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SYSTEMS ENGINEERING CAPSTONE REPORT

INCREASING FLEET DATA TRANSFER CAPABILITIES USING AN UNMANNED AERIAL VEHICLE (UAV)

by

Antoin J. Abboud, Katrina M. Granada, Alex R. Kemeny,
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December 2020

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Naval Surface Warfare Center Port Hueneme Division identified the need for an improved ship-to-shore data transfer capability in order to meet future data demands. The demand for a better ship-to-shore data transfer system has been a growing concern in recent years, primarily due to the increasing complexity of combat system elements. These data needs, coupled with advancements in communication technology, will aid in providing an effective and efficient data-transfer system beyond the current limitations of bandwidth. One approach to enhance data transfer capability and supplement existing methods of ship data transfer is the use of unmanned systems as either a primary or secondary means of communication. This capstone delivers a concept of operations, system architecture, and modeling and simulation analysis for a conceptual system intended to meet the United States Navy's need of increasing ship-to-shore data transfer capability. The results shown in the conceptual application of this approach yield a significant operational time reduction when compared to the current method of data transfer. Supported by simulation and data analysis, this reduction in operational time achieves positive results for both the feasibility of using an unmanned aerial vehicle and increasing the capability for ship-to-shore data transfer onboard Navy vessels.

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ABSTRACT

Naval Surface Warfare Center Port Hueneme Division identified the need for an improved ship-to-shore data transfer capability in order to meet future data demands. The demand for a better ship-to-shore data transfer system has been a growing concern in recent years, primarily due to the increasing complexity of combat system elements. These data needs, coupled with advancements in communication technology, will aid in providing an effective and efficient data-transfer system beyond the current limitations of bandwidth. One approach to enhance data transfer capability and supplement existing methods of ship data transfer is the use of unmanned systems as either a primary or secondary means of communication. This capstone delivers a concept of operations, system architecture, and modeling and simulation analysis for a conceptual system intended to meet the United States Navy's need of increasing ship-to-shore data transfer capability. The results shown in the conceptual application of this approach yield a significant operational time reduction when compared to the current method of data transfer. Supported by simulation and data analysis, this reduction in operational time achieves positive results for both the feasibility of using an unmanned aerial vehicle and increasing the capability for ship-to-shore data transfer onboard Navy vessels.

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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	analysis of alternatives
ASK	amplitude shift keying
AUV	autonomous underwater vehicle
BDD	block definition diagram
CONOPS	concept of operations
COTS	commercial-off-the-shelf
CPU	central processing unit
CS	combat system
CSSQT	combat system ships qualification trials
CyE	cyber engineering
DAD	Deployable Aerial Datalink
DOD	Department of Defense
DOE	design of experiments
DT	developmental training
EMD	engineering and manufacturing development
EMI	electromagnetic interference
EVM	earned value management
FCE	forward connection error
FFBD	functional flow block diagram
FRPDR	full-rate production decision review
FSK	frequency shift keying
FSO	free-space optical
GB	Gigabyte
Gbps	gigabits per second
GCS	ground control station
GOTS	government off the shelf
GUI	graphical user interface
HPA	high power amplifier

IAW	in accordance with
IBD	internal block diagram
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
IOT&E	initial operational testing and evaluation
ISEA	In-Service Engineering Agent
Kbps	kilobits per second
KPP	key performance parameter
KU	Kurtz-unter
KVM	keyboard, video, mouse
LAN	local area network
LOS	line of sight
LRIP	low-rate initial production
LTE	long-term evolution
Mbps	megabits per second
MBSE	model-based systems engineering
MIMO	multiple-input multiple-output
MOE	measure of effectiveness
MOP	measure of performance
MSA	materiel solutions analysis
MSSE	Master’s of Science in System Engineering
NAVSEA	Naval Sea Systems Command
NCC	network collection center
NISE	Naval Innovate Science and Engineering
NPS	Naval Postgraduate School
NRC	National Research Council
NSWC PHD	Naval Surface Warfare Center Port Hueneme Division
O&S	operations and support
OAM	orbital-angular momentum
PD	production and deployment

PMS	Project/Program Manager, Ship
PSK	phase shift keying
QAM	quadrature amplitude modulation
RF	radio frequency
RMDA	remote memory direct access
RMF	risk management framework
RN	relay nodes
RoCE	remote memory direct access over converged ethernet
RTB	return to base
SE	systems engineering
SF	ship’s force
SME	subject matter expert
SoI	system of interest
SysML	systems modeling language
TMRR	technology maturation and risk reduction
TOC	total ownership cost
TPM	technical performance measure
TPO	Thesis Processing Office
T&E	test and evaluation
UAV	unmanned aerial vehicle
USN	United States Navy
USV	unmanned surface vehicle
VSU	variable speed unmanned aerial vehicle
Wi-Fi	wireless fidelity
WAN	wireless area networks
WBS	work break down structure
XLUUV	extra-large unmanned underwater vehicle

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EXECUTIVE SUMMARY

This capstone was developed in response to a need for an improved ship-to-shore data transfer capability in support of United States Navy (USN) test events, identified by the Naval Surface Warfare Center Port Hueneme Division (NSWC PHD). Specifically, there was a demand for a faster data transmission method to augment existing ship-to-shore communication networks to support USN test events. Test event analysis and distance support efforts necessitate tremendous amounts of data to be transferred to and from shore-based activities. Data transfer constraints imposed by existing communications systems can prohibit the possibility of timely test event data analysis and distance support efforts. Test events are typically conducted post ship delivery or after an availability period where major system upgrades are implemented. With the current goal of a 355-ship fleet (O'Rourke 2020) and increasing complexity of ship systems, there will be consistent and immediate demand for an improved data transfer capability to support test events for the foreseeable future. In response, the capstone team captured relevant information to develop the capstone problem statement:

> The demand for a better ship-to-shore (bidirectional) data transfer system has been of paramount concern in recent years, primarily due to the increasing data needs of combat system elements. These data needs coupled with advancements in communication technology will aid in providing improved decision-making support and operational capabilities beyond the current shipboard system limitations.

The capstone team identified a technological opportunity to fill this capability gap by leveraging capabilities of existing unmanned aerial vehicle (UAV) platforms to facilitate a supplementary line of communication capable of fulfilling stakeholder requirements. Additionally, this system would have to operate in environmental conditions associated with USN test events, interface with operators at the ship and ground station, establish and maintain a bidirectional data connection as required between the ship and ground station, and have the capability to interface and write data to approved removable media. A conceptual system design was created, named Deployable Aerial Datalink (DAD), with the intent to show that utilizing a UAV platform can

achieve stakeholder objectives. This system was intended to provide increased availability of data from ship-to-shore. The DAD system operational concept consists of using removeable media provided by ship’s force to upload to an external system, which will then communicate with a bolt-on subsystem deployed on a UAV for data upload or relay. In Figure 1, a USN ship equipped with a DAD modular computer subsystem is utilizing the DAD system line of communication to receive or transmit data from the DAD modular computer subsystem via the UAV equipped with a DAD bolt-on subsystem.

Figure 1 - DAD Operational View

The capstone team used a tailored Systems Engineering Vee model during system conceptualization, adapted from International Council on Systems Engineering (INCOSE) and Wiley (2015). The study produced a concept of operations, technical approach, set of feasible candidate solutions, system architecture, system model and simulation, and feasibility results. The derived conceptual system was an aggregate of analysis of existing communication methods and related systems paired with the operational objectives. An analysis of alternatives (AoA) was conducted and four potential solutions were identified for analysis; (1) keep using the existing satellite technology, (2) using a UAV as a relay, (3) using a UAV for receipt and transmission, and (4) using a UAV for data upload and hard drive removal.

From the derived system requirements, a physical architecture was developed by applying partitioning criteria to translate requirements into system functions. System and subsystem functions were then further decomposed, and feasibility criteria was applied to develop a physical system architecture. Functions, interfaces, and system composition were further defined and captured in the system architecture for which the capstone team used the model-based systems engineering (MBSE) tool Innoslate to create the conceptual system. Figure 2 provides a high-level DAD system block definition diagram (BDD).

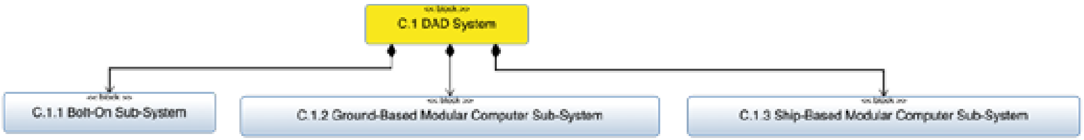

Figure 2 - DAD System BDD

With system requirements and system architectures defined, a modeling methodology was determined in order to derive expected system performance. The modeling and simulation tool ExtendSim was used to analyze relationships between operational time and data rates using specific scenario conditions. Analyses supported the use of UAVs as a data transfer platform and revealed preferable system configurations and system employment methods. Preliminary findings showed promise that the conceptual systems utilizing UAVs have potential to deliver an increased data transfer capacity over existing communications systems at a lower operational cost to the USN.

References

INCOSE and Wiley. 2015a. *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. New York: John Wiley & Sons. http://ebookcentral.proquest.com/lib/ebook-nps/detail.action?docID=4040424.

O'Rourke, Ronald. 2020. *Navy Force Structure and Shipbuilding Plans: Background and Issues for Congress*. Washington, D.C.: Congressional Research Service. https://www.dau.edu/cop/test/DAU%20Sponsored%20Documents/PM%20Cybersecurity%20Guidebook%20v1%200%20with%20publication%20notice.pdf.

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Lastly, and most importantly, the team would like to thank their families for their continuous support, understanding, and encouragement throughout the capstone process.

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I. INTRODUCTION

A. PROJECT OVERVIEW

This capstone report is a result of a collaboration effort formed between Naval Postgraduate School (NPS), Naval Surface Warfare Center Port Hueneme Division (NSWC PHD), and Project/Program Manager, Ship (PMS) 500, to address the issue of existing fleet data transfer limitations**.** The issue addressed in this report was presented to the NPS Systems Engineering (SE) 311–192S cohort capstone team by NSWC PHD.

NSWC PHD provides the United States Navy (USN) surface fleet with integration, test and evaluation (T&E), life-cycle engineering, and product support for today's and tomorrow's warfare systems. NSWC PHD participates in numerous certifying events such as combat system ships qualification trials (CSSQT) and various other developmental and operational test events (Commander Naval Sea Systems Command 2020a). As one of the sponsors of NSWC PHD, PMS 500 "manages the design and construction of destroyers, amphibious ships, special mission and support ships, as well as a wide range of boats and craft for United States (U.S.) agencies and foreign military sales" (Commander Naval Sea Systems Command 2020b).

The capstone team employed a combination of various engineering disciplines (aerospace, computer, mechanical, industrial, and marine engineering), experience supporting the Department of Defense (DOD), research, and subject matter expert (SME) input to develop a potential solution to address an existing data transfer capability gap to support USN test events. The principal goals of this capstone were to investigate the feasibility of utilizing unmanned aerial vehicles (UAVs) to improve ship-to-shore data transferring capabilities and develop a conceptual deployable datalink system.

B. BACKGROUND

As described in 'A Design for Maintaining Maritime Superiority' version 2.0 and the DOD modernization strategy, the global threat landscape is continually changing and the U.S. no longer has the competitive advantage in all areas, making it crucial to modernize our digital world to maintain competitiveness. To ensure advantage in all areas (Department of Defense 2019), the focus must include the role of data in decision making (United States Chief of Naval Operations 2018). USN involvement in maintaining a competitive advantage is instrumental and as a maritime nation, the USN must increase naval power and warfighting capability through “improved readiness and reliability of systems to ensure combat mission capable ships” (Naval Sea Systems Command 2019). Availability of data is at the center of ensuring ships’ combat readiness and meeting the DOD modernization strategy, as it enables “identification needed for subsequent actions, lessons learned, design of improved tactics and systems” (Duren and Pollard 1991), along with “improved decision making support and enhanced operational capabilities” (Office of the Chief Information Officer 2000).

As the In-Service Engineering Agent (ISEA) for multiple USN surface ship combat system elements, NSWC PHD provides distance and on-site support, training, troubleshooting, maintenance, and other logistics and engineering functions. Increased availability of data will enable NSWC PHD to more effectively perform ISEA functions by bypassing typical delays in receiving data and ultimately will contribute to combat system readiness. Typical delays include data shipment and waiting for ships to return from deployment.

C. PROBLEM OVERVIEW

USN T&E events generate immense quantities of data, due to the increasing complexity of modern Naval combat systems. Post-event analysis and distance support efforts require combat system data to be transferred from ship to ground-based activities. Bandwidth limitations imposed by existing methods of data transfer can affect the timeliness of associated analysis required for test event certification or distance support. These issues are central to the vision statement provided by the capstone vision owners:

> Transferring data from ship-to-shore has been and continues to be a challenge for the USN. Unless we come up with a dynamic solution, soon, we will carry this problem onto new developments/platforms. The idea behind this project is to develop a system capable of transferring classified and unclassified data from an UAV to a shore-based site. Although intended for UAVs, the system should also be compatible with other platforms with minimum to no impact to the platform’s infrastructure.

In line with NSWC PHD’s role with providing T&E and direct fleet support to surface ships, the intent of this project is to conceptually design a data transfer platform for UAV deployment to enable faster availability of data for analysis (Commander Naval Sea Systems Command 2020a). The concepts fundamental to design of the data transfer platform included being standalone and external to ships’ infrastructure. This design concept addressed one of the challenges identified by the National Research Council (NRC). According to the NRC, the U.S. continues to struggle to meet the changing needs of ship communications due to constraints regarding available space for communication suites and upgrading infrastructure to rapidly expanding needs (National Research Council 2000). Another important aspect of the conceptual system is the intent to provide a method of ship-to-shore data transfer additional to existing ships’ communication capabilities. As stated in the 2020 USN Information Superiority Vision, a major challenge the USN faces with the transfer of data from ship-to-shore is bandwidth limitations. The path for the data to transit is too constrained to achieve data transfer in time requirements(Office of the Chief Information Officer 2020). One approach to enhance data transmission capability is to supplement existing methods of ship-to-shore data transfer through use of UAVs as communication nodes.

The capstone team developed a system concept named Deployable Aerial Datalink (DAD) to address the deficiencies identified by the capstone vision owners. Accounting for resources and schedule, the capstone team limited the project scope to preliminary design of the DAD system concept.

D. PROJECT OBJECTIVES

The primary objective of this capstone was to investigate the feasibility of utilizing a UAV as a communication node for ship-to-shore data transfer. A secondary objective for this capstone was increasing data availability to ultimately contribute to combat system readiness. A tertiary objective was to provide NSWC PHD and other DOD activities with a feasible option to supplement existing data transfer methods. The last objective of this capstone was to provide NPS and NSWC PHD with the deliverables identified in Table 1.

Table 1. Capstone Deliverables

Deliverable	Description
Analysis of Alternatives	A comparison and evaluation of alternative solutions that meet desired stakeholder capabilities.
Architecture	A graphical representation that defines the structure of the system.
Concept of Operations	A description of integrated system characteristics and objectives from the stakeholder perspective.
Literature Review	A review of available scholarly resources related to the system concept.
Requirements	Definitions of various system functional and non-functional needs.

E. TEAM STRUCTURE

Team Rico organization was structured as shown in Figure 1. Each team member was designated responsible for at least one section, and each team member was expected to contribute to remaining sections. High level descriptions of roles and responsibilities for each project area are described in Table 2.

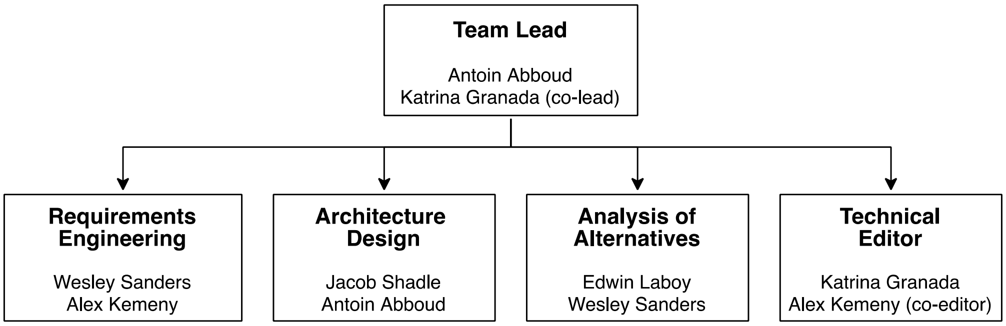

Figure 1. Team Rico Structure

Table 2. Team Roles and Responsibilities

Role	Responsibilities
Project Lead	Led the development of the capstone project and was the focal point for communication with project sponsors; was responsible for setting expectations and direction for the team during the project, developed a project plan, managing deliverables, assign tasks to team, and provided updates on a regular basis to advisors; was responsible for keeping team members and stakeholders informed of key developments and any changes in the project plan; was responsible for mitigating any risk involved as the project progresses
Engineering Analyst	Included responsibility of gap analysis associated with alternative solutions; identified risks associated with each alternative solution
Tech Writers/ Editors	Included responsibility of overall project documentation and ensured proper spelling, grammar, and formatting; tasked with project report management and submission to the Thesis Processing Office (TPO)
System Architects	Included responsibility for the design and documentation of system interface, key system components, and infrastructure; tasked with the overall design of the system and ensuring modeling of system meets technical and functional requirements
Requirements Engineers	Included definition, documentation, and requirements maintainment; modeling and simulation; analysis of stakeholders needs and conversion to requirements into a standard format.

F. STAKEHOLDERS

A list of stakeholders and their primary areas of interest are identified in Table 3. The most important stakeholder identified is the Fleet, as the main goal of increasing availability of data is to contribute to Fleet readiness through improved ISEA support. Other stakeholders for this capstone include NSWC PHD, not only as the vision owners, but as the command that plays a vital role in supporting combat and weapon systems during T&E and ISEA activities; Naval Sea Systems Command (NAVSEA); and Program Executive Offices (PEOs) (Commander Naval Sea Systems Command 2020a).

