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Application of Executable Architecture in Early Concept Evaluation using the DoD Architecture Framework

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APPLICATION OF EXECUTABLE ARCHITECTURE IN EARLY CONCEPT EVALUATION USING THE DOD ARCHITECTURE FRAMEWORK

THESIS

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Zhongwang Chua

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List of Acronyms

ABEP	Architectural-Base Evaluation Process
AO	Area of Operations
CI	Confidence Interval
CONOPS	Concept of Operations
CPN	Color Petri-Net
CRRA	Capability Review and Risk Assessment
DM2	DoDAF Meta Model
DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
EA	Executable Architecture
ESM	Extended Sequence Modeling
ISR	Intelligence, Surveillance and Reconnaissance
MDA	Model-Driven Architecture
MDAP	Major Defense Acquisition Program
MoDAF	Ministry of Defense Architecture Framework
MOE	Measure of Effectiveness
MOF	Meta-Object Facility
MOP	Measure of Performance
OMG	Object Management Group
PIM	Platform Independent Model
PSM	Process Sequence Modeling
SE	Systems Engineering
SoS	System-of-Systems
SysML	System Modeling Language
TBM	Theater Ballistics Missile
TSEO	Time Sensitive Effects Operation
UAS	Unmanned Aircraft System

UML	Unified Modeling Language
UPDM	Unified Profile for DoDAF/MoDAF
XMI	XML Metadata Interchange
XML	Extensible Markup Language

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Abstract

The increasing complexity in the development of today's modern warfighting systems required a systematic evaluation approach in the assessment of the envisaged capability and estimating the cost effectiveness, especially in the early stages of Concept Development. This research focused on the development of early Concept Evaluation methodology through the use of Executable Architecture (EA) through the System Architecting process. Particularly, the methodology was applied in the assessment of a proposed fictitious Multi-tiered Unmanned Aircraft System System-of-Systems that was designed to provide target acquisition and conduct dynamic strike on Theater Ballistic Missile launchers.

Through the implementation of the evaluation methodology using dynamic modeling of the system-under-design, the research was able to provide quantitative assessment of different design parameters on the overall system effectiveness, as measured using a set of pre-determined Measures-of-Effectiveness. Innoslate was used to develop the EA model of a fictitious multi-tier Unmanned Aircraft System System-of-Systems, and provided quantitative assessment of the overall system performance due to changes in the design parameters. The research showed that the proposed evaluation methodology provide system architects with the tool to 1) evaluate different design parameters, 2) understand the overall system capability given sub-system capabilities, and 3) determine sub-system requirement given desired system performance.

APPLICATION OF EXECUTABLE ARCHITECTURE IN EARLY CONCEPT EVALUATION USING DOD ARCHITECTURE FRAMEWORK

I. Introduction

Overview

The increasing complexity in today's modern warfighting systems demands a systematic approach in evaluating the envisaged capability, and estimating the cost-effectiveness of the proposed weapon system in the early stages of Concept Development. To address this challenge, it is necessary that the evaluation methodology has the capability and capacity to process highly complex system with many unknowns under widely varying scenario. This research thesis builds on the efforts of Maj Ryan Pospisal (Pospisal, 2015) in the use of executable architecting, and extends the research focus to assess the impact of different design parameters to system performance and cost.

This research reviews an existing system architecting process as a viable solution to provide program offices with early assessment and evaluation of Department of Defense (DoD) projects and proposes a methodology using Executable Architecture (EA) and dynamic models to provide a holistic evaluation of the proposed concept across operational time and space. In this regard, this research will focus on the domain of tactical Intelligence, Surveillance, and Reconnaissance (ISR) system development, involving the use of multi-tiered Unmanned Aircraft Systems (UAS) to provide target acquisition and conduct dynamic strike.

Motivation

The focus of this research is driven to achieving two key deliverables during Concept Development phase—1) impact of system parameters on overall system-design and operational effectiveness during early stage development, and 2) accuracy of cost estimates for cost-effectiveness evaluation.

Impact of System Parameters during Concept Development Phase

During the early stages of Concept Development, the system-under-design is often ill-defined, with many different possible configurations and design parameters that can be implemented into the system to meet user requirements to varying degrees of success. Indeed, MITRE defined Concept Development as:

> *a set of activities that are carried out early in the systems engineering life cycle to collect and prioritize operational needs and challenges, develop alternative concepts to meet the needs, and select a preferred one as the basis for subsequent system or capability development and implementation.*

From the above definition, it is essential that there exist a method to qualitatively and quantitatively evaluate the different configurations and design parameters of the proposed concept to select the optimal design parameters that best fulfil the user's requirements.

The Conceptual Preliminary Design phase is the phase where trade-studies are conducted. During this stage, the system designers have the highest leverage over the eventual design of the system with maximum impact on the overall design and operating cost of the system, as illustrated from Figure 1 below adapted from Blanchard and Fabrycky (1998). However, at this stage, there are still many unknowns and the concept is still ill-structured (Maier et al, 2009). Furthermore, new modern weapon systems are often too complex to rely only on technical engineering analysis alone for effective evaluation and comparisons.

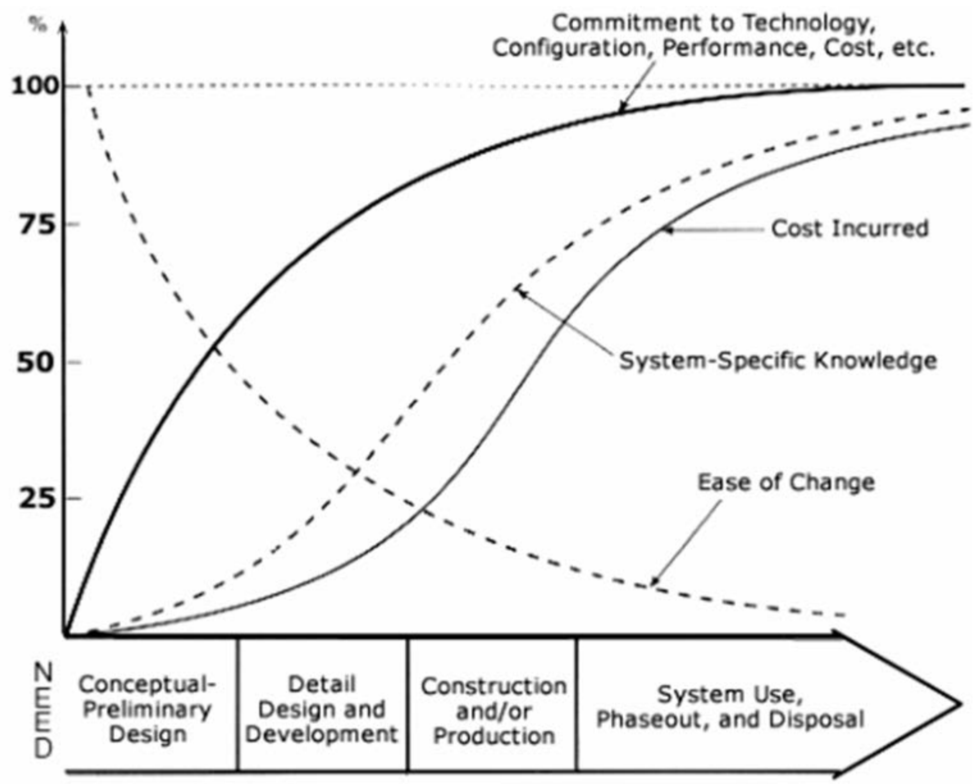


Figure 1: Commitment, system-specific knowledge, cost incurred and east of Change (Blanchard & Fabrycky, 1998).

Accuracy of Cost Estimates for Cost-effectiveness Evaluation

The procurement and introduction of new technology continues to be a vital force multiplier in the military. With the introduction of new technology and advancement in System-of-Systems (SoS) operations, it is evident that there is an ever increasing complexity in technology, software density and system integration, resulting in the challenging task of estimating accurate system development costs at the inception of major development activities (Arena et al., 2006). Indeed, a study by Younossi et al. (2007) on 46 completed programs showed that the average cost growth ratio across all programs was 1.46, or 46% higher than estimated at Milestone B. The team further quantified that this could be attributed to higher level of new technology adaptation in most DoD programs, resulting in inherently higher levels of cost and schedule uncertainty and hence poor initial budget estimates by program offices.

With increasing complexity in today's modern warfighting systems, a systematic analytical approach from Concept Formulation to System Design and eventual operation of the weapon systems is needed. However, the growing complexity has resulted in rising risk to development cost and time. Indeed, from the Government Accountability Office's study (Berteau et al., 2011) in 2011, the 98 Major Defense Acquisition Programs (MDAPs) had a total cost over-run of $402 billon and an average schedule delay of 22 months. The main reason for cost over-run was attributed to inaccurate cost estimates as shown in Figure 2. Similar to the cost growth study, technical complexity and inaccurate cost estimates are identified as key root causes driving cost increases and schedule delays (Michael, 2011; Tom, 2009).

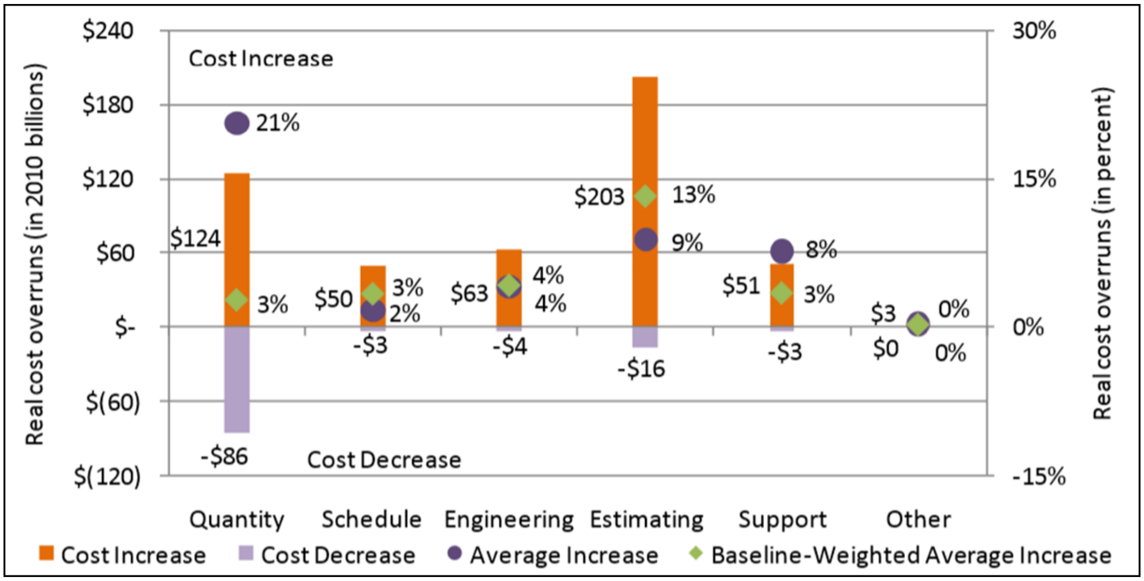


Figure 2: Functional Reasons for Cost Over-run (Berteau et al., 2011)

Problem Statement

Currently, most architectural modeling focuses on the static evaluation of architectural products and is disconnected from the performance evaluation of the system-under-design. However, the use of static architectural modeling during early concept evaluation and performance assessment does not capture the impact of variations in design parameters, as well as the impact of these parameters to design and operational costs.

Research Objectives

This thesis investigates the utility of Executable Architecture in conducting early concept evaluation of DoD-related projects, based on architectural products using Department of Defense Architecture Framework (DoDAF). In particular, the research focuses on addressing the following questions based on a hypothetical defense development program to design and build a multi-tiered UAS ISR SoS:

Research Question 1: Which views of DoDAF are critical for effective construction of EA?

Research Question 2: What level of operational or functional hierarchy of component sub-systems is required for EA to be effective?

Research Question 3: How can EA be used to identify and evaluate the impact of design parameters on Measure-of-Effectiveness (MOE) level and Measure-of-Performance (MOP)?

Research Question 4: Which are the key parameters that have significant impact to design and operational cost for the multi-tiered UAV architecture considered here-in?

Research Focus

The focus of this research is to evaluate the utility of EA in the early assessment of defense related projects based on DoDAF-driven architecture design. Specifically, the research will focus on the domain of tactical ISR system development in an effort to provide a basis for application in future ISR SoS development. Specifically, the system-under-design aims to provide tactical ISR and dynamic strike through the use of a fictitious multi-tiered UAS SoS that optimizes the deployment of UAS from different tiers to effective search, locate and destroy theater ballistic missiles (TBM) launchers.

Methodology Overview

This thesis focuses on the following 3 areas: 1) Understand current EA technology; 2) Develop EA models based on a proposed design concept; and 3) Evaluate the effectiveness of the EA in response to the research questions.

Understand current EA technology. To achieve this, a literature review is conducted in the field of EA to understand the different approaches to achieving an accurate depiction of the proposed system architecture. In particular, the review will focus on examining the different modeling languages in system architecting, and the process to automate the transformation of static models to dynamic models. From the result of the review, a suitable methodology and software, namely Innoslate (Innoslate, 2012), is selected for the implementation of EA.

Develop EA models based on proposed design concept. Different EA models with architectural variations are developed based on a plausible Concept of Operations (CONOPs) for multi-tiered UAS tactical ISR and dynamic strike systems. These EA models are constructed based on the requirements set-forth under DoDAF.

Evaluate effectiveness of EA in response to research questions. The EA models are evaluated, and different architectural variations are introduced to the system-under-design to assess their impact to the overall performance. The results from these simulations will be used to answer the research questions.

Assumptions

For the purpose of this research, the following assumptions are identified during the system modeling and evaluation phase:

1. The methodology is scalable to include more complex individual systems and SoS.
2. The selected sets of parameters under study are adequate to determine future system performance.
3. A commercial tool, Innoslate (Innoslate, 2012), currently exists, and is accessible to the author, and includes an executable modeling capability to meet the fidelity requirements for this thesis.

Preview

While this research thesis focuses on the application of EA in providing early concept evaluation of DoD-related problems, the methodology introduced in this thesis can be easily modified to be implemented in other government agencies or commercial entities to achieve the desired outcome. A preview of the thesis work is provided below:

Chapter 2: This chapter summarizes the results of the literature in the area of EA, focusing on the different modeling languages and transformation techniques. This chapter concludes with a comparison of the different approaches, and compares and contrasts the main benefits and drawbacks of these approaches.

Chapter 3: This chapter elaborates on the methodology in the application of the research efforts, and illustrates how the results were collected and analyzed.

Chapter 4: This chapter summarizes the results obtained from the conduct of the research efforts, and the analysis of these results in fulfilling the research objectives.

Chapter 5: This chapter concludes the thesis with the interpretation of the results, and address the research questions put forth in Chapter 1. This chapter concludes with a recommendation for future studies.

II. Literature Review

Overview

As part of the research effort, an extensive literature review is conducted to better understand the development in the field of EA, and how EA can be implemented to provide program and development planning offices with the ability to conduct early concept evaluation. This chapter is further divided into three sub-sections:1) Elaborations on the key drivers that enables System Architecting to be a viable solution for early concept evaluations; 2) Different approaches to better understand the system architectural models; and 3) Evaluation of EA as a tool in performance assessment based on DoDAF.

System Architecting as a viable solution

Definition

System Architecting can be defined as an interdisciplinary, integrative approach and means to specify the structure and behavior of envisioned systems. Maier (1996) further espoused that the architecting process aims to establish a "satisfactory and feasible system concept at the earliest stage of system development … and for certifying the fitness of the resulting system for use by the client or customers".

