrates the resource flows that are exchanged between the subsystems as part of the HMT System. The SV-1 highlights HMT as it relates to the navigation system control as being autonomous, human controlled, or a combination to enable interdependency for our system. Live stream video feeds are displayed in the GCS and VTOL which enables teaming to facilitate hybrid operations. The SV-1 provides insight to the machine learning capability that is provided by the MPAAS. This allows a cloud based server to store preloaded images, as well as enable the HMT system to upload new images and data as part of the mission debrief for future operations to support AI learning.

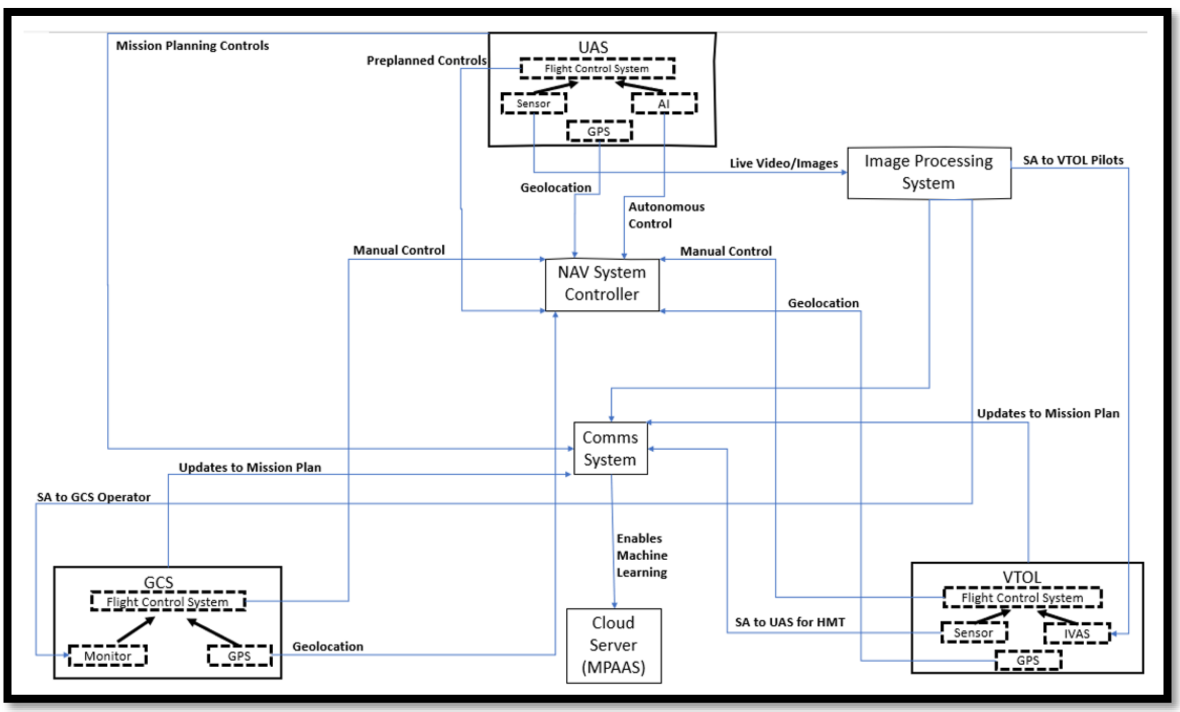

Figure 18. SV-1 of HMT System

2. Top-Level Inputs, Controls, Outputs & Mechanisms (ICOM) Analysis

According to INCOSE, the ICOM of a function represents certain system principles: inputs, outputs, controls, and mechanims. The inputs of the system are transformed into outputs, controls determine under what conditions transformations occur, and mechanisms illustrate how the function is achieved (INCOSE 2007). Figure 19 displays the primary inputs and outputs of the high level HMT system function, Conduct SCAR Mission. The control for this system is led through mission command which is the direct responsibility of the Marine Corps. Mechanisms that influence how the function is achieved are friendly fires, staff, and the communication system.

Friendly units operate in the battlespace of the HMT system. Establisihing roper coordination measures for fires achieves the primary outputs, coordination with adjacent units and neutralizing the enemy. Staff supports the system by planning, analyzing, and providing information and intelligence on the battlespace. They also supervise the execution of plans and orders, receive and issues reports, and relay updates to the Marine Corps for command and control. The communication platform enables the HMT system to collaborate and exchange information between friendly units executing the mission, providing a common operating picture.

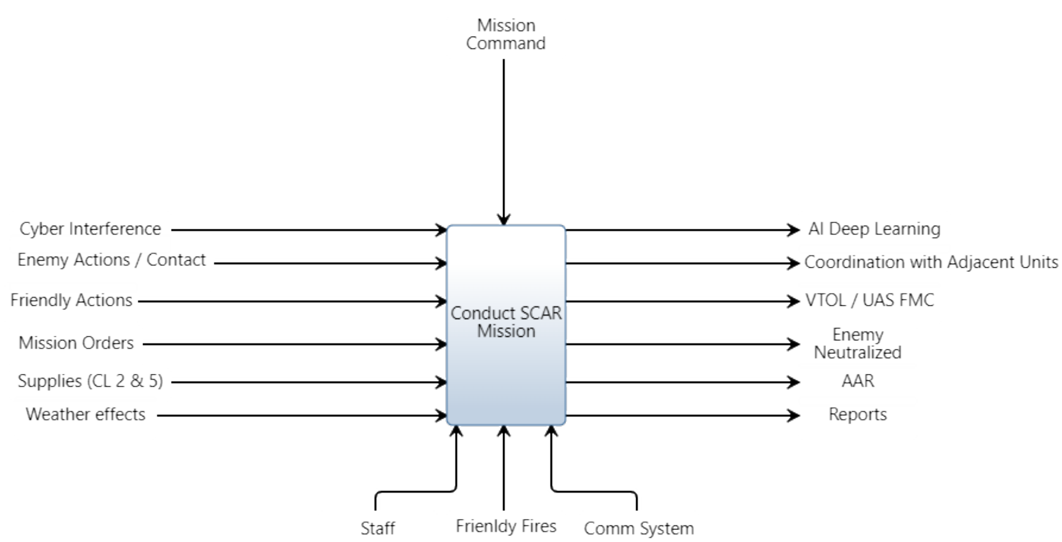

Figure 19. Top-Level ICOM Diagram

3. Integration Definition for Functional (IDEF0) Model Analysis

An IDEF0 diagram depicts an integrated illustration of inputs, control, outputs, and mechanisms for a systems decomposition. According to Buede, an IDEF0 model "is a set of diagrams that answer definitive questions about the transformation of inputs into outputs by a system and establishes the boundary of the system on the context page" (Buede 2009, 87). Figure 20 lists the inputs, outputs, controls, mechanisms, and depicts five secondary level functions from the functional hierarchy described in Figure 14 which supports the execution of the high-level function, Conduct SCAR Mission. For example, cyber interference and enemy actions are inputs for the secondary function, Conduct Area Recon. Mission command is a control and friendly fires is a mechanism. Enemy neutralized and report are outputs for this function.

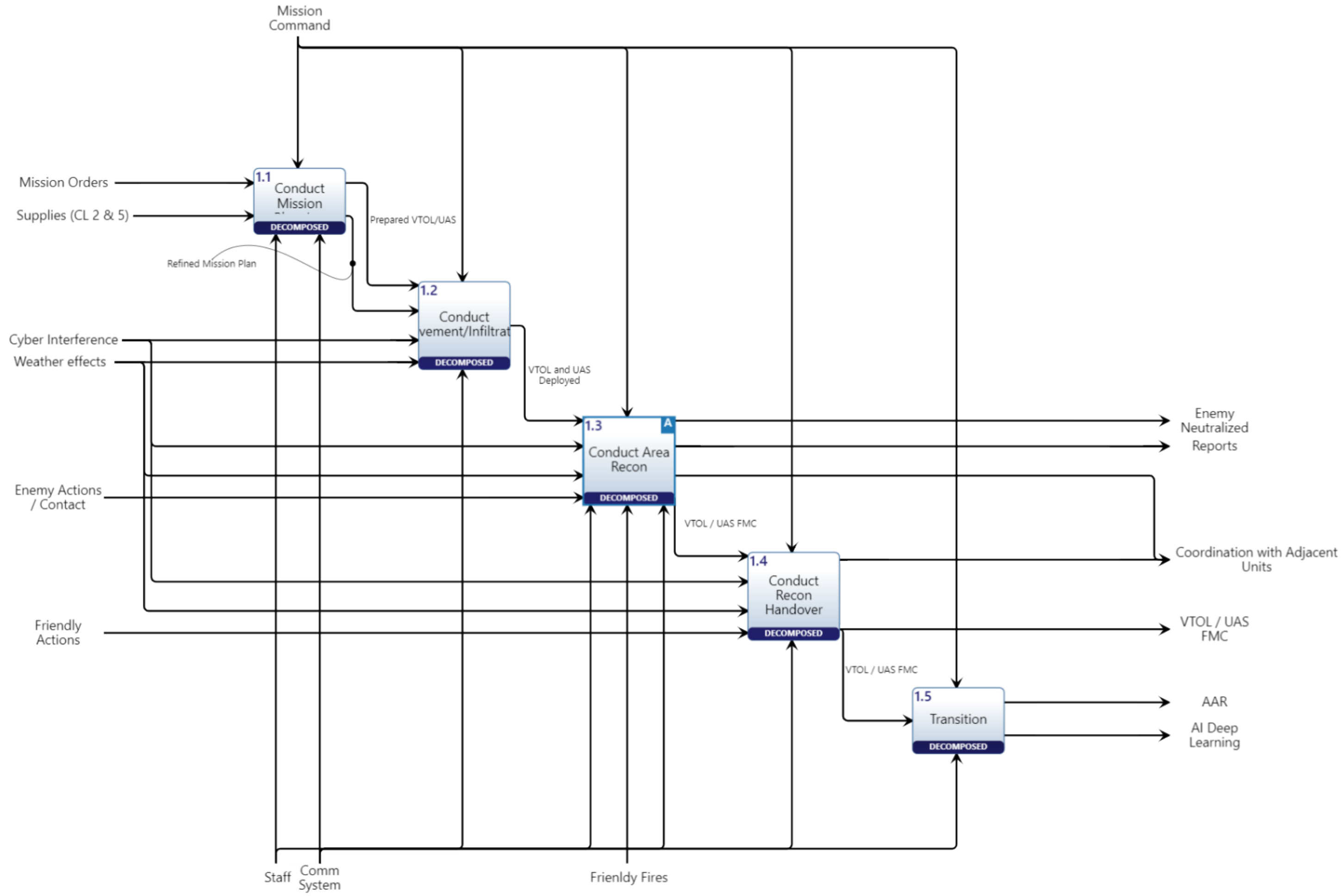

Figure 20. SCAR IDEF0 Diagram

F. CHAPTER SUMMARY

This chapter describes the systems analysis methods used to facilitate the development of the IA table and determine the HMT requirements between a VTOL, GCS, and UAS for hybrid operations. Assumptions for this capstone project were also described to support the SCAR scenario in a combat environment and reduce variability. In addition, stakeholder key concerns were described to establish a set of clear and concise needs related to the HMT system and SCAR mission. The OV-5 is depicted in Chapter IV to facilitate the development of an HMT experiment highlighted in Chapter V. Results of the research team's interdependence analysis will be discussed in the following chapter.

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IV. INTERDEPENDENCE ANALYSIS AND RESULTS

In this chapter, the following sections describe how the research team integrated the coactive design method into the systems analysis process using the Vee model and IA framework to support the HMT system. The IA framework depicts the primary tasks, sub-hierarchical tasks, and required capacities to successfully execute a SCAR mission. Through IA, the research team produced HMT requirements based on the interdependency factors: observability, predictability, and directability.

A. INCORPORATING SYSTEMS ANALYSIS AND COACTIVE DESIGN

1. Overview of Coactive Design combined with the Systems Analysis

Traditional systems engineering models, like the Vee model, specifically focus on the machine part of the system. Since this research project focused on the human portion of machine teaming, both the Vee model and the coactive design model were incorporated together. Combining the systems analysis and coactive design methods ensured that the research team considered the human interaction perspective inside the VTOL through its interdependence relationship with the UAS and GCS. The results of the coactive design analysis determined the interdependency requirements across the HMT. Understanding the requirements for the interaction between the system and sub-systems helped determine the level of assistance the machine can provide the human and what the human can provide the machine to complete its mission.

2. Incorporating Coactive Design in the Systems Engineering Vee Model

For the systems requirements phase the team implemented an interdependence analysis table, as depicted in Table 11, that identified possible interdependencies of HMT represented in the Coactive Design Process in Figure 6. This research analyzed the relationships between one primary performer and two supporting performers, with a focus on the UAS as the primary performer and VTOL and GCS as supporting performers.

Table 11. Interdependence Analysis (IA) Table. Source Johnson (2014)

Tasks	Hierarchical Sub-tasks	Required Capacities	Team Member Role Alternatives								OPD requirements
			Alternative 1				Alternative 2				
			Performer	Supporting Team Members			Performer	Supporting Team Members			
			A	B	C	D	B	C	D	A	
task	subtask	capacity									
task	subtask	capacity									
		capacity									
		capacity									
	subtask	capacity									
task	subtask	capacity									
		capacity									
	subtask	capacity									
		capacity									

Traditional hierarchical task analysis

Enumeration of viable team role alternatives

OPD requirements specification

Identification of required capacities including situation awareness information, knowledge, skills, and abilities

Assessment of capacity to perform and capacity to support, as well as identification of potential interdependence relationships in the joint activity

The first step was to determine the relevant tasks and hierarchal sub-tasks that will support the SCAR mission and order them chronologically. Next, sub-tasks for the performer and supporter were established based on the required capacities. Relating capacities to sub-tasks indicates an initial range of specifications the VTOL, GCS and UAS team requires to perform the SCAR mission.

Once capacities were established, each systems' ability to perform or support those capacities was identified as depicted in Table 11. The agents' abilities to perform and support the tasks was identified in addition to any interdependencies which would contribute to the development of OPD requirements between the VTOL, UAS and GCS.

Together the required capacities and OPD requirements form the system-level HMT requirements and baseline for the subsystem requirements which support the detailed design phase as described in the Vee model. Traceability was created to serve as a visual representation of the sequential execution of a SCAR mission and the required capacities for all agents seen in Figure 39. This workflow was then used throughout the remaining stages of the Vee process.

Figure 21 illustrates the detailed steps that were used in the coactive design process. The three major processes are the (1) identification process; (2) selection and implementation process; and (3) evaluation of change process. In the first process, the research team identified tasks and their interdependence relationships, then assessed the relationships according to observability, predictability, and directability to develop appropriate HMT requirements. The second process required the research team to identify suitable mechanisms to support the OPD requirements. In the third and final process, the research team assessed the relationships between those mechanisms.

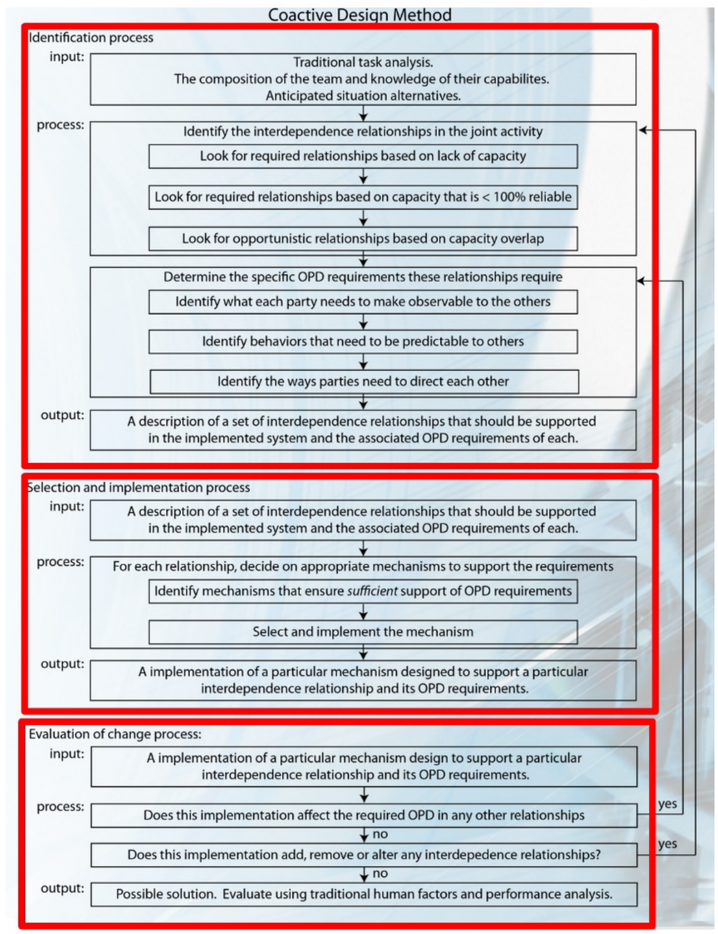


Figure 21. Coactive Design Method. Source: Johnson (2019)

Using the IA table shown in Table 11 and steps shown in Figure 21, the research team constructed a reliable HMT design in support of the SCAR mission. Obtaining the necessary data for the IA table was the most challenging task. This requires the design team to define the system's hierarchical tasks and subtasks and enumerate viable team role alternatives. It also requires the design team to assess the capacity of the human operators and intelligence of the AI system to determine the interdependency relationships between tasks and performers.

B. HMT INTERDEPENDENCE ANALYSIS

Interdependence analysis is designed to generate human machine teaming requirements, understand possibilities for resilience and reliability, and help designers set assumptions and prioritize design needs. IA for this capstone is designed to focus primarily on human machine teaming requirements between the VTOL, GCS and UAS. The following sections show IA analysis broken down by tasks. Each task analysis includes a description and an IA table showing the hierarchal sub-tasks, required capacities, and performers. Each task analysis paragraph will include a list of derived requirements, found in Appendix C (USMC Requirements Table).

1. Conduct Mission Analysis

This section describes how the VTOL, GCS and UAS must have a common operating digital system. To conduct continuous missions, the after-action review or "debrief" must be conducted digitally. Using a digital form of debrief will ensure the UAS's "AI" can learn and assist with HMT by building trust and new techniques, tactics, and procedures (TTPs). During the entire Conduct Mission Analysis task, teaming is occurring between performer and supporter since the GCS is required for the UAS to accomplish this task. The UAS can analyze terrain, weather, friendly capabilities, and enemy capabilities, however, reliability is improved through the GCS as a supporting team member. Currently, machines and computers execute tasks by digitally processing information. There must be a common framework that allows digital data to provide meaning and understanding across all three platforms. To achieve compatibility the digital interfaces used to communicate between the VTOL, UAS and GCS must be compatible. As the number of different systems working together on a mission increase, the number of required interfaces increases creating the potential for additional configuration problems. We suggest that the USMC implement one general mission planning system that interfaces with the VTOL, UAS, GCS, air, ground, and maritime units.

For the SCAR scenario, this Marine Planning and After-Action System (MPAAS; an idea, not a real system) would continuously monitor incoming traffic between the VTOL, GCS, and UAS. Upon receipt of a SCAR mission, the MPAAS would generate mission planning information for the VTOL, UAS, and GCS. Mission planning information includes mission data from previous missions and any current information which will assist the UAV in mission execution. Digital execution of AARs between the systems is a requirement that must be supported by the MPAAS. This will be accomplished by uploading all recorded data gathered during the mission. Digital interpretation of the human's activities during the mission must also occur. Interpreting human activities may improve the possibility the data provides added information for an AI system to achieve learning. AI learning will improve the UASs' ability to analyze historic data resulting in detailed and reliable future mission planning.