Table 3. Capstone Stakeholders

Stakeholder	Primary areas of interest
Fleet	Improve combat and weapon system readiness, increase availability of system data for decision making
NSWC PHD	Increase availability of combat and weapon system data to improve readiness, increase knowledge, improve ISEA support
NAVSEA	Improve fleet readiness, increase ISEA effectiveness and support, reduce total ownership cost (TOC)
PEOs	Improve fleet readiness, reduce combat system failure trends, reduce TOC

G. SUMMARY

Maintaining maritime advantage continues to drive the USN to seek new and improved methods of increasing naval power and warfighting capability. Increased availability of data from ship-to-shore contributes to warfighting capability through combat system readiness and enabling ISEAs to better effectively address life cycle issues. The purpose of this capstone was to investigate the feasibility of increasing data through use of UAVs as nodes between ship-to-shore data transfer.

II. TECHNICAL APPROACH

The intent of the DAD system is to increase fleet data transfer capabilities using UAVs. In order to realize this intent, this project used the SE methodology in line with the concepts outlined in the International Council on Systems Engineering (INCOSE) handbook (INCOSE and Wiley 2015a). The same INCOSE handbook provided the following explanations of SE terminology:

> SE is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem… A life cycle can be defined as the series of stages through which something (a system of manufactured product) passes… Functionality of a system is typically expressed in terms of the interactions of the system with its operating environment, especially the users…System architecture is the fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution… The Vee model is a sequential method used to visualize various key areas for SE focus, particularly during the concept and development stages.

A. SCOPE

For this capstone, the Vee model aligned best with the expected deliverables as it provided the framework for system conceptualization. The capstone team tailored the Vee model to fit the unique requirements of conceptualizing the DAD system, as seen in Figure 2 and Figure 3. The scope of this capstone only considered the left side of the Vee model and included aspects of key SE processes defined by INCOSE (2020):

> Establishing stakeholders’ success criteria and concerns, and defining actual or anticipated customer needs and required functionality, early in the development cycle, and revising them as new information is gained and lessons are learned…Investigating the solution space, proposing alternative solution and operational concepts…Architecting a solution or set of solutions based on the selected concept(s)…Modeling (or otherwise evaluating) the solution at each relevant phase of the endeavor…in order to establish required capability and performance; increase confidence that the solution will work as expected and required…Providing the SE knowledge and information required by all stakeholder groups to ensure

coherence of the whole endeavor – typically including a vision statement, operational concepts, architecture definition.

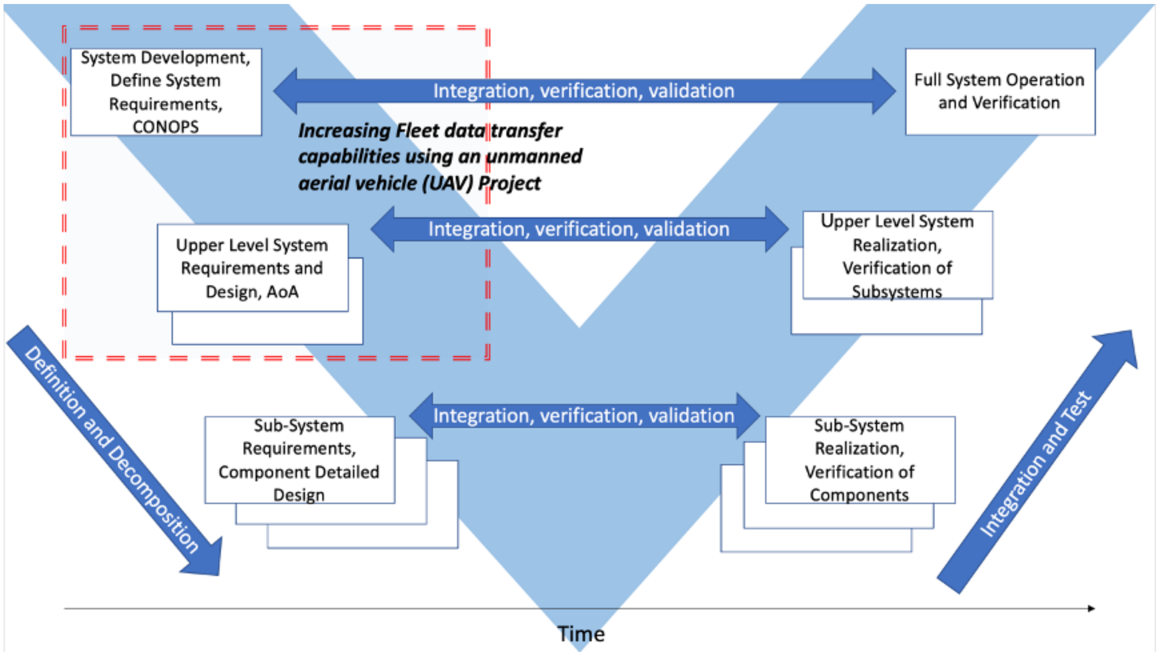

Figure 2. Tailored Vee Model. Adapted from INCOSE and Wiley (2015a).

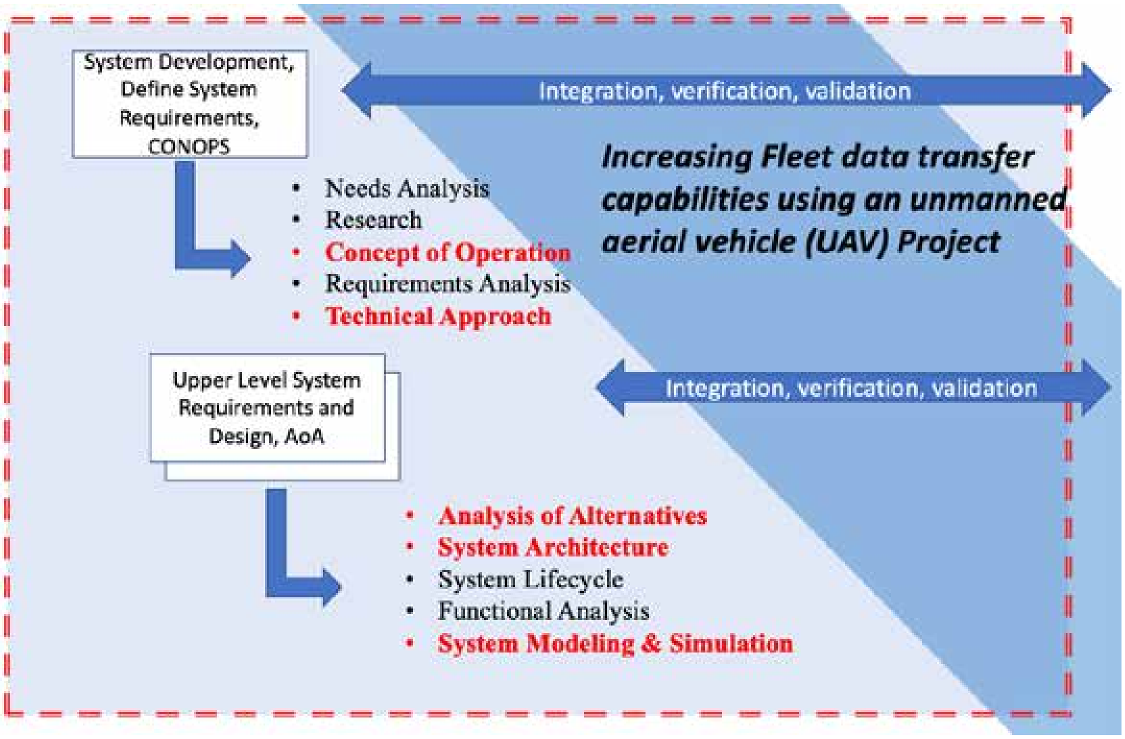

Figure 3. Tailored Vee Model Detail. Adapted from INCOSE and Wiley (2015a).

In conjunction with the tailored Vee model, the capstone team developed a work breakdown structure (WBS) to further detail the SE method. Figure 4 shows the high-level processes used to define stakeholder needs through system architecture design and solution recommendation. Table 4 lists the tools used to perform the SE processes outlined in Figure 4.

B. PROCESS

The first step taken to define stakeholder needs was to translate the stakeholders' vision statement into the capstone problem definition and capstone objectives. This process required review of existing technologies in the fields of ship-to-shore communications, ship to UAV, UAV to shore communications, and bandwidth limitations. The development of the concept of operations (CONOPS) for the DAD system resulted from this process.

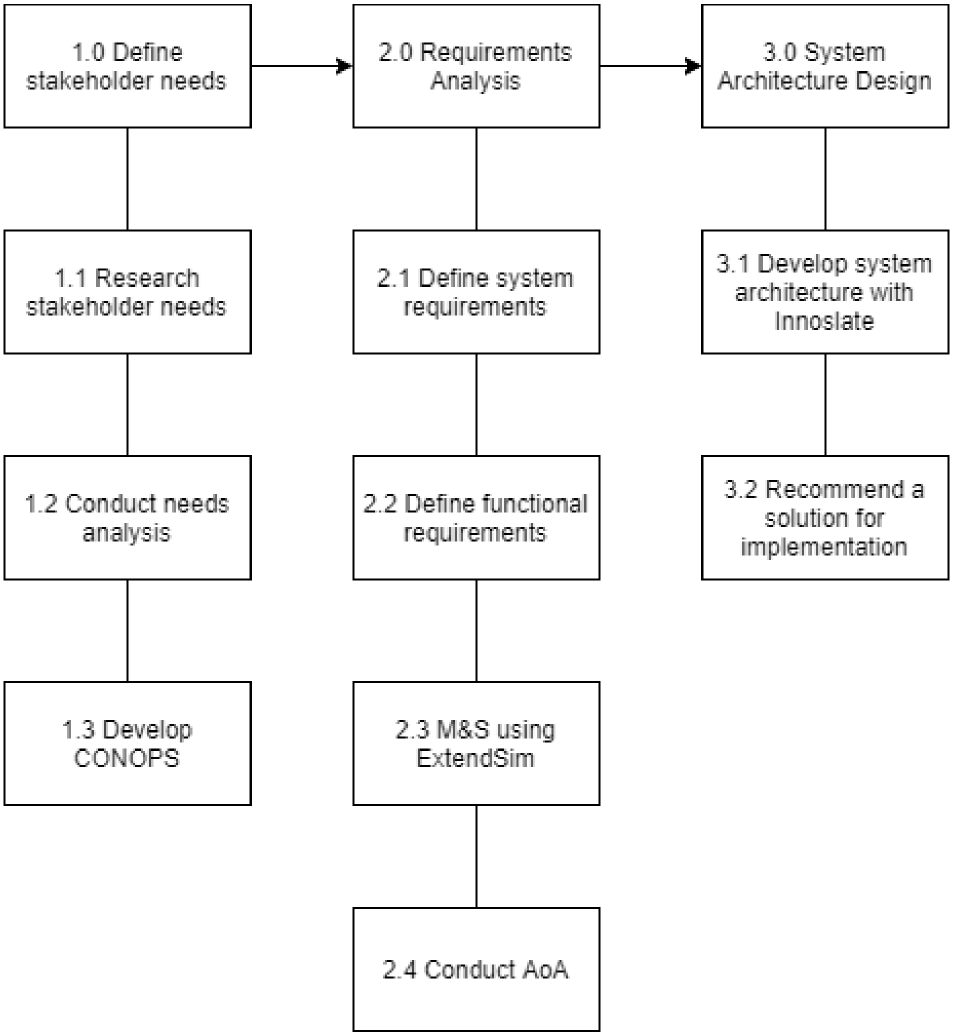

Figure 4. High Level WBS

The next phase in system conceptualization was requirements analysis. During this phase, the capstone team identified system and operational requirements through the analysis of the existing technology review and decomposition of stakeholder needs. ExtendSim software application was utilized to create a mathematical model of the DAD system and simulated the effects of inputs on output performance (Law 2013). Another aspect of the tailored SE process during the requirements analysis phase is the analysis of alternatives (AoA). The AoA enabled evaluation of solutions generated to meet DAD system requirements and identified associated potential risks (AcqNotes 2018b).

Table 4. Tools Used

Program	Description
Microsoft Word	Word processor software used for document creation and editing.
Microsoft Excel	Spreadsheet software used for data visualization, analysis and calculations.
Microsoft Project	Project management software used to outline milestones, deliverables, budget, schedule, and project progress.
Microsoft Power Point	Presentation software used to present project briefings.
Microsoft SharePoint	Cloud service used for file sharing and storage.
Innoslate	Architecture and system modeling software tool used to create diagrams, drawings, and schema of the project.
ExtendSim	Simulation software used for modeling and optimization.

The process of system architecting builds upon the derived system requirements to develop an architecture as a foundation to guide system design (The MITRE Corporation 2013). In line with DOD architecture framework 2.0, the team utilized a multi-step process to develop the architecture framework, as seen in Figure 5. These steps included determining the intended use of the architecture, determining the architecture scope, determining data required to support architecture development, collecting architecture data, conducting analysis of architecture objectives, and presenting results in accordance with decision-maker (or stakeholder) needs (Office of the Deputy Chief Information Officer 2020). Innoslate modeling software was used to create the architectural views that are later provided in this report.

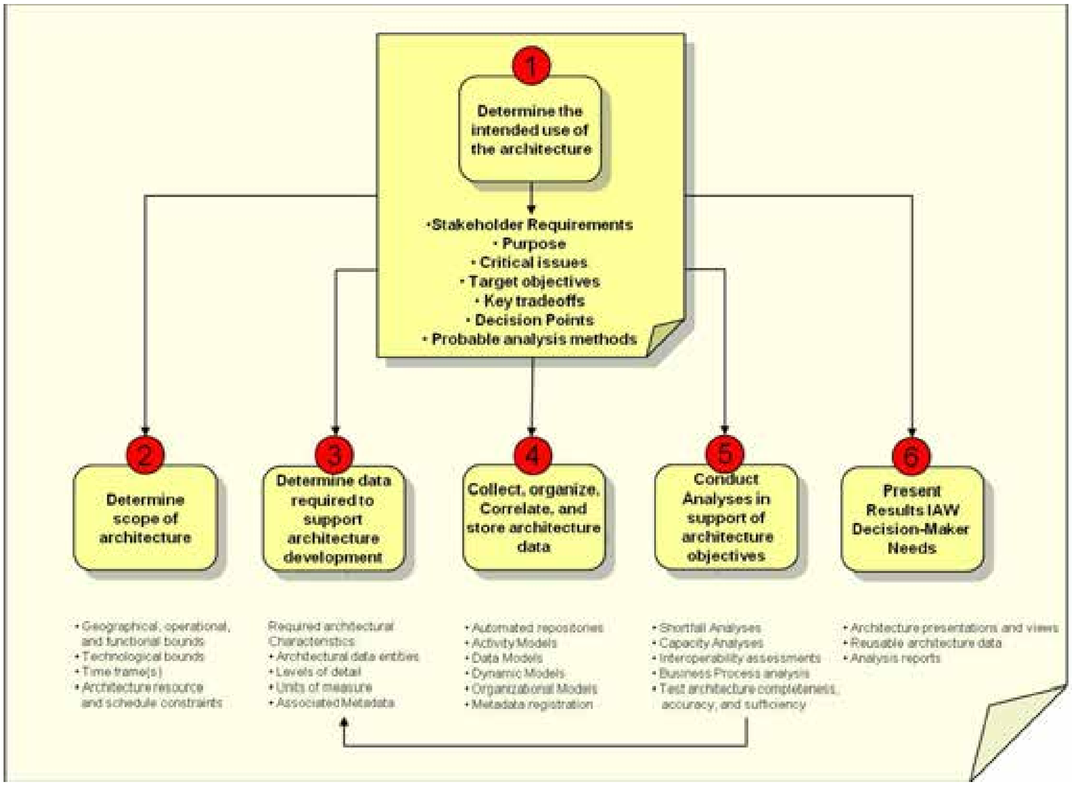

Figure 5. Architecture Development Six-Step Process. Source: Office of the Deputy Chief Information Officer (2020).

C. ASSUMPTIONS AND CONSTRAINTS

The team developed the following set of assumptions and constraints applicable to this capstone scope:

1. Assumptions

- The intent of the system is to supplement existing methods of data transfer.

- The intent of the system is to be temporarily deployed on USN surface vessels for CSSQTs or other test events.

2. Constraints

- Capstone schedule has limited the scope of system development.

- System concept will include use of UAV as directed by vision owners.
- Depth of system concept development is limited to keep capstone unclassified.
- The team did not have the ability to purchase, manufacture, prototype, functionally test, or verify the system outside of conceptualization and model-based systems engineering (MBSE) methods.

Assumptions regarding the operation of the DAD system are listed in Chapter III, Section A.

D. SUMMARY

The scope of this capstone included SE activities found in the left side of the Vee model, including system development, definition of system requirements, a CONOPS, an alternatives analysis, and preliminary system architecture. The required tasks for the capstone were broken down into three main focuses; defining stakeholder needs, requirements analysis, and system architecture design. Assumptions and constraints applicable to the scope of the capstone were identified.

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III. LITERATURE REVIEW

The purpose of this literature review was to research current knowledge and identify knowledge gaps. It includes scholarly reports, scientific journals, technological patents, and academic theses. The research was divided into three sections to enable greater understanding of the different components that are covered by the scope of the capstone project. These documents were analyzed with specific focus on how the capstone team could apply the information to the DAD system. The first section summarizes studies found regarding design considerations. The second section covers performance parameters which focused on findings of effectiveness and efficiency for different data transfer methods. The third section compiles a list of UAV characteristics and performance specifications

A. DESIGN CONSIDERATIONS

Creed and Glenn (2000) were able to transfer data in real-time using radio frequency (RF) links. In order to establish ship-to-shore data communication, each vessel had its own local area network (LAN) which communicated with the shore command center via FreeWave Spread Spectrum Data Transceiver/Ethernet bridge. During their effort, requirements were that it must have high speed data transfer, be able to transfer data over a 20-mile distance and be low cost. Based on their requirements, FreeWave Technologies Spectrum Wireless Data Transceivers provided capabilities required (Creed and Glenn 2000).