System Architecting for Early Assessment

By the definition stated in the preceding section, the system architecting process provides program and development planning offices with the ability to conduct early assessment and evaluation of the project during the early phases of Concept

Development. At this phase, most projects are still in their infancy, and are often ill-structured with many unknowns. System Architecting provides a systematic methodology to create and build systems that are too complex to be treated by technical engineering analysis alone. Indeed, the system architecting process is applicable across different domains and is often used as an initial tool to model and evaluate systems. Some examples in different domains include the evaluation of Interplanetary Manned Missions (Rudat et al.,2013), risk reduction in the architecting of a Maritime Domain Protection System (Buurman et al., 2009), as well as the business domain (Biemans et al., 2001).

System Architecting Improve Cognitive Understanding and Decision Making

One of the key challenges in developing complex systems is in recognizing and identifying the emergent properties that arise due to the interactions between the elements within the system. Some of these emergent behaviors are methodically designed into the system as part of the system requirements, while other behaviors are unintended consequences that can be desirable or undesirable to the system. Crawley et al. (2004) in their research on “The influence of Architecture in Engineering Systems” illustrated some of the examples in emergent properties that are reproduced in Table 1.

Table 1: Examples of Desirable and Undesirable Anticipated and Emergent System Properties Influenced by Architecture (Crawley et al., 2004)

	Anticipated	Emergent
Desirable	Electric power networks share the load.	Blackouts are associated with increased births.
	Hub-spokes airline routes shorten the length of trips.	Hub-spokes plus waiting time creates a business opportunity in airport malls.
Undesirable	Power networks can propagate blackouts.	Result in loss of productivity during blackouts.
	Hub-spokes cause huge swings in workload and resource utilization at airports.	Airport operators become dependent on mall rental income, making it difficult to modify airline route structures.

In system architecting, the architects develop multiple perspectives of the system-under-design that provide coherent views of the system in different domains. Five broad types of system architecture perspectives can be described (Habayeb, 2005): 1) Operational, 2) Conceptual, 3) Functional, 4) Physical, and 5) Integration and Interfaces. With detailed design and ensuring concordance between the different architectural perspectives, decision makers are presented with a holistic view of the system-under-design and the ability to delve deeper into details.

Architectures provide decision makers with a good overview of the system, including the complexity and the relationship between different components, thus enabling better cognitive understanding of the overall system. As aptly put forth by Rechtin (1992), 'rarely, if ever, is there a single optimal solution for all parties and circumstances', and the system architecture and perspectives provide decision makers with the information required at the early stages of concept development for evaluation and assessment.

DoDAF as Tool for Early Concept Evaluation in DoD

As stated in the preceding section, when effectively utilized, system architecting provides system architects with a tool to enable assessments and achieve quantifiable trade-studies. Similarly, the concept of system architecting can be employed in the current DoD development and acquisition process to evaluate programs during early Concept Evaluation. Recognizing this, the DoD already has a system architecting framework, DoD Architecture Framework (DoDAF, 2009), in place. Before embarking on EA for DoD projects, it is necessary for the system architects to have a good understanding of DoDAF.

DoD Architecture Framework

DoDAF is the over-arching comprehensive framework and conceptual model that prescribes a set of architectural artifacts in the development of architecture. It is data-centric and emphasizes *fit-for-purpose* architectural development. The purpose of DoDAF is to manage complexity by facilitating the ability of DoD decision makers to make key decisions more effectively through organized information sharing across the Department, Joint Capabilities Areas, Mission, Component, and Program boundaries. DoDAF sets the common framework to standardize architectural descriptions and ensure that these descriptions can be compared, related, understood, exchanged, and reused across multiple stakeholders by employing common language and rules (DoDAF, 2009a).

Eight viewpoints are provided under DoDAF as described in DoDAF Volume 2 (DoDAF, 2009b):1) All Viewpoint provides the overarching perspective of the system-under-design, including information such as scope, context, and vocabulary; 2) Capability Viewpoint that provides perspective on the capability of the system; 3) Data and Information Viewpoint provides the operational and business information requirements and rules that are managed within and used as constraints on the organizations business activities; 4) Operational Viewpoint describes the tasks and activities, operational elements, and resource flow exchanges required to conduct operations; 5) Project Viewpoint describes how programs, projects, portfolios, or initiatives deliver capabilities, the organizations contributing to them, and the dependencies between them; 6) Services Viewpoint describes services and their interconnections providing or supporting DoD functions; 7) Standards Viewpoint describes the set of rules governing the arrangement, interaction and interdependence of parts or elements of the architectural description; and 8) Systems Viewpoint describes the systems and interconnections providing for, or supporting, DoD functions. Together, these viewpoints provide a comprehensive and complete description of the system-under-design.

Central to these viewpoints are the set of artifacts that are defined under the Data Meta-Model (DM2). With the transition to DoDAF v2.02, the framework shifted from a product-centric process to a data-centric process, focusing on providing decision-making data to the decision makers (DoDAF, 2010). In DoDAF v2.02, models based on DM2, such as documents, spreadsheets, or other graphical representations, enable decision makers to visualize architectural data (DoDAF, 2009a).

System Architecting—From Static Viewpoints to Dynamic Executable Models

With a better understanding of DoDAF, the literature review will now focus on the current technology in developing dynamic executable mode for EA. It is therefore necessary to understand the two difference between the two broad categories in system architectures: 1) Static Architecture; and 2) Executable Architecture (EA).

Static Architecture can be defined as static views of the architecture based on the development of static products, such as specification documents, drawings, and plans while Executable Architecture can be defined as executable dynamic simulations that are automatically or semi-automatically generated from architecture models or products as defined by Hu et al (2014). In addition, Wang et al (2014) further deliberate that each EA comprise three main components—1) Executable Model, 2) Execution Mechanism, and 3) Execution Process.

To better understand EA, it is necessary to first have an understanding of Model-Based System Engineering (MBSE). MBSE is defined by INCOSE in "System Engineering Vision 2020" (2007) as 'the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases'. The introduction of MBSE also drives the development of executable architecture through the creation of system models, as seen in the Model-Driven Architecture (MDA) approach championed by the Object Management Group (Brown et al., 2004, Pastor et al., 2007, Kleppe et al., 2003).

With the increasing complexity in the modern defense acquisition program, SA is no longer sufficient to provide the level and depth of analysis required. In particular, the relations and interactions between different nodes are difficult to define and model in a static view, where the type of events, as well as the sequence in which these events occur, has a big impact on system performance. In this regard, EA provides the capability for system architects to include dynamic models and interactions in the architecture, thus providing a more complete model across operational time and space.

Methodology for Implementing EA from Static Architecture

To achieve dynamic simulations based on the static architectural models, three different methodologies can be implemented: 1) Develop software that simulates the architectural models; 2) Import the models into simulations software; and 3) Direct transformation of static architecture models into dynamic executable models. The methodologies are summarized in Table 2 and further elaborated in the subsequent paragraphs.

Table 2: Comparisons of Methodologies

Methodologies	Pros	Cons
Develop Simulation Software based on Static viewpoints	1. Flexibility in development. 2. Customizability to provide level of abstraction and user-interface	1. Interpretation Errors. 2. Longer lead time and development cost. 3. Substantial re-programming efforts may be incurred during changes.
Import models into simulation software	1. Built-in functionality for basic evaluation. 2. Less programming required.	1. Interpretation Errors. 2. Need for expert in simulation software.
Direct Transformation of static architecture models into dynamic models	1. Reduce intermediate interpretation error. 2. Ease of introducing architectural variation.	1. Lack of flexibility. 2. Constrained by Software.

Software Development. The system models are designed using modeling languages, with rules and behaviors articulated in the diagrams. Similar to the software system engineering process, these system models form the basis for programmers to design executable codes (similar to Agile software development process articulated by Larman (2004)). Here, the system interactions and behaviors are implemented in software that are specifically customized to the static models. The key benefits of this method are: 1) Flexibility for the programmer to implement different aspects of the models, such as special rules and relationships; and 2) Customizability to provide the level of abstraction and user-interface required to enable better understanding of the trade-space, and for effective communications between stakeholders. However, there are also several disadvantages, namely: 1) Need for software programmers to interpret the static models and design the software products, which can introduce interpretation errors into the system where the software does not represent the static models accurately; 2) Need for longer lead time and developmental cost in simulation software development; and 3) Changes to the static models may results in substantial re-programming efforts.

Use of Simulation Software. Another method to assess static models is to import these models into simulation software packages, such as Arena or Simulink in Matlab. Using simulation software, the architectural models and their attributes are designed and simulations are carried out to obtain the results of the architectural design. The key benefits of this method are: 1) Simulation software packages often have stochastic functionality built-in to provide basic results evaluation; and 2) Less programming is required as compared to developing a software from scratch. Similarly, this method also has disadvantages, namely: 1) Need for simulation programmers to interpret the static models and develop equivalent models in the simulation software, hence the possibility of introducing interpretation error, similar to that in software development; and 2) Need for additional simulation software and experts who are able to effectively and accurately implement the static models in the simulation software.

Direct Transformation of Static Model. In this method, the static models are designed using software which then transforms them into dynamic executable models. The main benefits for this method are: 1) No intermediate interpretation and design is required by additional parties such as programmers, hence minimizing interpretation errors; 2) Ease of introducing architectural variation into the design, as changes to the static models can be transformed into executable models directly. The main disadvantage for this method is the lack of flexibility in the implementation of additional rules, which can only be implemented with additional programming scripts into the EA software. The direct transformation of the static models forms the basis of EA which are further elaborated in the next sub-section. For example, the Enterprise software by Sparx and Innoslate are able to perform this transformation.

Evaluation of Different Modeling Languages

DoDAF v2.02 provides system architects with a clearly defined framework and viewpoints for the development of architectures. The use of models within DoDAF further enables system architects to utilize MBSE techniques to implement executable

DoDAF architectures. To ensure that DoDAF Operational Views are accurately captured in the modeling process, Bueno et al (2014) proposed an integrated methodology to build an executable architecture based on the system dynamics of the Operational Views to achieve concordance. With the emerging development in MBSE and EA, several modeling languages have been introduced and extended to support the modeling and simulation of system architecture. To effectively create an EA, there is a need to accurately create architectural structures through the use of modeling language, and to convert the static models into dynamic models using transformation methods. Here, the following modeling languages and profiles are introduced and evaluated, namely: 1) Unified Modeling Language (UML), 2) System Modeling Language (SysML) and 3) Unified Profile for DoDAF/Ministry of Defense Architecture Framework (MoDAF) (UPDM), for the development of DoDAF models. It is noted that while UPDM is not a modeling language, it is a subset of UML that is developed specifically for DoDAF, and therefore it is important to include UPDM in the evaluation.

a. Unified Modeling Language (UML): UML is a modeling language that supports Object-Oriented Analysis and Design (OOAD) and is primarily used in the area of software development (Larman, 2004). Currently in version 2.5, UML enables architects to develop models in three major categories of model elements, namely—1) *Classifiers* that describe a set of objects, 2) *Events* that describe set of possible occurrences, and 3) *Behaviors* that describe a set of possible executions (OMG UML, pg 12, 2015).

In this regard, it is important to introduce the set of semantics in UML. The semantics of UML refers to how the system can be modeled, and can be generally characterized into Structural semantics or Behavioral semantics as seen in Figure 3. Here, the Behavioral semantics builds on the Structural semantics and addresses communication and associated state changes between different structural objects that are event-driven.

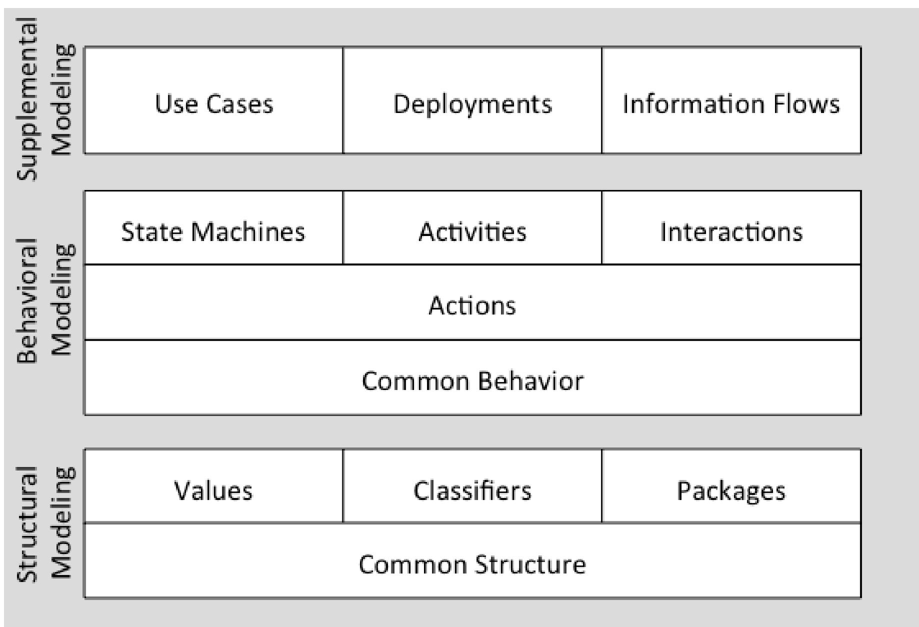


Figure 3: Semantic Areas of UML (OMG UML, pg 14, 2015)

It is important for executable architecture to have the ability to include behavior models and characteristics into the architecting process. Here, *behavioral features* may be designed into *Classifiers* to define behavioral characteristics into an otherwise static model. With the use of suitable tools, such as Enterprise Architect by Sparx System, these *Behavior* models can be translated into an executable format that may be executed dynamically over time, in accordance with the *Events* and triggers that occur, and hence provide the architect with a dynamic view of the system-under-design (OMG UML, 2015).

To achieve common understanding in UML models, there is a need to develop common standards, syntax, and semantics. The syntax in UML is achieved through the Meta-Object Facility (MOF) framework that serves as the platform-independent metadata management foundation for Model-driven architecture (MDA) (OMG MOF, pg 5, 2015). The syntax determines how UML models may be constructed, represented, and interchanged.

b. <u>System Modeling Language (SysML)</u>: SysML is a modeling language that is tailored for system engineering applications that supports the specification, analysis, design, verification, and validation of a broad range of systems and systems-of-systems (Friedenthal et al, 2014). The language is an extension of a subset of the UML language as depicted in Figure 4 below (OMG, 2015):

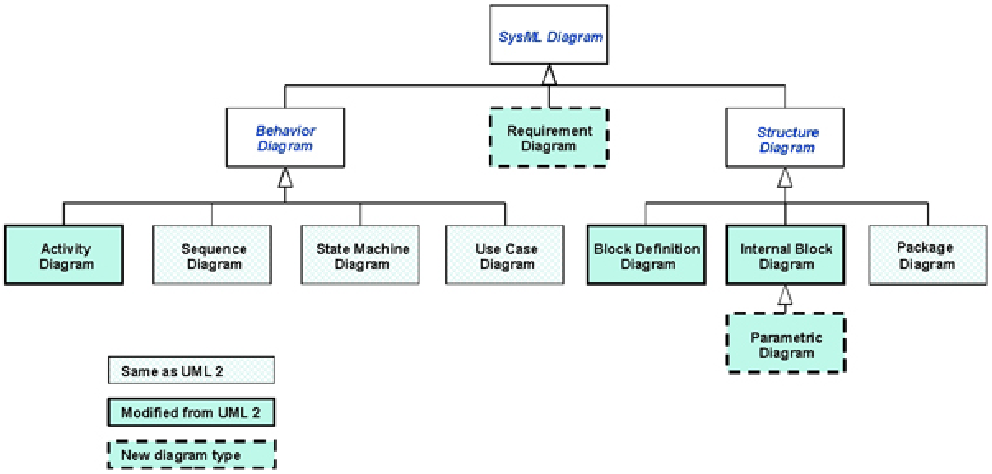


Figure 4: Relationship between SysML and UML (OMG, 2015)

Similar to UML, SysML allows architects to create dynamic models through the use of *Behavior* diagrams. In addition, with the modifications and new diagrams, SysML is better equipped to enable EA. Some of the examples are: 1) Enabling rate of data flow to be specified between activities; 2) Introducing *Control Operators* that are able to enable or disable other actions; and 3) Supporting assignment of probabilities to activities (Balmelli, 2007). These improvements directly improve SysML's functionality to support EA.

c. <u>UPDM (Unified Profile for DoDAF/MoDAF)</u>: UPDM is a visual modeling standard that supports the development of architectures that comply with the USA DoDAF and UK MODAF (OMG UPDM, 2010). It is an extension of UML/SysML that is tailored to provide a consistent and standardized means to describe DoDAF and MODAF architectures (Hause et all, 2010). This is an important improvement in operationalizing UML/SysML in supporting concept evaluation using EA for DoD related projects, since the models from UPDM are aligned with DoDAF prescribed products (UPDM, 2012). Specifically, UPDM is developed using a model-driven approach where models conforming to DM2 specification are defined defined using UML class models to enable data-centric architecture development. Since UPDM is based on UML/SysML, it is also primarily a static modeling language that will need to be transformed into an executable model.