One challenge that emerges from the two capacities, "Create Assumptions and Establish Battle Tracker" is keeping the UAS, and VTOL mission plans current, accomplished by updating mission requirements. These updates improve the capability to predict future UAS and VTOL actions, and for the UAS and VTOL to understand GCS and other human actions. However, in a D-DIL (Denied Disrupted Intermittent Limited) environment this is not guaranteed. Necessary redundant communications can be achieved using a primary, alternate, contingency, and emergency (PACE) communications plan and should be required for the UAS, GCS and VTOL. One key observation is that the human requirement poses a risk to the HMT aspect of the mission analysis task due to cognitive overload and the potential for human error. This implies that the MPAAS needs to be designed with redundant layers of error checking while in the planning mode. The MPAAS must be treated as a machine in a human machine teaming environment and will require its own IA analysis of that relationship.

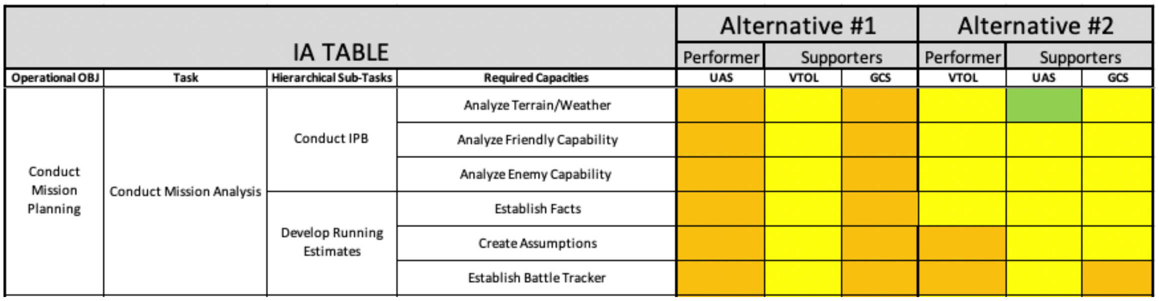


Figure 22. IA Table Depicting the "Conduct Mission Analysis" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the "Conduct Mission Analysis" derived requirements are shown in Table 12.

Table 12. Conduct Mission Analysis Requirements Based on IA Analysis

Requirements to Conduct Mission Analysis	
1	(O) The UAS must have the capability to connect to a redundant digital network with mission planners to ensure updated mission data is transferred and understood by humans and AI instantaneously.
2	(O) The Marines must have an automated digital common operating system that can connect the physical attributes of the world into a digital cloud-based storage system accessible by humans and AIs.
3	(P) The UAS must have a high automation level able to respond at the same speed as humans.

a. Task Collection Assets

This task requires updates prior to deploying the UAS into areas with the NAIs. Human interactions are required to provide updated mission requirements improving predictability. Due to operating in a D-DIL environment, the mission has an extremely low probability of success if these updates are not executed. To improve mission success, planners amongst the GCS, VTOL, and UAS should implement a validated PACE plan to ensure mission updates are completed. While the IA does not explicitly identify this requirement, it is implied.

A second observation from this task is that there are continuous transmissions and receipts of information between all systems. Humans in aviation related missions use a set of communications procedures designed to assure transmission and receipt. Often, there is an unspoken context behind these transmissions. Unspoken context, however, is not understood by the UAS, so it must be explicit. Designers will want to identify specific procedures and technical capabilities to ensure transmissions are received and understood. In human communications, a technique is to repeat the message received, signifying both receipt and understanding. This is another technique designers must consider. TCP/IP communications protocols have built in transmit and receipt codes which are not explicit to humans. Simply relying on a protocol may not support suitable human machine teaming.

IA TABLE				Alternative #1			Alternative #2		
				Performer	Supporters		Performer	Supporters	
Operational OBJ	Task	Hierarchical Sub-Tasks	Required Capacities	UAS	VTOL	GCS	VTOL	UAS	GCS
Conduct Mission Planning	Task Collection Assets	Develop IC Collection Matrix	Develop NAI						
			Assign LTIOV						
			List Assets						
			Assign Assets to NAI						

Figure 23. IA Table Depicting the "Task Collection Assets" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the "Task Collection Assets" derived requirements are shown in Table 13.

Table 13. Task Collection Assets Requirements Based on IA Analysis

Requirements to Task Collection Assets	
1	(O) The UAS must have the capability to connect to a redundant digital network with mission planners to ensure updated mission data is transferred and understood by humans and AI with minimal delay.
2	(O & P) The UAS must understand the mission coordination input from the human and provide automated feedback on risks and opportunities instantaneously.

b. Develop Control Measures

The same two issues arise in this task as the one prior. The IA specifically recognizes the importance of communications to enable updates to the control measures. We also see the requirement for a human-in-the-loop because the UAS is unable to adjust graphic control measures or approve changes. This follows USMC doctrine stating that a commander's operation staff is the entity charged with deconfliction of the area of operation. Also, we see the approval of the different area of operations being given to either the commander's operation cell or the commander themselves. The GCS acts as the tactical operations center (TOC) where the commander and the staff conduct current and future planning. This further highlights the requirement for the entire team to be able to continuously communicate through out this phase.

An assumption the team made is that the UAS can provide recommendations during mission planning. The purpose of this recommendation is to reduce the cognitive load on the staff. If the UAS can provide immediate feedback to the staff on its capability during the planning process the staff can focus on mission synchronization rather than the technical aspects of the mission. This may reduce the amount of time required to plan and be beneficial when planning operations on a condensed timeline. Further research is required to investigate the feasibility of AI being allowed to approve or adjust graphic control measures therefore which may also lead to expedited mission planning.

These discussions suggest another implied requirement for both the UAS and VTOL. Currently, both are designed with flight control computers that perform a variety of functions. For instance, in the UAS, the flight control computer captures the waypoints from planning, designs a flight path, checks for altitude constraints, and compares routes to the Airspace Control Order (ACO) to deconflict with other air platforms. The flight control computer for the VTOL differs but supports similar functions. The above discussion, though, implies that both platforms would benefit from a mission control computer, designed to function as the brain that interprets orders, reasons on changes to the predicted situation, and uses AI or algorithms to determine next actions.

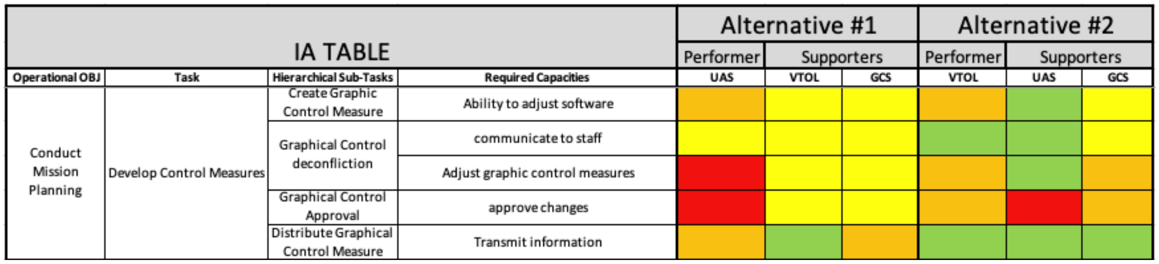


Figure 24. IA Table Depicting the "Develop Control Measures" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the "Developing Controls Measures" derived requirements are shown in Table 14.

Table 14. Develop Control Measures Requirements Based on IA Analysis

Requirements to Develop Control Measures	
1	(O)The UAS must have the capability to connect to a redundant digital network with mission planners to ensure updated mission data is transferred and understood by humans and AI with minimum delay.
2	(O) The UAS must have the capability to interpret the USMC doctrine utilized in the physical environment.
3	(D) The UAS must have the capability to overlay graphics onto the physical environment.

c. *Conduct Rehearsals*

Conducting rehearsals synchronizes all mission participants and ensures a detailed understanding of their tasks. Integrating the VTOL, UAS, and GCS into a team increases mission success while improving AI learning. Rehearsals are conducted using both analog techniques and digital simulations. For the HMT interaction in the SCAR scenario, the rehearsal is digitally based since the UAS cannot participate without a digital framework. Another consideration is to determine if all unmanned systems need a rehearsal which may potentially allow the machine to speed up learning and improve reliability.

A long-term goal is for the UAS to improve its employment of AI by participating in rehearsals. In theory, the unmanned system could learn about human behavior, and share it with other similar unmanned machines. The digital rehearsal will support improved human behavior as well. For example, the UAS might be aware of terrain features used by the enemy to deploy ground-to-air assets and notify the human on how to identify them. This creates increased human awareness and decreases cognitive load on the pilot.

IA TABLE				Alternative #1			Alternative #2		
				Performer	Supporters		Performer	Supporters	
Operational OBJ	Task	Hierarchical Sub-Tasks	Required Capacities	UAS	VTOL	GCS	VTOL	UAS	GCS
Conduct Mission Planning	Conduct Rehearsals	Individual Rehearsal	Execute rehearsal						
			Cognitive Load Checklist						
		Team Rehearsal	Coordinate with team						

Figure 25. IA Table Depicting the "Conduct Rehearsals" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for "Conduct Rehearsals" derived requirements are shown in Table 15.

Table 15. Conduct Rehearsals Requirements Based on IA Analysis

Requirements to Conduct Rehearsals	
1	(P & D) The UAS must have the capability to run an internal modeling simulation from the physical world attributes and mission plan within minutes and provide feedback of the results.
2	(O & D) The USMC must have a common operating system which the VTOL and GCS can interact with the UAS in a digital environment.
3	(D) The USMC must have the capability to direct the UAS to enter a team rehearsal mode.

2. Conduct Movement/Infiltration

a. Pre-Maintenance Checks (PMC; Pre-Flight)

In this task, HMT is occurring between the UAS and the VTOL. The UAS is required to have a high level of automation to perform the mission, therefore, the UAS is not required in the PMCs of the VTOL. However, the UAS must conduct its PMCs which requires minimal HMT. Building human trust built in the results provided by the UAS may be challenging, since high levels of risk are associated with Marine Combat Operations.

One solution maybe for the Marines to develop a redundant system to validate the status of the UAS. Implementing a redundant system may not be a requirement if a high level of trust between the UAS and human is achieved. Developing a high level of trust with the UAS's status will reduce the time and the number of Marines involved in pre-flight maintenance checks. It may also be that rehearsal and pre-mission checks might be intertwined. If a UAS satisfies the rehearsal, then the operators will be confident it is ready. During UAS PMCs, a graphical user interface (GUI) is required for the human in the machine team to validate the UAS has conducted all pre-flight checks and is prepared to execute operations. One recommendation is to integrate the GUI into the MPAAS which will provide compatibility with other systems and eliminate the need for additional software or hardware.

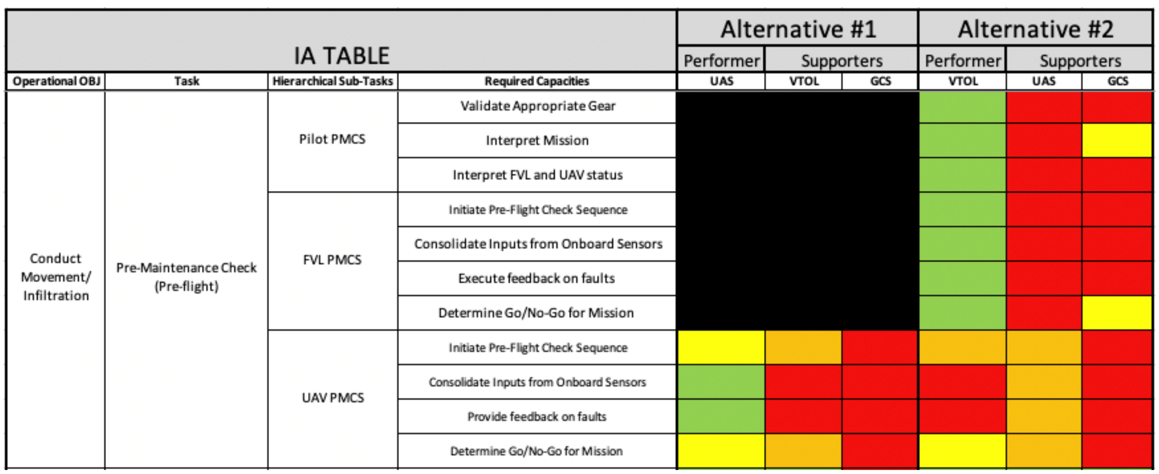


Figure 26. IA Table Depicting the "Pre-Maintenance Check" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for conducting "Pre-Maintenance Checks" derived requirements are shown in Table 16.

Table 16. Pre-Maintenance Requirements Based on IA Analysis

Requirements to Pre-Maintenance Check	
1	(P) The UAS must have the capability to understand the mission timeline and conduct PMCs during the prescribe timeline.
2	(O & P) The Marines must have a digital common operating system capable of providing updated timelines thereby allowing the UAS to autonomously conduct specific task within the required timeline and provide any feedback to challenges or opportunities.

b. Communicate to Headquarters

As the performer, the UAS has the processing power to execute all hierarchal sub-tasks when communicating to the VTOL and GCS. Degraded communications due to weather or enemy jamming capabilities is expected during any combat mission. A key requirement for communication between all systems is a redundant plan for degraded communications effecting the UAS. This requirement will be a validated PACE communications plan. Implementing a PACE plan will ensure there are at least three redundant forms of communications available between VTOL, UAS and the GCS. Future research for this IA may be required to determine alternate techniques in addition to a PACE plan in non-permissive environments.

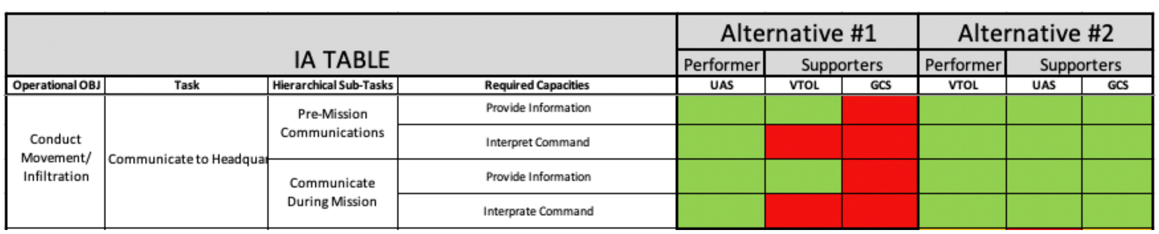


Figure 27. IA Table Depicting the "Communicate to Headquarters" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for "Communicate to Headquarters" derived requirements are shown in Table 17.

Table 17. Communicate to Headquarters Requirements Based on IA Analysis

Requirements to Communicate to Headquarters	
1	(D) The system (UAS, VTOL, & GCS) must implement a validated PACE communications plan that provides redundancy for digital communications
2	(D) The system (UAS, VTOL, & GCS) must require a digital common operating infrastructure which can transmit secure information and commands.

c. *Move to Mission Area*

Since the UAS is being moved to the mission area attached to the VTOL there are no supporting tasks. Once the UAS is powered on prior to mission launch, updates are uploaded providing renewed situational awareness for the UAS. Updates might include coordinates of NAIs, additional mission tasks or a complete change of mission. New information is automatically uploaded using the PACE plan, but both the VTOL and the GCS can input updated data into the UAS if required.

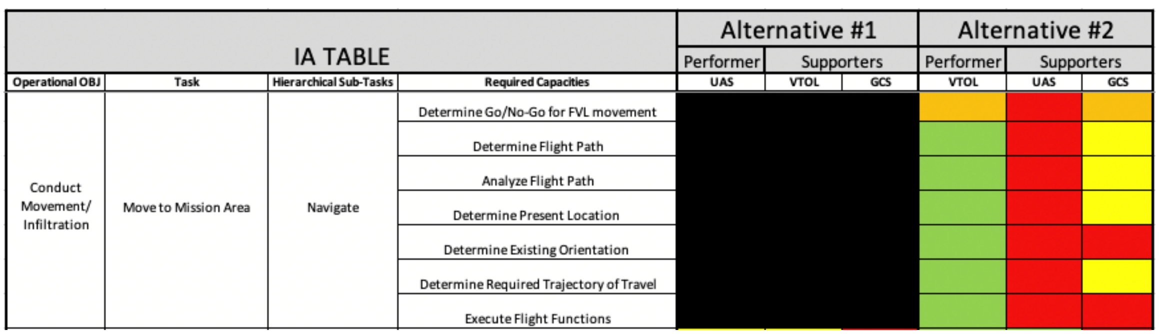


Figure 28. IA Table Depicting the "Move to Mission Area" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for "Move to Mission Area" derived requirements are shown in Table 18.

Table 18. Move to mission area Requirements Based on IA Analysis

Requirements to Move to Mission Area	
1	(D) The system (UAS, VTOL, & GCS) must implement a validated PACE communications plan that provides redundancy for digital communications
2	(D) The system (UAS, VTOL, & GCS) must require a digital common operating infrastructure which can transmit secure information and commands.

d. Deploy UAS

Once powered, the UAS conducts a functions check. Determining go/no-go criteria requires additional assistance from the VTOL since unexpected weather or changes in mission may cancel deployment of the UAS. The UAS will determine connectivity of the PACE plan and validate coordinates on its own. GPS sensors on the UAS determine coordinates and provides navigation throughout the entire mission. A back up navigation system is required to protect against enemy GPS jamming. Alternate range and location determining technologies recommended are Lidar (Light Detection and Ranging), and three Honeywell developed technologies known as Vision-Aided Navigation, Celestial-Aided Navigation and Magnetic Anomaly-Aided Navigation. Establishing communications in this task requires a functioning voice and data PACE plan.

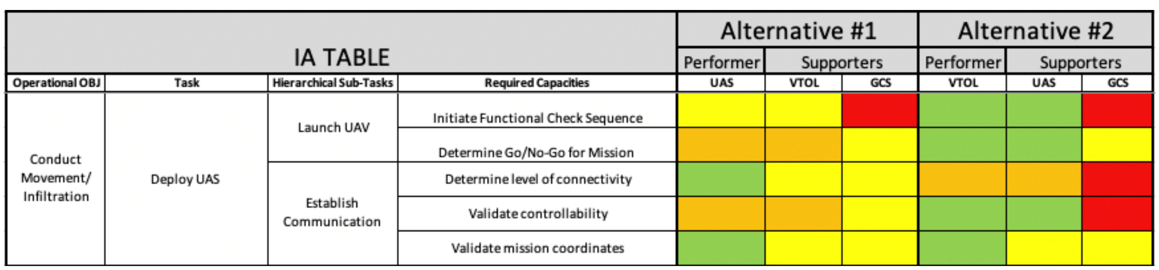


Figure 29. IA Table Depicting the "Deploy UAS" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the "Deploy UAS derived requirements are shown in Table 19.

Table 19. Deploy UAS Requirements Based on IA Analysis

Requirements to Deploy UAS	
1	(O & D) The UAS must report its status prior to its launch immediately after conducting a final functional check.
2	(O) The UAS must require redundant location sensors to protect against GPS jamming.
3	(D) The system (UAS, VTOL, & GCS) must require a digital common operating infrastructure to transmit secure information and commands.

3. Conduct Area Recon

a. Observe

The UAS is fully capable of controlling its sensor based on mission planning and the mission updates, which reduces the cognitive load on the VTOL aircrew. However, the human must observe what the UAS is looking at and direct the UAS to orient on a specific area.

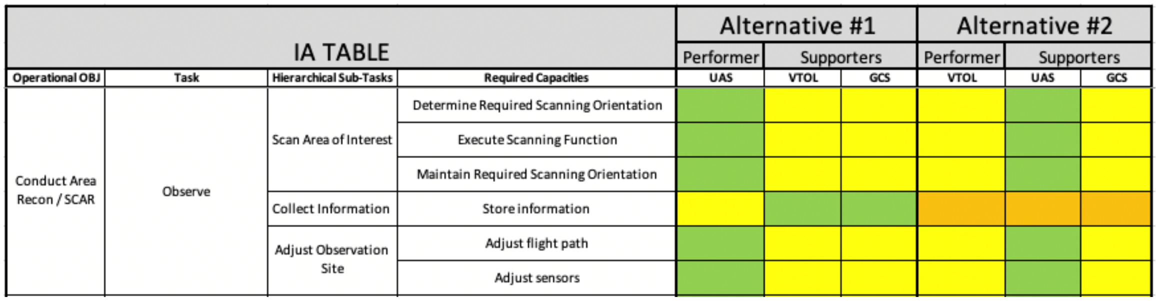
One implied requirement regarding UAS operations and the observe task is that the UAS needs to support senor processing at the edge. Many current systems merely transmit the raw sensor take to the GCS, where the actual processing takes place. This demands that the UAV possess a sizeable bandwidth throughput, necessitating, either a tactical communications data link or a satellite link. These may be untenable in a D-DIL environment. An alternative is to record all the sensor collection on board the platform, then just download it via a storage device when it returns to base. This of course, means that the UAV cannot provide real time information.