Jawhar, Muhamed, Trabelsi and Al-Jaroodi (2016) explored the significance of UAV’s in wireless signal networks (WSN) for data collection as a median between relay nodes (RN) and distribution sinks/Network Collection Centers (NCC). Using a series of UAV algorithms, they developed models that compared the data collection strategies across multiple testing parameters, including UAV flight routes (constant speed, variable speed, adaptable speed) and different data links (RN to UAV, UAV to sink). Such parameters are important to consider for relaying data from an AEGIS platform ship via UAV to a land-based site. With a Variable Speed UAV (VSU), the algorithms considered both when the UAV was in communication with the RN, and when no communication was taking place. Once the data connection was made between the RN nodes and the UAV, Jawar explained that medium range protocols- such as IEEE.802.11- have a data rate ranging from between 1 megabyte per second (Mbps) and 70 Mbps, depending on the height of the UAV's flight. Jawar concluded from the various models that the data transfer rate was dependent on the buffer size of the RN - as the buffer size increased the UAV could deliver more packets to sinks, but the average delay of receiving the data also increased (Jawhar et al. 2016).

Frink (2005) introduced a patent for a data retrieval system which uses a UAV to retrieve collected data from at least one surface data collection instrument. Frink's invention can be placed in a ship and other types of marine vehicles. He stated that satellite data retrieval was limited by at least three constraints: uplink time allocations must be monitored and adjusted frequently, limited time slots available, and required significant amount of power from ground station to communicate effectively. One of the features for this invention was eliminating the need for personnel to retrieve data on-site by launching a UAV to the ground-based data collection instrument which had a transceiver attached to it (Frink 2005).

Wells (2010) discusses the major components associated with a high data rate architecture. These components include a power supply, data interface, modulator, demodulator, transmitter, receiver, combiner, and an antenna. According to Wells, the most important aspect of a power supply is that it has to have a high reliability as well as avoid power loss. The power supply must also "be designed to tolerate poor quality input power with high levels of noise and/or transient spikes and avoid feeding back noise or interference." Techniques to increase "robustness of the data stream" were listed and include forward correction error (FCE), interleaving, and encryption. Four classes of modulation are examined; amplitude shift keying (ASK), frequency shift keying (FSK), phase shift keying (PSK), and quadrature amplitude modulation (QAM). An issue often faced with demodulation is discussed, multipath fading, as well as a common solution, adaptive equalization. The importance of a power detector is to control high power amplifier (HPA) output and output power. A concern for unregulated power output is the possibility of violating licensing rules and interfering with other nearby wireless services. A critical aspect of a receiver is to control the gain of the amplifier, otherwise the signal is at risk for being distorted or the demodulator could be overloaded. Wells introduced a combiner as a method for efficient use of hardware, through utilization of one antenna to perform the actions of a transmitter and receiver. Antenna types are compared for different uses; including highly directional reflector and aperture for long-distance communications, and parabolic and flat panel for high capacity systems. Wells also discusses methods for achieving gigabit per second data rates. These methods include single channel transmission, adjacent channel transmission, dual-polarization transmission, dual channel dual polarization, data compression, and multiple-input multiple-output (MIMO) transmission (Wells 2010).

B. PERFORMANCE PARAMETERS

Yang (2018) proposed more effective data transfer means from a ship to coastal area by designing three different data structures. These data structures included one for RF and long-term evolution (LTE) based networks, one for satellite-based networks (conventional method), and the last for emergency alerts. In this study, Yang states that “satellite-based networks cover the entire ocean, but the costs are very expensive” (Yang 2018).

Johansen et al. (2014), developed experiments testing a UAV as a wireless relay between an autonomous underwater vehicle (AUV) and a local ground control station (GCS). Using geometric calculations to determine optimal data upload based on antenna location, along with constructing an IEE802.11 Wireless fidelity (Wi-Fi) modem link provided five test setups with results in average data rate between 326 kilobits per second (Kbps) and 790 Kbps. The conclusion showed the driver behind the reduction in data rates was the proprietary wireless system on the AUV that provided “a relatively low capacity wireless data link regardless of signal strength and quality,” from the 802.11 standards of 11 Mbps to 54 Mbps (Johansen et al. 2014).

Li et al. (2017), considered the potential of optical communications between a ground transmitter and a ground receiver by using a UAV. By utilizing orbital-angular momentum (OAM) multiplexing, there was significant increased capacity of free-space data transmission to moving platforms. This free-space optical (FSO) communication system included the ground station as well as the OAM transmitter and receiver while the UAV hovered in the air. In the conducted experiments, the authors were able to measure a data transfer rate of up to 80 Gigabits per second (Gbps) over a short roundtrip link (100m) (Li et al. 2017).

Burdakov et al. (2009), presented two algorithms that were capable of generating relays in order to transmit sensor information back to a ground station. For their thesis, all UAVs had the same range for communication. They explained that in order to minimize transmission degradation UAVs require line of sight communication, and, that even though it can be amended by increasing altitude, that will mean greater ranges (Burdakov et al. 2009).

Tierney et al. (2012), compared data transfer protocols over high latency network paths in an effort to achieve efficient and high-performance data transfer. This study was focused on meeting expanding scientific data transfer needs for distributed architectures. Although Tierney, Kissel et al., found that typical data transfers had a 10 Gbps connection or had data transferred in parallel to circumvent bandwidth limitations, their evaluation showed the best per-stream performance was around 13 Gbps, including 40 Gbps hosts. They recommended improvements to data transfer methods including the use of zero-copy systems over the typical send()/recv() and the use of remote memory direct access (RMDA) over converged ethernet (RoCE) (Tierney et al. 2012).

In a UAV cellular communications study, Xiao, Xia, and Xia (2016) discussed the potential issues associated with utilizing a moving communication node. Some of the issues they identified included blockage, beamforming, and propagation loss. Significant signal degradation can occur when line of sight (LOS) from the ground-based station to the UAV is blocked by any structure, but the proposed solution to address this issue is to incorporate adaptive cruising algorithms. Xiao, Xia, and Xia identified thorough beamforming was found to be timely and costly due to a large number of directions for the antenna to train. A hierarchical beamforming structure was investigated and they recommended as a method to significantly reduce search time. Use of a directional antenna was shown to contribute to higher powered received signals (Xiao, Xia, and Xia 2016).

C. UAV CHARACTERISTICS AND SPECIFICATIONS

Table 5 compiles a variety of UAV physical characteristics and performance specifications.

Table 5. UAV Characteristics and Performance Specifications

UAV	Max Takeoff (lb)	Range (mi)	Max Altitude (ft)	Cruise (mph)	Max Speed (mph)	Endurance (Hours)	Wingspan (ft)	Length (ft)
Proteus[1]	12500	1150	61000	219	313	14	78	56
Altus II[2]	2130	460	65000	81	120	24	54	24
MQ-9 Reaper[3]	10500	1150	50000	230	300	14	66	36
MQ-1 Predator IB[4]	2250	770	25000	84	135	24	55	27
RQ-21 Blackjack[5]	135	58	19500	63	100	16	16	8
Tigershark[6]	610	-	14000	63	92	10	22	14
RQ-2 Pioneer[7]	416	185	15100	-	126	-	17	14
Outlaw Sea Hunter[8]	-	-	18000	86	150	9	16	10
RQ-7 Shadow[9]	-	68	15000	81	130	9	14	11
Scan Eagle[10]	49	-	19500	69	92	24	10	6
Vindicator II[11]	-	22/ 100 (with relay)	15000	65	200	3	9	9

[1] Jackson, Peacock, and Munson (2003)

[2] “General Atomics ALTUS” (2019; Gibbs (2017)

[3] “General Atomics MQ-9 Reaper” (2020); United States Air Force (2015b)

[4] “General Atomics MQ-1 Predator” (2020); United States Air Force (2015a)

[5] “Boeing Insitu RQ-21 Blackjack” (2020); Insitu Inc. (2017)

[6] NASC (2020)

[7] “AAI RQ-2 Pioneer” (2020); Military (2020)

[8] “Griffon Aerospace” (2020)

[9] “AAI RQ-7 Shadow” (2020)

[10] “Boeing Insitu ScanEagle” (2020)

[11] QinetiQ (2017)

D. ALTERNATIVES

In order to effectively find potential solutions for increasing availability of data through ship-to-shore data transfer, the capstone team adopted the AoA framework in Figure 6 identified by The MITRE Corporation (2013b). The capstone team identified objectives from the stakeholder vision statement and then defined analysis criteria. The capstone team also utilized the knowledge gained from the literature review and SME feedback to identify, assess, and compare alternatives. This section of the AoA identifies and describes the alternatives that were analyzed using modeling and simulation. Additional detailed analysis is provided in Chapter VI, Section B.

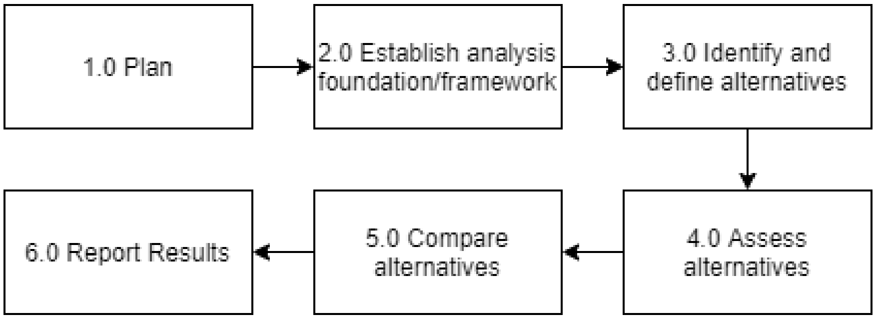

Figure 6. AoA Framework. Adapted from The MITRE Corporation (2013b)

The research of design constraints, performance parameters, and UAV characteristics and performance aided the capstone team with identification of alternatives and important design considerations. Information provided by Johansen et al. (2014); Tierney et al. (2012); Jawhar, Muhamed, Trabelsi and Al-Jaroodi (2016); and Li et al. (2017) was found to be outside of the scope of the capstone. Information provided by Creed and Glenn (2000), Yang (2018), and Frink (2005) were important design and performance considerations but technologies discussed did not fit the scenario in which the DAD conceptual system was going to be utilized. Research by Xiao, Xia, and Xia (2016) was helpful to understand design considerations if utilizing a LOS with a directional antenna. Information provided by Wells (2010) was useful to understand important transceiver design considerations and limitations with range and environment. Data rates and data transfer technologies provided by wells in Figure 7 made a significant contribution, as microwave technology provided the best potential for a data rates and was used as input for modeling and simulation. The data listed in Table 5 provided insight into bolt-on subsystem design constraints as well as flight time limitations for data transfer. The ranges identified for each UAV platform also provided insight into potential use beyond CSSQT scenarios, permitting a data transfer technology that can support longer ranges.

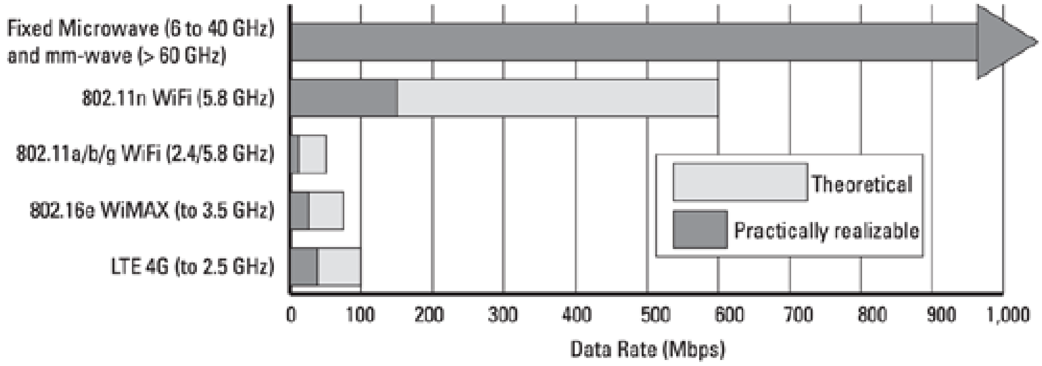

Figure 7. Theoretical and Practical Data Rates via Commercial Technology. Source: Wells (2010)

Based on stakeholder feedback, DOD experience, CSSQT knowledge, and UAV operating knowledge, the capstone team prioritized communication range and potential data rate as focal aspects for alternative solution development. Alternative solutions regarding UAV or ship system integration were not developed or analyzed as they were considered high risk for schedule and cost. The alternatives analyzed were chosen based off limited integration requirements and potential for rapid development and deployment. As specified in the vision statement, the alternatives developed in addition to the baseline data transfer method were centered around UAV utilization.

1. Alternative 1: Existing Satellite Technologies

This alternative will keep the conventional satellite connection as the only method of ship-to-shore data transfer. This method is the control and the benchmark for comparison. Stakeholders identified current data transfer rates range from 9 – 12 Mbps.

2. Alternative 2: UAV as a Relay

The second alternative identified is using a UAV-deployed DAD subsystem as a relay. This method is constrained by technology capability because the range at which the UAV is required to position is equidistant between ship-to-shore. The increase in distance rules out many data transfer technologies due to reduced capability at further distances, as well as some of the UAV platforms listed in Table 5 due to limited endurance and longer data transfer times. Also, increased distance requires greater power for data transmission over longer ranges, a design consideration that may impact UAV platform selection. This alternative enables bidirectional ship-to-shore data transfer.

3. Alternative 3: UAV Wireless Receive and Transmit

The third alternative is using a UAV deployed DAD subsystem with wireless technology for both receiving and transmitting functionality. This method is constrained by UAV platform range capability, as a wireless receive and transmit subsystem would enable the ship to be at a further distance from shore. This method is also constrained by UAV platform endurance due to the increased flight time associated with uploading and downloading data to/from the DAD system components. The ability to have the UAV in closer proximity to the ship widens the data transfer technologies available for utilization. This alternative enables bidirectional ship-to-shore data transfer.

4. Alternative 4: UAV Wireless Receive and Land

The fourth alternative is using a UAV-deployed DAD subsystem to wirelessly receive and store data from the ship onto a removeable hard drive, then return to base (RTB) for personnel to retrieve the hard drive. This method is constrained mainly by the size of the UAV-deployed DAD subsystem, as it cannot exceed maximum UAV payload capacity. The benefit to selecting this alternative is the potential avoidance of limiting UAV platform selection to those with greater endurance, as the UAV would only be required to transit to ship proximity for data upload and RTB for hard drive removal. A second benefit to selecting this alternative is also the avoidance of a more complicated UAV-deployed DAD subsystem design that accounts for data transmission. This alternative restricts data transfer from ship-to-shore and is not bidirectional.

5. Alternative 5: UAV Wireless Receive and Transmit + Land

A fifth alternative identified is a combination of UAV wireless receive and transmit technology with a removeable hard drive. This method has the same constraints as Alternative 3 but has the benefit of hard drive retrieval in case of emergency. This method allows for the time saving benefits of alternative 4 but also for the transmission of data to the ship to support troubleshooting efforts, or as mission dictates. This alternative will not be analyzed as it will be covered through alternatives 3 and 4.

E. SUMMARY

Through the literature review, the capstone team was able to identify different data transfer methods, technologies, and alternatives to ultimately increase data transfer capability. In addition to the current USN date transfer method, alternatives identified were utilization of the UAV as a relay, for wireless receipt and transmission, and for wireless receipt and RTB. The research conducted and alternatives identified showcased important information about the design constraints associated with use of a UAV as a platform for data transfer. This literature review provides multiple perspectives on how the information found can be applied to the conceptualization of the DAD system.

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IV. SYSTEM CONCEPTUALIZATION

A. OPERATIONAL CONCEPT DEFINITION

The capstone team developed a system concept that addressed the data transfer capability gap identified by the vision owners. In addition to increasing availability of data, the system concept was centered around modularity to avoid the complexities of integrating with at least two host platforms. As displayed in Figure 8, the DAD conceptual system is composed of:

- One ship-based modular, standalone computer system capable of having no direct interface with the ship's combat system.
- One bolt on assembly unit external to the UAV, capable of having no direct interaction with the UAV's systems. This bolt on unit will provide the capability of using the UAV as a communication node for data transfer.
- One ground-based modular, standalone computer system capable of using power provided by the ground station.

Figure 8. DAD Operational View

1. Benefits

The operational concept of the DAD system was to transfer ship’s combat system data through utilization of UAVs outfitted with a bolt on deployable data transfer system, enable faster availability to data for SME analysis, and decrease elapsed time between events and decision making. The DAD system will increase ship-to-shore data transfer effectiveness through the following benefits:

- providing an additional method of data transfer redundant to existing methods
- providing an increase to battlespace awareness and an improvement to tactical decision making through faster availability of critical data
- fulfilling a capability gap identified by USN leadership through an increase in data transfer rate
- providing a system with the ability to update software and hardware at a faster rate and potentially lesser cost than existing shipboard systems

2. Operations and Support Descriptions

Operation and support of the DAD system involves participation from ship’s force (SF), DAD operators, UAV pilots, UAV launch and recovery team, element SMEs, and CSSQT team. SF will be responsible for maneuvering the ship to the best UAV link location and downloading the combat system data onto removeable media. The DAD operators will be responsible for uploading/downloading data and establishing communications with the bolt-on subsystem. The UAV pilots will be responsible for guiding the UAV to both ship-based and ground-based link locations and to the launch/ recovery site(s). The UAV launch and recovery team will be responsible for UAV preparation, launch, recovery, and any associated post flight requirements. The UAV launch and recovery team will also be responsible for mounting and unmounting the bolt-on DAD subsystem. The element SMEs will be receiving the downloaded data and will perform analysis as required. The CSSQT team will be responsible for coordinating and executing the data transfer with all involved activities during at-sea events.

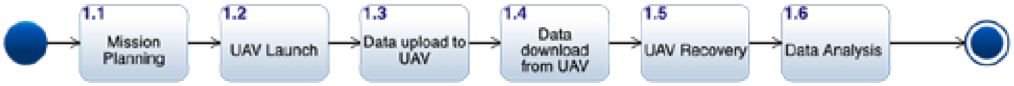

Figure 9. DAD High Level Activity Diagram

Figure 9 shows the various phases associated with utilization of the DAD system. To accomplish data transfer from ship-to-shore via the DAD system, the following general actions have been identified:

1. The CSSQT team, DAD SMEs, UAV teams, and SF will coordinate the planning and execution of using the DAD system for data transfer.