Different Implementations for Transforming Static Models into Executable Models

It is important to note that modeling languages such as UML, SysML, and UPDM are by themselves a modeling and diagramming language, and are not executable without the use of additional processing or translation into EA. In addition, while UML and its extensions serve as an effective tool for the development of static models for software architecture, there are limitations in UML for EA due to the lack of informal execution semantics (Wang, 2011) and the difficulty in achieving concordance between different diagrams within UML (Wagenhals et al, 2009).

With the growing interest in creating EA, there are further efforts to develop a methodology to transform these static models into executable dynamic models. In this regard, two different methodologies are presented: 1) Model-driven Architecture; and 2) Colored Petri-Nets.

a. Model-driven Architecture (MDA). MDA is an initiative introduced by OMG to enable the development of executable software from static models. Here, two terms are introduced—1) Platform-independent-model (PIM) is the static model that describes the architecture of the system-under-design, and 2) Platform-specific-model (PSM) that is executable in a specific platform (such as Java).

Central to MDA is the set of standards: UML, MOF, Extensible Markup Language (XML) Metadata Interchange (XMI) and Common Warehouse Metamodel (CWM). Through the use of UML and MOF standards, UML-based modeling languages (such as UML, SysML, and UPDM) can create PIM with well-defined parameters that can be interpreted and automatically transformed into PSM, which can then be executed as an EA. To achieve this, a transformation pattern is first applied to the model to transform it to software codes (such as C# or Java) (OMG MDA, 2014).

One example of MDA implementation can be found in *executable and translatable UML*, also known as the ${}^{X}_{T}$UML, modeling language. ${}^{X}_{T}$UML combines a subset of UML graphical notation with executable semantic and timing rules (Starr, 2002), and ${}^{X}_{T}$UML creates PIM that can be automatically transformed into PSM, and have been tested and verified by Siljamaki et al (2008) and Ciccozzi et al (2010). A study by Burden et al (2011) showed that students do not need an extensive course in $^{X}{}_{T}$UML to be proficient in the language. Other software tools also enable users to create executable models using UML. For example, Sequence Diagrams, State-Machine Diagrams and Activity Diagrams can be executed in Enterprise Architecture Software with the use of additional Javascripts (Sparx, 2016).

b. Color Petri-Net: Color Petri-Net (CPN) is a very general discrete event dynamical system model that is mathematically rigorous, executable, and enables both simulation and analysis of properties (Wagenhals et al, 2009). To achieve EA using CPN, it is necessary to transform the static models (such as UML, SysML models) into executable models. For example, Liles (2008) created the process for the auto-generation of an executable CPN model of an architecture description that is DoDAF compliant using UML, specifically the transformation of UML Activity Diagrams to create executable model of a System-of-Systems; while Wang et al. (2008) translated SysML-based specifications into CPN to achieve discrete-event simulation.

CPN utilizes the concept of typed tokens to represent objects within the systems. The state of the system is determined by the distribution of tokens over different nodes, and transitions represent actions within the system. CPNs are well suited for modeling concurrent behavior of distributed systems as multiple transitions are enabled and allow for the non-deterministic firing of transition actions (Wang et al, 2015).

Introducing Life-cycle Modeling Language

In addition to the static and dynamic models derived from UML-based modeling language, there is also a relative new language that is designed specifically for systems engineering—Life-cycle Modeling Language (LML) (LML, 2015). LML focuses on the use of easy to understand ontology to allow system architects to model complex interrelationship between system components, as well as artifacts such as schedules and risk management plans. The basis for LML formulation is the Entity, Relationship, and Attribute (ERA) meta-model. By using everyday language in its implementation, LML is easy to understand and communicate between stakeholders and the design team.

With pre-defined *Actions* and *Input/Output* entities, LML enables system architects to develop EA using Action Diagrams. The Action Diagrams represents the functional sequencing of *Actions* along with the data flow provided by the *Input/Output* entities. The *Actions* such as "OR", "SYNC" or "LOOP" are predefined and allow LML to be executable in accordance with the rules associated with *Actions* and the conditions in the *Input/Output* entities. Innoslate, a web-based LML system, allows users to create LML diagrams that can be executed. In addition, Innoslate has incorporated DM2 into the LML ontology, and hence users are able to create artifacts in accordance with the specification in DM2 as well as to create other DoDAF products. However, being a relatively new language, LML does not have the full range and depth of modeling capabilities as seen in more matured languages such as UML/SysML.

Summary of EA languages and models types

In summary, there are several different methods to enable EA through the use of architectural models. All methodologies begin with the creation of graphical models using either UML-based languages (UML/SysML/UPDM) or LML. For UML-based models, there is a need to further process the models, either through MDA mapping and transformation into executable PSM, or to map into CPN for simulations. For LML, the pre-defined *Actions* allow the Action diagram to be executable by using LML tools. The relationships are stated below.

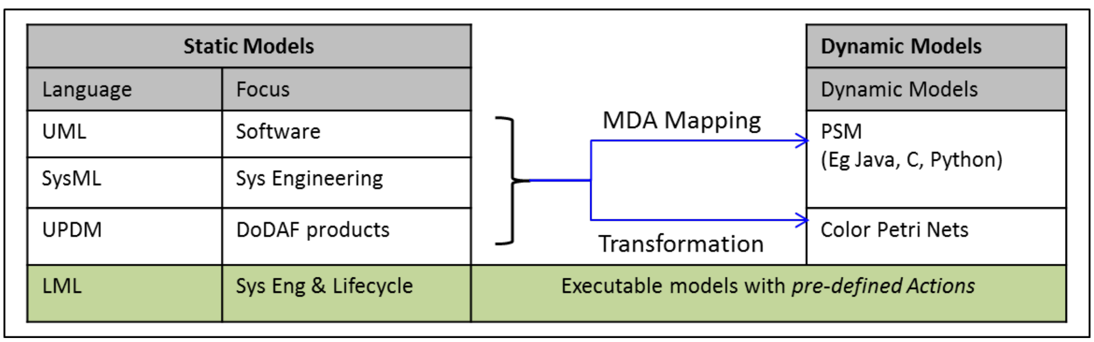


Figure 5: Relations between Static and Dynamic Models

Illustrative Example on use of EA for Concept Evaluation

With a better understanding of the capability of EA, it is apt to illustrate how EA is used to evaluate projects during early stages of Concept Evaluation. Three examples are presented to show how EA is used for concept evaluation: 1) Conceptual Design for a manned mission to Mars (Colombi et al., 2015); 2) Assessment of the Weapon Born Battle Damage Assessment (WBBDA) for Time Sensitive Effect Operations (TSEO) (Rodriguez, 2005); and 3) Extended Sequence Modeling (ESM) for Capability Review and Risk Assessment (CRRA) (Mastro et al, 2009).

Conceptual Design for Manned Mission to Mars (Colombi et al., 2015). In this research the team developed 14 Candidate Architecture (CA) models and Cost Models to evaluate different variations of the CA. Here, the EA is developed through the employment of methodology of using simulation software. Here the EA was implemented in Satellite Tool Kit (STK), and the use of EA, the team was able to stimulate and evaluate the dynamic performance of key parameters over time (Figure 6). From these results, the Pareto frontier for performance value was developed and provided the baseline for quantitative evaluation as shown in Figure 7. These results form the basis for decision makers and enhance the cognitive understanding of the system by providing performance values over time, against different parameters.

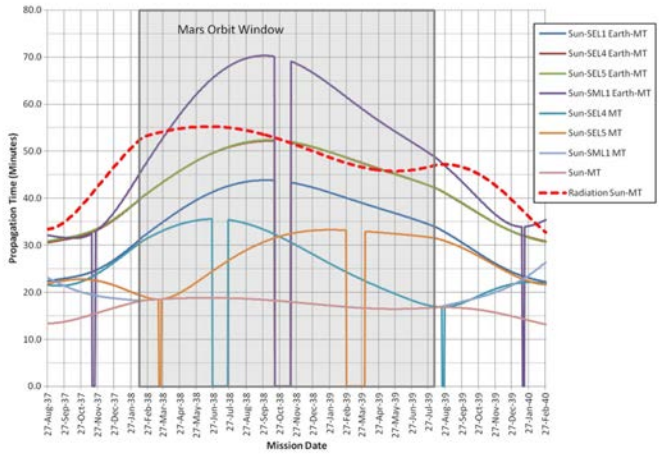


Figure 6: Example of Dynamic Results over time (Colombi et al., 2015)

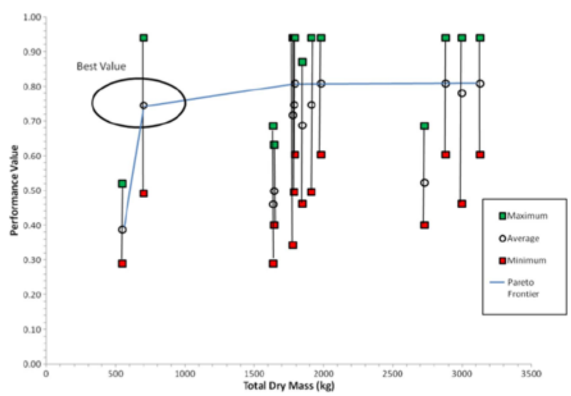


Figure 7: Example of Pareto Frontier for different variation within each CA (Colombi et al., 2015)

Assessment of WBBDA (Rodriguez, 2005). In this research, the team utilized EA to compare the effectiveness of WBBDA in TSEO. Specifically, methodology of direct transformation of static model was used. Here, the different variants of the system, utilizing different warheads and WBBDA combinations were implemented in Core™ software and Monte Carlo simulations were done. From the results, the team was able to conclude that a low lethality warhead system would benefit from the implementation of WBBDA, and provide recommendation for future analysis.

ESM in CRRA (Mastro et al, 2009). As part of this research, the team introduced the concept of ESM to improve the Process Sequence Modeling in the CRRA process. Unlike PSM which employs a binary result (pass or fail) in the activity models, ESM allows the practitioner to incorporate Probability Distribution Function (PDF) in the modeling process. Specifically, ESM can be defined as a type of executable dynamic architecture that has been specifically developed to analyze the CRRA, and provide CRRA practitioners with the ability to evaluate capabilities by varying the activities of interest or their dependencies. To implement the EA, the team used the methodology of software development, where the team developed Matlab codes for the dynamic models. The research team then implemented the ESM technique to a portion of an Agile Combat Support PSM in support of the 2009 CRRA and provided effects of dependencies such as number of people required in support of surge operations.

Conclusion

From the literature review, it is shown that executable architecting has the potential to provide program offices with the capability to assess and evaluate projects during the early Concept Development stage. This was further illustrated using the work done on concept evaluation of manned-mission to Mars. In addition, with the continuous refinement of DoDAF and improvement in the modeling languages, system architects are better equipped to develop architectures for DoDAF related systems.

III. Methodology

Chapter Overview

The purpose of this thesis is to evaluate the effect of architectural variance during the early concept development phase for the implementation of a multi-tiered UAS SoS for tactical ISR and dynamic strike operations to destroy Theater Ballistics Missiles (TBM) launchers. Modified from the Architectural-Based Evaluation Process (ABEP) (Dietrichs et al, 2006), the proposed methodology is developed from the perspective of the development team, after the team receives the Concept of Operations (CONOPS) and user's requirements. This methodology aims to evaluate different architectural variations based on implementation of the CONOPS and the effectiveness in fulfilling the user's requirement, and provide the users with a quantitative assessment of the different variations.

The methodology will begin with an overview of the operational need and scenario, followed by a summary of a fictitious CONOPS that envisage how UAS from different tiers could be employed cooperatively to locate and strike TBM launchers. This is followed by the development of high level DoDAF Operational Views of the system. Next, the architectural variants are identified, and an assessment is made to determine which user requirements and corresponding MOEs will be affected by the architectural variants. Lastly, the EA models are designed to simulate the different variants, and the results are evaluated based on the identified MOEs. The architectural products and EA are designed and implemented using Innoslate (Innoslate, 2012), a web-based EA tool.

Overview of Research Methodology

The proposed research methodology is a six-step process, namely: 1) Understand and analyze Scope and Operational Use for system-under-design; 2) Identify key user requirements and MOEs; 3) Develop high level DoDAF architectural products; 4) Identify architectural variants for evaluation; 5) Develop simulation scenario and EA models; and finally 6) Simulate and conduct data analysis.

Step 1: Understand and analyze Scope and Operational Use for system-under-design. To effectively answer the research questions, it is necessary for the development team to have a comprehensive understanding of how the System will be deployed and operated by the users. This is achieved by understanding the operational need, and the CONOPS to identify key design parameters and the key user requirements.

Step 2: Identify key user requirements and MOEs. Following the analysis, the key user requirements are further developed into quantifiable MOEs. For a more effective comparison between the results of the different variants, the MOEs are weighted through the use of the Analytic Hierarchy Process (AHP) to better evaluate the effectiveness, based on the relative importance of each MOE.

Step 3: Develop high level DoDAF architectural products. Next, to ensure that the CONOPS are understood correctly, the following architectural products are developed and presented to the users. As this is an early concept evaluation, the focus is on developing high level All Views and Operational Views, namely AV-1 (Overview and Summary Information), OV-1 (High Level Operational Concept Graphic), OV-2 (Operational Resource Flow Description), OV-5 (Operational Activity Decomposition Tree and Operational Activity Model), and OV-6a (Operational Rules Model). These products aid communication and ensure that both development team and users have the same understanding for the system-under-design.

Step 4: Identify architectural variants for evaluation. Next, based on the OVs developed, the development team will identify possible architectural variants. These architectural variants must fulfill the CONOPS as stipulated by the users, and will drive design parameters that impact the effectiveness of the system-under-design. To determine the effect, the operational activities are analyzed and the effect of respective variants on each activity are identified.

Step 5: Develop simulation scenario and EA models. Based on the CONOPS, a simulation scenario is developed that depicts how the system-under-design will be operationalized. Next, the different architectural variants are incorporated into the EA models based on OV-5b, using the results of the analysis from step 4. For this research thesis, the EA models are developed using Innoslate.

Step 6: Data Collection and Analysis. For the results to be statistically significant, Monte Carlo simulation will be executed, with at least 30 runs to be completed. For the purpose of this research, the Monte Carlo simulation will be executed with 50 runs. From the results, each variant is scored based on the MOE weightings (from Step 4), and a Pareto Frontier can be charted.