By providing adequate processing for the UAV's sensors, the useful information can be pared down to a much smaller bandwidth size (like an enhanced track), giving the UAV several options for both using the information in its mission computer to update its own situation awareness, and immediately generating useful information for the GCS and VTOL. Also, because the message size is smaller, there may be multiple communications/networking operations available via the PACE approach.

An important factor in the HMT with the UAS is the ability for the UAS to predict actions of its team and act on those actions. When the UAS observes an indicator that may lead to the positive identification of a target it must autonomously adjust itself to do what it can to confirm or deny the indicator and taking appropriate avoidance action if that target is potential threat. The UAS sending a notification to the VTOL or GCS every time an indicator is identified may cause cognitive overload for the two team members and may result in the loss of trust. The UAS must be able to autonomously adjust itself and understand the situation the VTOL or GCS is in before sending information. If the UAS identifies an indicator of a high value target list (HVTL) which may be a danger to the VTOL, the UAS must predictively understand that it needs to notify the VTOL immediately. However, if the indicator is low on the HVTL and the VTOL is conducting some other action which requires maximum cognitive use, then the UAS needs to wait before sending a notification to the VTOL and continue to adjust itself to better observe the indicator. This also highlights the need for the UAV to be able to observe the actions of the VTOL and GCS. In normal dismount teaming operations, a subordinate will wait to make a routine report to their supervisor if their supervisor is communicating with the commander. The dismount team member can observe their supervisor's action which allows the team member to predict when to communicate the actions.

It is important to note that most individuals think of interaction with UASs being limited to a monitor feed. During this phase of our IA table, we understood that sensors are not limited to visual feeds therefore the means of notifications or directability should not be limited to normal camera feeds. The USMC must investigate other means of communications such as auditory means.

Attempting to stream a constant video feed hundreds of miles back to the GCS is not feasible. Once the UAS locates an enemy target the VTOL can confirm if the target is of a low or high priority level. The VTOL can then direct the UAS on what to do next. Again, a key requirement to ensure redundancy in video transmission from the UAS to the VTOL and GCS is a validated and functioning PACE plan. Part of this plan, for instance, might mean that the UAV just sends a small file size thumbnail image of the target, instead of the full resolution image or stream.



IA TABLE				Alternative #1			Alternative #2		
				Performer	Supporters		Performer	Supporters	
Operational OBJ	Task	Hierarchical Sub-Tasks	Required Capacities	UAS	VTOL	GCS	VTOL	UAS	GCS
Conduct Area Recon / SCAR	Observe	Scan Area of Interest	Determine Required Scanning Orientation						
			Execute Scanning Function						
			Maintain Required Scanning Orientation						
		Collect Information	Store information						
		Adjust Observation Site	Adjust flight path						
			Adjust sensors						

Figure 30. IA Table Depicting the "Observe" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the "Observe" derived requirements are shown in Table 20.

Table 20. Observe Requirements Based on IA Analysis

Requirements to Observe	
1	(O) The UAS must observe the actions of the VTOL as they are occurring and assess the status of the VTOL immediately.
2	(O) The VTOL and GCS must observe the data provided from the UAS during the mission.
3	(O & P) The UAS must provide a roll up of data from the sensor if there is a communication break from the VTOL.
4	(O) The UAS must store sensor data to include video feeds for the full duration of the mission.
5	(D) The VTOL and GCS must have a visual or auditory interface to direct the UAS to change its observation behavior or specific observation.
6	(O & P) The UAS must require a suite of sensors to react to the different forms of immediate contact including direct (kinetic projectile), indirect, NBC, obstacles, visual, and electronic.

b. Assess

It is assumed that the UAS has the capability to identify targets (computer vision systems that do this already exist in the DOD), determine target location, analyze targets, and maintain situation awareness throughout the entire mission. Over time, the UAS utilizes AI learning to enhance the database of enemy weapons and equipment (the G2 element would build and curate the original dataset). Using the knowledge gained, the UAS improves the efficiency and effectiveness for assessing targets and shares it with the VTOL pilots. A challenge for the USMC will be developing an interface used by VTOL pilots and the GCS. A requirement for the interface must be to bridge the human-machine team through trust. As an example, the interface in the VTOL will receive an update from the UAS with course of action recommendations for an identified target. This interfaces between the human and the machine must be executed rapidly to avoid increasing the aircrew's cognitive load.

Developing an efficient interface will require rigorous testing and training between VTOL pilots and the UAS using simulations. Testing in a simulation's environment will develop and enhance trust between humans and machines. Through training over time, the Marine will learn to recognize incorrect or illogical recommendations being made by the UAS and vice versa. The interface developed must support trust, provide rapid feedback, and be simple to operate. Together with a common digital mission planning system and interface training in a simulated environment with pilots and UAV, improved collaboration between humans and machines can be achieved.

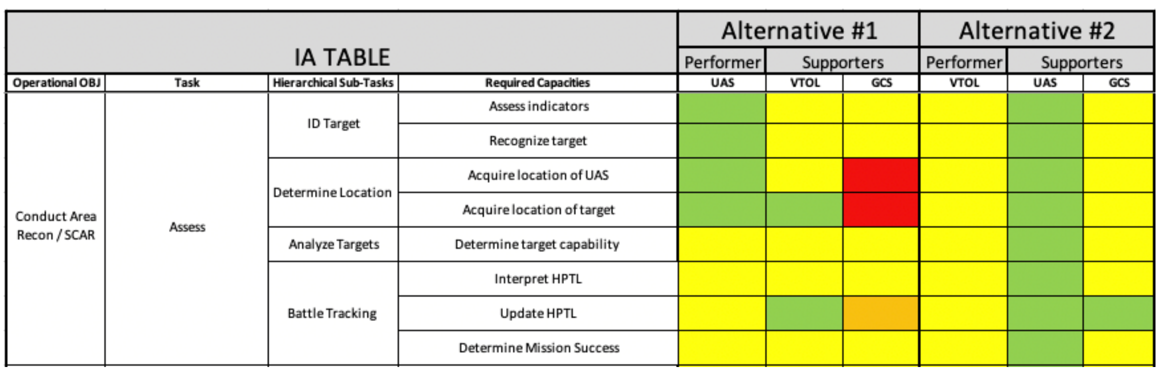


Figure 31. IA Table Depicting the "Assess" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the "Assess" derived requirements are shown in Table 21.

Table 21. Assess Requirements Based on IA Analysis

Requirements to Assess	
1	(P) The UAS must have the capability to identify friendly, neutral, enemy, and natural items immediately with a limited number of indicators.
2	(O) An interface for the VTOL and GCS must be developed so the UAS can provide information which can improve the efficiency of assessing targets while reducing the cognitive load on the human.

c. Report

Timely and accurate reporting is a core tenet of reconnaissance missions; however, new standard operating procedures may need to be developed when teaming with the UAS. For the UAS, we assume it provides a continuous stream of data, however, creating and sending concise reports at the appropriate time in the correct format can be challenging. During the mission planning phase, the UAS receives direction on the type of reports that will be submitted and frequency they are reported. However, humans may want to access the UAS data at any point in the mission, emphasizing the importance of storing information that was shown in Figure 25. It may be unfeasible to access the UAS data continuously during the mission due to bandwidth degradation, therefore, the VTOL and GCS needs the capability to download data from the UAS and review the information.

Throughout the reporting task we see the UAS is capable of interpreting information, however, the team must have active input into determining the accuracy of the report before being confirmed. This will increase report accuracy and expand the learning between human and machine. For example, the UAS may report that it sees two unknown trucks but the pilots in the VTOL may identify the truck as friendly civilian vehicles. The VTOL and GCS must have the capability to update the UAS report before the report moves further up the chain of command.

IA TABLE				Alternative #1			Alternative #2		
				Performer	Supporters		Performer	Supporters	
Operational OBJ	Task	Hierarchical Sub-Tasks	Required Capacities	UAS	VTOL	GCS	VTOL	UAS	GCS
Conduct Area Recon / SCAR	Report	Provide Recommendations	Interpret environment	Yellow	Yellow	Yellow	Yellow	Green	Yellow
			Interpret Mission	Yellow	Yellow	Yellow	Yellow	Green	Yellow
			Interpret situation	Yellow	Yellow	Yellow	Yellow	Green	Yellow
			Interpret METT-TC	Yellow	Yellow	Yellow	Yellow	Green	Yellow
			Determine time to communicate information	Yellow	Green	Green	Yellow	Green	Green
			Send data	Yellow	Green	Red	Yellow	Green	Red

Figure 32. IA Table Depicting the "Report" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the "Report" derived requirements are shown in Table 22.

Table 22. Report Requirements Based on IA Analysis

Requirements to Report	
1	(O) The UAS must provide consolidate reports including sensor data prescribed on the timeline outlined during the mission planning.
2	(D & P) The UAS must notify the humans when a report timeline is not inputted into the mission plan prior to mission take-off.
3	(O) The system must have a digital or auditory reporting format that is understood by humans and machines immediately.
4	(O & D) The Marines must have a natural language processing system that can interpret auditory reports and convert it to a means the UAS can understand.
5	(O & D) The VTOL and GCS must edit the reports received from the UAS prior to submitting reports to a higher chain of command.

d. Destroy

The scenario assumes that the UAS is restricted in its capability to destroy a target by itself therefore, it requires human-in-the-loop interaction with the VTOL (or GCS). We also assumed that the VTOL will be the ultimate deciding factor in our scenario with the GCS assisting the VTOL on whether a weapon system should be deployed or not. Finally, in our scenario the UAS has no weapon systems, however, the VTOL can deploy air-to-ground ordnance.

For HMT interaction, the USMC must create policies and procedures addressing autonomous lethal decision-making capabilities. In our scenario, the UAS has the capability to request a fire mission on a particular target. To offload cognitive work, we suggest the UAS recommends the weapon system to be used. The UAS can observe the VTOLs current weapon systems and other assets available in the AO. This will reduce the time to destroy the target.

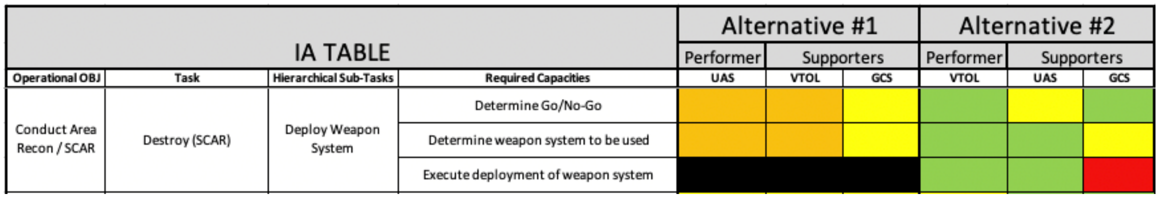


Figure 33. IA Table Depicting the "Destroy" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the "Destroy" derived requirements are shown in Table 23.

Table 23. Destroy Requirements Based on IA Analysis

Requirements to Destroy	
1	(D) The USMC must create policy and procedures addressing autonomous lethal decision-making capabilities before the use of the autonomous UAS.
2	(O) The UAS must have the capability to observe the status of the weapon systems and current actions of the VTOL.
3	(O & P) The UAS must have the capability to determine appropriate weapon system to be used against a specific target immediately after the assessment of the target.
4	(O) The UAS must have the capability to operate with all militaries guided munitions thereby allowing it to act as a forward observer.

e. Self-Defense

Using a UAS in military operations provides the opportunity to reduce the risk of losing human life. However, in our human machine teaming scenario we want to ensure high survivability of both human and machine. The UAS, as often the most appropriate sensor for the mission, requires the capability to sense all forms of contact and react in a way the rest of the team could predict. Rehearsals between the UAS and VTOL increase predictability within our system. For example, during rehearsals, the two team members can rehearse actions to take if electronic warfare (EW) takes place. When the action occurs during the mission, both team members should act as they did during the rehearsal.

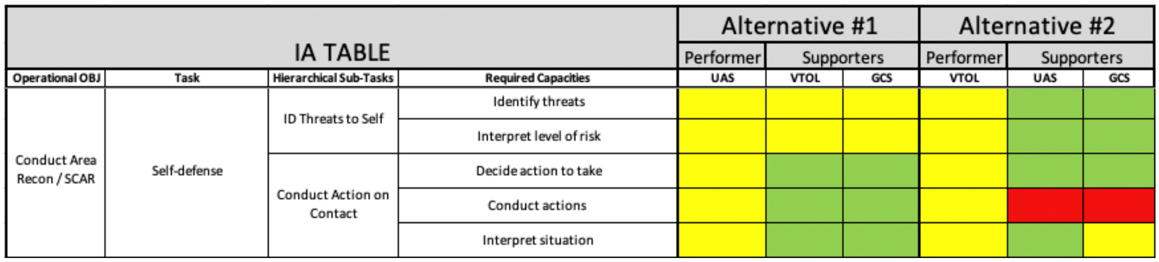


Figure 34. IA Table Depicting the "Self-Defense" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the "Self-Defense" derived requirements are shown in Table 24.

Table 24. Self-Defense Requirements Based on IA Analysis

Requirements for Self-Defense	
1	(O) The UAS sensors must identify the eight forms of contact and notify its system immediately.
2	(P) The UAS must react to contact as based on USMC doctrine and approved TTPs.

4. Conduct Recon Handover

a. Communicate with Headquarters

Communicating with headquarters requires constant communications between all systems to execute a recon handover. Specifically, the UAS must have communications with both the VTOL and GCS. To accomplish this, a PACE communications plan is implemented and ensures several redundant communications platforms are available.

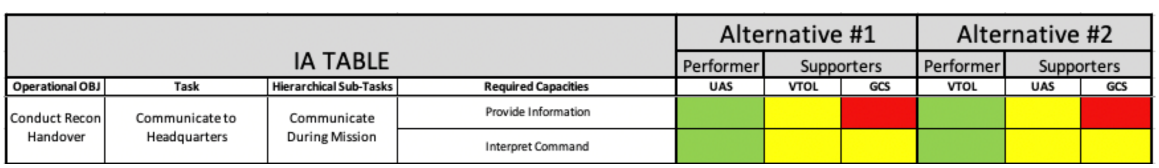


Figure 35. IA Table Depicting the "Communicate to Headquarters" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

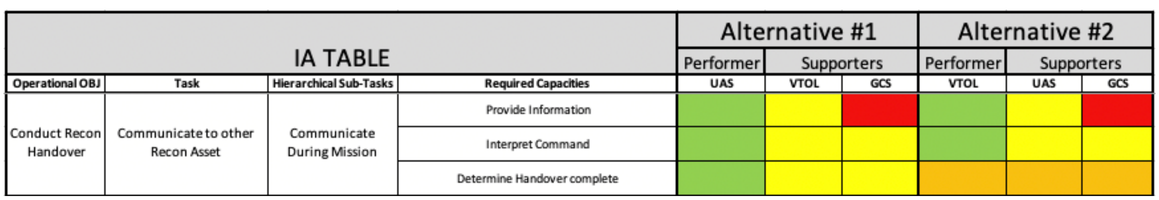
Interdependence analysis for "Communicate to Headquarters" derived requirements are shown in Table 25.

Table 25. Communicate to Headquarters Requirements Based on IA Analysis

Requirements to Communicate to Headquarters	
1	(D) The system (UAS, VTOL, & GCS) must implement a validated PACE communications plan that provides redundancy for digital communications
2	(D) The system (UAS, VTOL, & GCS) must require a digital common operating infrastructure which can transmit secure information and commands
3	(O & D) The USMC must have a natural language processing system that can interpret auditory reports and convert it to a means the UAS can understand.

b. Communicate with Recon Assets

Secure communications protocols and a validated PACE plan are requirements for communicating with recon assets. Bad actors and enemy combatants will conduct EW operations against the UAS, VTOL, GCS, and Marine ground units. A PACE plan will provide alternate forms of communications if degradation or a complete loss of communications occurs.



IA TABLE				Alternative #1			Alternative #2		
				Performer	Supporters		Performer	Supporters	
Operational OBJ	Task	Hierarchical Sub-Tasks	Required Capacities	UAS	VTOL	GCS	VTOL	UAS	GCS
Conduct Recon Handover	Communicate to other Recon Asset	Communicate During Mission	Provide Information						
			Interpret Command						
			Determine Handover complete						

Figure 36. IA Table Depicting the "Communicate to Other Recon Assets" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for "Communicate to other Recon Asset" derived requirements are shown in Table 26.

Table 26. Communicate to Other Recon Assets Requirements Based on IA Analysis

Requirements to Communicate to Other Recon Assets	
1	(D) The USMC must create a protocol to grant authority over the UAS which has secure directability.
2	(D) The system (UAS, VTOL, & GCS) must implement a validated PACE communications plan that provides redundancy for digital communications.

c. *Move to Base*

When conducting movement back to base, the UAS can determine its orientation and flight plan. A key predictability requirement is that the GCS and UAV ought to be able to view the UAV's proposed route. The GCS observes the location, flight data, and heading of the UAS. If the communications link is broken or degraded the PACE plan will be utilized. The PACE plan ensures redundant communications are available between the GCS and UAS. Using the VTOL to execute flight functions is not recommended since it increases cognitive load on the pilots. The VTOL must have the option of controlling the UAS which requires future work in coactive design. If an emergency with the UAS occurs pre-established procedures will be executed. UAS emergency procedures are those that the system has learned over time and is a part of its AI. If the UAS fails to execute the correct procedures the GCS and VTOL can take over and direct the UAS.

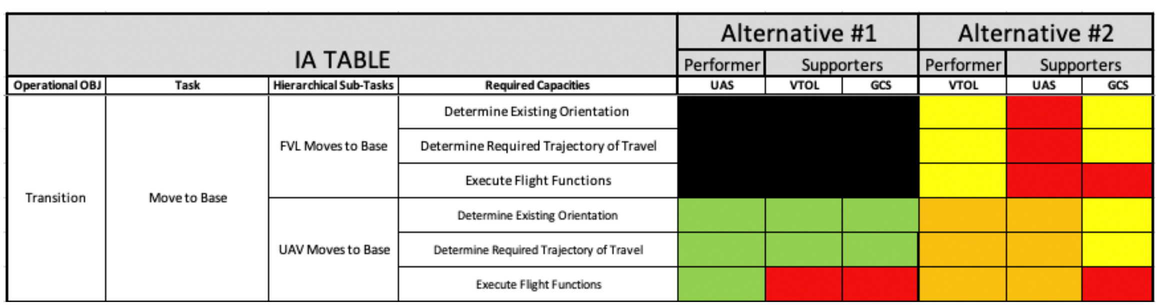


Figure 37. IA Table Depicting the "Move to Base" Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for "Move to Base" derived requirements are shown in Table 27.

Table 27. Move to Base Requirements Based on IA Analysis

Requirements to Move to Base	
1	(O) The UAS must have the capability to report its location if its unable to return to base.
2	(D) The UAS must have the capability to navigate by itself in any mild inclement weather conditions or cyber conflicted areas.
3	(D) The UAS must have an energy source which will allow it to move back to base after a mission.

d. Post Mission

During the post mission task, a digital debrief occurs. A digital debrief consists of downloading all pertinent data collected during the mission by both the UAS and the VTOL. Data collected includes atmospheric conditions, flight performance, flight condition, enemy analysis, any data inputs by the VTOL, and UAS video feeds. A separate pilot debrief will also occur with VTOL pilots as part of the post mission task. Data collected from the pilots, VTOL and UAS will be uploaded into a database and will improve AI learning for the UAS in future missions.