2. Launch team will prepare UAV with the DAD bolt-on subsystem and will launch UAV.

3. Ship’s technician will pull data from the combat system and will store on removeable media.

4. Ship’s technician will provide the removeable media to the ship-based DAD operator.

5. Ship-based DAD operator will load the combat system data onto the modular computer subsystem.

6. UAV will arrive at designated location; ship-based DAD operator will initialize communications with the DAD bolt-on subsystem and will begin data transfer process.

7. UAV will travel to a designated location near the ground station, ground-based DAD operator will initialize communications with the DAD bolt-on system and will begin data transfer process.

8. Ground-based DAD operator will verify data transfer and download completion with ship-based DAD operator and UAV operator.

9. UAV will continue mission or RTB for recovery.

10. Ground-based DAD operator will upload combat system data to a designated server for combat system element SME access.

11. Combat system element SME will analyze data and provide solutions/ recommendations to decision makers.

3. Operational Assumptions

To keep in line with the scope of this capstone and to simplify the operational process, the following assumptions were made with regards to transferring data via the DAD system:

- DAD system utilization will occur on a predetermined day during CSSQT execution, after completion of specified event(s). This will include all requirements relative to test range scheduling.
- The UAV that will carry the bolt-on subsystem will be identified prior to CSSQT execution during the course of planning phase.
- Data transfer was limited to combat system data but can be expanded to any data available for transfer via removeable media.
- The modular computer subsystem will utilize available shipboard removeable media to transfer and upload data.
- The ship will be responsible for properly handling the removeable media after the ship-based DAD operator has completed the data transfer.

- No distinction was made between the transfer of classified and unclassified data.
- DAD system utilization was limited to use of one UAV, but multiple UAVs with bolt-on subsystems can be used as communication nodes to relay data from further distances.
- Data transfer will not exceed UAV loiter time.
- The ground-based DAD operator and applicable SMEs will have access to the same server.

B. SYSTEM LIFE CYCLE

DOD acquisition models subdivide the system life cycle into a set of basic steps that separate major decision milestones. The decisions of these milestones are based on the result of completed system objectives in the preceding life cycle phase, as shown in Figure 10.

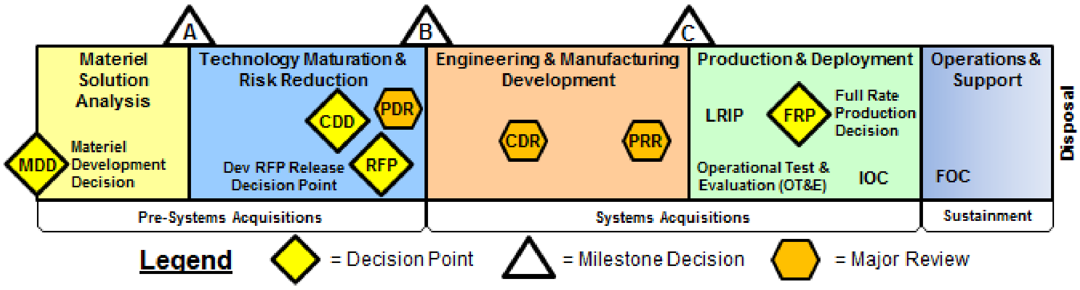

Figure 10. DOD Acquisition Management Model (DOD 5000.2). Source: AcqNotes (2018c).

1. Materiel Solutions Analysis (MSA) Phase

As identified by AcqNotes (2018d):

> The purpose of the MSA Phase is to analyze all potential material solutions for an identified need. This phase consists of an AoA and material solution activities to include measures of effectiveness, cost estimates, schedule, CONOPS and risk assessment. The goal of this phase

is to recommend possible solutions for further exploration in the Technology Maturation & Risk Reduction (TMRR) Phase.

The MSA Phase for this capstone is divided into three stages: needs analysis, concept exploration, and concept definition. Given the scope of this capstone, project deliverables and objectives are met through the MSA activities, highlighted in Chapter IV, Section C through Chapter IV, Section E of this report, as well as the AoA in Chapter VI, Section B.

During the MSA phase, cyber engineering (CyE) efforts focus on gaining an understanding of the system mission, operational environment, and the program's risk management strategy. The CyE tasks for this phase include development of cyber functional requirements driven by assurance of mission critical functions, system categorization based on mission, and the initiation of security control selection. These functional requirements can serve as the baseline for the Cybersecurity Battle Plan, which includes a Cybersecurity Strategy, Program Protection Plan, Security Assessment Report and Security Authorization Package (Department of Defense 2015).

a. Needs Analysis

The capstone team conducted an extensive literature review and used stakeholder and SME feedback throughout the first phase of system conceptualization. As a result, the capstone team was able to identify existing operational deficiencies and capability gaps in current data transfer methods. "Without proper understanding of the user needs, any system runs the risk of being built to solve the wrong problems" (Fairley, Forsberg, and Madachy 2020). Section C, Needs Analysis, answered the questions "Is there a need for a new system?" and "How will this need be satisfied?." The purpose of the needs analysis was to provide a description of capabilities needed in the system of interest (SoI).

b. Concept Exploration

The concept exploration phase provides an initial set of system performance requirements which will be measured later against a set of required capabilities and performance. This set of requirements are described in Section D for the DAD system concept. Evaluation parameters were identified and deemed critical in order to evaluate system operational effectiveness. In order to proceed to the concept definition phase, the following elements needed identification: the system boundary, system functions, system elements, system sub-elements, and system element interactions.

c. Concept Definition

The goal of the concept definition phase is to identify a set of SoI functional specifications. Section E describes in detail the SoI's intended usage and its capabilities. These sets of functional requirements described the DAD system operational intent and the capability that will be provided to its stakeholders. This phase delivered a set of architecture models created using Innoslate. For the AoA discussed in Chapter II, verification matrices were created and supporting details are provided with supporting details for each of the alternatives analyzed.

2. Technology Maturation and Risk Reduction (TMRR) Phase

As identified by AcqNotes (2018d), the purpose of the TMRR phase is to "reduce technology risks and to determine the appropriate set of technologies to be integrated into a future system that satisfies the needs. . . . This phase will consist of risk reduction, cost estimations, and programmatic activities." The major product of the TMRR phase is competitive prototyping from which an applicable program office will determine at Milestone B which prototype will proceed as a funded, program of record.

The continued development of the DAD system would allow government contractors to compete with government off the shelf (GOTS), commercial-off-the-shelf (COTS), or new development DAD system components. Based on the complexity and design requirements for the modular computers, multiple vendors could bid on any or all of the data transfer computer subsystems.

During this phase, it is important to design hardware and software concepts with cyber capabilities in mind. In the case that the DAD system is fielded, stakeholders must analyze the best method to address obsolescence while accounting for both cost and schedule. With risk management, the system development team must consider the effects of hardware and software obsolescence on the overarching acquisition process and cyber capability issues.

3. Engineering and Manufacturing Development (EMD) Phase

The purpose of the EMD phase is the realization of the system design. “The goal of the EMD phase is to complete the engineering development and proceed into production and development”(AcqNotes 2018d). Major activities in this phase include developmental testing (DT) and initial operational test and evaluation (IOT&E) (AcqNotes 2018a).

If the DAD system development continued to this phase, the selected prototype vendor(s) would be funded to further design and test through laboratory and experimental scenarios. DT and IOT&E at land-based test sites can showcase data transmission capabilities and can progress to sea-based testing when the system is demonstrated as mature.

Regarding CyE efforts during this phase, the security T&E engineer must have security controls and requirements assessed, the cyber risk assessment updated, and the risk management framework (RMF) package submitted. It is critical that cyber capabilities maintenance procedures and manuals include system administration requirements, procedures for patching, virus scanning, antivirus signature updates, amongst others.

4. Production and Deployment (PD) Phase

Defined by AcqNotes (2018d), the objective of the PD phase is to:

> Achieve an operational capability that satisfies the users and mission needs. This phase consists of two efforts: low-rate initial production (LRIP) and full-rate production decision review (FRPDR). The phase will also include operational testing of the capability to determine its effectiveness.

An operational DAD system finishes operational testing in a sea-based scenario with a USN vessel with full system validation, and the applicable program office will fully fund contractors to build and deploy DAD systems.

5. Operations and Support (O&S) Phase

"The purpose of the O&S phase is life-cycle sustainment and disposal. The life-cycle sustainment activities overlap the FRPDR effort of the PD phase. The phase ends with the final disposal of a system" (AcqNotes 2018d).

The sustainment efforts of the DAD system depend on a number of factors, including ISEA support, DAD system inventory across the U.S. fleet (potentially including Foreign Military Sales to allied nations), and adaptability of the system to upgrade across newer UAV platforms, hardware/software upgrades, and hardware/software obsolescence.

C. NEEDS ANALYSIS

The objective of conducting a needs analysis is to identify that a valid operational need exists and that a new system will fulfill that need at an affordable cost with an acceptable level of associated risk. The needs analysis is critical in revealing why a new system is needed and allows for a conceptualization of a successful system to form in the minds of stakeholders by producing arguments that support the stated needs. The needs analysis should answer the following questions: (Blanchard and Fabrycky 2011)

(1) What is required of the system in "functional" terms?

(2) What functions must the system perform?

(3) What are the "primary" functions?

(4) What are the "secondary" functions? What must be accomplished to alleviate the stated deficiency: when must this be accomplished?

(5) Where is it to be accomplished?

(6) How many times or at what frequency must this be accomplished?

As seen in Figure 11, the primary inputs of the needs analysis are operational deficiencies and technological opportunities. The team first derived inputs for the needs analysis from the provided vision statement, followed by a more in-depth exploration of background information, stakeholder needs, and a technical review.

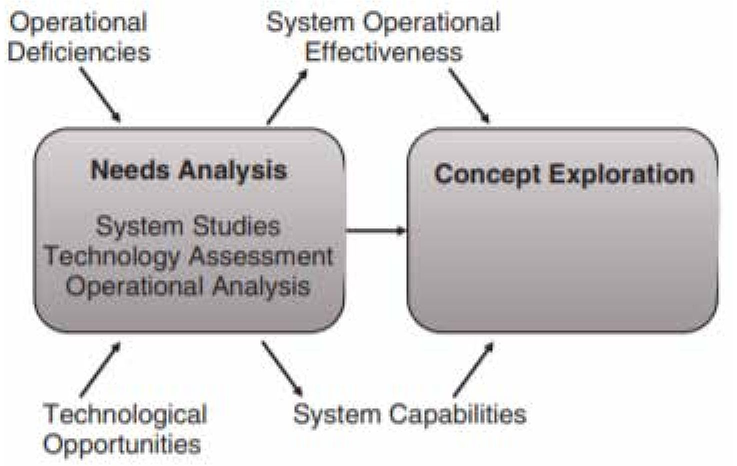

Figure 11. Needs Analysis Phase in the System Life Cycle. Source: Kossiakoff (2011).

Operational deficiencies were initially identified by the stakeholder vision statement and were further refined by follow-on research in the background and technical review. The primary operational deficiency identified was the demand for a faster data transmission method to augment existing ship-to-shore communication networks to support USN test events. Test event analysis and distance support efforts necessitate tremendous amounts of data to be transferred to ground-based activities. Bandwidth constraints imposed by existing communications systems can prohibit the possibility of both timely test event data analysis and distance support efforts.

The capstone team identified a technological opportunity to fill this capability gap by leveraging capabilities of existing UAV platforms to facilitate a new line of communication capable of fulfilling stakeholder requirements. The capstone team set out to develop a novel system to augment existing USN communication systems with one that can handle the steep data transfer requirements associated with USN test events. Additionally, this system would have to operate in environmental conditions associated with these events, interface with operators at the ship and ground station, establish and maintain a bidirectional data connection as required between the ship and ground station, and have the capability to interface and write data to approved removable media. Test events are typically conducted post ship delivery or after an availability period, where major system upgrades were implemented. With the current goal of a 355-ship fleet

(O’Rourke 2020) and increasing complexity of ship systems, there will be consistent and immediate demand for an improved data transfer capability to support test events for the foreseeable future. The majority of test events occur on ranges in U.S. territorial waters. These ranges have an existing infrastructure and established distances between ship operational areas and ground stations.

Partitioning criteria was applied to translate that information into functions and further allocate those functions into subsections. System and subsystem functions were then further decomposed, and feasibility criteria was applied to formulate the feasibility of the DAD concept. The derived conceptual system was an aggregate of analysis of predecessors and related systems and paired with operational objectives.

D. REQUIREMENTS ANALYSIS

Maintaining progression through the systems engineering process, the requirements analysis phase examines the operational perspective of the DAD system and states requirements in terms of project objectives. The intent of the requirements analysis is to restate or amplify both the system capabilities and system operational effectiveness associated with the overall operational objectives. The analysis performed in this section is derived from the definition of stakeholder needs as well as background research applicable to system designs regarding UAV data transfer.

The requirements analysis can be expanded into a process of tasks to transform the system capability inputs into more specific functional system performance requirements. By utilizing the Institute of Electrical and Electronics Engineers (IEEE) P1220, the capstone team was able to follow the systems engineering standard for performing a comprehensive process in completing the Requirements Analysis (Defense Acquisition University 2001). The capstone team tailored the list to consider all necessary DAD system requirements.

1. Customer Expectations

The vision owners for this project understood both the project objectives in their entirety and the validation process for the DAD system. Throughout our collaborative meetings they expected our evidence to achieve its intended use in the conceptual, operational environment within the academic timeframe allowed.

2. External Constraints

The list of external constraints can be sub-categorized by Academic Compliance constraints and System Capability constraints.

a. Academic Compliance

Given the educational aspect of this hypothetical data transfer system, the information released for viewing and referencing purposes to the general public must comply with DISTRIBUTION STATEMENT A: Available for Public Use (Defense Technical Information Center 2012) .This restricts sharing any potential classified, proprietary, operational or otherwise vulnerable data and information.

b. System Capability

The scenarios in which the DAD system operates involves the respective subsystems and their components to interact with both existing ship and shore software and hardware systems, which can limit the interface capabilities. There are additional cybersecurity risks to be considered when transferring classified data between ship and shore subsystems.

3. Operational Scenarios

In order to achieve the project objectives in the allotted academic timeframe, the operational scope consists of a small scale, single UAV to transfer data as a communication node from ship-to-shore, during a CSSQT or other test events. Chapter VI explains a post feasibility study that allows for expansion of the operational scenario capabilities.

4. Utilization Environments

The hypothetical operational scenarios include ideal maritime environmental conditions to transfer data from ship-to-shore during CSSQT or other test events. These ideal conditions include daytime, clear weather (no low-pressure systems present in the operational area), with steady sea-state conditions.

5. System Boundaries

There are multiple boundary considerations for this project- operational, hardware, software- that define the full capabilities of the DAD system. We have greater interest in the hardware and software boundaries of the system, as these are best represented by the systems architecture framework. The framework can outline the UAV, ship and shore subsystem locations and their physical components, including operators and removable media, as well as the operating system functional data paths within the communication relay of the system.

Given the conceptual design scope of this project, physical interfaces were considered as a suggestion based on both ergonomic principles and existing shipboard installation availability. The physical configuration spaces on both ship and shore may allow a smaller subsystem that is deployable, with modularity and a quick setup.

6. System Requirements

System requirements were partitioned between functional and non-functional requirements. The capstone team developed the following requirements for the DAD system after multiple feedback discussions with subject matter experts on both UAV's and communication relays:

a. Functional Requirements

Functional requirements were further decomposed in Chapter IV, Section E.

- System shall have a human interface for the ground-based and ship-based subsystems.
- System shall have a user-friendly graphical user interface (GUI) for the ground-based and ship-based subsystems.
- System shall operate in clear weather conditions.

- System shall establish and maintain a bidirectional data connection.
- System shall receive/write data via authorized removable media.
- System shall have an operational availability of xx% (threshold) or xx% (objective).
- Bolt-on subsystem shall be able to withstand takeoff, landing, and in-flight conditions
- Bolt-on subsystem shall be deployable with xx minutes.
- Bolt-on subsystem shall be uninstalled within xx minutes.

b. Non-functional Requirements

- System shall transfer data at a minimum rate of xx Mbps (threshold) or xx Mbps (objective)
- Ship-based modular computer subsystem shall utilize 110v electrical outlet.
- Systems shall encrypt data at rest on portable and removeable media.
- All DAD system sub-components shall have an encryption and decryption capabilities.
- System shall encrypt data in transit.
- Bolt-on subsystem shall have a minimum battery life of xx hours (threshold) or xx hours (objective).
- Bolt-on subsystem shall be under xx pounds (lbs) and xx cubic feet (ft).
- Bolt-on subsystem shall be battery powered.

E. FUNCTIONAL ANALYSIS

There is an importance to analyze what the system must do before describing how those system capabilities are to be completed. The Functional Analysis offers a decomposition of the system functional requirements through several subsystems arranged in a hierarchical structure (Whitcomb 2000). The DAD system can be decomposed into its modular and bolt on subsystems' functional flow with respect to the functional requirements listed in Section D.

1. Functional Flow Block Diagram (FFBD)

Utilizing an FFBD relates the inputs and outputs of the DAD system while providing insight into the flow between the different system functions (INCOSE and Wiley 2015b). The conceptualized scenario involves data input from either a ship-based or ground-based user on the respective modular computer subsystem. That data package is sent from one modular subsystem through a UAV's transmitter/receiver bolt-on subsystem as a relay for data retrieval to the other modular subsystem. A system level FFBD is illustrated in Figure 12.

Figure 12. DAD System Level FFBD (ship-to-shore data transfer)

Figure 12 defines the functional scope of the DAD system, showing both communications between the ship and shore on UAV services, and the data transfer interactions between the modular and bolt-on subsystems. Note that this functional example did not implement bi-directional flow in the same diagram, but each of the functional steps would proceed in the same order had the shore requested UAV services to send data from the shore modular subsystem to the ship modular subsystem.