Implementation of Methodology

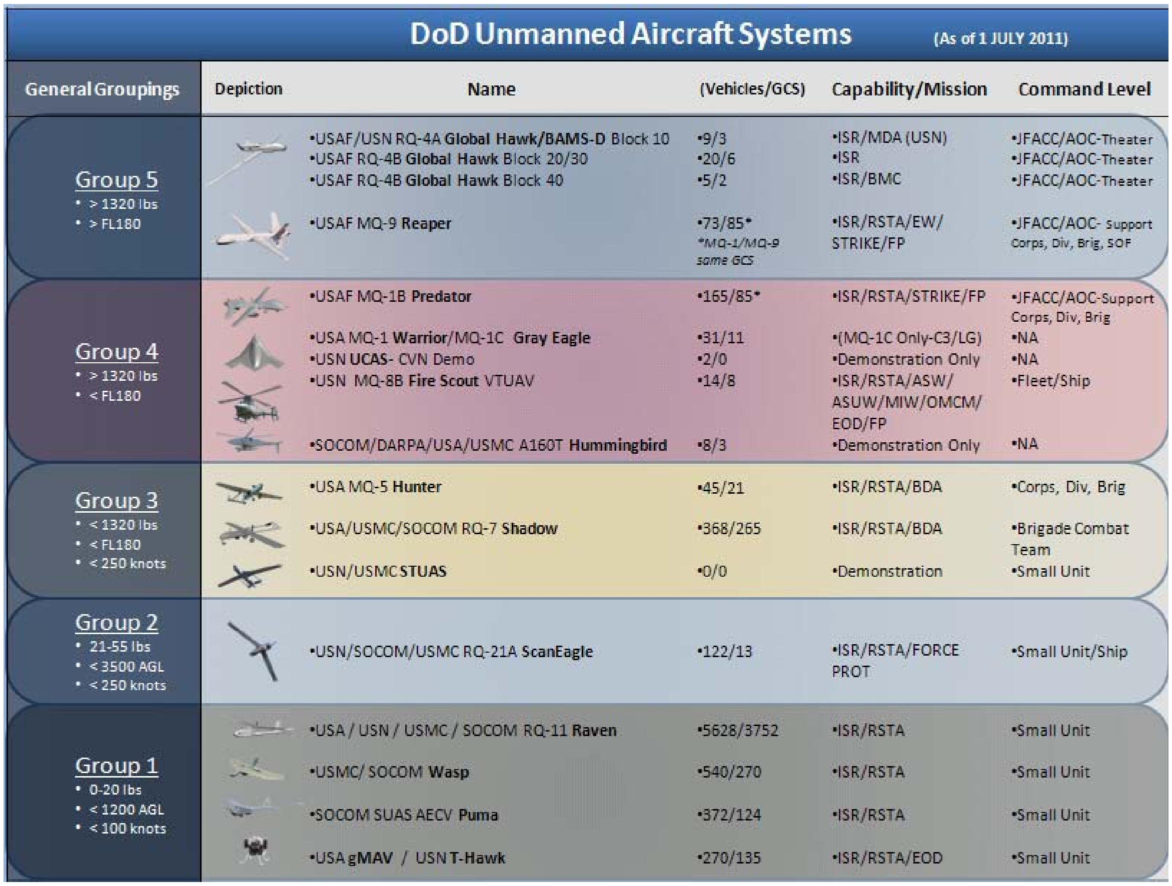
Using the proposed methodology described in the preceding section, the different architectural variants of the Multi-tiered UAS SoS is evaluated. The following sections detail the implementation of each of the steps in the methodology.

Step 1: Understand and analyse Scope and Operational Use for system-under-design

The System-under-design is a SoS of multi-tiered UAS that will be deployed for ISR and dynamic strike on Theater Ballistics Missile (TBM) launchers. The scope and use for the system will be driven by the operational need and CONOPS. To further expand on the system-deployment and understanding, the use-cases for the system are developed according to the CONOPS. The CONOPS was developed as part of a course requirement by four authors, including the author of this thesis.

Operational Need. Rapid improvements of TBM technology and increases in weapons proliferation to non-allied nations have resulted in new and constantly changing threats to friendly forces. The high accuracy of many TBM systems allow them to inflict serious damages from significant stand-off distances, even when the missiles are armed with only conventional warheads. To further compound the problem, TBM launchers employ a shoot-and-scoot technique which makes counter-TBM operations challenging. To address this threat, the military needs to have a capability that can preemptively seek and destroy TBM launchers. This multi-tiered UAS SoS provides the capability to maintain persistent situation awareness over a designated area to search and locate possible TBM launchers and dynamically target and strike these TBM launchers with minimal cost or risk to personnel.

<u>CONOPS Overview</u>. The multi-tiered UAS SoS focuses on the efficient employment of different groups of UAS to maintain persistent situational awareness over the Area of Operations (AO), to seek and identify possible TBM launchers, and to dynamically direct targeting and strike operations. It leverages the capabilities of different groups of UAS and sensor systems to achieve a system capable of optimizing UAS employment for mission effectiveness, while minimizing operational cost and risk. Specifically, the multi-tiered UAS SoS will need to employ cooperative control among various UAS groups in the AO to assign roles and plan safe routes for ingress and egress. The different tiers of UAS, as defined in the Unmanned System Roadmap, are shown in Figure 8 below. The details of the CONOPS can be found in Appendix A.



DoD Unmanned Aircraft Systems (As of 1 JULY 2011)					
General Groupings	Depiction	Name	(Vehicles/GCS)	Capability/Mission	Command Level
Group 5 • > 1320 lbs • > FL180		•USAF/USN RQ-4A **Global Hawk/BAMS-D** Block 10 •USAF RQ-4B **Global Hawk** Block 20/30 •USAF RQ-4B **Global Hawk** Block 40 •USAF MQ-9 **Reaper**	•9/3 •20/6 •5/2 •73/85* *MQ-1/MQ-9 same GCS	•ISR/MDA (USN) •ISR •ISR/BMC •ISR/RSTA/EW/ STRIKE/FP	•JFACC/AOC-Theater •JFACC/AOC-Theater •JFACC/AOC-Theater •JFACC/AOC- Support Corps, Div, Brig, SOF
Group 4 • > 1320 lbs • < FL180		•USAF MQ-1B **Predator** •USA MQ-1 **Warrior**/MQ-1C **Gray Eagle** •USN **UCAS**- CVN Demo •USN MQ-8B **Fire Scout** VTUAV •SOCOM/DARPA/USA/USMC A160T **Hummingbird**	•165/85* •31/11 •2/0 •14/8 •8/3	•ISR/RSTA/STRIKE/FP •(MQ-1C Only-C3/LG) •Demonstration Only •ISR/RSTA/ASW/ ASUW/MIW/OMCM/ EOD/FP •Demonstration Only	•JFACC/AOC-Support Corps, Div, Brig •NA •NA •Fleet/Ship •NA
Group 3 • < 1320 lbs • < FL180 • < 250 knots		•USA MQ-5 **Hunter** •USA/USMC/SOCOM RQ-7 **Shadow** •USN/USMC **STUAS**	•45/21 •368/265 •0/0	•ISR/RSTA/BDA •ISR/RSTA/BDA •Demonstration	•Corps, Div, Brig •Brigade Combat Team •Small Unit
Group 2 • 21-55 lbs • < 3500 AGL • < 250 knots		•USN/SOCOM/USMC RQ-21A **ScanEagle**	•122/13	•ISR/RSTA/FORCE PROT	•Small Unit/Ship
Group 1 • 0-20 lbs • < 1200 AGL • < 100 knots		•USA / USN / USMC / SOCOM RQ-11 **Raven** •USMC/ SOCOM **Wasp** •SOCOM SUAS AECV **Puma** •USA **gMAV** / USN **T-Hawk**	•5628/3752 •540/270 •372/124 •270/135	•ISR/RSTA •ISR/RSTA •ISR/RSTA •ISR/RSTA/EOD	•Small Unit •Small Unit •Small Unit •Small Unit

Figure 8: Classification of Different UAS tiers

a. Larger tiers UASs (Group 4 and 5):

i. Persistent ISR. The larger tiers of UASs have the greatest range, endurance, airspeed, and altitude capabilities in the family of UAS. As such, these UAS are typically employed to conduct persistent ISR over the AO. They will be equipped with the necessary sensors to identify possible Surface-to-Air (SAM) sites and possible TBM launchers in the AO.

ii. Dynamic Strike. These groups of UAS are also capable of carrying kinetic weapons, and could be loaded with the necessary munitions to provide a dynamic strike capability.

b. Smaller tiers UASs (Group 1 and 2):

i. Target Verification. The smaller UAS groups have a smaller footprint and are used for target verification and can be equipped with Automatic Target Recognition (ATR) software to determine phases of TBM launcher deployment.

ii. Battle Damage Assessment (BDA). These UAS groups will also be used to perform BDA after the conclusion of the dynamic strike to confirm mission success.

Use-Case: The Use Case diagram and the terse use-case of the system is as shown in Figure 9, and Table 3 describe this diagram in details:

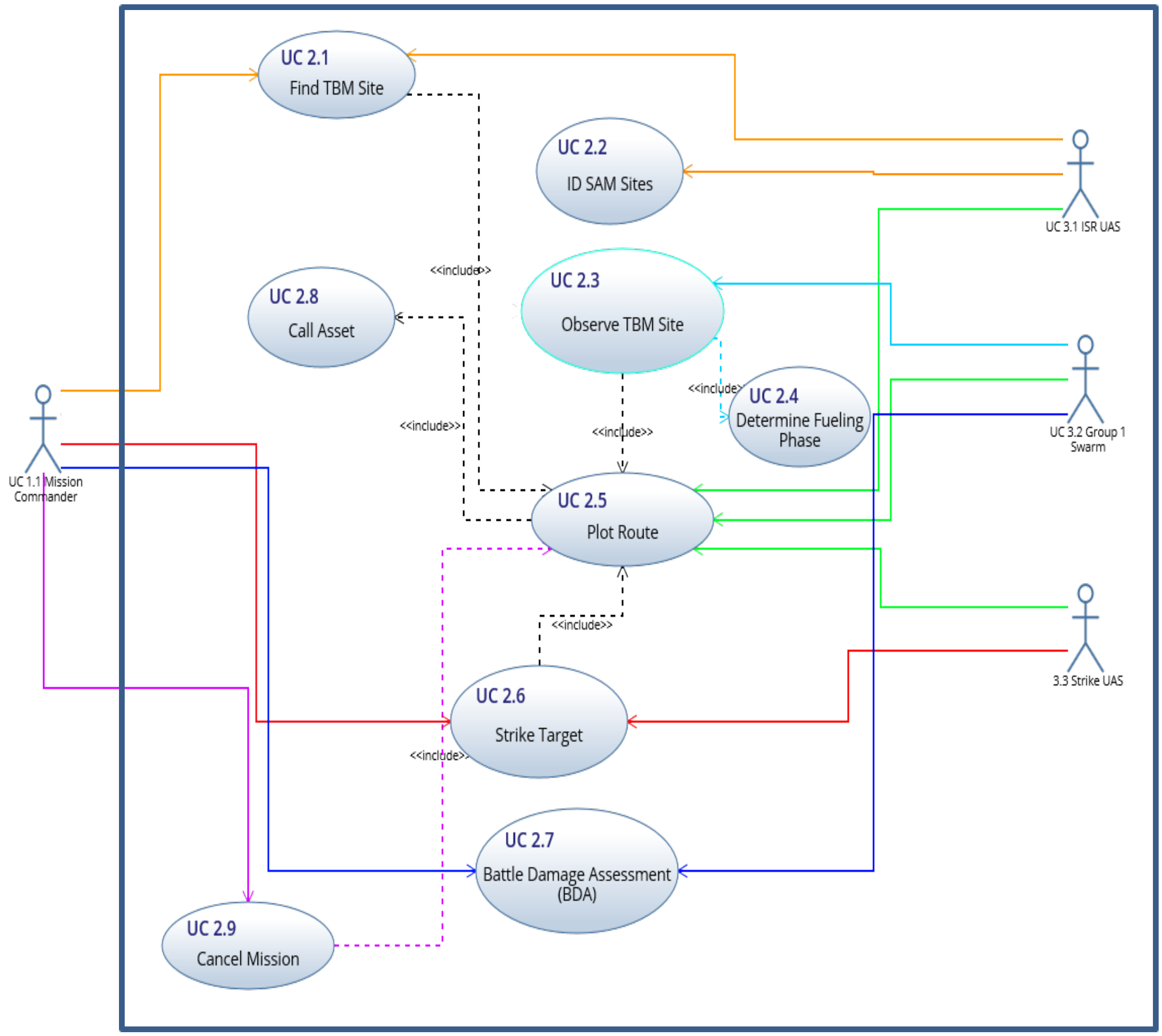


Figure 9: Use Case Diagram

Table 3: Terse Use Cases

No	Name	Terse Use Case Write-up
UC 2.1	Find TBM Site	The Mission Commander inputs mission parameters into System. The System identifies available ISR UAS and assigns ISR UAS to find TBM Site. ISR UAS continues loiter above AO and uses sensor data

No	Name	Terse Use Case Write-up
		to identify TBM site. ISR UAS update System on possible TBM site.
UC 2.2	ID SAM Sites	ISR UAS loiters around AO. ISR UAS picks up SAM Sites signature through its onboard sensors. ISR UAS determines location of SAM Sites. ISR UAS updates System with the SAM Site locations. The System stores the site locations within the database for plotting UAS ingress routing. Note: this use case is not simulated in the EA.
UC 2.3	Observe TBM Site	System receives the possible TBM site locations from ISR UAS. System initiates Observe TBM Site function. System identifies available Group 1 Swarm and assigns the Group 1 Swarm to Observe TBM Site. System calculates and plot route for Group 1 UAS Swarm to area-of-interest. System sends routing information and Target information to Group 1 UAS Swarm. Group 1 Swarm proceeds to TBM site and utilize onboard sensors and software to identify TBM launchers and the phase of operations. Proceed to *Determine Fueling Phase* use case if the Group 1 Swarm confirmed TBM launcher is in the Fueling Phase.
UC 2.4	Determine Fueling Phase	Group 1 Swarm identifies that phase in which the TBM launcher is in. Group 1 Swarm confirms TBM Launcher is in Fueling Phase using onboard software and send TBM launcher status to System.
UC 2.5	Plot Route	System confirms the Start position of the UAS and the desired Final loiter location of the UAS which maximizes coverage of the target. System identifies possible SAM sites within the AO. System plots the optimal route for UAS from Start to Final position, avoiding SAM

No	Name	Terse Use Case Write-up
		sites. System transmits flight path to the respective UAS.
UC 2.6	Strike Target	System receives confirmation of TBM launcher in Fueling Phase. System selects the available Strike UAS within the AO and assigns the Strike UAS to strike the TBM launcher. System determines the best route for Strike UAS ingress and egress and transmits the information the Strike UAS. Strike UAS enters range of target and acquires target TBM launcher. Strike UAS updates System that target is acquired. D- Mission Commander approves and launch instructions is transmitted to Strike UAS. Strike UAS launches missiles and sends launch confirmation to Mission Commander.
UC 2.7	Battle Damage Assessment (BDA)	System receives confirmation that weapon payload has launched against TBM launcher. System identifies available Group 1 Swarm and assign Group 1 Swarm to execute BDA. System calculates and plot route for Group 1 UAS Swarm to area-of-interest. System sends routing information and Target location to Group 1 UAS Swarm. Group 1 Swarm proceeds to TBM site and utilize onboard sensors and software to identify and confirmation of TBM launchers destruction.
UC 2.8	Call Asset	System scans the current deployed UAS assets in the AO. System identifies all available assets in the AO and selects the optimal Asset based on the type of UAS and type of payload to meet the required mission requirement. The System communicates with the UAS and assign tasks to the UAS.