IA TABLE				Alternative #1			Alternative #2		
				Performer	Supporters		Performer	Supporters	
Operational OBJ	Task	Hierarchical Sub-Tasks	Required Capacities	UAS	VTOL	GCS	VTOL	UAS	GCS
Transition	Post Mission	Analyze	Debrief						
			AI learning						

Figure 38. IA Table Depicting the “Post Mission” Task, Hierarchal Sub-Tasks, Required Capacities, Performers and Two Alternatives

Interdependence analysis for the “Post Mission” derived requirements are shown in Table 28.

Table 28. Post Mission Requirements Based on IA Analysis

Requirements for Post Mission	
1	(O) The UAS must have the capability to connect to a redundant digital network with mission planners to ensure updated mission data is transferred and understood by humans and AI instantaneously.

Requirements for Post Mission	
2	(P) The USMC must consolidate best practices and lessons learned from the mission transmitted throughout the UAS cloud infrastructure immediately after conclusion of the Post Mission requirement.
3	(O & P) The UAS must have the ability to provide a way to communicate why it conducted the actions during the missions with humans during post mission analysis.

C. OPERATIONAL VIEWPOINT-5B: CONDUCT AREA RECON OPERATIONAL ACTIVITY MODEL

In Figure 39, the OV-5b depicts the operational activities and capabilities of the VTOL, UAS, and GCS within the function, Conduct Area Recon. The figure displays the HMT interactions occurring between each activity. In the first activity, the VTOL/UAS begin to observe the mission environment. The UAS exhibits predictability by continuously scanning until making contact while also providing observability by transmitting imagery and data to the VTOL and GCS throughout the mission. Once contact is made, the UAS provides predictability by assessing the threat and sending a contact report to the VTOL and GCS for improved observability. The VTOL assesses the report, improving reliability in determining the contact as enemy, friendly, or neutral.

If the UAS receives direction from the VTOL and the actor is identified as a threat the UAS reaches a decision point to execute self-defense. If no threat is detected or the positive assessment is overridden by the VTOL, the UAS consolidates its identification report and continues scanning. The VTOL can provide input into the UAS's threat assessment and direct the UAS to take specific action combining all three factors of HMT. If the threat assessment is confirmed, the UAS provides directability by initiating its targeting functions and sends a COA recommendation to the VTOL. Concurrently, the UAS is maintaining observability of the NAI and identified target by providing information to the VTOL. A final decision to destroy the target is made by the VTOL. Once the VTOL engages and destroys the target, a consolidated BDA report is generated. The consolidated BDA report includes data provided by the additional observability of the UAS. Following a successful engagement or targeting action, a final report is consolidated for the mission.

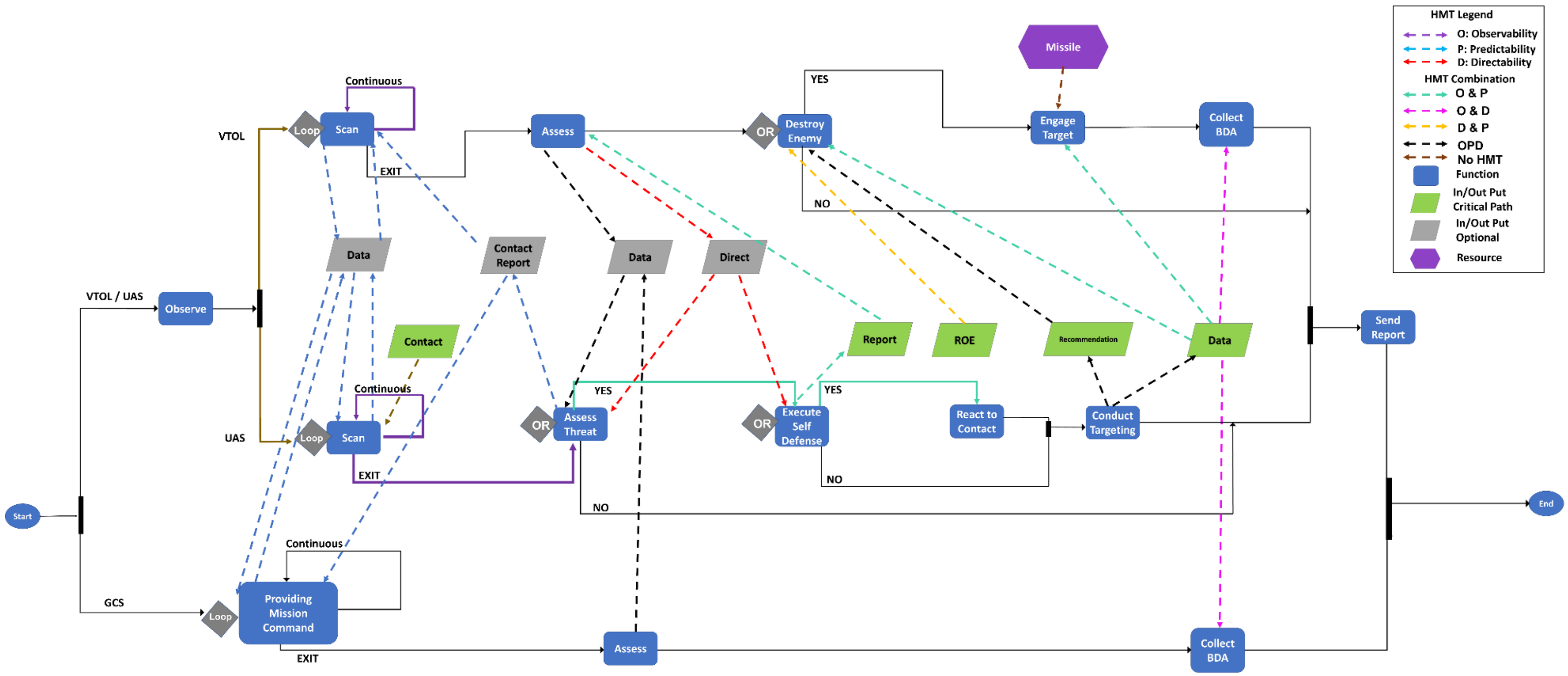


Figure 39. Conduct Area Recon OV-5b

D. CHAPTER SUMMARY

The IA conducted in this chapter generated requirements between the VTOL, UAS, and GCS for the USMC. First, there is a requirement for a robust digital mission planning system like an upgraded MPAAS that facilitates machine learning by storing data from previous missions and lessons learned. Second, the USMC will face challenges in processing power and storage of information on the UAS. All efforts should be made to add to the processing power of the UAS. Third, a validated PACE plan must be implemented to ensure redundancy across all communication platforms between the UAS, VTOL, and GCS. Lastly, the USMC must implement interfaces that supports trust, provides rapid feedback, and are simple to operate.

V. EXPLORATORY EXPERIMENT WITH LIVING LAB

As reported above in the previous chapters, the HMT of the future involves a VTOL crew, GCS, and an autonomous UAS integrated to complete a mission. To explore factors and evaluate designs to facilitate this integration, research team incorporated the Living Lab and specifically adapted a flight simulator to allow human pilots to fly with a virtual autonomous UAS. The Living Lab consists of three features that must work together to provide an environment for human participants to operate their simulated aircraft with an autonomous UAS: hardware/software, flight scenarios, and measurements.

A. DESIGN

The design of the experiment is a two-group comparison design with one group controlling the UAS and the other group conducting HMT with the UAS. The hypotheses test: There is no significant advantage between Marine VTOL pilots completely controlling a UAS (μC) and Marine VTOL pilots that conduct human-machine teaming (μHMT) in a hybrid warfare environment.

$$Ho: \mu C = \mu HMT$$

$$Ha: \mu c \neq \mu HMT$$

Control group (teleoperated, Ho): The UAS in the experiment is fully controlled by the VTOL operator with GCS oversight. The VTOL operator must build a digital mission plan with dedicated waypoints within the area of operation. The VTOL operator must select what waypoints the UAS will move to throughout the mission.

Experimental group (HMT, Ha): The UAS in the teaming group will have the same digital pre-planned mission flight path utilizing X waypoints, but the UAS is fully autonomous and can now provide recommendations to the VTOL operator and GCS to allow for an updated flight path to be executed based on the observations. The VTOL communicates with both the UAS and GCS in the scenario and can use the UAS sensors to enable HMT. The UAS can execute a change in its flight path once its recommendation is approved by the VTOL operator.

B. PARTICIPANTS AND LOCATION

The target population of future VTOL/ UAS HMT systems are Marine Helicopter Pilots operating as a crew. To meet this demographic, those conducting the experiment would need to seek Active/Reserve Marine Helicopter Pilots. However, to assess the feasibility of the experiment, the researchers may utilize officer students at the Naval Postgraduate School (NPS) who have a background in Cavalry Operations, Targeting, and are comfortable with current video game technology. The experiment will require two groups of 40, with 20 in the control group and 20 in the HMT group. Each group will be broken down as a two-person crew to allow for 10 iterations on both the control and HMT groups.

The feasibility test of the experiment shall take place in the NPS MOVES Institute which is depicted below in Figure 40. The MOVES Institute is defined by NPS as an "interdisciplinary research and academic program dedicated to education and research in all areas of defense modeling and simulation" (Naval Postgraduate School [NPS] 2022). The MOVES Institute excels in 3D visual simulation, networked virtual environments, computer-generated autonomy and computational cognition, human performance engineering, combat modeling and analysis, and unconventional modeling (NPS 2022). The participants shall utilize the MOVES Institute simulation capabilities to execute the "Mission" within a virtual environment which matches conditions depicted in the research concept of operations, see Figure 41.

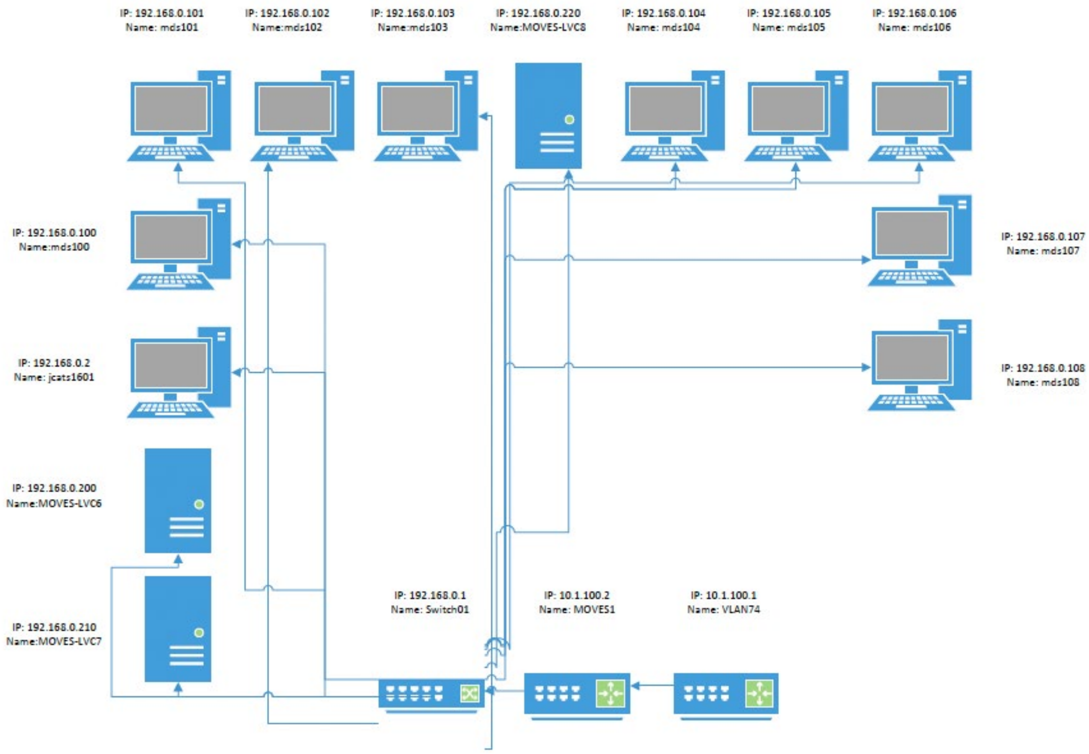


Figure 40. MOVES Lab Overlay. Source: NPS MOVES Lab (2022).

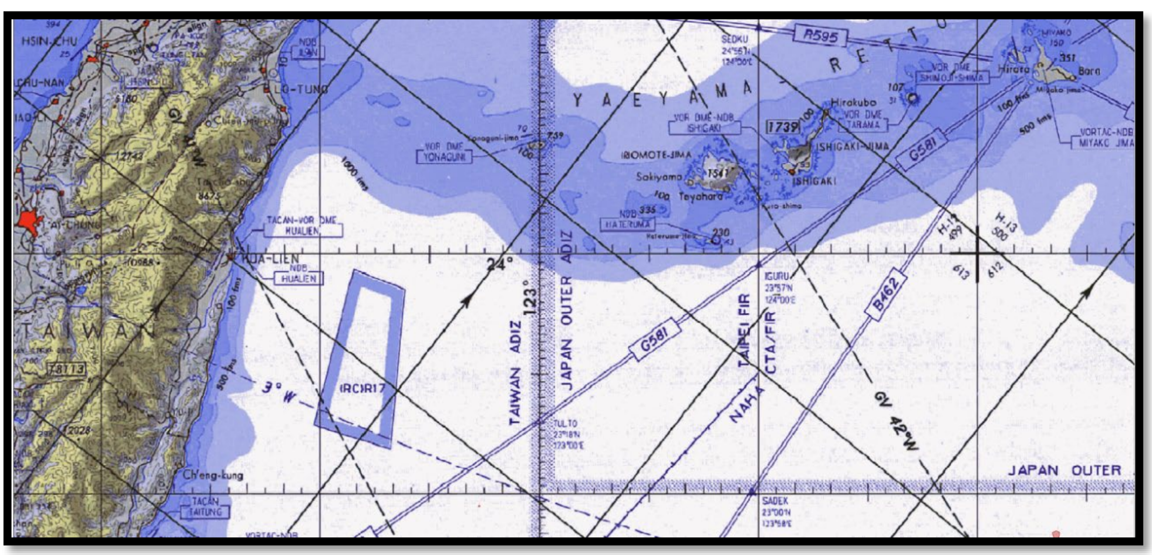


Figure 41. Virtual Environment South China Sea. Source: NPS MOVES Lab (2022)

C. MATERIALS

1. Participants Site

The following equipment set may be used to create the participant's site:

- Two Alienware Computers
- 1 large screen monitor
- 3 computer monitors
- AH-64E Modernization Lab (MODLAB)
- 2 x Oculus Headsets and controllers

Figure 42 shows the participants' site in the MOVES Lab. The station on the left is used by the pilot. The Pilot can use the Oculus headset or the two screens at their station. The Pilot will use the microphone to communicate the GCS (white cell). The pilot shall be equipped with a helicopter simulation controller. The co-pilot station is on the right. The co-pilot can use the Oculus headset or the two screens at their station. One of the screens at the co-pilot station will display the UAS feed and is used to direct the UAS. The co-pilot shall use the microphone to communicate with the GCS (white cell).

Figure 42. Pilot and Co-Pilot Station. Source: NPS MOVES Lab (2022).

Each team that executes the scenario is required to submit the SPOT Report seen in Figure 43.

SPOT REPORT/SALUTE	
LINE	ITEM
1	Size
2	Activity
3	Location
4	Unit/Uniform
5	Time observed
6	Equipment

Figure 43. SPOT Report/SALUTE. Source: DA (2021).

2. GCS Site (White Cell)

The research rep controls the scenario and executes CAS or other VTOL request during the mission to provide effects.

The following equipment is at the GCS site.

- Two Alienware M51 Laptop Computers
- 1 large monitor
- 2 computer screens
- 2 keyboards
- 2 mouses

Figure 44 shows the participants' site in the MOVES Lab. The Large screen gives the GCS (white cell) and other researchers a view of the actions occurring in the simulation. The screen on the left controlled by the keyboard and mouse allows the GCS (white cell) to control assets in the game, including OPFOR and friendly assets. The screen on the right controlled by the keyboard and mouse allows the GCS (white cell) to view data in real time.

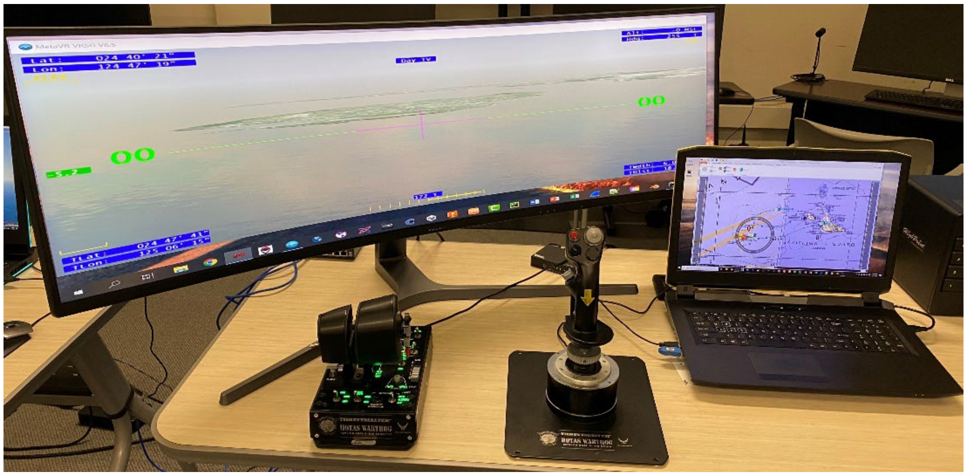


Figure 44. GCS (White Cell) Control Station. Source: NPS MOVES Lab (2022).

D. PROCEDURES

The expected number of 40 participants are divided into two equal groups and their participants numbers are randomly assigned to either Group A (μC) or Group B (μHMT). They are given selected times to report to the MOVES Laboratory located at the Naval Postgraduate School. Upon arrival, they are given the initial consent briefing and form. The participants are briefed and given their scenario.

> Like gaming systems, the scenario development focused on blending the narrative, graphical elements, and physics of the simulation to create an immersive experience for participants. The goal of this experiment is to replicate future operations in autonomous flight to a level where participants are highly engaged and motivated to succeed with the virtual autonomous UASs (Tossell et al. 2020, 249).

See Figure 45 for scenario summary.

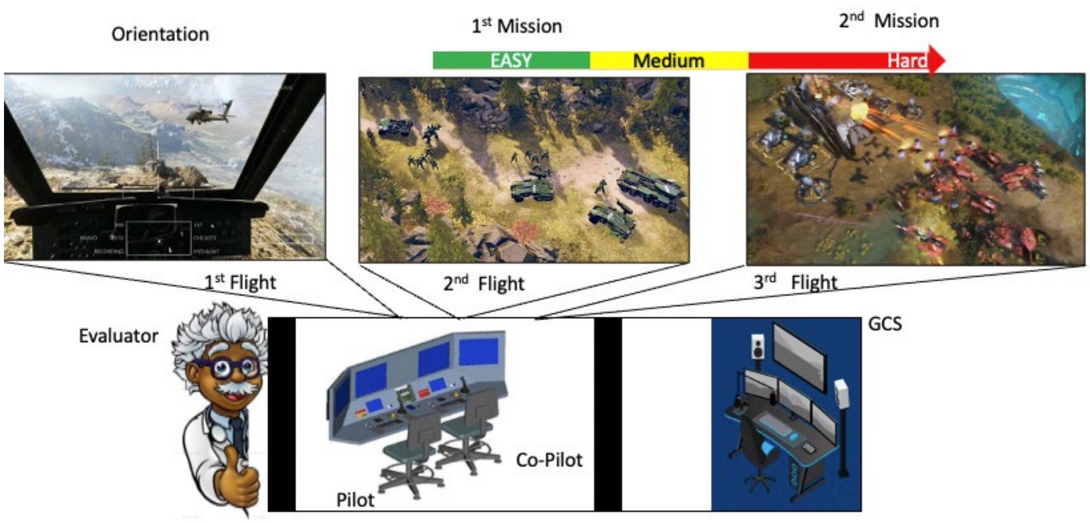


Figure 45. Scenario and Location Summary. Source: Carey 2021

> The pre-mission brief establishes the importance of the mission and how participants can do well. Our study will not include any real incentives for performing well in our scenarios. However, attempts can be made to increase motivation through artificial incentives (e.g., to succeed in this mission, all enemy must be destroyed without losing any assets) (Tossell et al. 2020, 250).