2. Functional Requirements Decomposition

a. System shall have a human machine interface for both ground-based and ship-based subsystem

For any ship test event, the process of communicating data starts with SF (both enlisted and officers) relaying data packages to be received and interpreted by government ISEAs. In order for the data to be extracted, both SF and ISEA must have the physical capability to access the means to insert/compress the data to be sent, as well as extract/decompress the relayed data package.

b. System shall have a user-friendly GUI for the ground-based and ship-based subsystems

To assist with efficient use of both computer subsystems, the GUI shall have an application that is easy to navigate with clear and concise information.

c. System shall operate during clear weather conditions

This requirement is necessary for reliably conducting data transfer operations using the DAD system. Inclement weather conditions provide increased risk for impaired data transfer capability, or event cancellation altogether.

d. System shall establish and maintain a bidirectional data connection as required to both ground-based and ship-based subsystems

The UAV will have a predetermined flight plan, based on the request from the ship. The UAV will proceed on course until in range to establish a data connection; the UAV would fly in a loitering pattern about the ship to ensure a stable connection to upload the data package. The ship would minimize its own change of course to keep a consistent loitering pattern. In the event of a loss of communications or loss of global positioning system (GPS) signal between the UAV and the ground operators, programmed protocols would guide the UAV back towards the ground station until communication link could be reestablished.

e. System shall receive/write data via authorized removeable media

The DAD system is conceptualized around existing shipboard spaces and overall physical attributes, as well as hardware/software suites within the applicable combat system baseline.

f. System shall have an operational availability of xx% (threshold) or xx% (objective)

Operational availability is a function of reliability, maintainability, and supportability. The better the operational availability, the greater the capability for the USN. (Office of the Chief of Naval Operations 2003)

g. Bolt-on subsystem shall be able to withstand takeoff, landing, and in-flight conditions

Exposure to extreme environmental conditions requires the bolt-on subsystem to be tested for shock, vibration, thermal cycling, salt-water, fog, electromagnetic interference (EMI), and others.

h. Bolt-on subsystem shall be deployable within xx minutes

UAV deployment is dependent on acceptable launch conditions, potentially decreasing the amount of time available to install the bolt-on subsystem. In order to be available for use during real time decision making, the bolt-on subsystem must be able to be installed within a given timeframe to avoid further launch delays.

i. Bolt-on subsystem shall be uninstalled within xx minutes

To be able to effectively maintain data control, is it important for the system to be easily uninstalled in order to perform any direct download or sanitization.

F. SUMMARY

The capstone team expanded the idea of a data transfer system into an operational concept that addressed the data transfer capability cap identified by the vision owners. Considering the program requirements of acquiring a future DAD system, a layout of the system life cycle was addressed by subdividing system deliverable across the multiple phases of DOD Acquisition. Given the conceptual scope of this project, most of the capstone deliverables were shown in the MSA phase. This included a needs analysis that identified an existing operational need and a concept exploration that included a requirements analysis restating both system capabilities and system operational effectiveness. Finally, a concept definition showed a functional analysis that described how the system capabilities were to be completed.

V. SYSTEM ARCHITECTURE

System architecture provides a foundation for design and development through organization of system components, their relationships to each other and to their environment (The MITRE Corporation 2013). System architecture communicates the system’s design through visual representation of functionalities, interfaces, and requirements to ensure desired stakeholder requirements will be met. The architecting process also helps to define system constraints, boundaries, and additional requirements.

The architecture for the DAD system was developed in accordance with (IAW) the DOD framework shown in Figure 5 (Office of the Deputy Chief Information Officer 2020) using the MBSE tool Innoslate. Different system diagrams were developed in order to showcase the DAD system and its functionalities on a broader level. Systems modeling language (SysML) was used to create the following diagrams: requirements diagram, package diagram, block definition diagram, use case, activity diagram, and a sequence diagram.

A. REQUIREMENTS DIAGRAM

Development of the DAD system architecture began with the identification of system requirements. The purpose of requirements diagrams is to represent relationships between requirements, as well as partition those requirements into functional and non-functional groups (SysML.org 2020b). DAD system requirements were initially conceptualized by stakeholder needs and were refined through research and technical review. Figure 13 shows a high-level requirements diagram for the DAD system. System functional requirements define basic system behavior and for the DAD system included interface, operational environment, data transfer, UAV launch, and availability requirements. Non-functional requirements define how the system will perform its behavior and for the DAD system included performance, design, and software security requirements (QRA Team 2019). The requirements identified in Figure 13 were previously discussed in Chapter IV, Section D.

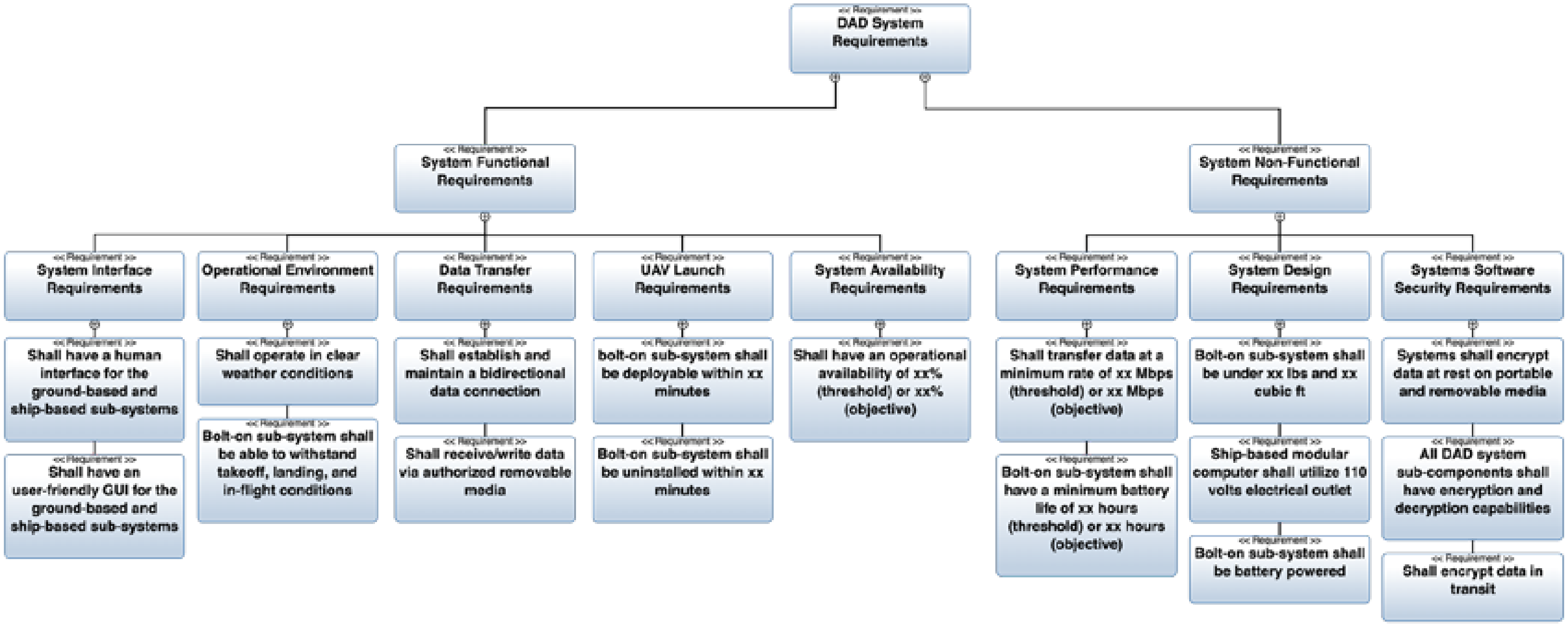

Figure 13. DAD System Requirements Diagram

B. HIERARCHY DIAGRAM

The purpose of a hierarchy diagram is to show the SoI with the physical context of its intended environment and external systems. Through visualization of physical relationships, a better understanding can be gained about the system interactions and boundaries. Figure 14 shows the upper levels of the DAD system alongside the external systems associated with utilization of the DAD system for data transfer. Fourth level subsystems were shown on select third level subsystems to simplify the hierarchy diagram.

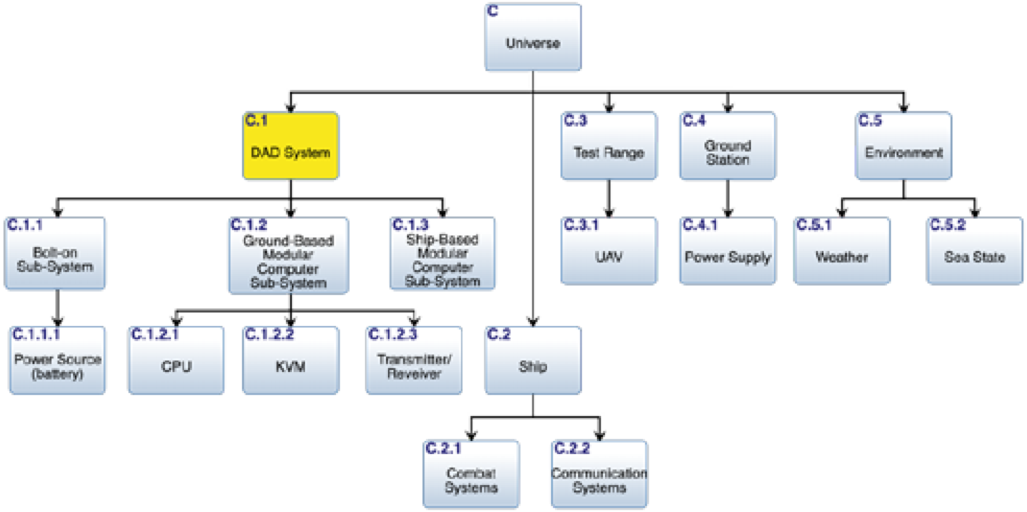

Figure 14. DAD System Hierarchy Diagram

C. PACKAGE DIAGRAM

The purpose of a package diagram is to support the organization of complex system architecture through ‘decomposed by’ (solid lines) or ‘ related to’ (dashed lines) relationships between elements packaged with unique identifiers (SysML.org 2020a). For this capstone, a mission planning package diagram was created to show the elements associated with using the DAD system for data transfer during a CSSQT. Figure 15 also shows how the DAD system fits into CSSQT execution. To keep in line with the scope of this capstone, the DAD system is shown as an additional method of data transfer, next to currently used methods of satellite and hand-carrying data transfer. Combined with the high-level physical relationships identified in the hierarchy diagram, the non-physical relationships identified in this package diagram helps to visually represent the activities and entities involved with using the DAD system to transfer data during a CSSQT.

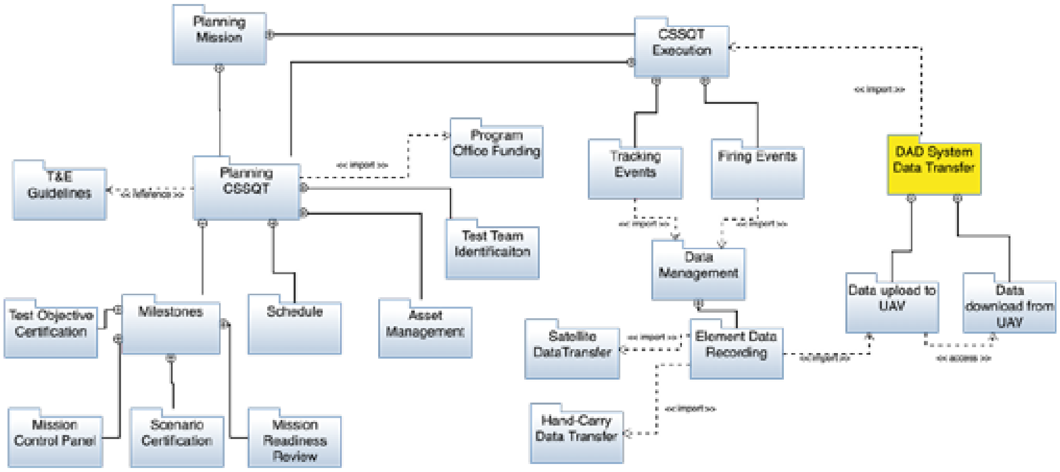

Figure 15. DAD System Mission Planning Package Diagram

D. BLOCK DEFINITION DIAGRAM (BDD)

The purpose of a BDD is to define the features of a block as properties, operations, and relationships; and relationships between blocks as associations and dependencies (No Magic, Inc. 2020). The BDDs shown in Figures 16 through 19 breaks down the DAD system into its subsystems and subcomponents. Additionally, the external actors are shown via aggregation. Figure 16 shows the DAD system decomposed into its three major subcomponents: the bolt-on UAV unit, ground-based modular computer subsystem, and ship-based modular computer subsystem.

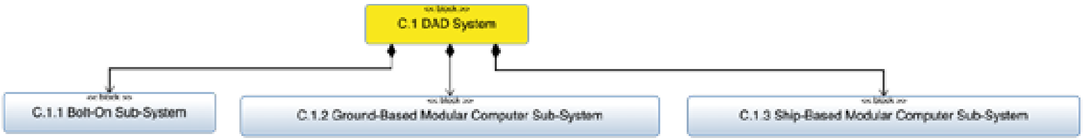

Figure 16. High Level DAD System BDD

Figure 17 decomposes the bolt-on UAV unit into its respective subcomponents including the transmitter receiver, power supply, power distribution module, network switch, and central processing unit (CPU). An aggregation relationship between the UAV and bolt-on UAV unit are shown.

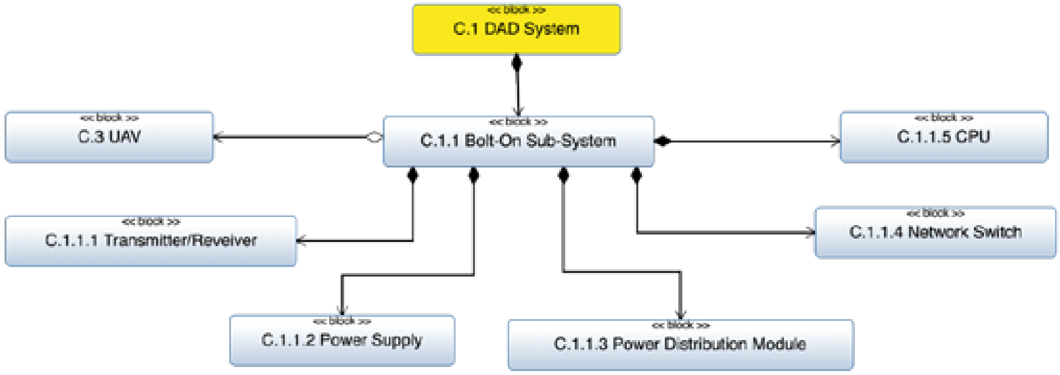

Figure 17. DAD Bolt-On UAV Subsystem BDD

Figure 18 decomposes the ground-based modular computer subsystem into its respective subcomponents, including the CPU, KVM (Keyboard, Video, Mouse), and transmitter/receiver. Aggregation relationships with the ground-based operator and ground station power supply are shown.

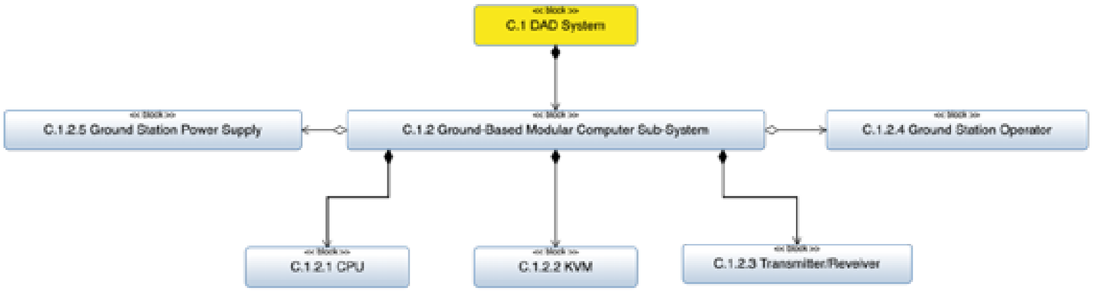

Figure 18. DAD Ground-Based Subsystem BDD

Figure 19 decomposes the ship-based modular computer subsystem into its respective subcomponents, including the CPU, KVM, and transmitter/receiver. Aggregation relationships with the ship-based operator and shipboard power supply are shown.

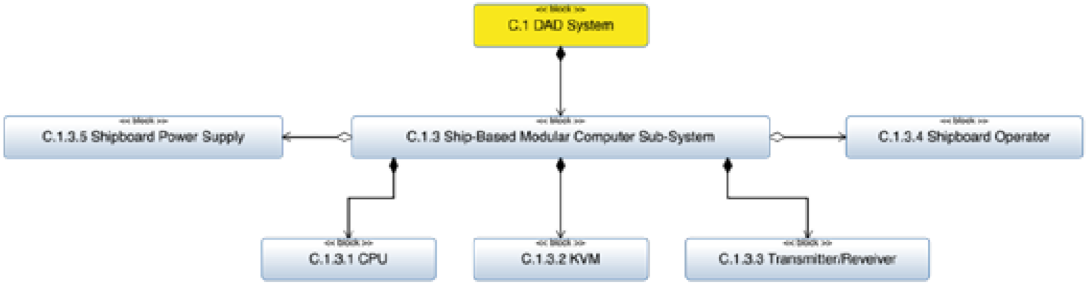

Figure 19. DAD Ship-Based Subsystem BDD

E. USE CASE DIAGRAM

A use case diagram represents system transactions with external actors. System transactions are represented by ovals with action-oriented verbs or phrases, system boundaries are represented by rectangles and have unique identifiers, and actors are represented by stick-figures. Use case diagrams can also be used to identify top level requirements (SysML.org 2020d).