No	Name	Terse Use Case Write-up
UC 2.9	Cancel Mission	Mission Commander recalls all active aircraft. System plots route safest for all UASs, taking into consideration location of possible SAM sites and UAS capabilities. System transmits flight-plans to all UASs. UASs acknowledge receipt and proceed to return to base.

Step 2: Identify key user requirements and MOEs

Based on the analysis of the CONOPS and the deployment of the system-under-design, the following are the key MOEs that are measured:

a. The system-under-design shall positively identify and confirm target location of 60% (threshold) and 80% (objective) of the targets encountered.

b. The system-under-design shall destroy 60% (threshold) and 80% (objective) of the targets encountered.

c. The system-under-design shall have less than 10% (threshold) and 5% (objective) in false target declarations out of all total target declarations.

d. The system-under-design shall strike the target within 1 hr 45 mins (threshold) and 1hr 30 mins (objective) after initial target acquisition. It is important to note that these duration requirements are set to be long due to the artificiality of the CONOPs.

The user requirements are then translated into MOPs that will be measured during each simulation run. The MOPs are as follows:

a. Target Acquisition (Percentage): Measures the capability of the system to effectively and positively acquire the TBM launcher. This is an important measure that demonstrate the system's capability to effectively locate TBM within the area of operations.

$$Target\ Acquisition\ (Percentage) = \frac{Target\ Positively\ Acquired}{Total\ number\ of\ Targets\ encountered} \times 100\%$$

b. False Alarm (Percentage): Measures the error rate of the system in picking up false target. A high false alarm rate results in possible strike on non-TBM that may result in negative repercussion on the mission.

$$False\ Alarm\ (Percentage) = \frac{False\ Target\ Acquired}{Total\ number\ of\ Targets\ declared\ in\ area} \times 100\%$$

c. Time-to-Strike: Measures the time from Target Acquisition to last Bomb-on-Target. This is important due to the nature of TBM launcher operations. The TBM launchers are equipped with the ability to "launch and scoot", and may not be located within the same coordinates for an extended period of time. As a result, it is important that the system is able to acquire and engage the target within a short time span.

$$Time\ to\ Strike = Bomb\ Launched\ Time - Target\ Acqusition\ Time$$

d. Target Destruction (Percentage): Measures the total number of confirmed targets that are positively destroyed. This MOP evaluates the overall capability of the system in achieving its user's requirement in TBM launcher destruction.

$$Target\ Destruction\ (Percentage) = \frac{Target\ Destroyed}{Total\ number\ of\ Targets\ encountered} \times 100\%$$

The MOPs will be tracked and pairwise comparison will be carried out. Next, the Objective Hierarchy Process (OHP) is used to assign weights to each of the MOPs, and an overall weighted score will be given for each variant based on the aggregated results.

Step 3: Develop High level DoDAF architectural products

Based on the analysis and the required MOEs, the following DoDAF architectural products are developed—1) All-View 1 (AV-1), 2) Operational View 1 (OV-1), 3) Operational View 2 (OV-2), 4) Operational View 5 (OV-5), Operational View 6 (OV-6) and 5) Logical Data View (DIV-2). Similar to the CONOPS, the AV-1 and OV-1 were developed as part of a System Architecting course requirement.

AV-1: The AV-1, derived from the CONOPS, provides an overview of the system-under-design. In addition, the AV-1 lists the architectural products that will be developed based on the requirement of the thesis investigation. The detailed AV-1 is found in Appendix B.

OV-1: The OV-1 is a pictorial depiction of the system-under-design and serves as an important visual communication tools to aid understanding between stakeholders. The OV-1 for the system is as shown in Figure 10. Specifically, the OV-1 shows the linkage and command links between the Command Post to the different tiers of UAS, and the sequence of operations leading to the strike of the TBM launchers.

OV-2**:** The OV-2 provides the high level summary of the resource flow between the different entities of the Multi-tiered UAS SoS. The key entities are—1) Decision Makers (Manual or autonomous), 2) ISR UAS, 3) Surveil UAS, 4) Strike UAS, and 5) BDA UAS. The key resource flows are information flows between the Decision Makers and the different UAS tiers, specifically Mission Parameters and Command instructions from the Decision Makers and telemetry and video data from the UAS. In addition, it is noted that the Information Data Cloud is implemented as a logic node, and not a physical node. The diagram is illustrated in Figure 11.

OV-5a: The OV-5a details the key activities in the Multi-tiered UAS SoS. The key Activities can be distinctly demarcated into six broad categories, namely—1) ISR UAS Operational Activities, 2) Surveil UAS Operational Activities, 3) Strike UAS Operational Activities, 4) BDA UAS Operational Activities, 5) Decision Making

Activities, and 6) Monitoring Activities. The OV-5a focuses on the activities executed by the different sub-system and hence may appear to be highly redundant. However, it is necessary as it forms the foundation for OV-5b. The OV-5a is illustrated in Figure 12.

OV-5b: The OV-5b details the flow of the activities and how the different entities operate within the multi-tiered UAS SoS. This is represented through the use of swim-lanes in the diagram, which activities associated to the particular entity appearing on its specific swim-lane. In addition, the OV-5b forms the foundation for the construction of EA, based on the characteristic and logic flow between the different activities. The OV-5b is illustrated in Figure 13.

OV-6a: The OV-6a details the operational rules for the key activities nodes in the activity flow diagram, OV-5b. These rules are essential for the development of the EA as they define the operational constraints of the system and the rules for the interaction between different activities nodes. The details are illustrated in Table 4 below.

DIV-2: The DIV-2 details the relationship between different assets and the flow of information between different assets. In particular, the DIV-2 focuses on establishing the data model and the detailed flow of data between different entities. The details are illustrated in Figure 14.