We will rely on our military participants competitiveness in these activities to measure the benefits of HMT.

> Following the pre-brief, participants fly in three different scenarios: first, a familiarization scenario, followed by two operational scenarios. The familiarization scenario introduces the participants to the information streams of the three screens and guides them through using each of the flight controls (Tossell et al. 2020, 250).

In addition, the participants perform radio calls and learn how to engage their autonomous UAS based off the objectives of the study. For example, future studies may assess the different ways to communicate with the autonomous UAS using supervisory control methods.

"With inputs from SMEs (i.e., experienced Marine helicopter pilots), we have developed a range of scenarios at different levels of difficulty and workload to assess different ways participants trust, communicate, and team with autonomous" UAS (Tossell et al. 2020, 250). One scenario requires participants to conduct a SCAR mission to an NAI with multiple enemy anti-air capabilities that must be destroyed. The participant will use a level 4 autonomous UAS to conduct the mission. The participant can engage each of the enemy anti-air vehicles (and likely fail) or rely on the autonomous UAS to assist.

> Workload and difficulty levels are increased systematically by introducing anti-air threats and/or increasing radio traffic. When anti-air enemy are introduced, participants must multitask with their autonomous UAS to neutralize the threat in addition to reporting enemies on the ground with a limited number of missiles and other fires (Tossell et al. 2020, 250).

After the final mission, the participants answer a 24-question online survey (see Appendix D). To transition to the survey, the display screen will collapse, and the survey would be started on the monitor. The researchers would enter the participant's number and group into the survey. The participant would then begin on the instructions page shown in Table 32 of Appendix D. The conclusion of the survey would end the experiment.

E. MEASUREMENTS

The overall objective of the experiment is to determine the effectiveness of the HMT requirements and survivability between a VTOL and UAS during hybrid operations while executing a SCAR mission. Through our IA analysis we determined that the following five functions are required to determine HMT effectiveness: observability, targeting, survivability, mobility, and cognitive overload. Table 29 converts these functional requirements into research questions which will form the basis of measurement. Next, utilizing a dendritic approach the research team developed critical operational issues (COI), measures of effectiveness (MoE), measures of performance (MoP), and data requirements (DR). Appendix E has the experiment operational data requirements in outline format. Through the simulation, researchers will capture data requirements through the software information collector and human factor sensors.

Table 29, Factors and Research Questions connect the research questions to the key factors for the experiment.

Table 29. Factors and Research Questions

Factors	Research Questions
Observability	What is the accuracy of HMT observability during hybrid operations?
Targeting	Will the HMT team effectively execute targeting in a maritime combat environment?
Survivability	Will the HMT team be detected by the enemy during a hybrid operation?
Mobility	Is the HMT team capable of traveling in all weather conditions for hybrid operations (speed and obstacles)?
Cognitive Overload	How does the increase cognitive overload affect the VTOL pilot in the control versus the experimental group or does HMT reduce cognitive overload for the VTOL pilot in the control group versus the experimental group?

Figure 46, the Dendritic Overview, utilizes the process of analyzing and separating issues into lower and more explicit sub-issues and continues until they have reached their lowest levels. This figure is used to trace each of the COIs to the experimental objectives. We will continue to reduce the issues until we are able to have our question answered using a numeric response or yes/no answer in the following figures.

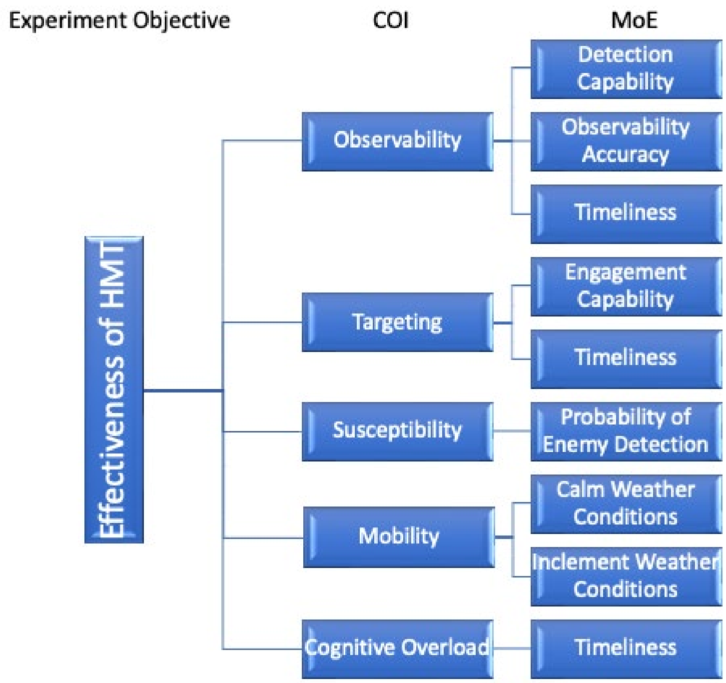


Figure 46. Dendritic Overview

Figure 47, Observability Critical Operational Issue Dendritic Chart, reaches the lowest level of sub-issues which are data requirements needed to answer the accuracy of HMT observability during hybrid operations. Each of the data points can be captured using the software the participants will use in the living lab. The GCS (white cell) at the end of each experiment shall consolidate the information onto the research team's main database.

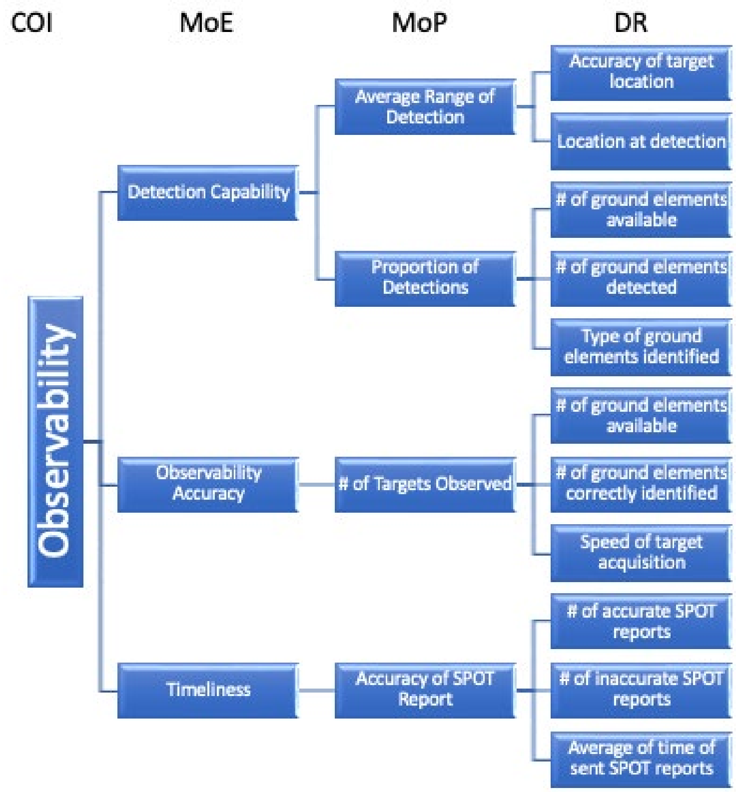


Figure 47. Observability Critical Operational Issue Dendritic Chart

Figure 48, Targeting Critical Operational Issue Dendritic Chart, reaches the lowest level of sub-issues which are data requirements needed to answer whether the HMT is effective in executing targeting in a maritime combat environment. Each of the data points can be captured using the software the participants will use in the living lab. The GCS (white cell) at the end of each experiment shall consolidate the information onto the research team's main database.

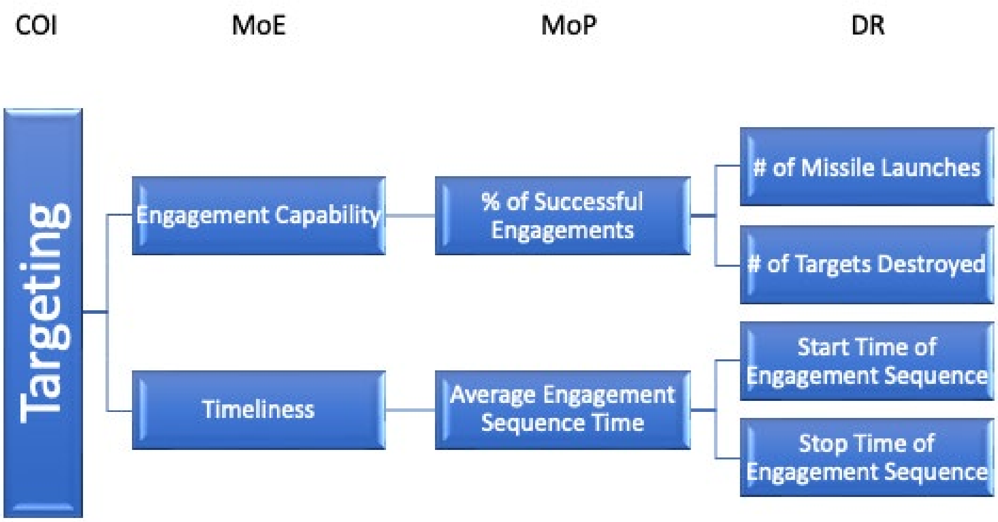


Figure 48. Targeting Critical Operational Issue Dendritic Chart

Figure 49, Susceptibility Critical Operational Issue Dendritic Chart, reaches the lowest level of sub-issues which are data requirements needed to answer whether the HMT is susceptible to detection by the enemy during a hybrid operation. Each of the data points can be captured using the software the participants will use in the living lab. The GCS (white cell) at the end of each experiment shall consolidate the information onto the research team's main database.

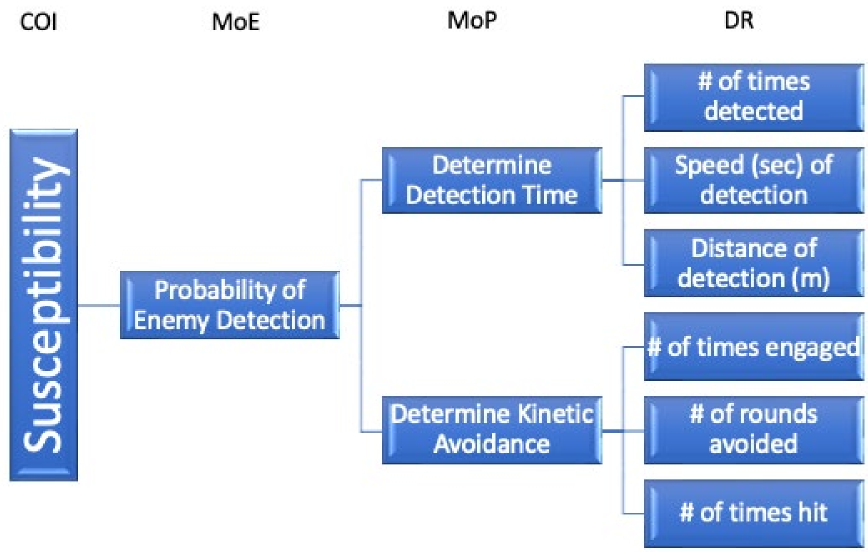


Figure 49. Susceptibility Critical Operational Issue Dendritic Chart

Figure 50, Mobility Critical Operational Issue Dendritic Chart, reaches the lowest level of sub-issues which are data requirements needed to answer whether the HMT can travel in all required weather conditions for hybrid operations. Each of the data points can be captured using the software the participants will use in the living lab. The GCS (white cell) at the end of each experiment shall consolidate the information onto the research team's main database.

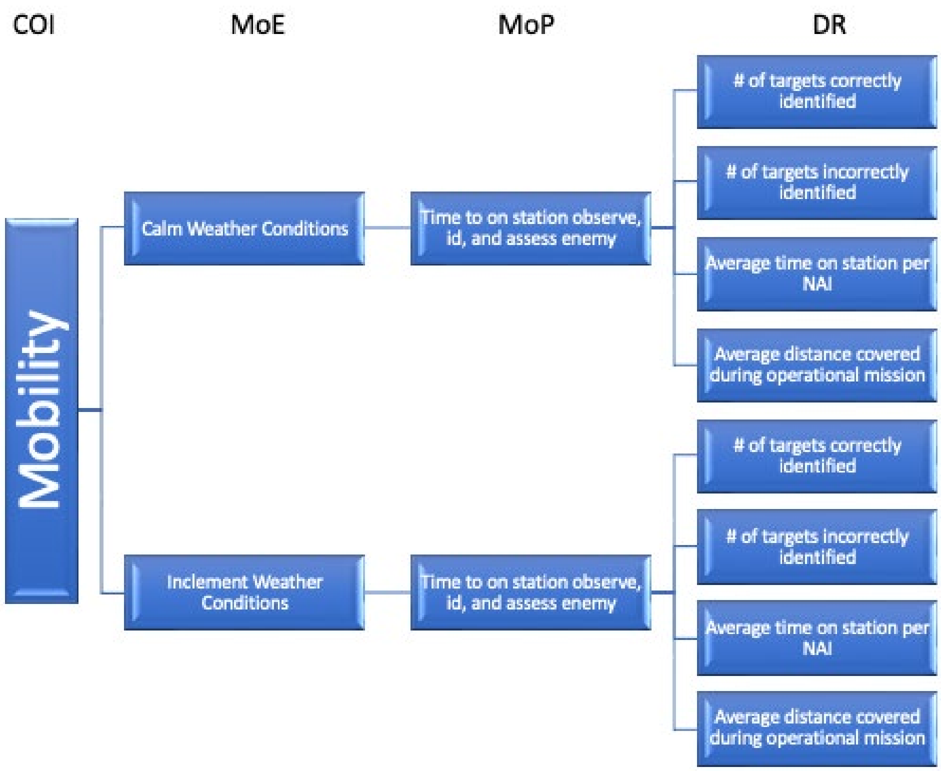


Figure 50. Mobility Critical Operational Issue Dendritic Chart

Figure 51, Cognitive Overload Critical Operational Issue Dendritic Chart, reaches the lowest level of sub-issues which are data requirements needed to answer whether the increased cognitive overload will affect the VTOL pilot in the control versus the experimental group, or does HMT reduce cognitive overload for the VTOL pilot in the control group versus the experimental group. Unlike the other data requirements, the human factors require additional data collection tools outside of the software being used. These collections tools may include heart rate monitor, telemetry, eye tracker, EcG, EEF, GSR, and post questionnaire. The GCS (white cell) at the end of each experiment shall consolidate the information onto the research team's main database.

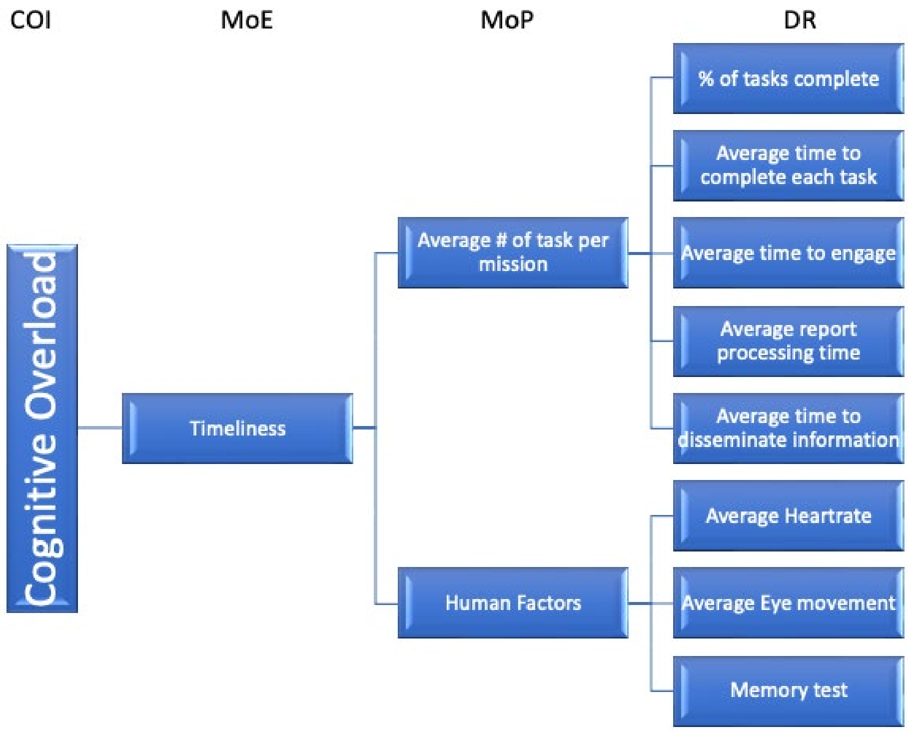


Figure 51. Cognitive Critical Operational Issue Dendritic Chart

F. CONCLUSION

Future NPS researchers can utilize the experiment outlined in this chapter to determine the effectiveness of HMT in a maritime combat environment. NPS has the simulation tools and capabilities that can measure the level effectiveness for four of the five critical operational issues inside the Living Lab. Other institutions at NPS, such as the Human System Integration Department, possess the required additional tools to measure the cognitive overload in this experiment. Continuous iterations and refinement of the experiment should provide NPS researchers and the USMC with relevant and realistic operational case studies that can be used for future research and operational applications.

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VI. CONCLUSION AND RECOMMENDATIONS

This capstone report aimed to decompose and describe an HMT concept and framework between human operators and UAS' utilizing Coactive Design and IA with the goal of constructing a USMC SCAR mission experiment. By combining the Coactive Design process with the use of systems analysis and MBSE, the research team discovered multiple complex human-machine interdependencies that require significant cognizant input when a human operator is the primary performer. The research also discovered via the IA that the future HMT concept and operational complexity of partnering human operators with machine systems will require substantial analysis and experimentation to understand the strengths and vulnerabilities that exist within an HMT system and operational concept. This chapter summarizes the research and results, provides recommendations for the SCAR mission HMT concept, and identifies areas for future work.

A. SUMMARY OF RESULTS

This research supports the credibility and applicability of combining the systems engineering framework and Coactive Design process to decompose and visualize high-level system requirements while also establishing interdependencies between humans and machines. This combination enabled the exploration of HMT interdependencies with direct traceability to high-level system requirements.

This research applied the IA process via Coactive Design to understand and visualize the HMT interdependencies across the USMC SCAR mission construct and depict areas that require machine assistance to human operators in support of observability, predictability, and directability. This analysis provided the foundation to understand and analyze the primary performer and supporting team member in the execution of a SCAR mission. The Master IA Table in Table 30 of Appendix B demonstrates the detailed analysis required to understand the complexity of human-machine teams and supports the criticality of relevant and realistic assumptions as the underpinning of relationship decomposition within the IA table.

The SCAR mission tasks that can be performed by human performers with and without assistance of machine systems are shown in Table 30. One key takeaway is the assumption that machine systems will possess Level 4 automation as shown in Table 6. This assumption was critical to ensure the HMT concept was adequate to support HMT trust, VTOL cognitive overload concerns, and real-time critical mission decision-making processes.

The results of the IA and development of the experiment demonstrate the applicability and feasibility of utilizing coactive design to better understand the observability, predictability, and directability requirements for an HMT system within the systems engineering framework. Through MBSE, the intricate coordination and collaboration of a HMT system consisting of a VTOL, GCS, and UAS will require extensive IA and experimentation to support USMC future developments in HMT systems.