Figure 20 shows the actors and transactions associated with the UAV launch and data upload to UAV boundaries. To simplify the diagram, top level actions were used within the shown system boundaries. For the UAV launch portion of the operational sequence, three main transactions were identified; equip UAV with bolt-on subsystem, prep UAV to launch, and launch UAV. The actors associated with the UAV launch transactions are the DAD team, launch team, and UAV pilot. For the data upload to UAV portion of the operational sequence, five main transactions were identified; pilot UAV, verify intercept location, upload data to the modular computer ship-based subsystem, upload data to bolt-on subsystem, download combat system (CS) data, and maintain bare steerage. The actors associated with this phase are the UAV pilot, DAD SME, bolt-on subsystem, ship-based modular computer subsystem, and ship's force.

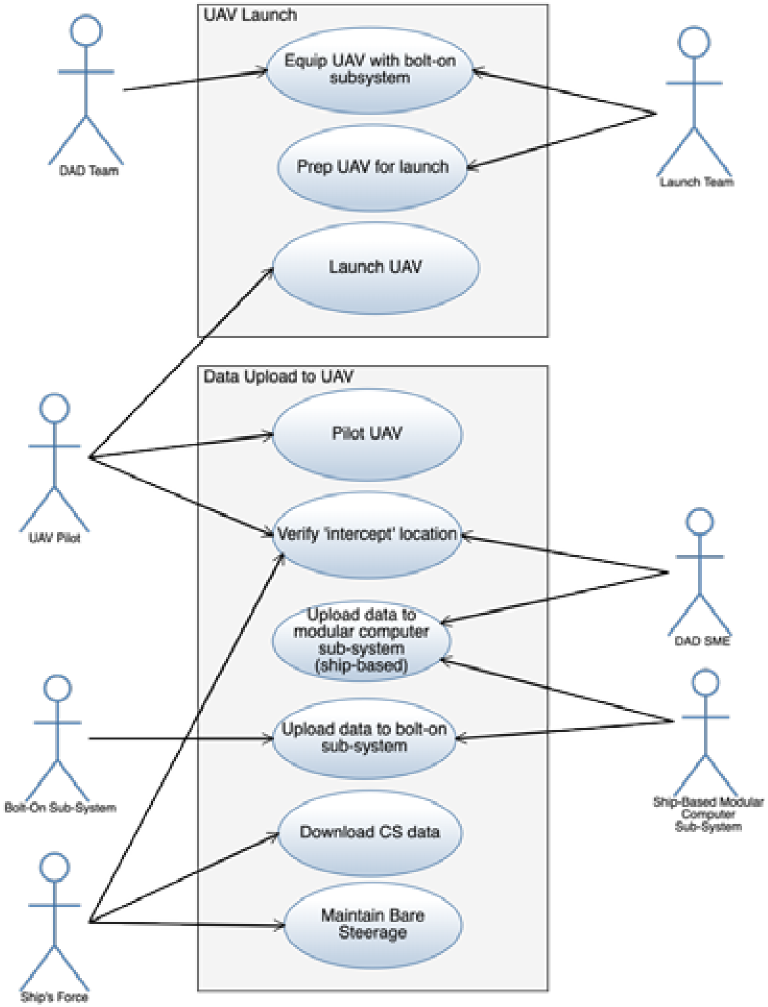

Figure 20. DAD System Use Case Diagram for Receive and Transmit Alternative

F. ACTIVITY DIAGRAM

An activity diagram is used to describe the control flow and object flow among actions. An action is defined as a primitive executable behavior, control flow is defined as the flow of functional behaviors, and object flow is defined as data flow of object inputs/outputs (SysML.org 2020e). In the activity diagram in Figure 21, actions are represented as white boxes, input/output are represented by green rectangles, and decision points are represented by white diamonds. The activity diagram flows from left to right and different actors are shown by different ‘lanes. Actors include personnel as well as equipment.

Figure 21 identifies the required actions for data upload and data transmission from the DAD SME, ship-based modular computer subsystem, bolt-on subsystem, UAV, UAV pilot, and SF. The data upload phase is initiated by verification of ‘intercept’ location by the DAD SME and the UAV pilot, or the location where the UAV is going to be positioned and be in range to communicate with the DAD ship-based modular computer subsystem. Once the location is determined/verified, the UAV pilot will maneuver the UAV to that location. Independent of those actions, the DAD SME will upload the CS data (removeable media previously obtained from SF) and verify if upload was successful. If upload was not successful, the DAD SME will attempt again or request another removeable media from SF. After CS data upload completion to the ship-based modular computer subsystem and arrival of the UAV on location, the DAD SME will establish a connection with the bolt-on subsystem and initiate data upload. The DAD SME will monitor upload status and upon completion will terminate connection with the bolt-on subsystem. Completion status will be relayed to the UAV pilot and the UAV pilot can then maneuver the UAV for ground station download. Due to variability of flight time without using a specific UAV, fuel consumption was not shown as a resource.

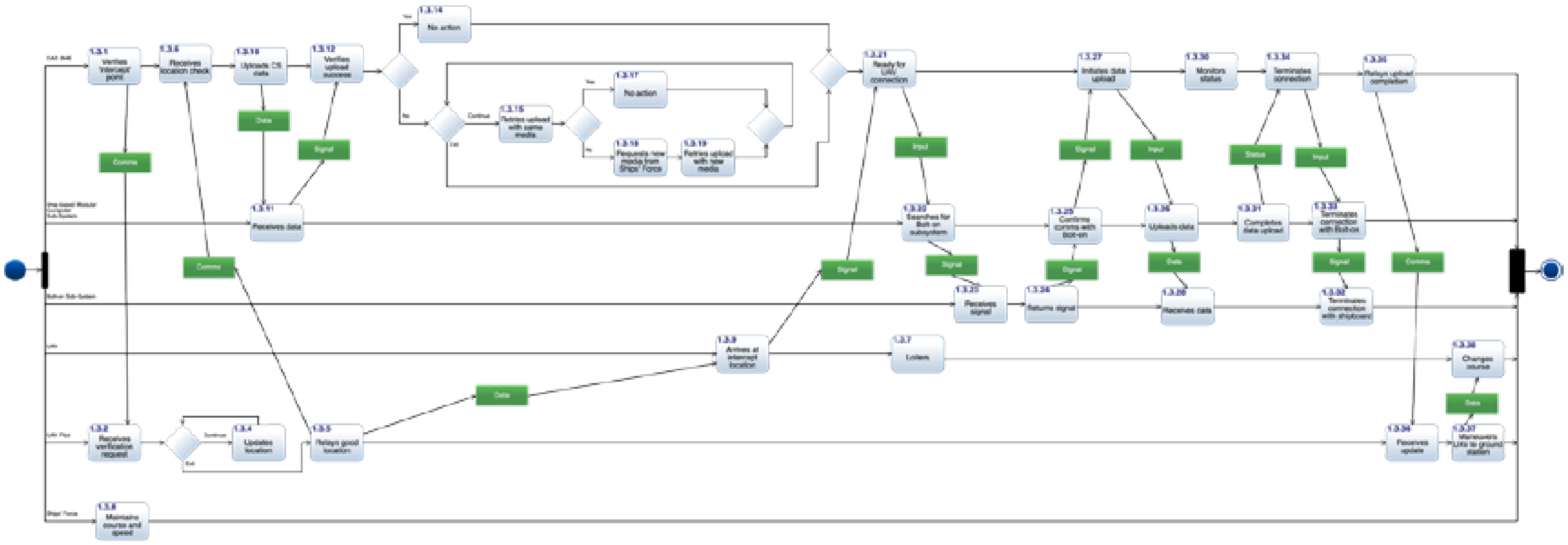

Figure 21. Data Upload to UAV (Receive and Transmit Alternative)

G. SEQUENCE DIAGRAM

The purpose of a sequence diagram is to display sequential system interactions/ behaviors as messages between actors (SysML.org 2020c). A sequence diagram is similar to an activity diagram in that both show interactions between entities, but a sequence diagram does not show input or output. Figure 22 shows the required actions for data download from the UAV to the ground station. Actors include the bolt-on subsystem, DAD SME, ground-based modular computer subsystem, UAV, and UAV pilot. The data download phase has similar actions to the data upload phase, with the exception of communications between the bolt-on subsystem and the ground-based modular computer subsystem. Upon completion, the UAV can RTB or continue mission.

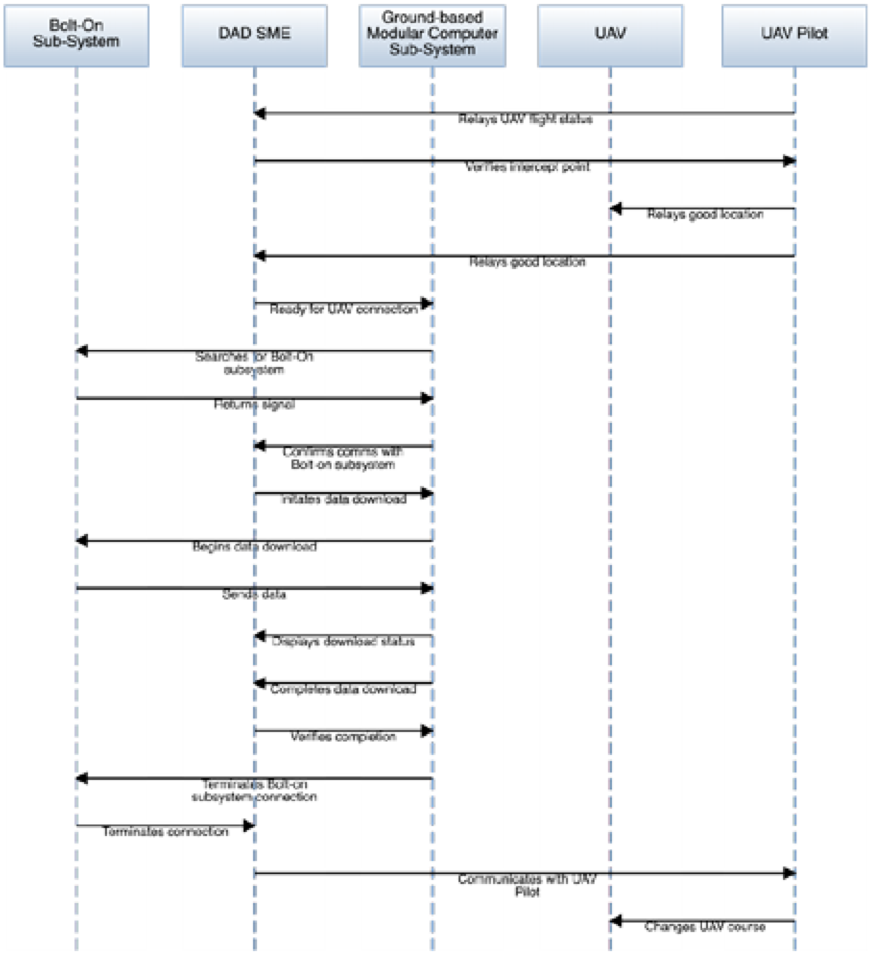

Figure 22. DAD Sequence Diagram

H. SUMMARY

System architecture serves as the organization of system elements with each other, as well as the environment. The visual representation provided through each diagram created in Innoslate assist in communication of system interfaces, relationships, boundaries, and constraints. The capstone team referenced the DOD architecture framework 2.0 multi-step process as a guide to develop DAD system architecture (2020), based off the requirements identified in Chapter IV, Section D, Subsection 6. Combined, all provided diagrams describe upper and lower level relationships between the DAD system and external activities.

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VI. MODELING AND SIMULATION

A. MODELING METHODOLOGY

The model used for this capstone was created using the modeling and simulation tool ExtendSim. The purpose of using ExtendSim for modeling and simulation was to (1) produce a model that was a representation of the intended construction of the SoI, (2) enable analyses to predict the effects of any changes made to the SoI, and (3) evaluate SoI behaviors and performance under different existing and proposed configurations (Maria 1997). The following steps to construct and execute the ExtendSim model was adapted from the *Introduction to Modeling and Simulation* (1997).

1. Problem Identification

Problem identification is discussed in Chapter I, Section C.

2. Model Development

The baseline model was developed with regards to real CSSQT scenarios. During a CSSQT on a controlled range, the ship is located within a specified number of miles offshore to enable communications with range safety and the test conductor. Proximity to shore allows for CS element data to be transferred and analyzed. The quantity of data that is typically transferred during any given CSSQT event was also taken into consideration.

The baseline model represented ship's current method for data transfer, satellite using Kurtz-unter (KU) band. The satellite scenario was the comparative control for amount of operational time required to transfer data from ship-to-shore. In the satellite model shown in Figure 23, the first function in the simulation was to set the file size to be transmitted. The second function was a human factor delay to account for establishing satellite connection. The data relay function was then used for calculating how long the data will take to transit based on data rates provided by Wells (2010) and file size for element data. The final function of the simulation was to tabulate the operational time and write it to a database for analysis, representing the data being received.

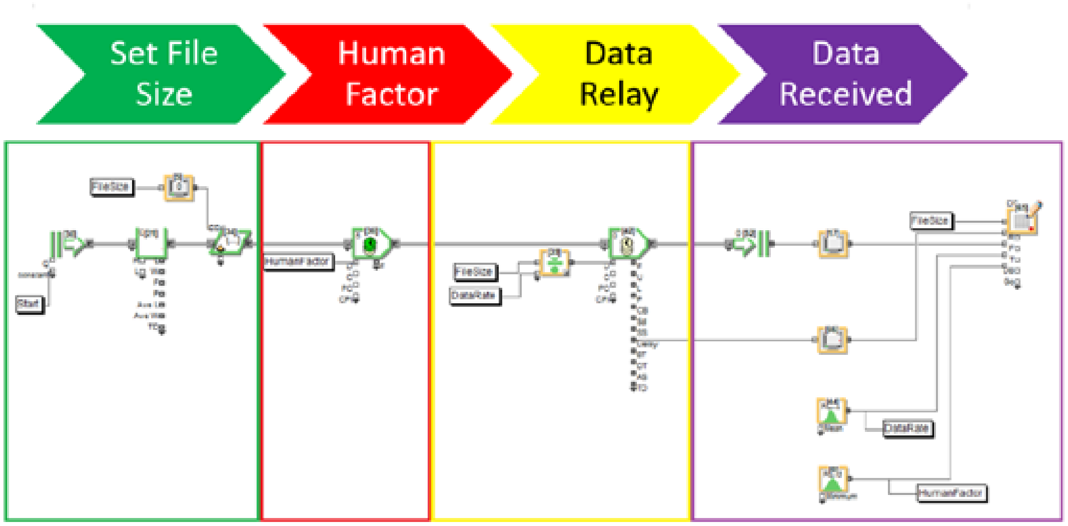

Figure 23. Satellite Baseline Model

3. Model Validation

Model validation was provided through research of existing and validated systems, SME and stakeholder feedback, as well as academic modeling and simulation SME feedback. Another method of model validation was comparison of simulation model outputs utilizing various input combinations, such as different data transfer technologies coupled with the different event condition inputs, such as human factor variations.

4. Experimental Design and Simulation Conditions

Three different data transfer scenarios utilizing UAVs were modeled. Simulation conditions included variations in human factor delays, data transfer capabilities, and time required for the UAV to maneuver from different locations. Simulation inputs also included variations in file size, UAV specifications, and distances from shore. Expected simulation outputs were data rates and operational times. Using these specific scenarios, data transfer technologies can be compared to show more coverage of current COTS capabilities. Statistical analysis of operational time and relation to specified variables aided in understanding the benefits and risks associated with utilizing unmanned vehicles to transmit data. Alternatives are compared in Section C.

a. UAV as a relay

For this scenario, the bolt-on subsystem was used as a communication node, similar to the KU band method, where the data will be wirelessly transferred through the subsystem to the ground station. The relay scenario represented a case where the ship is in such a proximity that the ship-based subsystem can communicate with the ground-based subsystem. As shown in Figure 24, the first function in this simulation was to set the file size and the second function was to set the human factor delay. The next function included in the simulation was the UAV transit function. This function was an added delay that accounted for UAV operational time, including flight speed variation. The next function was a data relay delay based on data rate and file size for transmission. The final function of the simulation was the same as the satellite version where the data is written to a data table and processed for analysis. This model incorporated complications for UAV power transmission.

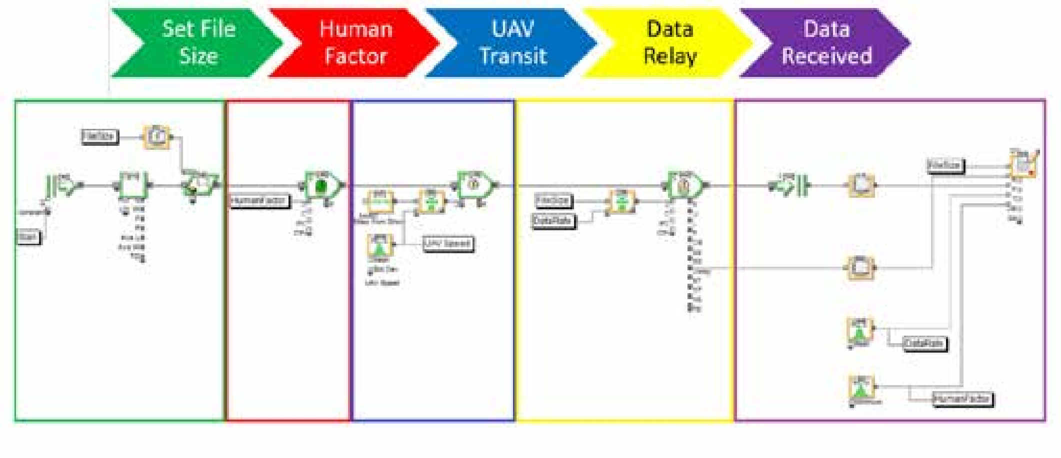

Figure 24. UAV Relay Model

b. UAV wireless receive and transmit

For this scenario, the data was wirelessly uploaded and stored on the bolt-on subsystem, then wirelessly transferred to the ground station. This scenario represented a case where the bolt-on subsystem had the required power transmission capacity for the specified data sizes, as well as UAV fuel capacity that supported the required transits and loiters. In Figure 25, the model incorporated functionality used in the UAV relay scenario but also accounts for additional time required for the UAV to transit to ground station proximity and transfer data. This scenario had a second human factor delay to account for the ground station operator establishing a connection with the bolt-on subsystem when the UAV is in proximity.