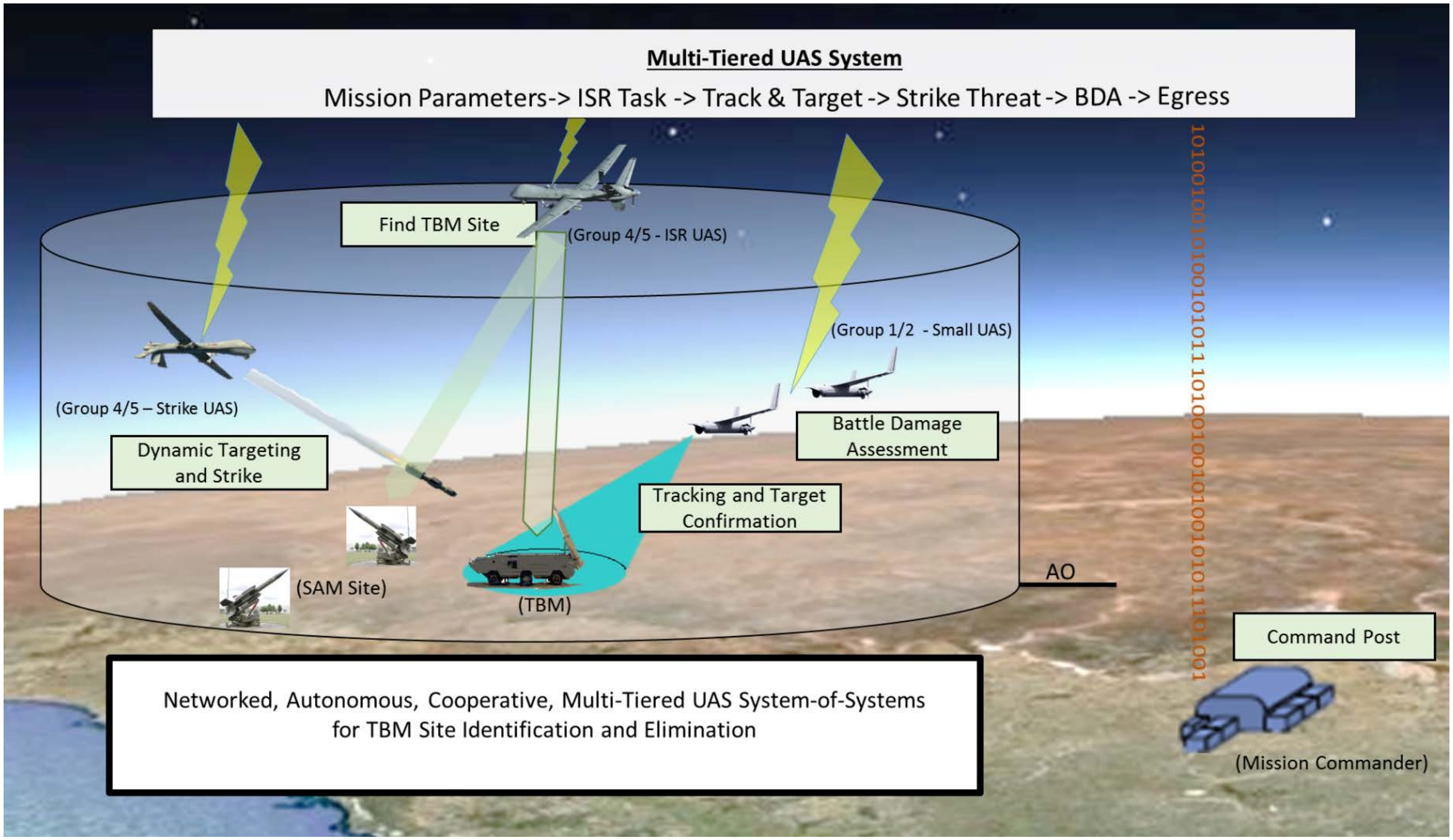


Figure 10: OV-1 of Multi-tiered UAS SoS

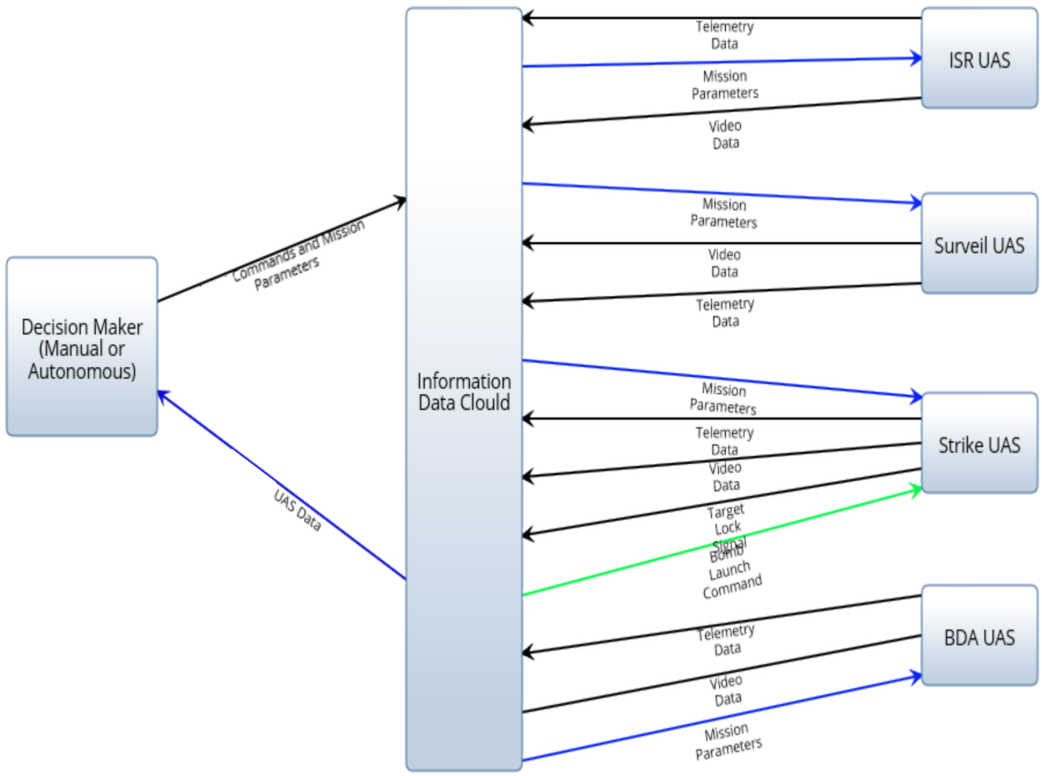


Figure 11: OV-2 High level Resource Flow Diagram of Multi-tiered UAS SoS

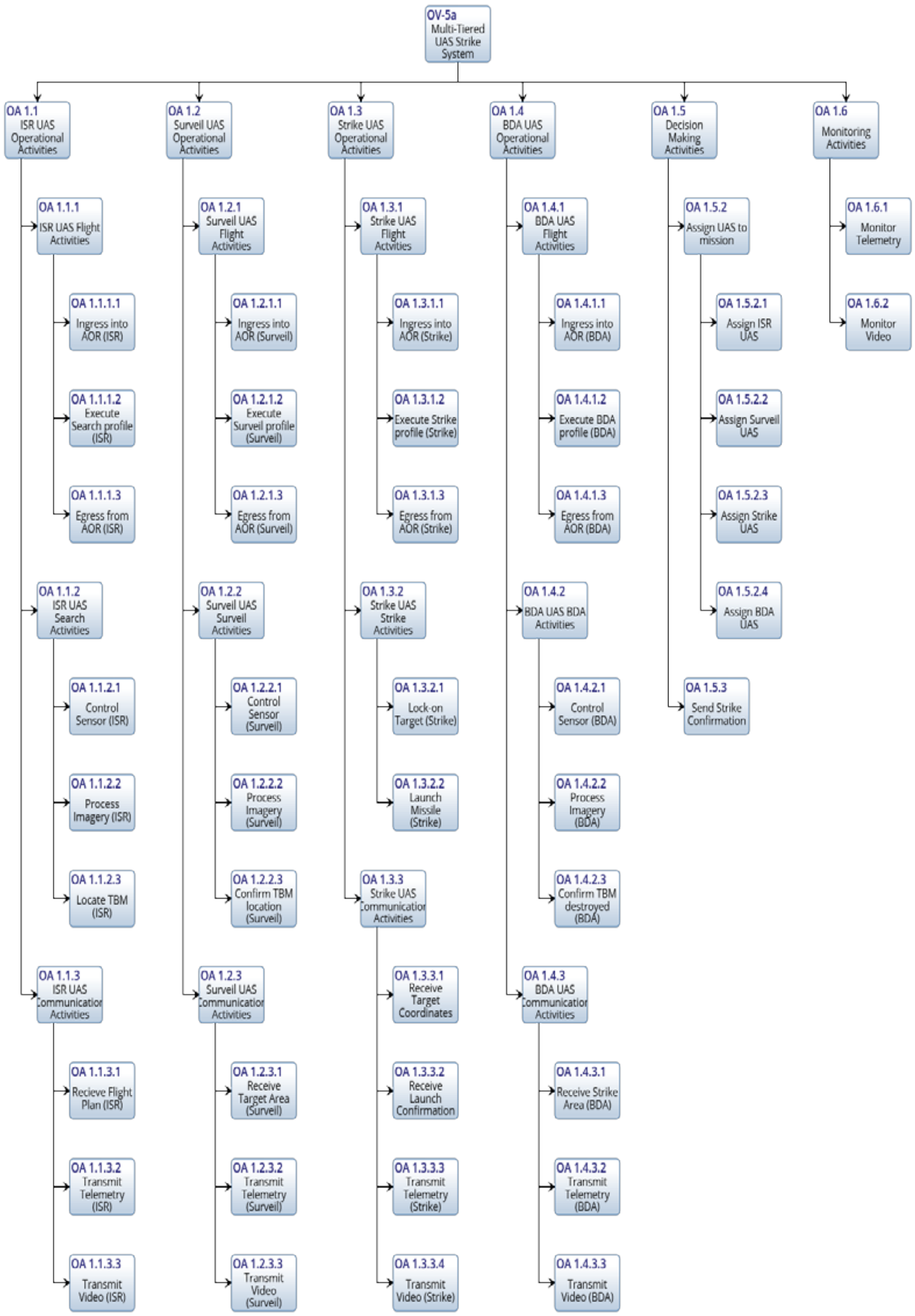


Figure 12: OV-5a Operational Activities Decomposition Tree

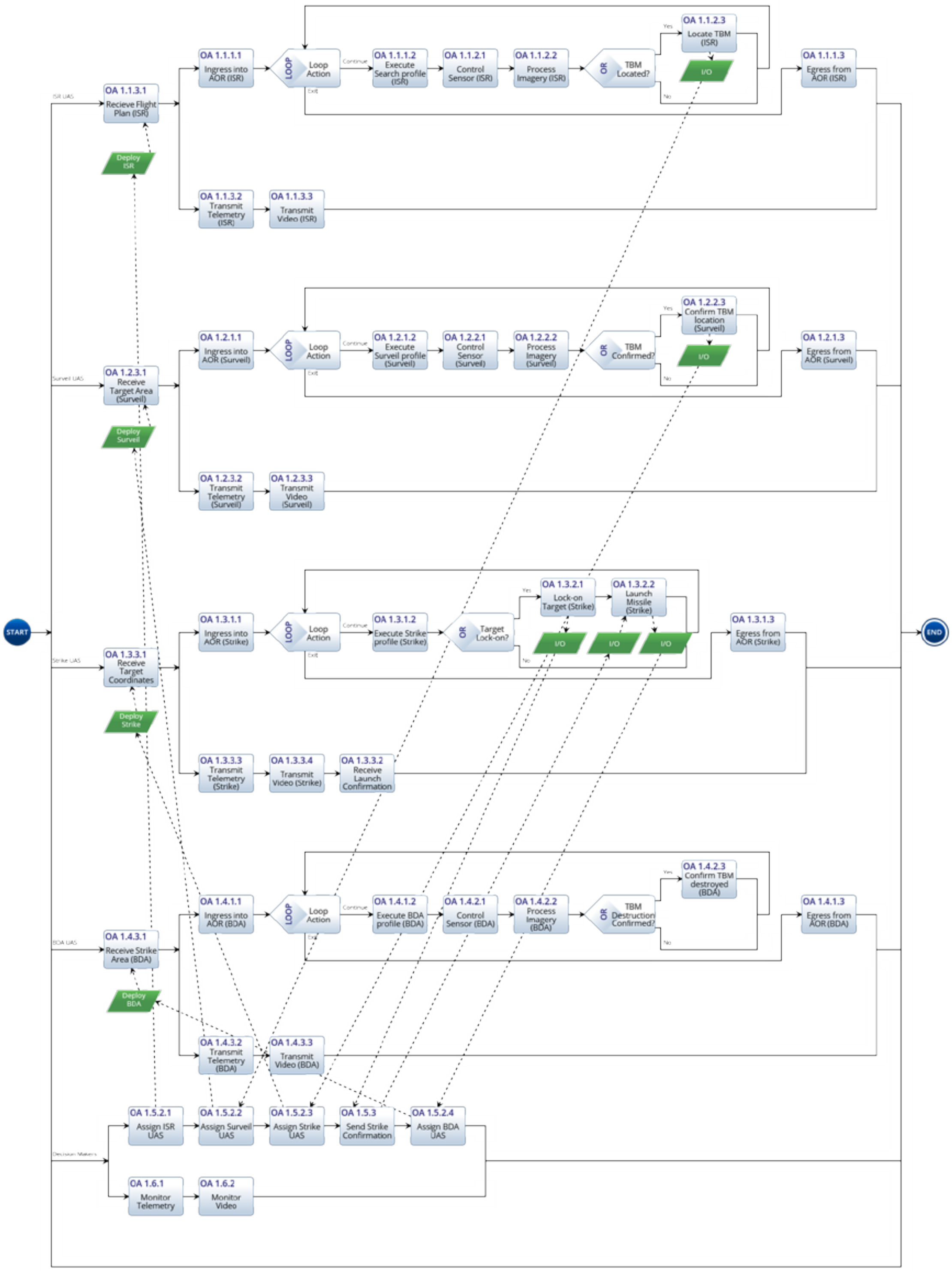


Figure 13: OV-5B Activity Flow Diagram of the Multi-tiered UAS SoS

Table 4: OV-6A Operational Rules Model

Operational Activity	Rules
Receive Flight Plan (ISR)	Activate by Decision Makers through the Assign ISR UAS activity. Signify the activation of the Multi-tiered UAS SoS,
Assign Surveil UAS	Activated by Decision Makers if TBM Located = TRUE.
Receive Flight Plan (Surveil, Strike or BDA)	Activated when Assign Surveil/Strike/BDA UAS = TRUE The time delay is dependent on Type of C2 and associated distribution.
Ingress into AOR	Activated after UAS Receive Flight Plan. The duration required for Ingress into AOR is dependent on Type of C2 and associated distribution.
TBM Located?	IF TBM located, activate Locate TBM (ISR) activity which updates Decision Makers, THEN Decision makers assign appropriate Surveil UAS through Assign Surveil UAS activity, ELSE continue TBM Located? Task UNTIL search is completed. The probability of TBM located is dependent on the Type of Sensors.
TBM Confirmed?	IF TBM confirmed, activate Confirm TBM confirmation activity which updates Decision Makers, THEN Decision makers assigned appropriate Strike UAS through Assign Strike UAS activity, ELSE continue TBM Confirmed? Task UNTIL search is completed. The probability of TBM Confirmation is dependent on the Type of Sensors.
Target Lock-on?	IF TBM lockon, activate Lock-on Target (Strike) activity that

	updates Decision Makers, THEN Decision makers activate Send Strike Confirmation activity and Strike UAS executes Launch Missile (Strike) Activity. The Decision makers are updated and activate Assign BDA UAS activity.
TBM Destruction Confirmed?	IF TBM destruction confirmed, the scenario ends, ELSE Decision makers assigned second Strike UAS if scenario dictates. The probability of TBM Destruction Confirmation is dependent on the probability of destruction of the Strike UAS.

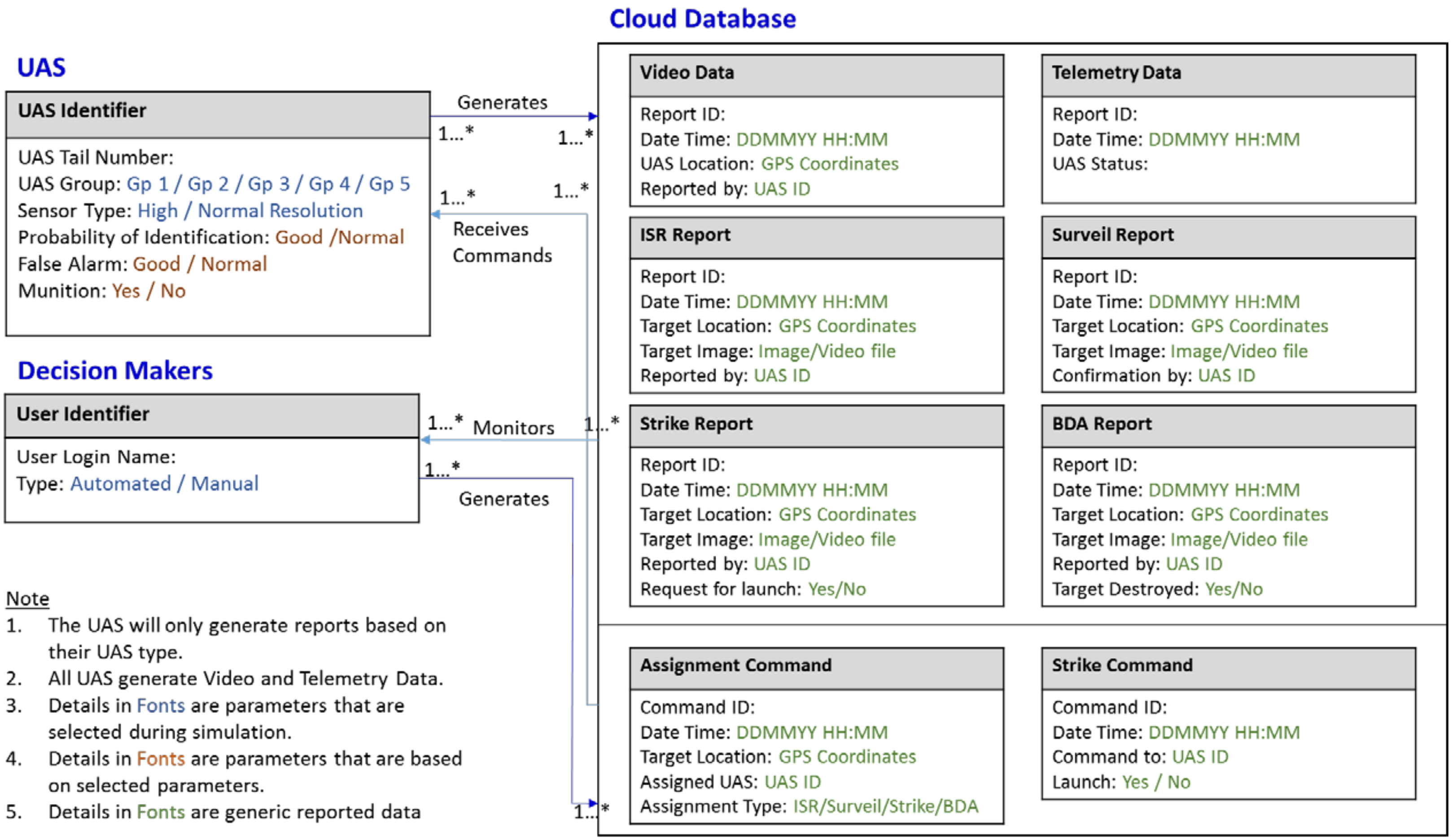


Figure 14: DIV 2 of Multi-tier UAS SoS

Step 4: Identify Architectural Variants for evaluation

The multi-tiered UAS SoS can be implemented with different capabilities that will allow the SoS to fulfil the CONOPS and meet the operational needs. However, different capabilities will result in different development and operational costs, as well as varying degree of mission effectiveness. For example, a decision-making algorithm can be developed for the SoS to achieve autonomy or new high-end sensors may be designed to improve overall effectiveness of the SoS. To effectively evaluate these design variants, it is necessary to identify the key design parameters and assess the effectiveness based on the MOEs through simulation using EA.

Due to the time limitation of the research study, the research will focus on the evaluation of three design parameters in the implementation of the SoS. However, this methodology is scalable and can be extended to evaluate new design parameters. The three parameters under considerations are:

a. Decision-making capability:

   1. Centralized Manual Command and Control (C2) by ground commander.
   2. Centralized autonomous C2 by pre-identified ISR UAS.

   ➔ Affects speed of decision making, and quality of decision-making.

b. ISR Sensor capability:

1. Normal Sensor with lower Probability of Detection and high False Alarm rate.

2. High-end sensor with high Probability of Detection and low False Alarm rate.

➔ Affects Target Acquisition and False Alarm percentages.

c. Number of Strike UAS deployment

1. 1 x Strike UAS deployment

2. 2 x Strike UAS deployment.

➔ Affects Target Destruction percentages.

Step 5: Develop simulation scenario and EA models

To evaluate system, a simulation scenario based on AV-1 and OV-1 is developed, and the dynamic models are designed based on OV-5, OV-6a and DIV-2. In this simulation, an Area of Operations (AO) is identified, as marked by the 40 squares in the diagram shown below. The Simulation is summarized in Figure 15 and the Executable Architecture is shown in Figure 16, with details from Figure 16a to 16e:

Figure 15: Overview of Simulation

The overview of the key processes in the Simulations are as follow:

1. Threat Assessment shows possible TBM deployment within Area of Operations (AO) [marked by Sq blocks 1 – 40].
2. UAS deploy from staging sites.
3. During each run, 2 targets and 2 false targets are randomly deployed over the 40 grids.
4. 1 x ISR UAS deployed to conduct ISR. Follow anti-clockwise search pattern over AO.
5. When potential target is located, a Surveil UAS is deployed to Confirm and track target. The simulation is limited to 2 x Surveil UAS.
6. Strike UAS deploy to strike target, once target confirmed.
7. Small UAS to conduct BDA.
8. Total of 50 runs are carried out per scenario, thus generating a total of 100 targets and 100 false targets.

During each run, the targets are re-deployed randomly over the 40 grids.