B. RECOMMENDATIONS

The research conducted in this capstone provides insights into the development and future application of HMT systems in operational environments. The USMC should continue to invest in the research and development of HMT concepts and continue to refine and construct the HMT relationships to understand the complexities of interdependence between humans and machines. For human-machine teaming, the USMC should continue to use the systems engineering framework in conjunction with Coactive Design and IA. This combined approach to system decomposition ensures the appropriate traceability can be achieved within the systems engineering framework and established architecture while also utilizing the benefits of IA to depict human-machine interdependencies. The continued investment in AI and designing AI into future HMT systems will be vital to achieve HMT effectiveness. A deeper understanding of AI and its applicability to future systems should follow the systems engineering approach to enable the visualization of future HMT system concepts.

C. FUTURE WORK

Future work should focus on the initial experimentation of HMT concepts as they apply to current doctrine and multi-domain operations. The use of the NPS MOVES laboratory presents the opportunity to simulate the HMT concept across the domains of air, land, and sea. This opportunity could provide the USMC with relevant and realistic feedback to support the continued refinement of HMT interdependencies and application of systems engineering across future human-machine systems.

Another area of future work is research into the use of digital mission planning systems and concepts in support of HMT concepts. This type of digital mission planning could provide the capability to leverage simulation environments to better understand the intricacies of HMT interdependencies while maintaining a cost effective and joint research approach that attempts to define the HMT concept of the future through sustained refinement of the IA and application of systems engineering and Coactive Design.

Finally, as DOD priorities change and adapt to future adversaries, the IA described and studied in this research report must be expanded and developed to encompass multiple future system platforms across the multi-domain environment of land, air, and sea. The systems engineering process and Coactive Design analysis provide the framework to expound on the HMT concept and move beyond the SCAR mission scenario objectives in a littoral environment. Foundational frameworks and architectures must be developed that enable the application of HMT across all concepts of operation while also supporting requirements development for future combat platforms and weapons systems.