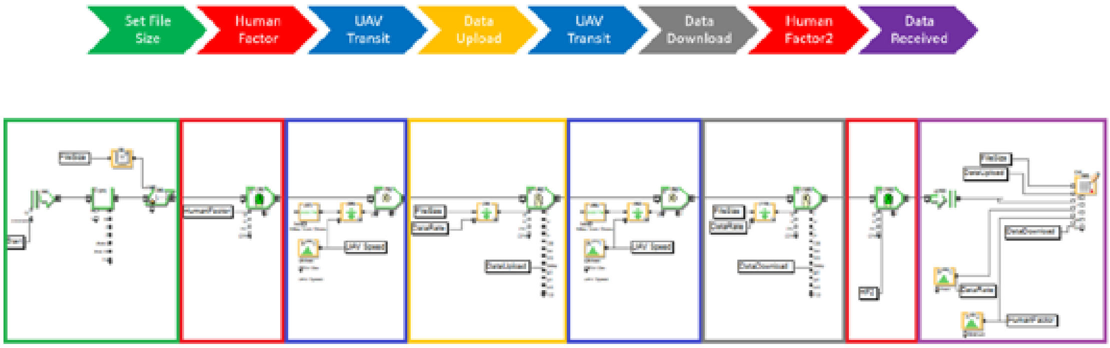

Figure 25. UAV Wireless Receive and Transmit Model

c. UAV wireless receive and land

For the UAV wireless receive and land scenario, the data was wirelessly uploaded and stored on a bolt-on subsystem hard drive, then recovered by ground station personnel after UAV RTB. This scenario represented cases where the power required for data transmission cannot be achieved due to system design constraints or where it is unfeasible for the UAV to transit back to ground station proximity for wireless data transfer. As shown in Figure 26, this scenario had model behavior similar to the UAV wireless scenario, without the added time for data download and with the second human factor delay accounting for hard drive retrieval.

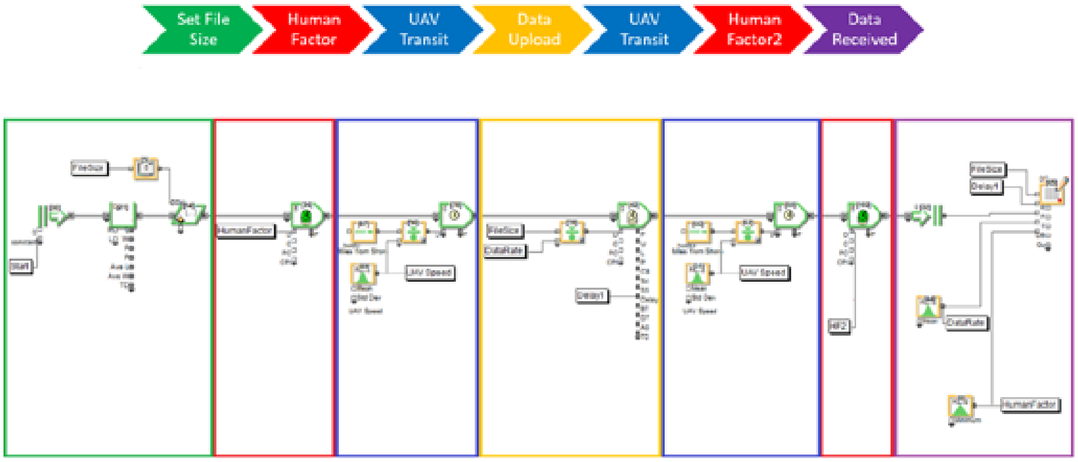

Figure 26. UAV Wireless Receive and Land Model

B. ALTERNATIVES ASSESSMENT

This section continues the AoA that is described in the Chapter II. The capstone team analyzed the related ExtendSim models' output data to determine overall UAV effectiveness as a replacement or as an augmentation to the existing methods of data transfer. For that reason, the focus was on operational time required to send and receive a file to compare the alternatives. The assessment consisted of an analysis of variance of means between different sets of output runs to determine model repeatability, descriptive statistics of the output relay times for the four models, and the regression analysis and factorial design of input factors to determine influence on the relay times themselves.

1. Statistics

The breakdown of analysis began with testability of the models. Using the data collection and analysis tool, Minitab, 2-sample t-tests were used to compare two separate 100 output runs for each model against each other, to determine if the null hypothesis (sample mean 1 = sample mean 2) could or could not be rejected. Table 6 details the t-test metrics, including the p-values for each model. With an alpha value of 0.05, the p-values show to be substantially greater, and the null hypothesis of equal means for multiple 100 output runs of the same model cannot be rejected. While the modeling methodology highlights relay scenarios for 15GB, 100GB and 1000GB file sizes, the respective comparisons for 15GB file sizes is an appropriate analysis baseline to compare the UAV effectiveness to the current Satellite data transfer capabilities.

Table 6. 2-Sample t-Test Results for Satellite and UAV Models' Testability

Total Time	**T-Value**	**DF**	**P-Value**	**Reject Null**
Satellite (hrs)	0.47	180	0.64	No
UAV Relay (hrs)	0.21	197	0.84	No
UAV Receive and Land (hrs)	0.38	197	0.70	No
UAV Receive and Transmit (hrs)	0.38	197	0.70	No

The average time (in hours), along with the standard deviation and range of 100 run time outputs for each model are shown in Table 7. These outputs consider a normal distribution of random inputs for each of the respective input factors. A clear observation would show that the satellite model takes well over three hours to completely send a package size of 15GB, while each of the UAV models show significant decreases in time required for data transfer. The UAV wireless receive and land and the UAV wireless receive and transmit models show similar outputs because the UAV loiter time provides the main action difference in the two models, providing little difference in variation.

Table 7. Descriptive Statistics for Satellite and UAV Models' Output Times for 15GB

Total Time at 15GB	**Mean**	**ST Dev**	**Min**	**Max**
Satellite (hrs)	3.66	0.44	2.96	5.47
UAV Relay (hrs)	0.52	0.15	0.29	0.79
UAV Receive and Land (hrs)	1.28	0.30	0.80	1.88
UAV Receive and Transmit (hrs)	1.32	0.30	0.83	1.92

2. Multivariant Regression Modeling

In order to analysis the significance in outputs, it was important to examine the decomposition of the models themselves. With the existing method simulated in the satellite model. All input factors- the file size, human factor delay, and data transfer rate- were compared against the output of satellite data relay time. For the UAV related models, the inputs all remain the same- the fixed transit distance of the UAV between ground station and ship, the human factor delay, the UAV flight speed, the file size and the UAV data rate- which are compared to three different outputs for the three UAV models- UAV relay, UAV grab and land, and UAV grab and beam.

Regression modeling determines the strength of relationship between the input factors and the output they are compared to. This helps determine if there is a level of predictability with all factors when the values are manipulated. Table 8 and Table 9 show the multivariable linear regression statistics tables for the satellite and UAV models, respectively, to highlight the regression values with the 100 model run observations. As the randomized inputs have shown, there proves to be no relationship to the output times themselves. Further analysis needed to be completed to examine the influence of each input.

Table 8. Multivariable Linear Regression Statistics for Satellite Model

Regression Statistics	
Multiple R	0.12
R Square	0.01
Standard Error	0.15
Observations	100

Table 9. Multivariable Linear Regression Statistics for UAV Models

Summary Output	**UAV Relay**	**UAV Receive and Land**	**UAV Receive and Transmit**
Multiple R	0.0967	0.0978	0.0980
R Squared	0.0094	0.0096	0.0096
Standard Error	0.1509	0.3086	0.3085
Observations	100	100	100

3. Factorial Design

The significance of input factors to a model can be dependent of the number of inputs present for the model itself. The fewer factors that contribute to the model, the more significance they hold in relation to the output's value. Because the satellite model has two controllable, non-fixed factors and the UAV models have three controllable, non-fixed factors (file size is a fixed input), then a creation of factorial design of experiments (DOE) without the requirement of a screening for influential factors is needed. The Factorial DOE created looks at two factors at two levels for the satellite model, and three levels at two levels for the UAV models. Based on previous data collected through research and SME discussion, the two levels "High" and "Low" are shown in Table 10.

Table 10. Level Values for Input Factors

Level	Human Factor	UAV Speed	Satellite Date Rate	UAV Data Rate
High	45	150	12	860
Low	15	80	6	800

The factorial design highlights the influence of each input with a high and low value with the other respective inputs in a randomized pattern. These sequences of 100 run samples are compared against each model, and against the default randomization of the four developed models.

Table 11. Factorial Design for Satellite and UAV Models' Output

Sequence	UAV Relay Mean	UAV Land Mean	UAV Receive/ Transmit Mean	SAT Mean
HF LOW, UAV Speed RAN, UAV Data RAN	0.29	0.81	0.85	X
HF HIGH, UAV Speed RAN, UAV Data RAN	0.79	1.81	1.85	X
HF RAN, UAV Speed LOW, UAV Data RAN	0.54	1.42	1.46	X
HF RAN, UAV Speed HIGH, UAV Data RAN	0.54	1.23	1.27	X
HF RAN, UAV Speed RAN, UAV Data LOW	0.52	1.26	1.31	X
HF RAN, UAV Speed RAN, UAV Data HIGH	0.53	1.28	1.32	X
ALL UAV RANDOM (Normal)	0.54	1.30	1.34	X
HF LOW, SAT Data RAN	X	X	X	4.20
HF HIGH, SAT Data RAN	X	X	X	4.66
HF RAN, SAT Data LOW	X	X	X	6.06
HF RAN, SAT Data HIGH	X	X	X	3.30
ALL SAT RANDOM (Normal)	X	X	X	4.45

Across the satellite model sequences, the data rate levels show the largest difference in output mean to the default mean- with a respective min and max of 3.29 and 6.06 hours against the default average of 4.45 hours. With the UAV model sequences, the human factor levels show the largest difference in output means to the default mean. Table 11 highlights the entirety of discussed values.

Because of the large difference in data transfer rate, it is clear that as the required data transfer time decreases, the influence of the human factor delay increases. A 30-minute human factor delay will provide a larger variance from the output relay time mean on the quicker UAV model than the conventional, slower satellite model.

C. ALTERNATIVES COMPARISON

In addition to statistical analysis, a comparison was performed between operational time and engineering complexity for each alternative solution at file sizes 15, 100, and 1000 Gigabytes (GB). The inputs listed in Table 12 resulted in the outputs found in Table 13 by utilization of a function that included UAV transit time (UAV alternatives only) and data transfer time.

Table 12. Comparison Inputs

Inputs	
Distance from Shore (mi)	30
UAV Speed (mph)	80-140
File Size (GB)	15, 100, 1000
Satellite Data Rate Variation (Mbps)	6-12
UAV Data Rate Variation (Mbps)	800-860
Human Factor Delay Variation (min)	5-15

Table 13 shows a weighted comparison of all the alternative scenarios that were simulated. The operational time shows the averages of 100 runs in the simulations for each category of file size. The fastest method correlates to the smallest number of hours. Each scenario was also rated in terms of design complexity low, medium, or high. The best combination of these two parameters describe the best way to apply the use of a UAV for data transfer.

Table 13. Alternative Data Transfer Methods

Alternative	File Size (GB)	Operational Time Average (hrs)[1]	Engineering Complexity[2]	Justification
Satellite	15	4.48	Low	Deployed on current USN
UAV Relay	15	0.54	High	Power to transmit needs attention as well as hardware increase for dealing with longer distances to track the UAV.
UAV Receive and Land	15	1.31	Low	Power to receive is a lot less than to transmit and landing the UAV saves time when getting the data to be analyzed.
UAV Receive and Transmit	15	1.35	Medium	Power to transmit needs attention as well as requirements for the UAV platform like loiter time and range.
Satellite	100	27.07	Medium	Starts to put pressure on event schedules and mission capability if requirements have a time window.
UAV Relay	100	0.77	High	Power to transmit needs attention as well as hardware increase for dealing with longer distances to track the UAV.
UAV Receive and Land	100	1.54	Low	Power to receive is a lot less than to transmit and landing the UAV saves time when getting the data to be analyzed.
UAV Receive and Transmit	100	1.80	Medium	Power to transmit needs attention as well as requirements for the UAV platform like loiter time and range.
Satellite	1000	266.17	High	Puts massive strain on scheduling and takes too long for Navy mission.
UAV Relay	1000	3.18	High	Power to transmit needs attention as well as hardware increase for dealing with longer distances to track the UAV and flight time starts to become a factor.
UAV Receive and Land	1000	3.95	Low	Power to receive is a lot less than to transmit and landing the UAV saves time when getting the data to be analyzed.
UAV Receive and Transmit	1000	6.62	High	Power to transmit needs attention as well as requirements for the UAV platform like loiter time and range.

[1] 0 - 2.0 hours is considered favorable for operational time and is highlighted as green. 2.0 - 5.0 hours is considered less favorable for operational time and is highlighted as yellow. 5.0+ hours are considered least favorable for operational time and is highlighted as red.

[2] Engineering complexity was categorized into three levels: low, medium, and high.

D. SUMMARY

This chapter detailed the approach taken to simulate alternative solutions in order to calculate the time it takes to transfer data from ship-to-shore. The capstone team developed four different models representing the alternatives discussed in Chapter III. From the operational simulations, the capstone team performed statistical analysis for alternative comparison. The data presented variations of mean output time and concluded that regardless of delay time, the UAV operational time outputs showed significant improvements over the traditional satellite model.

VII. CONCLUSION

A. SUMMARY

The primary objective of this project was to conduct a feasibility study to understand if a UAV can be used to improve the data transfer capability for the USN. From the literature review and knowledge gained from SMEs, the capstone team determined use of a UAV in ship-to-shore data transfer could provide benefit to the USN. The capstone team used defined initial system requirements, available research of communications systems, and available UAV characteristics to develop system architecture with the MBSE tool Innoslate. The utilization of MBSE tools supported the understanding and the ability to communicate interactions and functions of the DAD system within itself, external users, and the environment.

The team identified several alternatives in which a UAV platform could be used as part of a system to supplement existing USN communication systems for data transfer. One alternative considered was to use wireless communications to get the data from the ship to a UAV bolt-on subsystem, then have the UAV transit to ground station proximity for wireless transmission of the data to a ground-based subsystem. In order to do this, it is required that the bolt-on subsystem have sufficient power to transmit the data the required distance, as well as the UAV have an endurance that supports the entire mission. The design constraint and platform constraint will have to be considered if the DAD system progresses through the acquisition life cycle. A second alternative considered was to utilize a UAV bolt-on subsystem to wirelessly receive data and store to an onboard hard drive, then RTB for hard drive retrieval. This method would avoid the design constraint for having sufficient power within the bolt-on subsystem for data transmission. The third alternative considered was to utilize the UAV as a relay, such that the bolt-on subsystem would be used as a node, similar to the current data transfer method of using a satellite. This concept would include the design constraint for transmission power, as well as limitations on data transfer technologies available to meet the required transmission distance.

The capstone team used ExtendSim to incorporate aspects of CSSQT scenarios to be able to analyze operational time outputs that represented variations in human and system performance. This operational time measurement was compared for each of the alternatives and showed the influence of the input factors to their respective model operational time outputs.

B. FINDINGS

This influence, identified through a factorial DOEs, showed the variation of mean output time by controlling different valued levels of their inputs, as well as identifying different influential factors for the satellite model versus the three alternative UAV models. As a final point of data analysis, in the factorial DOE the influence of the human factor delay showed that, regardless of the delay time, the UAV operational time outputs showed significant improvements over the satellite model. Table 14 through Table 16 illustrate the percentage improvement of hours for each UAV model against the satellite model. All sequence columns relate to the factor level sequences in Value Modeling in Table 13.

Table 14. Percentage Improvement (Time) UAV Relay vs. Satellite Relay

SAT Mean	**Seq. 1**	**Seq. 2**	**Seq. 3**	**Seq. 4**	**Seq. 5**	**Seq. 6**
HF LOW, SAT Data RAN	1446%	531%	774%	783%	803%	798%
HF HIGH, SAT Data RAN	1605%	589%	859%	869%	892%	886%
HF RAN, SAT Data LOW	2089%	767%	1118%	1131%	1161%	1153%
HF RAN, SAT Data HIGH	1137%	418%	608%	616%	632%	628%

Table 15. Percentage Improvement (Time) UAV Receive and Land vs. Satellite Relay

SAT Mean	Seq. 1	Seq. 2	Seq. 3	Seq. 4	Seq. 5	Seq. 6
HF LOW, SAT Data RAN	517%	232%	296%	341%	332%	328%
HF HIGH, SAT Data RAN	574%	257%	328%	378%	368%	364%
HF RAN, SAT Data LOW	747%	335%	427%	492%	480%	473%
HF RAN, SAT Data HIGH	407%	182%	232%	268%	261%	258%

Table 16. Percentage Improvement (Time) UAV Receive and Transmit vs. Satellite Relay

SAT Mean	Seq. 1	Seq. 2	Seq. 3	Seq. 4	Seq. 5	Seq. 6
HF LOW, SAT Data RAN	493%	227%	287%	330%	321%	314%
HF HIGH, SAT Data RAN	547%	252%	319%	366%	357%	348%
HF RAN, SAT Data LOW	712%	328%	415%	477%	464%	453%
HF RAN, SAT Data HIGH	387%	178%	226%	259%	253%	247%

While all UAV alternatives with different input conditions provide significant improvements in data transfer capabilities by decreasing total operational time, there are a number of considerations for which options are both feasible and effective for the USN to consider implementing for future test events. These considerations include the engineering complexities and justifications listed in Table 13. While the alternative of using an UAV as a relay yields the shortest operational times, the engineering complexity with respect to transmit power and UAV loiter time have potential issues that have not been researched within the scope of this project. The alternative of using a UAV for receiving and landing yields significant improvements in operational time while the engineering complexity is low, as the transmit power issues do not exist. The receiving and landing alternative can permit the use of existing UAV platforms without extensive research and developmental testing on transmitting power requirements. Additionally, a business case analysis can show the cost of suitable UAV platforms for this alternative- which increase when additional power requirements are not considered- the labor costs for UAV operational personnel and ship-based personnel, and any cybersecurity/ information assurance requirements for successfully conducted the data transfer scenarios.