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APPENDIX A. SYSTEMS ANALYSIS LEVEL II FUNCTIONS

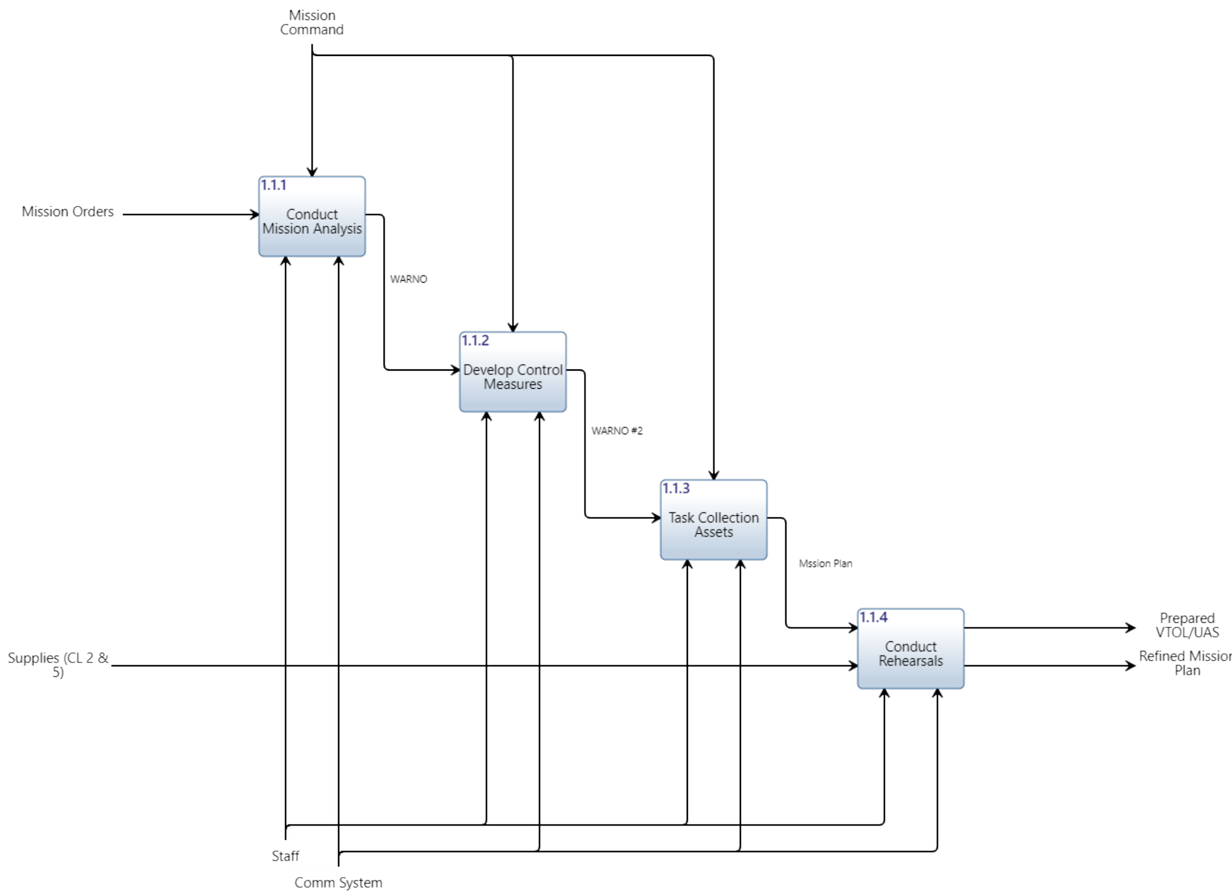

Figure 52. Conduct Mission Planning IDEF0

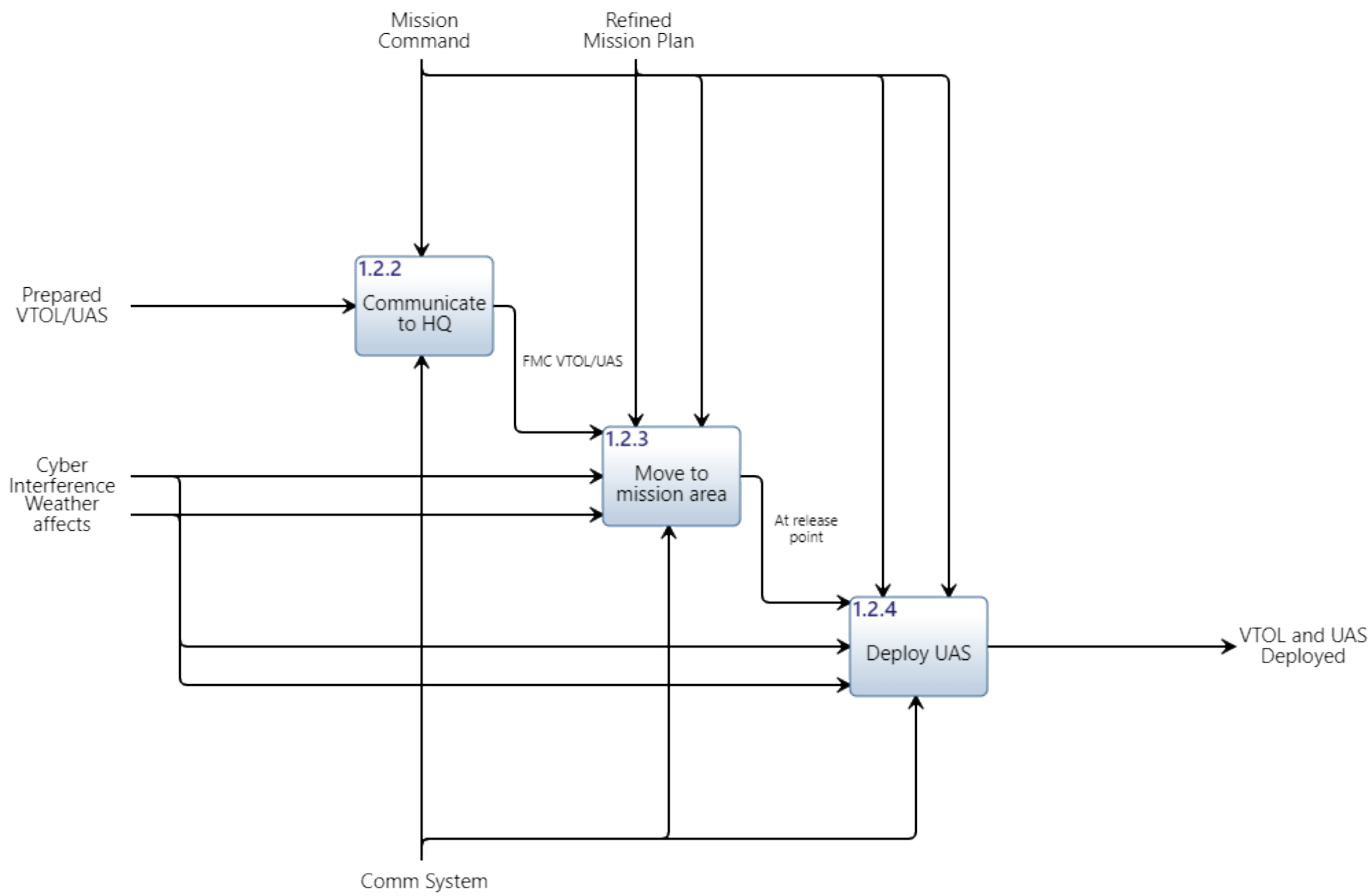

Figure 53. Conduct Movement/Infiltration IDEF0

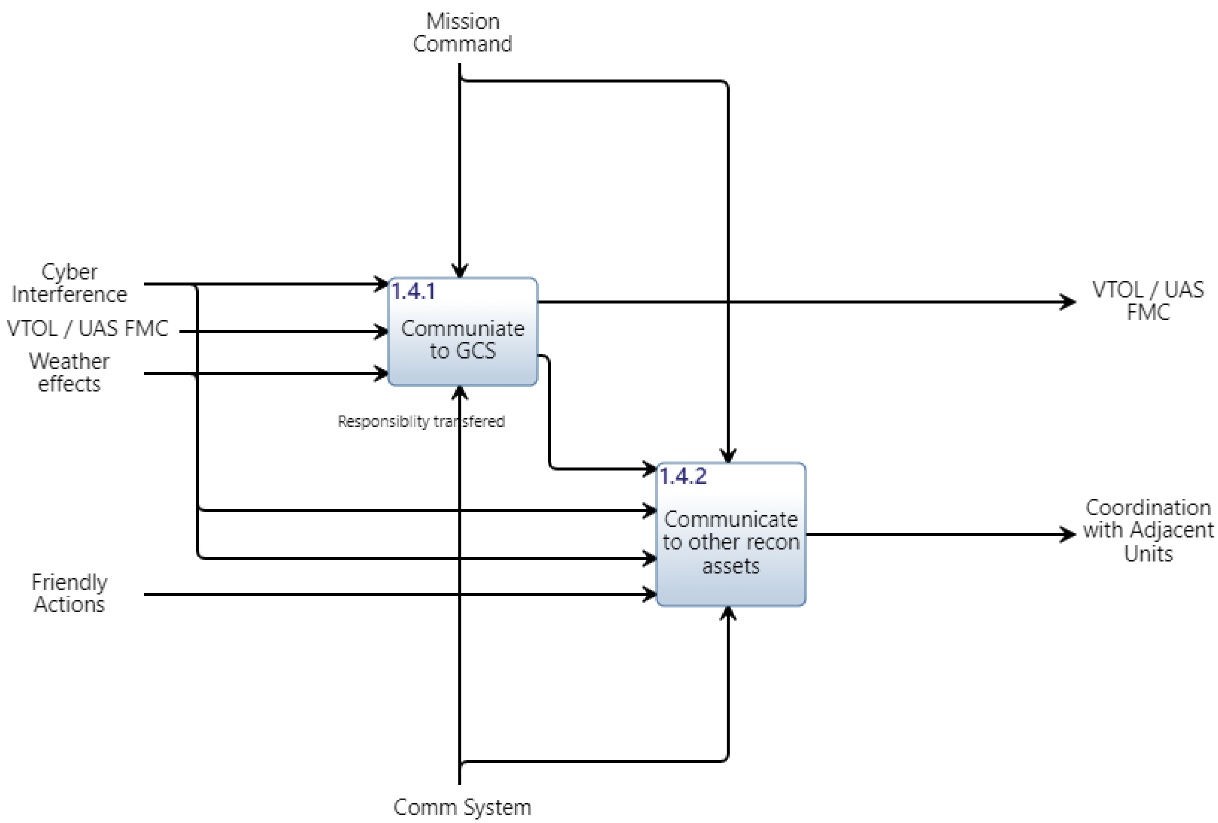

Figure 54. Conduct Recon Handover IDEF0

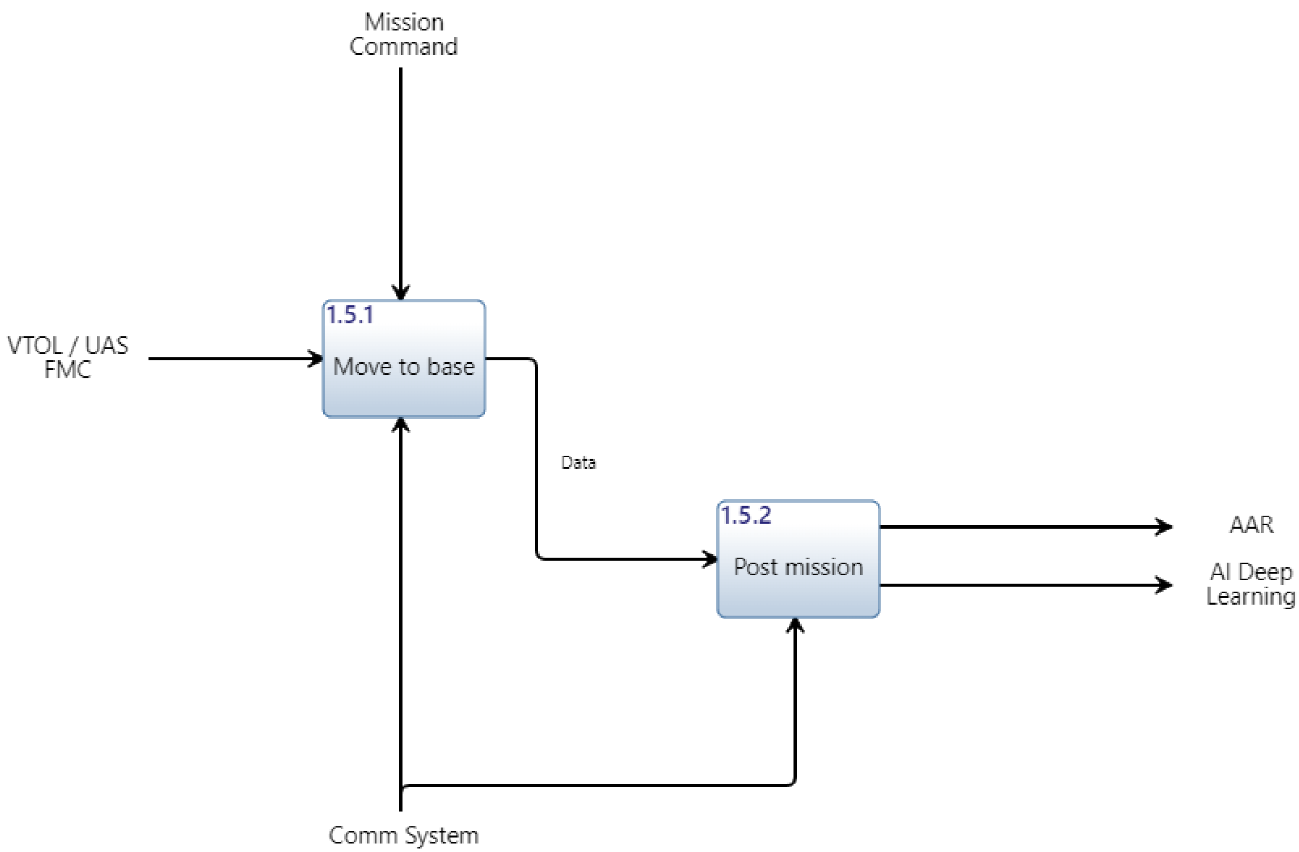

Figure 55. Transition IDEF0

APPENDIX B. MASTER IA TABLE

Table 30. Master IA Table

IA TABLE				Alternative #1			Alternative #2			Alternative #1	Notes/Assumptions	HMT - Task Level
				Performer	Supporters		Performer	Supporters		OPD		
Operational OBJ	Task	Hierarchical Sub-Tasks	Required Capacities	UAS	VTOL	GCS	FVL	UAS	GCS	UAS		
Conduct Mission Planning	Conduct Mission Analysis	Conduct IPB	Analyze Terrain/Weather							O- UAS requires the GCS and FVL to upload terrain/weather of mission location P- Prior to start of mission the UAS trust GCS/FVL provide most accurate mission requirements D- UAS notifies GCS/FVL that it requires mission updates	Its our assumption that the GCS is the main mission planning cell. The FVL will conduct additional refinement to the plan. The UAS does not have the capacity to conduct mission planning therefore requires assistance. However, it is programmed to inform the GCS and FVL that it requires	
			Analyze Friendly Capability							O- UAS requires the GCS and FVL to upload friendly capabilities P- Prior to start of mission the UAS trust GCS/FVL provide most accurate mission requirements D- UAS notifies GCS/FVL that it requires mission updates	Again can't analysis the capabilities but it can use the information to assess recommendations during the mission. This is critical during execution so it can give the most accurate recommendations.	Teaming is occurring since the GCS is required for the UAS to accomplish this task. FVL is capable of improving reliability for the HMT. The observability issue for the UAS requires human interactions to provide data resources to enable the UAS to provide predictability with the upload of the most current mission
			Analyze Enemy Capability							O- UAS requires the GCS and FVL to upload enemy capabilities P- Prior to start of mission the UAS trust GCS/FVL provide most accurate mission requirements D- UAS notifies GCS/FVL that it requires mission updates	Receiving information about the enemy is critical in order to facilitating teaming. If the UAS is unable to assist in the cognitive workload of the FVL "human" then its not teaming. It's just robotics.	Teaming is occurring since the GCS is required for the UAS to accomplish this task. FVL is capable of improving reliability for the HMT. The observability issue for the UAS requires human interactions to provide data resources to enable the UAS to provide predictability with the upload of the most current mission
		Develop Running Estimates	Establish Facts							O- The UAS needs to have access to updated facts charts. Also, it needs access during the mission. P- The UAS trust the GCS/FVL are prioritizing the facts so that it can more rapidly notify FVL during the mission. D- The UAS needs to notify the UAS when facts are inputted incorrectly or are not feasible.	At this point the excel. If you put in a formula in wrong the excel document is unable to find the answer. For the UAS if some facts are not feasible, like a building 100 miles tall, then it needs to notify the GCS/FVL team. FVL/GCS and UAS must have a common operating digital system.	Teaming is occurring since the GCS is required for the UAS to accomplish this task. FVL is capable of improving reliability for the HMT. The observability issue for the UAS requires human interactions to provide data resources to enable the UAS to provide predictability with the upload of the most current mission requirements.
			Create Assumptions							O- The UAS needs to have access to updated assumption charts. Also, it needs access during the mission. P- The UAS trust the GCS/FVL are prioritizing the assumptions so that it can more rapidly notify FVL during the mission. D- The UAS needs to notify the UAS when assumptions are inputted incorrectly or are not feasible.		Teaming is occurring since the GCS is required for the UAS to accomplish this task. FVL is capable of improving reliability for the HMT. The observability issue for the UAS requires human interactions to provide data resources to enable the UAS to provide predictability with the upload of the most current mission requirements.
			Establish Battle Tracker							O- The UAS needs access to the battle tracker to have situational awareness for the mission P- The UAS needs to trust that it will have access to the latest information D- The UAS needs to notify the GCS/FVL if it has not received the updated battle tracker	In order to conduct continuous missions, the after action review "debrief" will need to be conducted. That way the UAS's "AI" can learn. Also this will help with the HMT by building trust and new TTPs.	Teaming is occurring since the GCS is required for the UAS to accomplish this task. FVL is capable of improving reliability for the HMT. The observability issue for the UAS requires human interactions to provide data resources to enable the UAS to provide predictability with the upload of the most current mission requirements.
	Task Collection Assets	Develop IC Collection Matrix	Develop NAI							O- Needs access to the MACOOs that have been developed P- That the MACOOs are accurate and updated MACOOs will be provided D- UAS request MACOO.		Teaming is occurring since the GCS is required for the UAS to accomplish this task. FVL is capable of improving reliability for the HMT. The observability issue for the UAS requires human interactions to provide data resources to enable the UAS to provide predictability with the upload of the most current mission
			Assign LTIOV							O- Needs to observe synch matrix IOT understand how the LITOV align with the mission. P- Needs to trust that D- The UAS needs to provide the GCS/FVL the capability that it can provide based off the assign NAI. It's more reliable looking at a smaller NAI with less vegetation, in good weather, trying to identify something large		Teaming is occurring since the GCS is required for the UAS to accomplish this task. FVL is capable of improving reliability for the HMT. The observability issue for the UAS requires human interactions to provide data resources to enable the UAS to provide predictability with the upload of the most current mission requirements.
			List Assets							O- Access to assets that are acquired and requested (capabilities are requested not assets so this may be difficult) P- trust the FVL/GCS will provide list of assets that will be in the AO D- request list form FVL/GCS		Teaming is occurring since the GCS is required for the UAS to accomplish this task. FVL is capable of improving reliability for the HMT. The observability issue for the UAS requires human interactions to provide data resources to enable the UAS to provide predictability with the upload of the most current mission
			Assign Assets to NAI							O- Needs to know all the NAIs so it can recommendations for airspace deconfliction and in mission recommendations. This will also help with mission understanding. P- Needs to trust that it can observe the NAI that it is assigned D- The UAS needs to provide the GCS/FVL the capability that it can provide based off the assign NAI. It's more reliable looking at a smaller NAI with less vegetation, in good weather, trying to identify something large.		Teaming is occurring since the GCS is required for the UAS to accomplish this task. FVL is capable of improving reliability for the HMT. The observability issue for the UAS requires human interactions to provide data resources to enable the UAS to provide predictability with the upload of the most current mission requirements.
	Develop Control Measures	Create Graphic Control Measure	Ability to adjust software							O- UAS requires access to the master graphic control measure which is most likely encrypted P- That graphic control measure are the correct measure. Access to the master D- UAS request approval from FVL/GCS before adjusting any graphic control measure	we need to remember that the DoD is shifting to a system compromised approach.	Teaming is required for the UAS to observe the graphic control measures via an upload from a human. Directability issues arise when graphic control measures require changes, which require a human to direct the changes for final approval.
		Graphical Control deconfliction	communicate to staff							O- UAS needs to know who's available P- UAS trust the information it sends is sent to a secure source D- UAS is able to request actions or information from the GCS/FVL	Communication capability is critical in this phase. Traditionally, machines communicate through cables however, the UAS in the future may need to communicate cordless. Creating an infrastructure "think 5 G" that it can securely communicate will be critical.	Teaming is required for the UAS to observe the graphic control measures via an upload from a human. Directability issues arise when graphic control measures require changes, which require a human to direct the changes for final approval.
			Adjust graphic control measures							O- UAS is able to see the master graphic control measure P- UAS needs to trust that its recommendations will be taken seriously. D- UAS request changes due to its analysis.	The UAS can't control graphic control measures however, it can be a redundant source of validation. This will become more important the more aerial platforms that are located in the same AO.	Teaming is required for the UAS to observe the graphic control measures via an upload from a human. Directability issues arise when graphic control measures require changes, which require a human to direct the changes for final approval.
		Graphical Control Approval	approve changes							O- UAS has access to the latest approved graphic control measure P- UAS trust that the changes are official D- UAS notifies GCS/FVL that doesn't have the approved		Teaming is required for the UAS to observe the graphic control measures via an upload from a human. Directability issues arise when graphic control measures require changes, which require a human to direct the changes for
		Distribute Graphical Control Measure	Transmit information							O- UAS knows who to transmit too P- UAS trust the unit receiving the information is able to receive the information. D- UAS requires GCS to direct the transmission of graphics.		Teaming is required for the UAS to observe the graphic control measures via an upload from a human. Directability issues arise when graphic control measures require changes, which require a human to direct the changes for final approval.
	Conduct Rehearsals	Individual Rehearsal	Execute rehearsal							P- UAS requires the capability to predict the actions others will make. UAS trust that other participants are conducting rehearsals and that they will provide any updates if found during individual rehearsal. D- UAS request GCS/FVL their individual rehearsal updates.	The UAS needs continuous updates throughout the entire process. Teaming doesn't start at launch, teaming is continuous.	Teaming is an ongoing process between the UAS and FVL/GCS. Humans are required to provide reliability to this task. Humans and the UAS must be able to predict one another's actions based on observability and then have the capability to direct their own actions accordingly.
			Cognitive Load Checklist							O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
		Team Rehearsal	Coordinate with team							sort of virtual real time software P- UAS trust the actions taken during rehearsals are the same actions the GCS/FVL will take during the mission. D- The UAS notifies the GCS/FVL if an unfeasible action is taken place		Teaming is required for the UAS to observe the graphic control measures via an upload from a human. Directability issues arise when graphic control measures require changes, which require a human to direct the changes for final approval.

Conduct Movement/Infiltration	Pre-Maintenance Check (Pre-flight)	Pilot PMCS	Validate Appropriate Gear	O- P- D-		Teaming is not occurring in this task. Future research may look at how teaming may occur in the future however, it may require an additional participant.
			Interpret Mission	O- P- D-		Teaming is not occurring in this task. Future research may look at how teaming may occur in the future however, it may require an additional participant.
			Interpret FVL and UAS status	O- P- D-		Teaming is not occurring in this task. Future research may look at how teaming may occur in the future however, it may require an additional participant.
		FVL PMCS	Initiate Pre-Flight Check Sequence	O- P- D-		Teaming is not occurring in this task. Future research may look at how teaming may occur in the future however, it may require an additional participant.
			Consolidate Inputs from Onboard Sensors	O- P- D-		Teaming is not occurring in this task. Future research may look at how teaming may occur in the future however, it may require an additional participant.
			Execute feedback on faults	O- P- D-		Teaming is not occurring in this task. Future research may look at how teaming may occur in the future however, it may require an additional participant.
			Determine Go/No-Go for Mission	O- P- D-		Teaming is not occurring in this task. Future research may look at how teaming may occur in the future however, it may require an additional participant.
		UAS PMCS	Initiate Pre-Flight Check Sequence	O- FVL observes the UAS is ready to execute the sequence P- UAS must initiate sequence once notification to execute is sent D- FVL must be able to notify the UAS to initiate sequence	The UAS is always connected and conducting sequence checks however, for the actual pre-flight sequence check to be initiated a humans needs to start it.	This teaming is a hard constraint because the FVL is the only one authorized to begin the sequence. This is a directability issue requires some interface which the human can interact with the UAS.
			Consolidate Inputs from Onboard Sensors	O- FVL must be able to see status report P- UAS must progress to the next step automatically D- n/a		This is an independent action that the UAS conducts
			Provide feedback on faults	O- FVL must be able to see faults P- UAS must notify the FVL of the results D-		Teaming is not occurring since the UAS provides the output feedback on internal faults
			Determine Go/No-Go for Mission	sequence P- UAS must notify the FVL of the results D- FVL must be able to override the UAS decision		Teaming is occurring since the FVL is the final approving authority when determining a GO/NO-GO for mission. This minimizes the risk of the UAS deploying with internal issues.
	Communicate to Headquarters	Pre-Mission Communications	Provide Information	P- UAS predicts that the FVL will be able to receive comms D- UAS will receive notification from FVL if comms unsuccessful		Either could provide information to headquarters. However, a human may feel more comfortable with another human providing information.
			Interpret Command	O- UAS must be able to decrypt the message from an authorized participant P- UAS needs to trust the command that comes from an authorized participant D-		The UAS is independent when interpreting the information it has therefore, we predict the UAS has hardware and software (AI) with the processing power to interpret the command. However, the UAS may increase the efficiency a human understand a command by providing some easily identifiable observable image. The UAS shall have the capability of converting verbal commands from headquarters onto a digital screen.
		Communicate During Mission	Provide Information	O- UAS and FVL must be able to see comms status P- UAS predicts that the FVL will be able to receive comms D- UAS will receive notification from FVL if comms unsuccessful		The UAS and FVL are effective at providing information to one another. The teaming shall predict the information is securely sent and received and that each system is able to observe the information sent.
			Interpreted Command	O- UAS must be able to decrypt the message from an authorized participant P- UAS needs to trust the command that comes from an authorized participant D-		The UAS is independent when interpreting the information it has therefore, we predict the UAS has hardware and software (AI) with the processing power to interpret the command. However, the UAS may increase the efficiency a human understand a command by providing some easily identifiable observable image. The UAS shall have the capability of converting verbal commands from headquarters onto a digital screen.
	Move to Mission Area	Navigate	Determine Go/No-Go for FVL movement	O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
			Determine Flight Path	O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
			Analyze Flight Path	O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
			Determine Present Location	O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
			Determine Existing Orientation	O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
			Determine Required Trajectory of Travel	O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
			Execute Flight Functions	O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
	Deploy UAS	Launch UAS	Initiate Functional Check Sequence	O- FVL/GCS must be able to observe the functions check is initiated and completed P- FVL/GCS assumes the UAS will execute the functions check D-	The UAS has a sensor to determine its coordinates. The UAS has mission requirements uploaded and knows to initiate function check at a certain location. It shall notify the FVL/GCS of initiation and status.	Teaming is occurring since the FVL is observing the functional check sequence
			Determine Go/No-Go for Mission	FVL/GCS is required to execute this task O- P- D- FVL/GCS directs the UAS to execute launch		
		Establish Communication	Determine level of connectivity	UAS can execute this task by itself as the performer, but when the FVL is the performer it requires assistance from the UAS O- UAS sends message (GUI) that connectivity is established P- FVL/GCS expects a status shall be sent from the UAS D-		The UAS is critical in the human observing connectivity levels with its team member. There is a hard requirement that the UAS is able to provide observable information to the human. This can be done with a simple light indicator or GUI. The FVL and GCS shall predict that the UAS is always trying to provide its connectivity status to the FVL.
			Validate controllability	FVL/GCS is required to execute this task O- P- D- FVL conducts controllability validation test through a simple function test.		Teaming is occurring due to the FVL having final directability for the UAS. This is done through a controllability validation test where the FVL executes a function test to verify communication status.
			Validate mission coordinates	FVL/UAS both can execute this task by themselves O- FVL/GCS needs to observe the location of the UAS and its relations to the objective P- The UAS reliability moves to mission coordinates and reports status. D- FVL/GCS is able to direct the UAS to a new location if the UAS is at the wrong location		Each system is able to validate its own coordinates utilizing its onboard sensors. However, if the devices link are broken the FVL and UAS are able to detect each others location. In order to accomplish that task, the FVL and UAS must be able to observe each other using sensors that can map the location of an item utilizing means other than GPS.
	Observe	Scan Area of Interest	Determine Required Scanning Orientation	Both the UAS and the GCS can execute this task by itself O- The UAS must provide the direction coordinates its sensor is facing to FVL GCS. P- UAS/GCS assumes the orientation based on pre planned data D- FLV/GCS capable of overriding the orientation		The UAS is fully able to control its scanning which will reduce the cognitive load of the human. However, the human needs to be able to observe what the UAS is looking at and has the ability to direct the UAS to orient on a specific area. The UAS predicts that the human has additional information that it does not have which is why the human directs the UAS scanning orientation.
			Execute Scanning Function	O- P-UAS trusts that the FVL and GCS is viewing the feed D- UAS has the ability to direct the FVL or GCS to assume control	IOT for the FVL or the GCS to assist they must know what th	The UAS is able to execute this task, however, this soft constraint requires the FVL and GCS to observe the UAS sensors and direct the UAS's sensors utilizing a GUI or voice command.
			Maintain Required Scanning Orientation	O- P- UAS trusts that the FVL and GCS is viewing the feed D- UAS has the ability to direct the FVL or GCS to assume control	IOT for the FVL or the GCS to assist they must know what th	The UAS is able to execute this task however, this soft constraint requires the FVL and GCS to observe the UAS sensors and direct the UAS's sensors utilizing a GUI or voice command.
		Collect Information	Store information	O- UAS can asses the available storage space P- UAS can securely transfer and receive data D- UAS tells the FVL and GCS to store data	We assume the storage of information is primary on the UAS with additional space being provided by the FVL and GCS.	The UAS is able to store as much information as its hardware allows, however, it can upload data during the mission to either FVL or GCS. The UAS would need to be able to observe the data availability each system has and predict which system to upload the information too. The UAS may need to direct the FVL to receive the data if its critical.
		Adjust Observation Site	Adjust flight path	O- UAS must know where the FVL and GCS are P- UAS assumes that the FVL and GCS will deconflict air space D- UAS directs FVL/GCS to adjust flight parameters	Taking control of the UAS flight path should rarely occur. If the flight path needs to be adjusted the human shall utilize a GUI waypoint to direct the UAS. Flying the UAS the way you fly a plane shouldn't occur. Doing so would increase the human cognitive load.	The UAS is fully capable of adjusting its flight plan. The FVL can direct the UAS to make an adjustment if there is a reason to do so. The FVL and UAS will need to observe the UAS location and flight data regarding the direction the UAS is flying.
			Adjust sensors	O- P- UAS trusts that the FVL and GCS is monitoring the feed D- UAS directs FVL/GCS to adjust sensor parameters		The UAS is able to independently adjust its sensor however, the FVL/GCS shall observe what sensor is being used and how its being used. It can assist the UAS with the appropriate sensor to be used and direct the UAS.

Conduct Area Recon / SCAR	Assess	ID Target	Assess indicators	O- UAS has the ability to observe real time intel reports P- UAS properly analyze the intel report D-		The UAS is able to assess the indicators that it observes on the ground independently . The GCS/FVL shall be used to assist the UAS if there are indicators that the UAS has not previously learned. The GCS/FVL are soft constrains that improve the reliability of the assessment due to complicated indicators. The FVL/GCS need to be able to observe the same indicators the UAS is observing and the FVL/GCS needs to direct the UAS sensors to help make an assessment of the indicators.
			Recognize target	O- UAS has ability to observe and process targets based on the preloaded database P- UAS predicts accurate type of target based on database D- The UAS notifies FVL/GCS that target is recognized.		The UAS is able to recognize targets independently, however, FVL/GCS are able to increase the reliability of the target identified. In order for the FVL/GCS to assist, the systems must observe the target that the UAS is observing. The only case were FVL/GCS is required is if the UAS faces a scenario which it hasn't learned.
		Determine Location	Acquire location of UAS	O- UAS has ability to send FVL/GCS its location P- UAS can geolocate itself D- UAS can provide location to FVL/GCS		The UAS is able to independently acquire its location using GPS or land imagery mapping. However, in a permissive environment the UAS may break link requiring the FVL to use its sensors to determine where the UAS is located. The GCS is unable to assist because if the UAS breaks link then the GCS will be unable to observe its location.
			Acquire location of target	O- UAS has ability to consolidate imagery and GPS reports P- UAS can assume loaded data is accurate D- UAS has ability to tell FVL/GCS to move assets to target location		The UAS is able to independently acquire the location of a target using lasers and other sensors. However, the FVL is able to acquire the target itself and handover the location to the UAS. This increases the efficiency of the UAS. In order for the FVL to assist, the UAS needs to be able to observe the FVL targeting information and be directed by the FVL.
		Analyze Targets	Determine target capability	O- UAS has the ability to send FVL/GCS capabilities report P-UAS has ability to interpret the targets capabilities based on preloaded data D- UAS has ability to direct the FVL/GCS to conduct a secondary review of target capability to confirm or deny		The UAS is able to determine enemy capabilities based on pre-loaded data, however the FVL and GCS can improve the reliability of the initial capabilities identified by the UAS
		Battle Tracking	Interpret HPTL	O- P- D-		The UAS has the ability to interpret HPVT, however, the FVL and GCS can improve the reliability of target interpretation which correlates to the observability HMT interdependency.
			Update HPTL	O- P- D-		The UAS's ability to update the HPVTL is possible but the reliability is less than 100%. The FVL can improve the efficiency in the target list update, however, the GCS must assist in those updates as new information is obtained. This sub-task correlates with observability interdependency.
			Determine Mission Success	O- UAS is capable of providing FVL/GCS HPTL P- UAS has ability to remain on station until confirmation by FVL/GCS D- UAS relies on FVL/GCS to properly analyze HPTL		The UAS is able to provide BDA using it's sensors, however, due to the "fog of war" it's reliability is not 100%. Using observability the FVL and GCS can improve reliability of battle damage assessments.
	Report	Provide Recommendations	Interpret environment	O- P- D-		The UAS is able to interpret, however, the complex nature of conflict will require assistance from the FVL/GCS. The FVL/GCS are required to observe the UAS sensors and indicators. Also, the FVL/GCS requires the ability to observe the UASs interpretation and how it got to the interpretation. We predict the UAS will be able to provide its interpretation in a simple way which can easily be interpreted by the FVL/GCS.
			Interpret Mission	O- P- D-		The UAS is able to interpret, however, the complex nature of conflict will require assistance from the FVL/GCS. The FVL/GCS are required to observe the UAS sensors and indicators. Also, the FVL/GCS requires the ability to observe the UASs interpretation and how it got to the interpretation. We predict the UAS will be able to providing its interpretation in simple way which can easily be consumed by the FVL/GCS.
			Interpret situation	O- P- D-		The UAS is able to interpret, however, the complex nature of conflict will require assistance from the FVL/GCS. The FVL/GCS are required to observe the UAS sensors and indicators. Also, the FVL/GCS requires the ability to observe the UASs interpretation and how it got to the interpretation. We predict the UAS will be able to providing its interpretation in simple way which can easily be consumed by the FVL/GCS.
			Interpret METT-TC	O- P- D-		The UAS is able to interpret, however, due to the complex nature of conflict will require assistance from the FVL/GCS. The FVL/GCS are required to observe the UAS sensors and indicators. Also, the FVL/GCS requires the ability to observe the UASs interpretation and how it got to the interpretation. We predict the UAS will be able to providing its interpretation in simple way which can easily be consumed by the FVL/GCS.
			etermine time to communicate information	O- UAS is capable of providing updated reports based on a change in enemy P- UAS has the ability to compress data to mitigate latency D-		The human predicts the UAS shall send data when the cognitive load of the human is low. The FVL/GCS needs to be able to observe the data. The same time the UAS needs to be able to observe the actions of the FVL. If the FVL is in contact, the UAS predicts that sending data that is not critical is not require at that time. The UAS predicts the data should be sent once the FVL has completed its actions on contact and is ready to observe the information.
			Send data	O- UAS has the ability to send imagery to the FVL/GCS P- UAS has the ability to provide real time data D-	We assume this is data from the battlefield. The FVL and UAS are the only ones observing at this time therefore, the GCS is unable to help.	The UAS is able to send information however, due to its location on the front line it may direct the FVL to upload the data it has so it can send the data to the GCS. The FVL needs to be able to observe when the UAS is preparing to send data that is required for more than the FVL. The FVL predicts if its being used a preplan decision point has been met. However, the FVL is able to direct the UAS to provide data which can be observed on some GUI.
	Destroy (SCAR)	Deploy Weapon System	Determine Go/No-Go	O- UAS is capable of providing FVL/GCS a weapons status report P- UAS is capable of providing recommendations only based on preloaded data on enemy targets D-		Directability is occurring since the FVL and the GCS have final approving authority to determine GO/NO-GO criteria.
			Determine weapon system to be used	O- UAS is capable of providing FVL/GCS a weapon system that is capable of destroying the enemy target based on preloaded data P-UAS is capable of providing percentage of enemy target destruction based on weapon system selection D-		Directability is occurring since the FVL and the GCS have final approving authority to determine weapon system used.
			Execute deployment of weapon system		Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
	Self-defense	ID Threats to Self	Identify threats	O- UAS is capable of observing its environment P- UAS is capable of differentiating between air and ground threats D- UAS is capable of evasive maneuvers		Since the UAS can't identify all threats at a 100% reliability observability is occurring between both performer and supporter which improves reliability in identifying threats.
			Interpret level of risk	O- UAS is capable of interpreting levels of risk (risk matrix) P- UAS is capable of flight path changes based on risk level D- FVL and GCS improve UAS ability to interpret risk levels		The UAS can't interpret levels of risk at 100% so predictability is occurring between UAS (performer) and supporters (GCS/FVL) improving the reliability of identifying threats.
		Conduct Action on Contact	Decide action to take	O- UAS is capable of providing FVL/GCS a recommendation based on observed threats P-UAS is capable of determining the COA with the highest probability of survival. D- UAS relies on FVL/GCS for final approval		Since the UAS reliability is less than 100% when deciding to take action both the FVL and GCS use directability to improve efficiency
			Conduct actions	O- UAS provides real time feedback to FVL/GCS P-UAS will execute the highest probability survival COA D- UAS relies on FVL/GCS for final approval		Since the UAS reliability is less than 100% both the FVL and GCS use directability to improve efficiency
			Interpret situation	[illegible] situation P- UAS is capable of providing confirmation of command received by trusted agent D- UAS is capable of providing FVL/GCS COA based on the		Since the UAS reliability is less than 100% both the FVL and GCS use directability to improve efficiency

Conduct Recon Handover	Communicate to Headquarters	Communicate During Mission	Provide Information							O- UAS monitors FVL/GCS communication channels P- UAS is preloaded with all appropriate frequencies D-		While the UAS can provide information on its own, the FVL improves reliability through observability
			Interpret Command							(UAS provides confirmation of command through back brief)(layered imagery) P- UAS assumes that commands received are from a trusted agent D- UAS notifies FVL/GCS of received command and provides FVL/GCS with COA		The FVL & GCS improve reliability through observability by since there are is real time communication occurring with the UAS
	Communicate to other Recon Asset	Communicate During Mission	Provide Information							O- UAS monitors FVL/GCS and adjacent unit communication channels P- UAS is preloaded with all appropriate frequencies		The UAS and FVL are effective at providing information between each other. The teaming shall predict the information is securely sent and received and that each system is able to observe the information sent.
			Interpret Command							O- UAS provides applying logic based on observed imagery (UAS provides confirmation of command through back brief)(layered imagery) P- UAS assumes that commands received are from a trusted agent D- UAS notifies FVL/GCS of received command and provides FVL/GCS with COA		The UAS is independent when interpreting the information it has gathered. As a result, we predict the UAS has hardware and software (AI) with the processing power to interpret the command. However, the UAS may increase the efficiency of how a human understands a command, by providing some easily identifiable observable data output. The UAS shall have the capability of converting verbal commands from headquarters onto a digital screen.
			Determine Handover complete							agent P- UAS can predict that the other entities (FVL/GCS, Adjacent units) that the handoff occurred and now the GCS and UAS is now a team D- UAS is capable of directing both the FVL/GCS that the handover occurred		The UAS is able to identify a handover has occurred from the FVL to the GCS. The UAS shall provide a message to the FVL and GCS indicating the recon handover has occurred. Once the handover is complete the UAS predicts the authority is the new team member and shall prioritize the direction from one over the other.
Transition	Move to Base	FVL Moves to Base	Determine Existing Orientation							O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
			Determine Required Trajectory of Travel							O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
			Execute Flight Functions							O- P- D-	Even though the GCS and FVL are able to team, we are only focusing on teaming that includes the UAS.	The UAS is unable to provide any teaming benefit.
		UAS Moves to Base	Determine Existing Orientation							O- UAS notifies FVL and GCS of current orientation P- UAS is capable of determining orientation based on the magnetic heading D- UAS/GCS are capable of re-directing UAS if required	if link is broken the GCS is able to utilize other sensors such as satellite and radar to locate the UAS and determine its orientation.	The UAS is fully capable of determining its orientation, however, if there is any disruption with its GPS the FVL/GCS uses predictability to provide it's orientation. In order for the FVL/GCS to direct the UAS with information, it needs to observe its orientation which it would need to do with other sensors.
			Determine Required Trajectory of Travel							O- UAS provides feedback of its trajectory. The GCS/FVL is able to use imagery not provided by the UAS. P- The GCS/FVL is able to monitor the UAS heading. D- GCS/FVL is able to command the UAS to adjust its trajectory.	Taking control of the UAS flight path should rarely occur. If the flight path needs to be adjusted the human shall utilize a GUI waypoint to direct the UAS. Flying the UAS the way you fly a plane shouldn't occur. Doing so would increase the human cognitive load.	The UAS is fully capable of adjusting its flight plan and if directed from FVL the UAS predicts there's a critical reasoning for the FVL to make the adjustment. The FVL and GCS will need to observe the UAS location, flight data, and heading of the UAS.
			Execute Flight Functions							O- UAS provides real-time notification to FVL/GCS of flight functions P- UAS travels to base of operations through preplanned flight route D -		The UAS is independent in executing flight functions. The FVL and GCS are able to direct where the UAS flies, however, they are unable to direct the UAS the way the FVL is able to be manipulated by a human. The GCS predicts that it can observe the FVL system, location, and flight data therefore, it can take control and direct the flight functions.
	Post Mission	Analyze	Debrief							O- UAS is able to provide digital mission data (download and upload) P- UAS is providing information to a secure system D- UAS is commanded by the GCS to download or upload information		The UAS has a hard constraint which requires it be directed by the GCS for mission debrief. During mission debrief the human needs a way to observe the information in a meaningful package way. The UAS predicts that the human will review certain data packs and will request different interpretations from that data. The UAS needs the capability to observe the FVL debrief so that it can obtain the data in order to use it for its machine learning. The human predicts that the UAS shall require clarification on certain data sets.
			AI learning							O- UAS provides knowledgebase of mission data P- UAS builds trust with FVL and GCS as more missions are executed D- GCS compiles mission data improving AI learning for UAS by deconflicting conflicts that require a human team interaction	The UAS has AI software which is capable of machine learning. The machine learning is optimized connected to a cloud base network which computing power from other systems can be utilize. Should we say that the FVL has AI which it too can help the UAS learn. How is this information transferred to other UASs?.	The UAS machine learning needs to be observed from the network which is provided by the GCS. We predict the UAS will be connected to a secure network capable of uploading and downloading machine learning after the mission is complete. The FVL predicts that the UAS will provide a status update of the machine learning that is occurring.

APPENDIX C. USMC REQUIREMENTS DOCUMENT

Table 31. USMC Requirements Table

#	Op. Obj.	Task	OPD	System	Requirement
1	Conduct Mission Planning	Conduct Mission Analysis	O	UAS	The UAS must have the capability to connect to a redundant digital network with mission planners to ensure updated mission data is transferred and understood by humans and AI instantaneously.
2	Conduct Mission Planning	Conduct Mission Analysis	O	USMC	The Marines must have an automated digital common operating system that can connect the physical attributes of the world into a digital cloud-based storage system accessible by humans and AIs.
3	Conduct Mission Planning	Conduct Mission Analysis	P	UAS	The UAS must have a high automation level able to respond at the same speed as humans.
4	Conduct Mission Planning	Task Collection Assets	O	UAS	The UAS must have the capability to connect to a redundant digital network with mission planners to ensure updated mission data is transferred and understood by humans and AI with minimal delay.
5	Conduct Mission Planning	Task Collection Assets	O&P	UAS	The UAS must understand the mission coordination input from the human and provide automated feedback on risks and opportunities instantaneously.
6	Conduct Mission Planning	Develop Control Measures	O	UAS	The UAS must have the capability to connect to a redundant digital network with mission planners to ensure updated mission data is transferred and understood by humans and AI with minimum delay.
7	Conduct Mission Planning	Develop Control Measures	O	UAS	The UAS must have the capability to interpret the USMC doctrine utilized in the physical environment.
8	Conduct Mission Planning	Develop Control Measures	D	UAS	The UAS must have the capability to overlay graphics onto the physical environment.
9	Conduct Mission Planning	Conduct Rehearsals	P&D	UAS	The UAS must have the capability to run an internal modeling simulation from the physical world attributes and mission plan within minutes and provide feedback of the results.

#	Op. Obj.	Task	OPD	System	Requirement
10	Conduct Mission Planning	Conduct Rehearsals	O&D	USMC	The USMC must have a common operating system which the VTOL and GCS can interact with the UAS in a digital environment.
11	Conduct Mission Planning	Conduct Rehearsals	D	USMC	The USMC must have the capability to direct the UAS to enter a team rehearsal mode.
12	Conduct Movement/ Infiltration	Perform Pre-Flight Checks	P	UAS	The UAS must have the capability to understand the mission timeline and conduct PMCs during the prescribe timeline.
13	Conduct Movement/ Infiltration	Perform Pre-Flight Checks	O&P	USMC	The Marines must have a digital common operating system capable of providing updated timelines thereby allowing the UAS to autonomously conduct specific task within the required timeline and provide any feedback to challenges or opportunities.
14	Conduct Movement/ Infiltration	Comm to HQ	D	SoS	The system (UAS, VTOL, & GCS) must implement a validated PACE communications plan that provides redundancy for digital communications
15	Conduct Movement/ Infiltration	Comm to HQ	D	SoS	The system (UAS, VTOL, & GCS) must require a digital common operating infrastructure which can transmit secure information and commands.
16	Conduct Movement/ Infiltration	Move to Mission Area	D	SoS	The system (UAS, VTOL, & GCS) must implement a validated PACE communications plan that provides redundancy for digital communications
17	Conduct Movement/ Infiltration	Move to Mission Area	D	SoS	The system (UAS, VTOL, & GCS) must require a digital common operating infrastructure which can transmit secure information and commands.
18	Conduct Movement/ Infiltration	Deploy UAV	O&D	UAS	The UAS must report its status prior to its launch immediately after conducting a final functional check.
19	Conduct Movement/ Infiltration	Deploy UAV	O	UAS	The UAS must require redundant location sensors to protect against GPS jamming.
20	Conduct Movement/ Infiltration	Deploy UAV	D	SoS	The system (UAS, VTOL, & GCS) must require a digital common operating infrastructure to transmit secure information and commands.

#	Op. Obj.	Task	OPD	System	Requirement
21	Conduct Area Recon	Observe	O	UAS	The UAS must observe the actions of the VTOL as they are occurring and assess the status of the VTOL immediately.
22	Conduct Area Recon	Observe	O	VTOL & GCS	The VTOL and GCS must observe the data provided from the UAS during the mission.
23	Conduct Area Recon	Observe	O&P	UAS	The UAS must provide a roll up of data from the sensor if there is a communication break from the VTOL.
24	Conduct Area Recon	Observe	O	UAS	The UAS must store sensor data to include video feeds for the full duration of the mission.
25	Conduct Area Recon	Observe	D	VTOL & GCS	The VTOL and GCS must have a visual or auditory interface to direct the UAS to change its observation behavior or specific observation.
26	Conduct Area Recon	Observe	O&P	UAS	The UAS must require a suite of sensors to react to the different forms of immediate contact including direct (kinetic projectile), indirect, NBC, obstacles, visual, and electronic.
27	Conduct Area Recon	Assess	P	UAS	The UAS must have the capability to identify friendly, neutral, enemy, and natural items immediately with a limited number of indicators.
28	Conduct Area Recon	Assess	O	VTOL & GCS	An interface for the VTOL and GCS must be developed so the UAS can provide information which can improve the efficiency of assessing targets while reducing the cognitive load on the human.
29	Conduct Area Recon	Report	O	UAS	The UAS must provide consolidate reports including sensor data prescribed on the timeline outlined during the mission planning.
30	Conduct Area Recon	Report	D&P	UAS	The UAS must notify the humans when a report timeline is not inputted into the mission plan prior to mission take-off.
31	Conduct Area Recon	Report	O	SoS	The system must have a digital or auditory reporting format that is understood by humans and machines immediately.
32	Conduct Area Recon	Report	O&D	USMC	The Marines must have a natural language processing system that can interpret auditory reports and convert it to a means the UAS can understand.
33	Conduct Area Recon	Report	O&D	VTOL & GCS	The VTOL and GCS must edit the reports received from the UAS prior to submitting reports to a higher chain of command.
34	Conduct Area Recon	Destroy	D	USMC	The USMC must create policy and procedures addressing autonomous lethal decision-making capabilities before the use of the autonomous UAS.
35	Conduct Area Recon	Destroy	O	UAS	The UAS must have the capability to observe the status of the weapon systems and current actions of the VTOL.

#	Op. Obj.	Task	OPD	System	Requirement
36	Conduct Area Recon	Destroy	O&P	UAS	The UAS must have the capability to determine appropriate weapon system to be used against a specific target immediately after the assessment of the target.
37	Conduct Area Recon	Destroy	O	UAS	The UAS must have the capability to operate with all militaries guided munitions thereby allowing it to act as a forward observer.
38	Conduct Area Recon	Self-Defense	O	UAS	The UAS sensors must identify the eight forms of contact and notify its system immediately.
39	Conduct Area Recon	Self-Defense	P	UAS	The UAS must react to contact as based on USMC doctrine and approved TTPs.
40	Conduct Recon Handover	Comm to HQ	D	SoS	The system (UAS, VTOL, & GCS) must implement a validated PACE communications plan that provides redundancy for digital communications
41	Conduct Recon Handover	Comm to HQ	D	SoS	The system (UAS, VTOL, & GCS) must require a digital common operating infrastructure which can transmit secure information and commands
42	Conduct Recon Handover	Comm to HQ	O&D	UAS	The USMC must have a natural language processing system that can interpret auditory reports and convert it to a means the UAS can understand.
43	Conduct Recon Handover	Comm to other Recon Asset	D	USMC	The USMC must create a protocol to grant authority over the UAS which has secure directability.
44	Conduct Recon Handover	Comm to other Recon Asset	D	SoS	The system (UAS, VTOL, & GCS) must implement a validated PACE communications plan that provides redundancy for digital communications.
45	Transition	Move to Base	O	UAS	The UAS must have the capability to report its location if its unable to return to base.
46	Transition	Move to Base	D	UAS	The UAS must have the capability to navigate by itself in any mild inclement weather conditions or cyber conflicted areas.
47	Transition	Move to Base	D	UAS	The UAS must have an energy source which will allow it to move back to base after a mission.
48	Transition	Assess Post Mission	O	UAS	The UAS must have the capability to connect to a redundant digital network with mission planners to ensure updated mission data is transferred and understood by humans and AI instantaneously.
49	Transition	Assess Post Mission	P	USMC	The USMC must consolidate best practices and lessons learned from the mission transmitted throughout the UAS cloud infrastructure immediately after conclusion of the Post Mission requirement.
50	Transition	Assess Post Mission	O&P	UAS	The UAS must have the ability to provide a way to communicate why it conducted the actions during the missions with humans during post mission analysis.

APPENDIX D. QUESTIONNAIRE

A. FIRST SCREEN

This table shall be the first set of information collected by the participants.

Table 32. Questionnaire

Pilot & Co-Pilot Information	
Name:	
Grade:	
Age:	
Sex:	
Education level:	
Years of military service:	
Branch of service:	
Total flight hours:	
Flight school graduation year:	
Total active Marine pilot years:	
Type of platform:	
Total SCAR training missions:	
Total SCAR real life missions:	

B. SECOND SCREEN

The following table shall measure the level of comfortability each participant has during the experiment.

Answer from 1 to 5 with 1 being the worst and 5 being the best. Answer the following questions:

1. How comfortable are you in simulations?

2. How comfortable are you using UASs?

3. How comfortable are you with trusting autonomous machines?

4. How comfortable are you with an autonomous machine flying you in a combat mission?

5. How comfortable are you with an autonomous machine flying in our routine flight mission?

C. THIRD SCREEN

Answer from 1 to 5 with 1 being the worst and 5 being the best. Answer the following questions:

1. How useful was the UAS in the mission.

2. The UAS reduced the level of stress you experienced in the mission?

3. The UAS provided you useful information when you needed it?

4. The UAS is more of a team member compared to being just a tool?

5. The UAS was critical in the mission?

6. The UAS allowed you do other task while completing the mission?

APPENDIX E. OPERATIONAL TEST REQUIREMENTS

Overall Objective: Determine the effectiveness of the HMT requirements and survivability between a VTOL and UAS during hybrid operations while executing a SCAR mission.

Table 33. Operational Requirements Table

Critical Operational Issue	Measure of Effectiveness	Measure of Performance	Data Requirement
COI 1: Observability. What is the accuracy of HMT observability during hybrid operations?	MoE 1.1 Detection Capability	MoP 1.1.1 Average range of detection	DR 1.1.1.1 accuracy of target location
			DR 1.1.1.2 Location at detection
		MoP 1.2.1 Proportion of detections	DR 1.2.1.1 # of ground elements available
			DR 1.2.1.2 # of ground elements detected
			DR 1.2.1.3 type of ground elements identified
	MoE 2.1 Observability accuracy	MoP 2.1.1 Number of targets observed	DR 1.2.1.1 # of ground elements available
			DR 1.2.1.2 # of ground elements correctly identified
			DR 1.2.1.2 speed of target acquisition
	MoE 3.1 Timeliness	MoP 3.1.1 Accuracy of SPOT report	DR 3.1.1.1 #of accurate SPOT reports
			DR 3.1.1.2 # of inaccurate SPOT reports
			DR 3.1.1.2 average of time of sent SPOT reports
COI 2: Targeting. Will the HMT team effectively execute targeting in a maritime combat environment?	MoE 2.1 Engagement Capability	MoP 2.2.1 % of Successful Engagements	DR 2.2.1.1 # of Missile Launches
			DR 2.2.1.2 # of Targets Destroyed
	MoE 2.2 Timeliness	MoP 2.2.1 Average Engagement Sequence Time	DR 2.2.1.1 Start Time of Engagement Sequence
			DR 2.2.1.2 Stop Time of Engagement Sequence
COI 3: Susceptibility. Will the HMT team be detected by the enemy during a hybrid operation?	MoE 3.1 Probability of enemy detection at each NAI.	MoP 3.1.1 Determine detection time	DR 3.1.1.1 # of times detected
			DR 3.1.1.2 speed (time) of detection
			DR 3.1.1.3 distance of detection
		MoP 3.2.1 Determine kinetic avoidance	DR 3.2.1.1 # of times engaged
			DR 3.2.1.2 # of rounds avoided
			DR 3.2.1.3 # of times hit
COI 4 Mobility. Is the HMT team capable of traveling in all weather conditions for hybrid operations (speed and obstacles)	MoE 4.1 Calm weather conditions	MoP 4.1.1 Time to on station to observe, identify, and assess enemy	DR 4.1.1.1 # number of targets correctly identified
			DR 4.1.1.2 # number of targets incorrectly identified
			DR 4.1.1.3 average time on station per NAI
			DR 4.1.1.4 average distance covered during operational mission
	MoE 4.2 Hazardous weather conditions	MoP 4.2.1 Time to on station to observe, identify, and assess enemy	DR 4.2.1.1 # number of targets correctly identified
			DR 4.2.1.2 # number of targets incorrectly identified
			DR 4.2.1.3 average time on station per NAI
			DR 4.2.1.4 average distance covered during operational mission
COI 5 Cognitive Overload. Does HMT reduce cognitive overload for the VTOL pilot in the control group versus the experimental group?	MoE 5.1: Timeliness to complete mission tasks	MoP 5.1.1 Average number of tasks per mission	DR 5.1.1.1 Percentage of tasks complete
			DR 5.1.1.2 Average time to complete each task
			DR 5.1.1.3. Average time to engage
			DR 5.1.1.4. Average report processing time
			DR 5.1.1.5. Average time to disseminate information to HICON and friendly forces
		MoP 5.1.2 Human Factors	DR 5.1.2.1 Heartrate measurement, sensor movement, eye tracker
			DR 5.1.2.2 Memory test at post mission analysis
			DR 5.1.2.3 Visual Acuity

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