As shown in Tables 13 through 16, implementing any of the UAV alternatives would provide additional benefit with regards to data availability in a CSSQT application. The capability to provide larger amounts of data with reduced transfer times is invaluable in an operational environment, as it enables the ISEA to provide a faster turnaround for system analysis to support system reliability, maintainability, and availability.

C. RECOMMENDATIONS

There are several opportunities to improve the DAD system concept to close the data transfer gap and increase availability of data for the USN. For future effort, the capstone team recommends selecting an alternative from the proposed solutions (relay, receive and transmit, receive and land, or receive and transmit + land) for continued development. Selection of an alternative will enable identification of subsystem requirements, specific design constraints, and detailed design of the DAD system.

The following list provides areas associated with this capstone that require further research and development, and potentially could serve as a topic for other capstones at NPS or command Naval Innovate Science and Engineering (NISE) projects:

- Application of the DAD system concept for other unmanned vehicle platforms (unmanned surface vehicle (USV) and/or extra-large unmanned underwater vehicle (XLUUV))
- Application of microwave technology that can meet the range and future data rate needs of the USN

- Integration into ship and/or unmanned vehicle platforms, with special regards to cybersecurity compliance
- Bolt-on subsystem design that fits the design constraints of a majority of UAV platforms

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APPENDIX: RESEARCH NOT INCLUDED IN THE LITERATURE REVIEW

Wang proposed a patent to augment wireless communication and satellite positioning for machines at a worksite including one or more unmanned aerial vehicles (UAV) configured to be remotely operated above an area encompassing the worksite (Wang and Rybski 2017).

Li, Zhou and Lamont introduce four communication architectures for networking UAVs and review some military communication standards applicable to UAV communications (Li, Lamont, and Zhou 2013).

Howard describes the development of a stand-alone unattended ground sensor used to process signals or data. The data collected is provided to a digital signal processing computer and then it's sent to an UAV. He then states that UAVs make significant contributions to warfighting capability of operational forces and how they are

The naval studies board conducted a high-level assessment with the goal of advising the Department of Navy on how to achieve Naval Command and Information Infrastructure (NCII) functional capabilities. This study defines multiple technical needs to transition to be a network centric force. The naval studies board explains that being network centric is a key element in the Navy's transformation effort (Council 2000).

In the Design for Maintaining Maritime Superiority, Admiral Gilday, defines key actions on how the United States Navy is going to be trying to grow. He states that the Navy will be tremendously challenged to match the changing threat landscape in this period of great power rivalry and rapid technical transition (CNO 2018).

Kuleshov, Zaytseva, and Aksenov also considered using UAV routing algorithms as an implementation method for autonomous UAV interaction to search for best node positioning for uninterruptable transmission. The method, which involved an autonomous network of multiple UAVs, included using Active Data (AD) structure which could alter the data transmission process by controlling the network node's hardware. An AD structure on a repeater UAV network allowed for an extensive transmission distance for data transfer between RN nodes and applicable sinks (Kuleshov, A. Zaytseva, and Aksenov 2018).

Zwerger, Pirker et al., introduced an alternative of quantum repeater for long-range quantum communication with improved scaling with the distance. The quantum repeater improved long scale quantum communication that handles channel errors and losses, as well as operational and memory errors (Zwerger et al. 2018).

In Kam’s thesis, an autopilot guidance and control algorithm were developed which allowed relay vehicles to reposition themselves autonomously in order to maintain an optimal loitering flight path. This maximized the quality of the communication link between the command station and survey vehicle (Kam 2008).

LIST OF REFERENCES

"AAI RQ-2 Pioneer." 2020. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=AAI_RQ-2_Pioneer&oldid=973496196.

"AAI RQ-7 Shadow." 2020. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=AAI_RQ-7_Shadow&oldid=985532920.

AcqNotes. 2018a. "Acquisition Process - Engineering & Manufacturing Development (EMD) Phase." AcqNotes. May 22, 2018. http://acqnotes.com/acqnote/acquisitions/emd-phase.

———. 2018b. "Analysis of Alternatives (AoA)." AcqNotes. May 22, 2018. http://acqnotes.com/acqnote/acquisitions/analysis-of-alternatives.

———. 2018c. "Acquisition Process Overview." AcqNotes. May 30, 2018. http://acqnotes.com/acqnote/acquisitions/acquisition-process-overview.

———. 2018d. "Acquisition Phases." AcqNotes. June 7, 2018. http://acqnotes.com/acqnote/acquisitions/acquisition-phases.

Blanchard, Benjamin S., and W. J. Fabrycky. 2011. *Systems Engineering and Analysis*. 5th ed. Prentice Hall International Series in Industrial and Systems Engineering. Boston: Prentice Hall.

"Boeing Insitu RQ-21 Blackjack." 2020. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Boeing_Insitu_RQ-21_Blackjack&oldid=976436485.

"Boeing Insitu ScanEagle." 2020. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Boeing_Insitu_ScanEagle&oldid=985322475.

Burdakov, Oleg, Patrick Doherty, Kaj Holmberg, Jonas Kvarnstrom, and Per-Magnus Olsson. 2009. "Positioning Unmanned Aerial Vehicles as Communication Relays for Surveillance Tasks." *London, England: SAGE Publications* 29 (8): 1069–87. https://doi.org/10.1177/0278364910369463.

Commander Naval Sea Systems Command. 2020a. "NSWC Port Hueneme Division." Naval Sea Systems Command. May 22, 2020. https://www.navsea.navy.mil/Home/Warfare-Centers/NSWC-Port-Hueneme/What-We-Do/.

———. 2020b. "PEO Ships." Naval Sea Systems Command. May 22, 2020. https://www.navsea.navy.mil/Home/Team-Ships/PEO-Ships/.

Defense Acquisition University. 2001. *System Engineering Fundamentals*. Defense Acquisition University Press. https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-885j-aircraft-systems-engineering-fall-2005/readings/sefguide_01_01.pdf.

Defense Technical Information Center. 2012. “Distribution Statements and Their Corresponding Reasons for Use.” August 23, 2012. https://discover.dtic.mil/wp-content/uploads/2018/09/distribution_statements_and_reasonsSept2018.pdf.

Department of Defense. 2015. *DOD Program Manager’s Guidebook for Integrating the Cybersecurity Risk Management Framework (RMF) into the System Acquisition Life cycle Version 1.0.* Government Guidebook. Washington, D.C., 20301-3140. https://www.dau.edu/cop/test/DAU%20Sponsored%20Documents/PM%20Cybersecurity%20Guidebook%20v1%200%20with%20publication%20notice.pdf.

———. 2019. *DOD Digital Modernization Strategy*. June 5, 2019. https://media.defense.gov/2019/Jul/12/2002156622/-1/-1/1/DOD-DIGITAL-MODERNIZATION-STRATEGY-2019.PDF.

Duren, Bernard G., and James R. Pollard. 1991. *Combat Systems Vision 2030 Combat System Architecture: Design Principles and Methodology*. Fort Belvoir, VA: Defense Technical Information Center. https://doi.org/10.21236/ADA252668.

Fairley, Dick, Kevin Forsberg, and Ray Madachy. 2020. “System Life Cycle Process Models: Vee – SEBoK.” SEBoK Guide to the Systems Engineering Body of Knowledge. May 15, 2020. https://www.sebokwiki.org/wiki/System_Life_Cycle_Process_Models:_Vee.

Frink, Bentley D. 2005. Unmanned aerial vehicle apparatus, system and method for retrieving data. United States US6868314B1, filed June 27, 2002, and issued March 15, 2005. https://patents.google.com/patent/US6868314B1/en.

“General Atomics ALTUS.” 2019. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=General_Atomics_ALTUS&oldid=932379819.

“General Atomics MQ-1 Predator.” 2020. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=General_Atomics_MQ-1_Predator&oldid=984168394.

“General Atomics MQ-9 Reaper.” 2020. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=General_Atomics_MQ-9_Reaper&oldid=985312163.

Gibbs, Yvonne. 2017. “NASA Dryden Fact Sheet - ALTUS II.” NASA. Brian Dunbar. August 7, 2017. http://www.nasa.gov/centers/armstrong/news/FactSheets/FS-058-DFRC.html.

“Griffon Aerospace.” 2020. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Griffon_Aerospace&oldid=977691076.

Howard, Donald Benton. 1994. *Remote sensing, processing and transmission of data for an unmanned aerial vehicle*. *Calhoun: The NPS Institutional Archive.* June. Accessed April 2020. https://calhoun.nps.edu/bitstream/handle/10945/28501/remotesensingpro00howa.pdf?sequence=1&isAllowed=y.

INCOSE, and Wiley. 2015a. *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. New York, UNITED STATES: John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/ebook-nps/detail.action?docID=4040424.

———. 2015b. *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. New York, UNITED STATES: John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/ebook-nps/detail.action?docID=4040424.

Insitu Inc. 2017. “RQ-21A Blackjack.” Bingen, WA. https://www.insitu.com/images/uploads/pdfs/RQ-21ABlackjack_SubFolder_Digital_DU051217.pdf.

Jackson, Paul, Lindsay T Peacock, and Kenneth Munson. 2003. *Jane’s All the World’s Aircraft, 2003–2004*. Coulsdon, Surrey, UK; Alexandria, VA: Jane’s Information Group.

Jawhar, Imad Hussein, Nader Mohamed, Zouheir Trabelsi, and Jameela Al-Jaroodi. 2016. *Architectures and Strategies for Efficient Communication in Wireless Sensor Networks Using Unmanned Aerial Vehicles*. *Unmanned Systems* 04 (04): 289–305. https://doi.org/10.1142/S2301385016500126.

Johansen, Tor A., Artur Zolich, Torkel Hansen, and Asgeir J. Sorensen. 2014. “Unmanned Aerial Vehicle as Communication Relay for Autonomous Underwater Vehicle — Field Tests.” In *2014 IEEE Globecom Workshops (GC Wkshps)*, 1469–74. Austin, TX: IEEE. https://doi.org/10.1109/GLOCOMW.2014.7063641.

Kam, Khim Yee. 2008. “High Bandwidth Communications Links between Heterogeneous Autonomous Vehicles Using Sensor Network Modeling and Extremum Control Approaches.” Monterey, California: Naval Postgraduate School. http://hdl.handle.net/10945/3833.

Kossiakoff, Alexander, ed. 2011. *Systems Engineering: Principles and Practice*. 2. ed. Wiley Series in Systems Engineering and Management 67. Hoboken, NJ: Wiley.

Kuleshov, Sergey V., Alexandra A. Zaytseva, and Alexey Y. Aksenov. 2018. “The Conceptual View of Unmanned Aerial Vehicle Implementation as a Mobile Communication Node of Active Data Transmission Network.” *International Journal of Intelligent Unmanned Systems* 6 (4): 174–83. https://doi.org/10.1108/IJIUS-04-2018-0010.

Li, Jun, L. Lamont, and Yifang Zhou. 2013. “Communication architectures and protocols for networking unmanned aerial vehicles.” *2013 IEEE Globecom Workshops.* 7.

Li, Long, Runzhou Zhang, Zhe Zhao, Guodong Xie, Peicheng Liao, Kai Pang, Haoqian Song et al. 2017. *High-Capacity Free-Space Optical Communications Between a Ground Transmitter and a Ground Receiver via a UAV Using Multiplexing of Multiple Orbital-Angular-Momentum Beams*. *Scientific Reports* 7 (1): 17427. https://doi.org/10.1038/s41598-017-17580-y.

Maria, Anu. 1997. I*ntroduction to Modeling and Simulation*. Atlanta, Georgia: Winter Simulation Conference. http://acqnotes.com/Attachments/White%20Paper%20Introduction%20to%20Modeling%20and%20Simulation%20by%20Anu%20Maria.pdf.

Military. 2020. “RQ-2A Pioneer | Military.Com.” Military. 2020. https://www.military.com/equipment/rq-2a-pioneer.

NASC. 2020. “The NASC TigerShark XP.” Navmar Applied Sciences Corporation. 2020. https://www.nasc.com/nasc-tigershark-xp/.

National Research Council. 2000. *Network-Centric Naval Forces: A Transition Strategy for Enhancing Operational Capabilites, Chapter 6: Realizing Naval Command and Information Infrastructure Capabilities*. Washington, D.C.: The National Academy Press. https://doi.org/10.17226/9864.

Naval Sea Systems Command. 2019. “NAVSEA Campaign Plan to Expand the Advantage 2.0.” January 2019. https://www.navy.mil/navydata/people/cno/Richardson/Resource/Design_2.0.pdf.

No Magic, Inc. 2020. “SysML Block Definition Diagram.” 2020. https://docs.nomagic.com/display/SYSMLP190/SysML+Block+Definition+Diagram.

Office of the Chief Information Officer. 2000. *Department of the Navy (DON) Data Management and Interoperability (DMI) Strategic Plan*. Homeland Security Digital Library. United States. Department of the Navy. November 1, 2000. https://www.hsdl.org/?abstract&did=.

———. 2020. “Department of the Navy Information Superiority Vision.” February 2020. https://www.documentcloud.org/documents/6781951-DON-Information-Superiority-2020.html.

Office of the Chief of Naval Operations. 2003. *Operational Availbility Handbook.* Department of the Navy. https://www.secnav.navy.mil/doni/Directives/03000%20Naval%20Operations%20and%20Readiness/03-00%20General%20Operations%20and%20Readiness%20Support/3000.12A.pdf.

———. 2018. “A design for maintaining maritime superiority.” *Department of Navy.* December. Accessed March 2020. https://www.navy.mil/navydata/people/cno/Richardson/Resource/Design_2.0.pdf.

Office of the Deputy Chief Information Officer. 2020. *Architecture Development - DODAF - DOD Architecture Framework Version 2.02 - DOD Deputy Chief Information Officer.* Chief Information Officer U.S. Department of Defense. 2020. https://dodcio.defense.gov/Library/DOD-Architecture-Framework/dodaf20_arch_development/.

O’Rourke, Ronald. 2020. *Navy Force Structure and Shipbuilding Plans: Background and Issues for Congress*. Washington, D.C.: Congressional Research Service. https://www.dau.edu/cop/test/DAU%20Sponsored%20Documents/PM%20Cybersecurity%20Guidebook%20v1%200%20with%20publication%20notice.pdf.

QinetiQ. 2017. “Vindicator.” https://www.qinetiq.com/en/what-we-do/services-and-products/vindicator.

QRA Team. 2019. “Functional vs Non-Functional Requirements: The Definitive Guide.” QRA Corp. September 30, 2019. https://qracorp.com/functional-vs-non-functional-requirements/.

SysML.org. 2020a. “SysML FAQ: What Is a Package Diagram (PKG)?” SysML.Org. 2020. https://sysml.org/sysml-faq//sysml-faq//sysml-faq/what-is-package-diagram.html.

———. 2020b. “SysML FAQ: What Is a Requirement Diagram (REQ)?” SysML.Org. 2020. https://sysml.org/sysml-faq//sysml-faq//sysml-faq/what-is-requirement-diagram.html.

———. 2020c. “SysML FAQ: What Is a Sequence Diagram (SD)?” SysML.Org. 2020. https://sysml.org/sysml-faq//sysml-faq//sysml-faq/what-is-sequence-diagram.html.

———. 2020d. “SysML FAQ: What Is a Use Case Diagram (UC)?” SysML.Org. 2020. https://sysml.org/sysml-faq//sysml-faq//sysml-faq/what-is-use-case-diagram.html.

———. 2020e. “SysML FAQ: What Is an Activity Diagram (ACT)?” SysML.Org. 2020. https://sysml.org/sysml-faq//sysml-faq//sysml-faq/what-is-activity-diagram.html.

The MITRE Corporation. 2013a. “System Architecture.” MITRE. July 18, 2013. https://www.mitre.org/publications/systems-engineering-guide/se-life cycle-building-blocks/system-architecture.

———. 2013b. “Analyses of Alternatives.” Systems Engineering Guide. August 28, 2013. https://www.mitre.org/publications/systems-engineering-guide/acquisition-systems-engineering/acquisition-program-planning/performing-analyses-of-alternatives.

Tierney, Brian, Ezra Kissel, Martin Swany, and Eric Pouyoul. 2012. “Efficient Data Transfer Protocols for Big Data.” In *2012 IEEE 8th International Conference on E-Science*, 1–9. Chicago, IL, USA: IEEE. https://doi.org/10.1109/eScience.2012.6404462.

United States Air Force. 2015a. “MQ-1B Predator.” U.S. Air Force. September 2015. https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104469/mq-1b-predator/.

———. 2015b. “MQ-9 Reaper.” U.S. Air Force. September 2015. https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104470/mq-9-reaper/.

United States Chief of Naval Operations. 2018. “A Design for Maintaining Maritime Superiority, Version 2.0.” December 2018. https://www.navy.mil/navydata/people/cno/Richardson/Resource/Design_2.0.pdf.

Wang, Qi, and Edmund Rybski. 2017. *Augmented Communication and positioning using unmanned aerial vehicle*. United States of America Patent 20170146990A1. May 25.

Wells, Jonathan. 2010. *Multi-Gigabit Microwave and Millimeter-Wave Wireless Communications*. Mobile Communication Series. Boston: Artech House.

Whitcomb, Clifford. 2000. “Functional and Physical Decomposition for Ship Design,” March, 15.

Xiao, Zhenyu, Pengfei Xia, and Xiang-gen Xia. 2016. “Enabling UAV Cellular with Millimeter-Wave Communication: Potentials and Approaches.” *IEEE Communications Magazine* 54 (5): 66–73. https://doi.org/10.1109/MCOM.2016.7470937.

Yang, Hyun. 2018. “A Cost-Effective Ship Safety Data Transfer in Coastal Areas.” *Journal of Coastal Research* 85 (May): 1206–10. https://doi.org/10.2112/SI85-242.1.

Zwerger, M., A. Pirker, V. Dunjko, H. J. Briegel, and W. Dür. 2018. “Long-Range Big Quantum-Data Transmission.” *Physical Review Letters* 120 (3): 030503. https://doi.org/10.1103/PhysRevLett.120.030503.

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