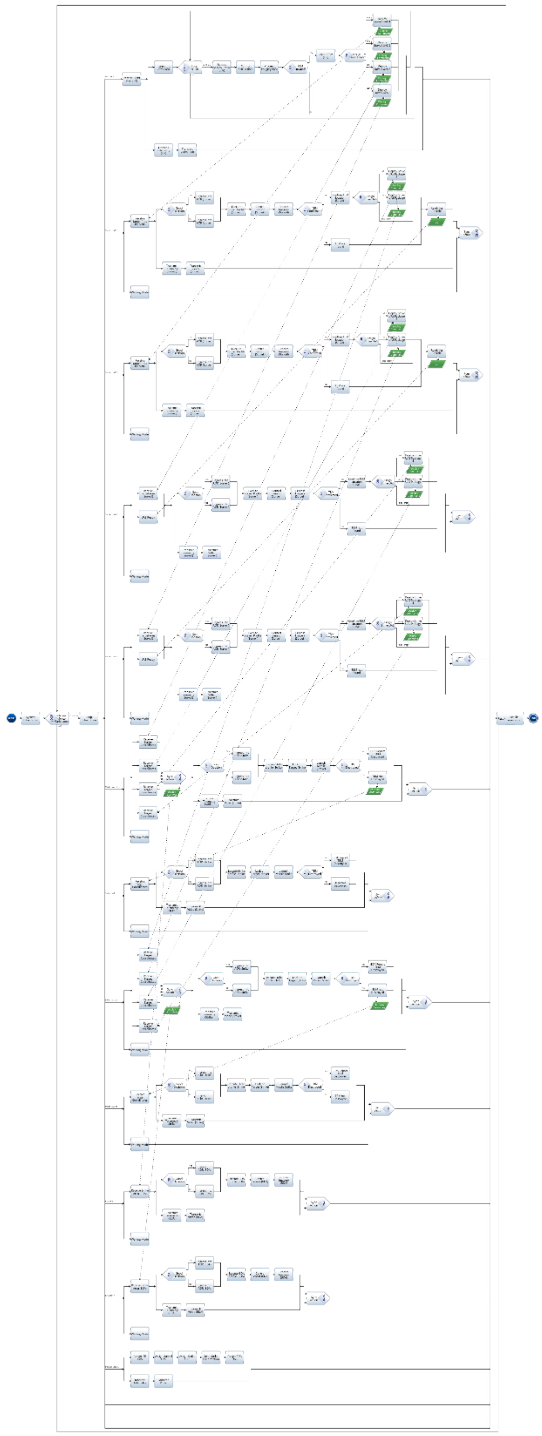


Figure 16: Modified 0V-5B for Simulation

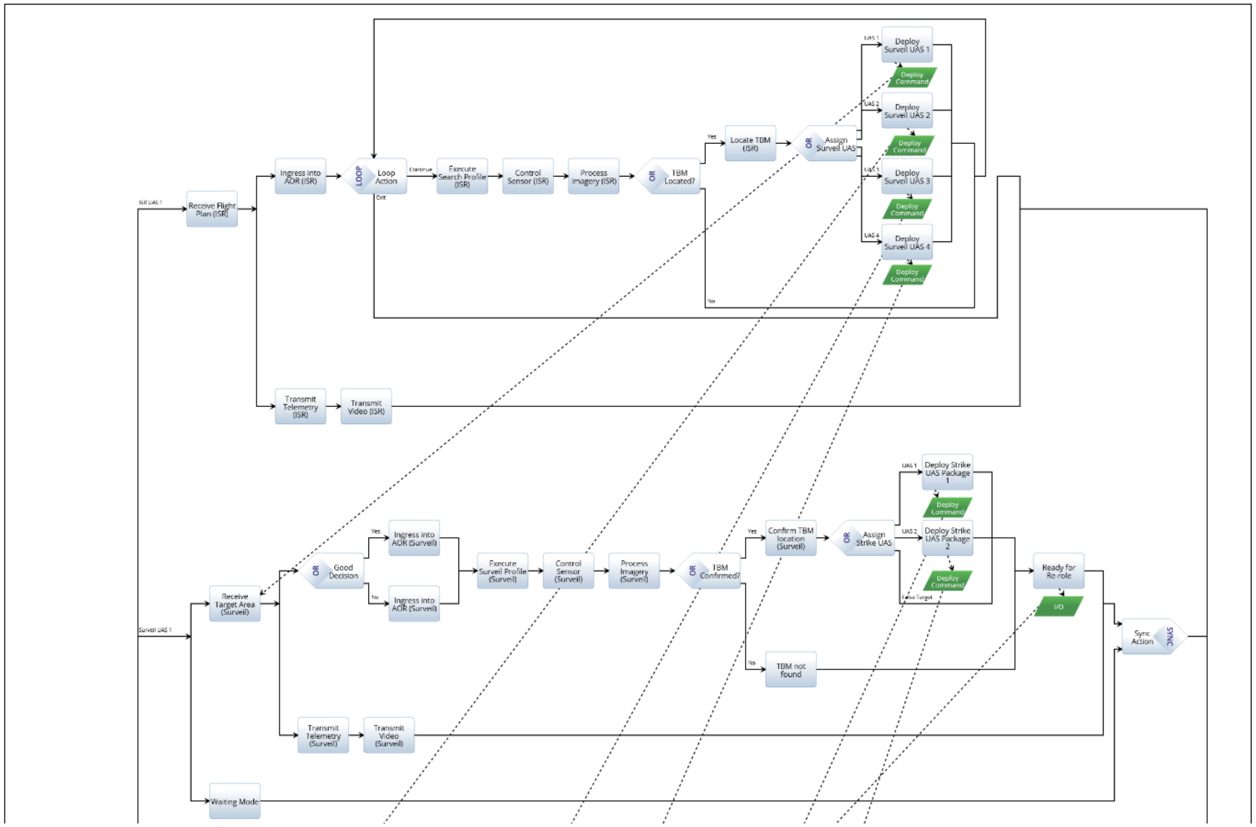


Figure 16a: Details on Modified OV-5B

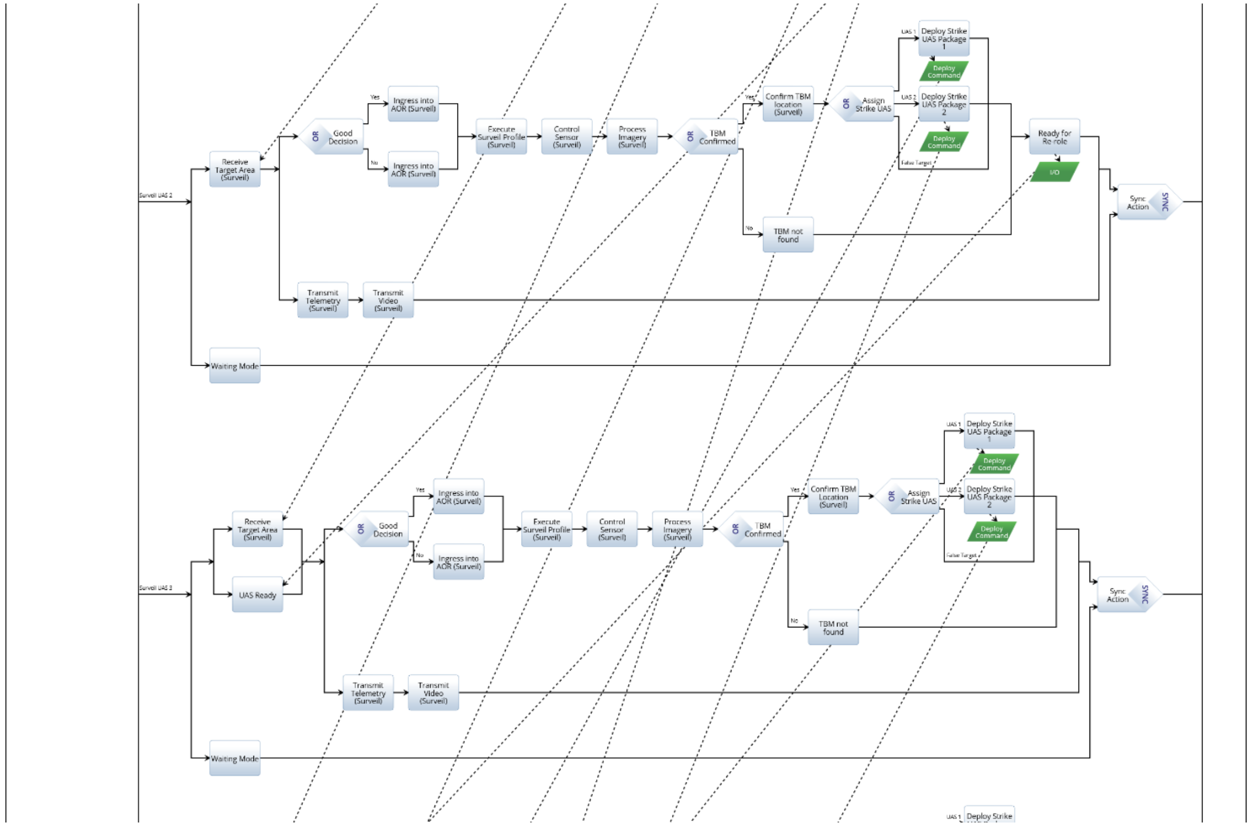


Figure 16b: Details on Modified OV-5B

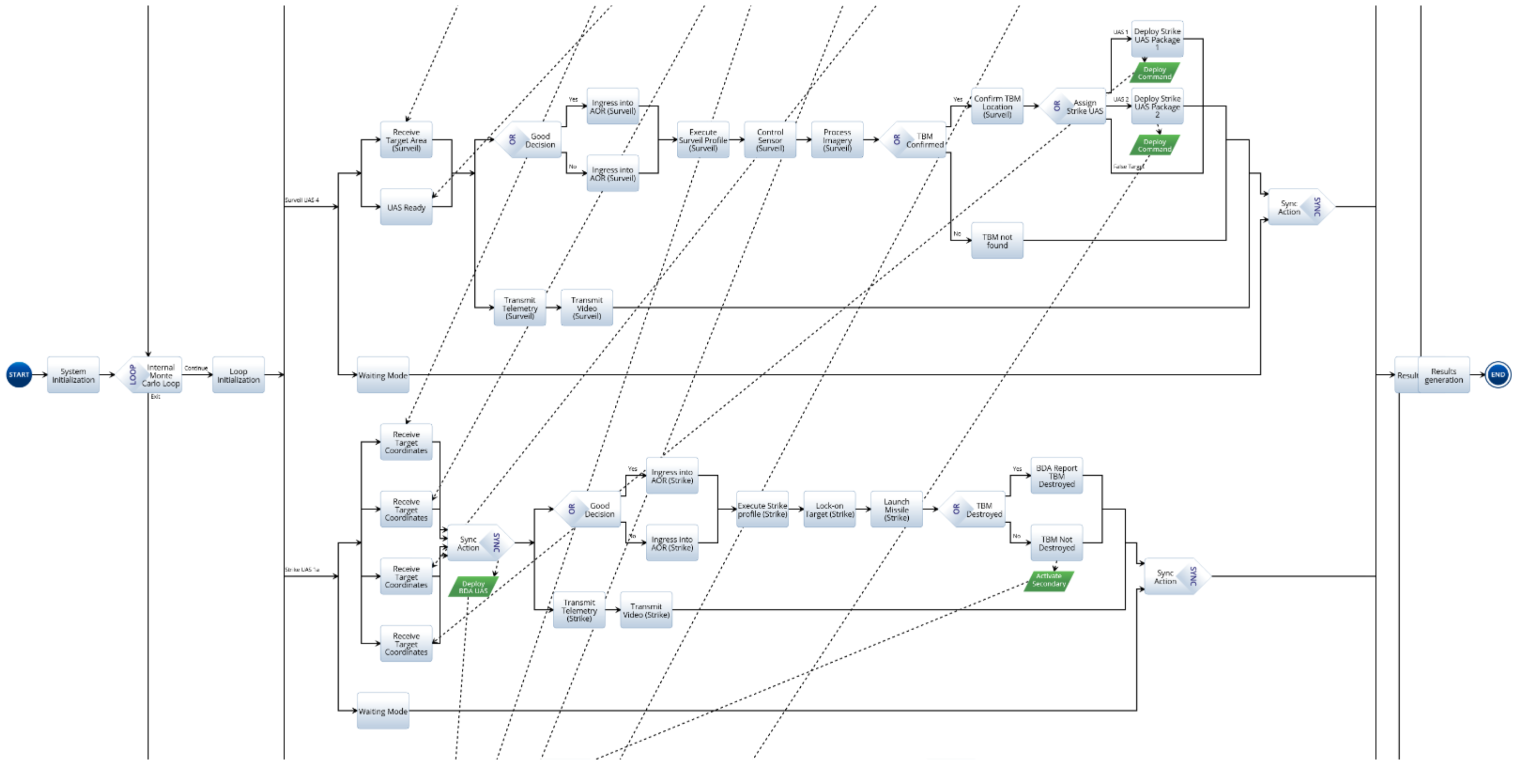


Figure 16c: Details on Modified OV-5B

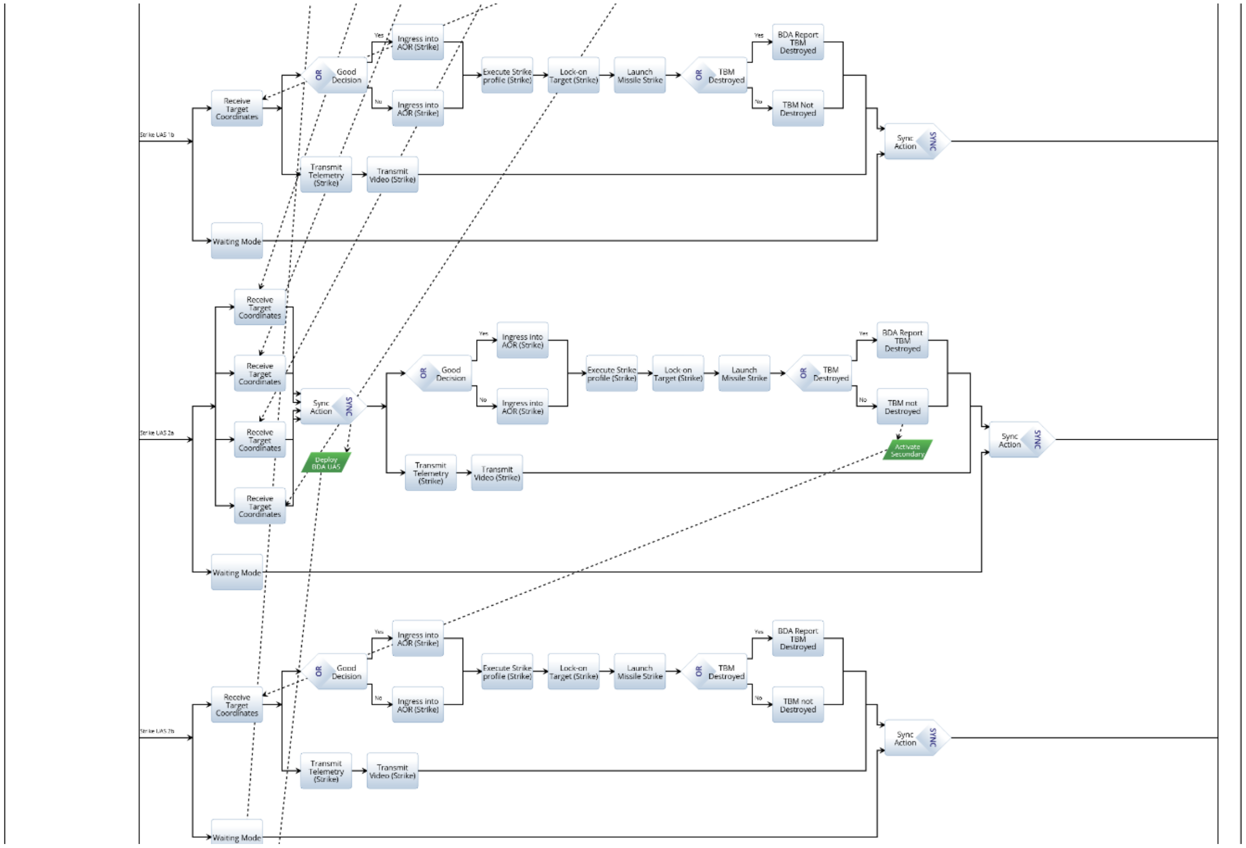


Figure 16d: Details on Modified OV-5B

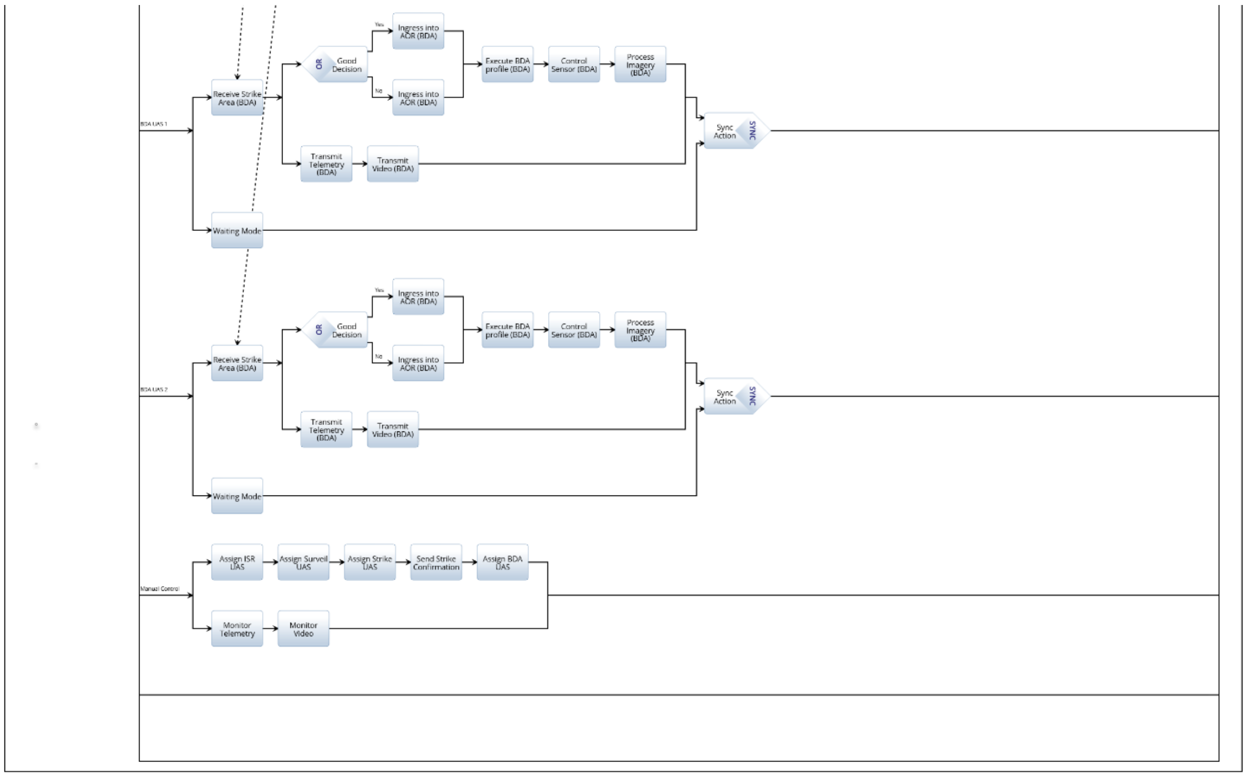


Figure 16e: Details on Modified OV-5B

To compare between the effectiveness of the different architectural variants, the following changes are applied to the simulation scenarios as shown in Table 5:

Table 5: 8 Architectural Variants of Multi-tiered UAS SoS for concept evaluation

	Centralized Manual C2	Autonomous C2 Operations
Normal ISR Sensor	1 x Strike UAS	1 x Strike UAS
	2 x Strike UAS	2 x Strike UAS
High End ISR Sensor	1 x Strike UAS	1 x Strike UAS
	2 x Strike UAS	2 x Strike UAS

The scenario will be implemented using Innoslate software. Here, the OV-5b will form the basis for the development of the EA, and Javascript will be used to incorporate the decision logic of the systems, and to collect the MOE data, namely:

1. Percentage of Target Confirmed
2. Percentage of False Target
3. Time to Strike
4. Percentage of Target Destroyed

The impact of different variants are incorporated into the different activities nodes in the OV-5b during simulations:

1. Manual vs Autonomous C2: Affects the speed of decision making and quality of the decision.

a. Speed. The speed of the decision making determines the time delay in which the respective UAS receive their flight command. As part of the simulation, it is assumed that the human operator will take longer time to integrate information before making a decision, while the automated system will be more efficient in consolidating data and determining the course of action. Hence, as part of the simulation, the decision making delay for the human operator process is assumed to twice as long as the automated system. In addition, it is expected that the automated system will have a smaller standard deviation as compared to the human operator, as efficiency of the human operator will vary based on factors such as experience level and training. This will be implemented in the following Activities nodes, with the details shown in Table 6:

- Receive Target Area (Surveil) : Time Delay
- Receive Target Coordinates (Strike) : Time Delay
- Receive Strike Area (BDA) : Time Delay

Table 6: Time delay for different Activities Nodes

	Receive Target Area (Surveil)	Receive Target Coordinates (Strike)	Receive Strike Area (BDA)
Manual C2	Normal Distribution: Mean = 15 min Std Dev = 5 min	Normal Distribution: Mean = 12 min Std Dev = 5 min	Normal Distribution: Mean = 12 min Std Dev = 5 min

Autonomous C2	Normal Distribution: Mean = 8 min Std Dev = 1 min	Normal Distribution: Mean = 6 min Std Dev = 1 min	Normal Distribution: Mean = 6 min Std Dev = 1 min

b. Quality. The quality of the decision making will be simulated based on the probability the Ground Commander or the autonomous system selects the correct UAS in achieving the mission requirement. A good decision will result in the selection of a better UAS which will have a short time to reach the target coordinates. For the purpose of this simulation, it is assumed that the human operator will have a higher probability of selecting the better solution due to better understanding of the overall system and operational environment. To provide a quantifiable assessment of the quality of decision making, a “Good” decision will result in the selection of a UAS that can ingress and reach the operation areas faster, while a “Bad” decision will result in selecting the UAS with a longer ingress time. This is implemented in the following activities nodes, with details shown in Table 7:

- Ingress into AOR (Surveil) : Duration
- Ingress into AOR (Strike) : Duration
- Ingress into AOR (BDA) : Duration

Table 7: Duration for Ingress Activities for different Variants

		Ingress into AO (Surveil)	Ingress into AO (Strike)	Ingress into AO (BDA)
Manual C2	Good Decision 90%	Duration: Normal Distribution: Mean = 15 min Std Dev = 2 min	Duration: Normal Distribution: Mean = 20 min Std Dev = 2 min	Duration: Normal Distribution: Mean = 15 min Std Dev = 2 min
	Bad Decision 10%	Duration: Normal Distribution: Mean = 25 min Std Dev = 2 min	Duration: Normal Distribution: Mean = 30 min Std Dev = 2 min	Duration: Normal Distribution: Mean = 25 min Std Dev = 2 min
Autonomous C2	Good Decision 70%	Duration: Normal Distribution: Mean = 15 min Std Dev = 2 min	Duration: Normal Distribution: Mean = 20 min Std Dev = 2 min	Duration: Normal Distribution: Mean = 15 min Std Dev = 2 min
	Bad Decision 30%	Duration: Normal Distribution: Mean = 25 min Std Dev = 2 min	Duration: Normal Distribution: Mean = 30 min Std Dev = 2 min	Duration: Normal Distribution: Mean = 25 min Std Dev = 2 min

2. Normal ISR Sensor Capabilities vs High End ISR Sensor Capabilities: Affects the positive target acquisition and false target acquisition percentages.

   a. Target Acquisition. The ISR Sensor capability can be defined as the sensor's capability to positively identify a target, given that the target is present. The different between a normal ISR and a high end ISR sensor can be stimulated using a probability function, with the high end ISR sensor having a higher probability for true target acquisition. This will be implemented in the following Activities node, and details are shown in Table 8.

- Locate TBM (ISR) : Probability of Positive detection
- Confirm TBM Location (Surveil): Probability of Positive detection

Table 8: Probability of Detection given Real Target

	Locate TBM (ISR)	Confirm TBM Location (Surveil)
Normal ISR Sensor	Prob of positive detection: 70%	Prob of positive detection: 75%
High End ISR Sensor	Prob of positive detection: 90 %	Prob of positive detection: 95%

b. False Target Acquisition. Similarly, the false target acquisition can be defined as the sensor's inability to distinguish false targets and erroneously declare a false target as true. Likewise, the difference between a normal ISR and a high end ISR sensor can be stimulated using a probability function, with the high end ISR sensor having a low probability for declaring false target. This will be implemented in the following Activities node, and details are shown in Table 9.

- Locate TBM (ISR) : Probability of False detection
- Confirm TBM Location (Surveil): Probability of False detection

Table 9: Probability of False Target detection

	Locate TBM (ISR)	Confirm TBM Location (Surveil)
Normal ISR Sensor	Prob of false detection: 30%	Prob of false detection: 20%
High End ISR Sensor	Prob of false detection: 10 %	Prob of false detection: 5%

3. 1 x Strike UAS vs 2 x Strike UAS: Affects the target destruction percentage and duration of Time-to-Strike.

   a. Strike Accuracy. The strike accuracy can be defined as the Strike UAS's capability to lock-on and launch the missile to the designated area. In this regard, the strike accuracy can be stimulated using a probability function, that will be implemented in the following Activities node, and details are shown in Table 10.

   - TBM Destroyed : Probability of destruction

Table 10: Probability of TBM Destruction

	TBM Destroyed
1 x Strike UAS	Prob of Destruction: 80%
2 x Strike UAS	Prob of Destruction per UAS: 80 % Prob of Destruction of 2 UAS: $[(1 - (1 - 0.8)^2]$ x 100% = 96%

Step 6: Data Collection and Analysis

For the data to be statistically significant, Monte Carlo simulation is used. First, as part of the simulation, each scenario will be simulated with 50 runs across the 40 grids. Next, the scenario is then simulated 50 times to achieve the Monte Carlo simulations. Hence, the total number of runs per variants will be 2,500 runs comprising of 50 Monte Carlo simulation of the scenario and 50 runs within each scenario. The analysis will focus on the key areas—1) Pairwise comparisons will be carried between the respective variants to determine the impact of each parameter to the overall system, and 2) OHP analysis will be conducted to determine the overall performance of each variant across the different MOEs.

Conclusion

This chapter provides the details in the methodology used in the investigation of and analysis of the system-under-design through the use of DoDAF models and simulation using Innoslate software. The results from the simulation are analysed and presented in Chapter 4.

IV. Analysis and Results

Chapter Overview

This chapter provides detailed analysis from the results of the simulation scenarios. In particular, the analysis focuses on: 1) The overall effects of the design parameters (independent factors) on each MOE (dependent factor) in meeting the Threshold and Objective values; 2) Statistical significance of each design parameters and their interaction effect; and lastly 3) OHP study combining the overall effect of MOEs.

Statistical Methods Application

Simulation Scenarios

To evaluate the impact of the design parameters on the overall Concept, a factorial design methodology is implemented. In this case, three design parameters, namely, 1) Type of C2, 2) Type of Sensor, and 3) Number of Strike UASs, are evaluated through the implementation of 8 simulation scenarios as shown in Table 11 below.

Table 11: Scenarios and variation of Design Parameters

Scenario	Type of C2	Type of Sensor	No. of Strike UAS
1	Manual	Normal	2
2	Auto	Normal	2
3	Manual	High	2
4	Auto	High	2
5	Manual	Normal	1
6	Auto	Normal	1
7	Manual	High	1
8	Auto	High	1

Statistical Analysis Methodology

The following analytical methodologies are used to assess the results from the simulations to determine the overall effectiveness of the design parameters on the overall MOEs, and the individual effect of specific design parameters.

1. Overall Fulfilment of MOEs (Threshold and Objectives): Hypothesis testing is done to determine if each scenario fulfills the Threshold and the Objective for the respective MOEs. A one-tail test at 95% confidence interval is used for each scenario:

Threshold Testing

H_0: The mean of the simulation results is equal threshold value (for Target Acquisition Percentage MOE and Target Destruction Percentage MOE), or;

The mean of the simulation results is more than threshold value (for False Alarm Percentage MOE and Time-to-Strike MOE).

$H_{Alternate}$: The mean of the simulation results is equal threshold value (for Target Acquisition Percentage MOE and Target Destruction Percentage MOE), or;

The mean of the simulation results is less than threshold value (for False Alarm Percentage MOE and Time-to-Strike MOE).

α = 0.05 (5% Significance level)

Objective Testing

H_0: The mean of the simulation results is equal to objective value (for Target Acquisition Percentage MOE and Target Destruction Percentage MOE), or;

The mean of the simulation results is more than objective value (for False Alarm Percentage MOE and Time-to-Strike MOE).

$H_{Alternate}$: The mean of the simulation results is equal to objective value (for Target Acquisition Percentage MOE and Target Destruction Percentage MOE), or;

The mean of the simulation results is less than objective value (for False Alarm Percentage MOE and Time-to-Strike MOE).

α = 0.05 (5% Significance level)

Mathematical Formulae

$$\bar{x}_{results} = \frac{\sum_1^n x_i}{n}$$

Where: $\bar{x}_{results}$ = Sample Mean of simulation results

n = Number of runs in the simulation

x_i = Result from individual run

$$s = \sqrt{\left(\frac{1}{n-1}\right)\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Where: s = sample variance

$\bar{x}_{\text{results}}$ = Sample Mean of simulation results

n = Number of runs in the simulation

$$z = \frac{\bar{x}_{results} - \mu}{s/\sqrt{n}}$$

Where: z = test score

μ = threshold or objective value for testing

The null hypothesis is rejected when the z-score is > 1.645 (for one-tail test, α = 0.05) for Target Acquisition Percentage and Target Destruction Percentage MOEs, or when the z-score is < -1.645 (for one-tail test, α = 0.05) for False Alarm Percentage and Time-to-Strike MOEs.

2. Impact of Individual Design Parameters: To access the effect of individual design parameters on each MOE, a one-way ANOVA analysis. Here the F-value is calculated and the p-value is obtained. A p-value of less than 0.05 shows that the effect of the design parameter on the MOE is statistically significant at a 95% CI. The data is calculated using MiniTab software.

3. OHP analysis: The OHP analysis is implemented by calculating the accumulated performance by each variant across all MOEs. In this regard, it is assumed that all four MOEs are weighted equally, and a score of 2 is awarded for meeting the MOE objective value, score of 1 for meeting the MOE threshold value and a score of 0 for failing to meet threshold value.

Analysis of Results: MOE 1—Target Acquisition Percentage

Overview: The Target Acquisition Percentage MOE measures the ability of the Multi-tiered UAS SoS in positively acquiring the targets. The summary of the simulations of the eight scenario are shown in the Box plot in Figure 17. The segments in the box plots represent the 1st quartile, the Median and the 3rd quartile, while the whiskers indicate the variability outside the lower and upper quartiles (Microsoft, 2016).

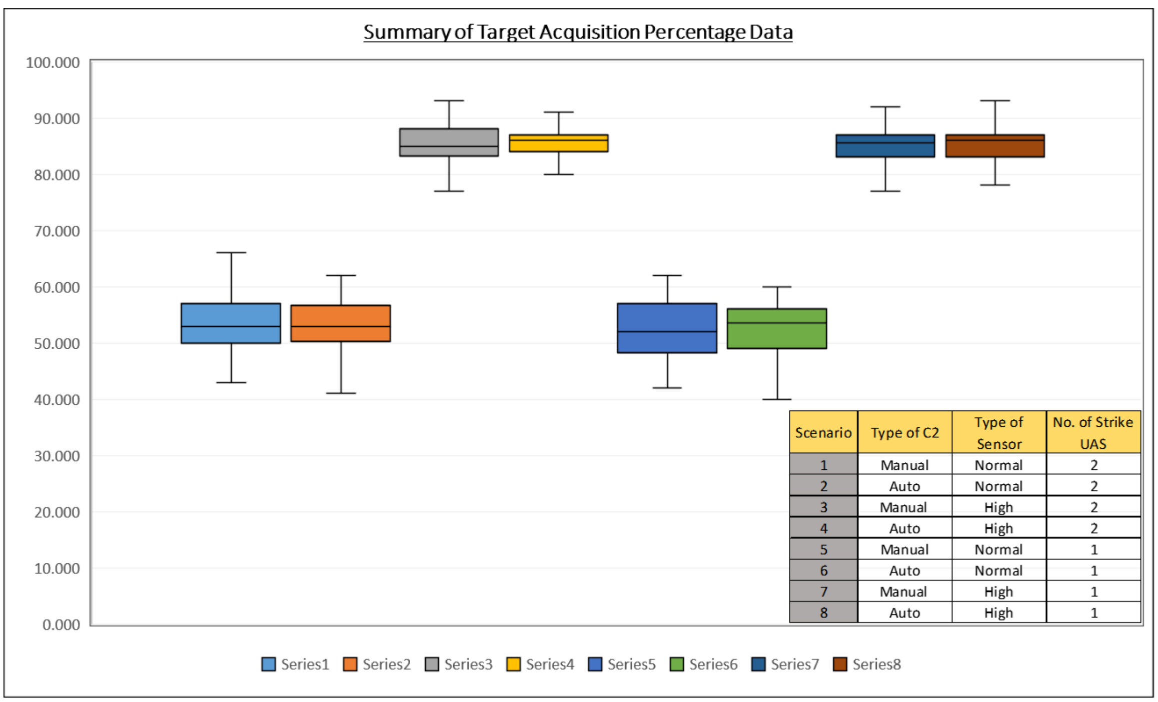


Figure 17: Summary of Target Acquisition Percentage

From the chart, it can be seen that the MOE performance fall in two distinct categories, in the 50-60% range for Scenario 1, 2, 4 and 5, and in the 80-90% range for Scenario 3, 4, 7 and 8. Further analysis are done in subsequent sections to determine the effect of design parameters on the MOE. A chart of 95% CI is also included to illustrate possible overlaps in the results between different scenarios, as shown in Figure 18.

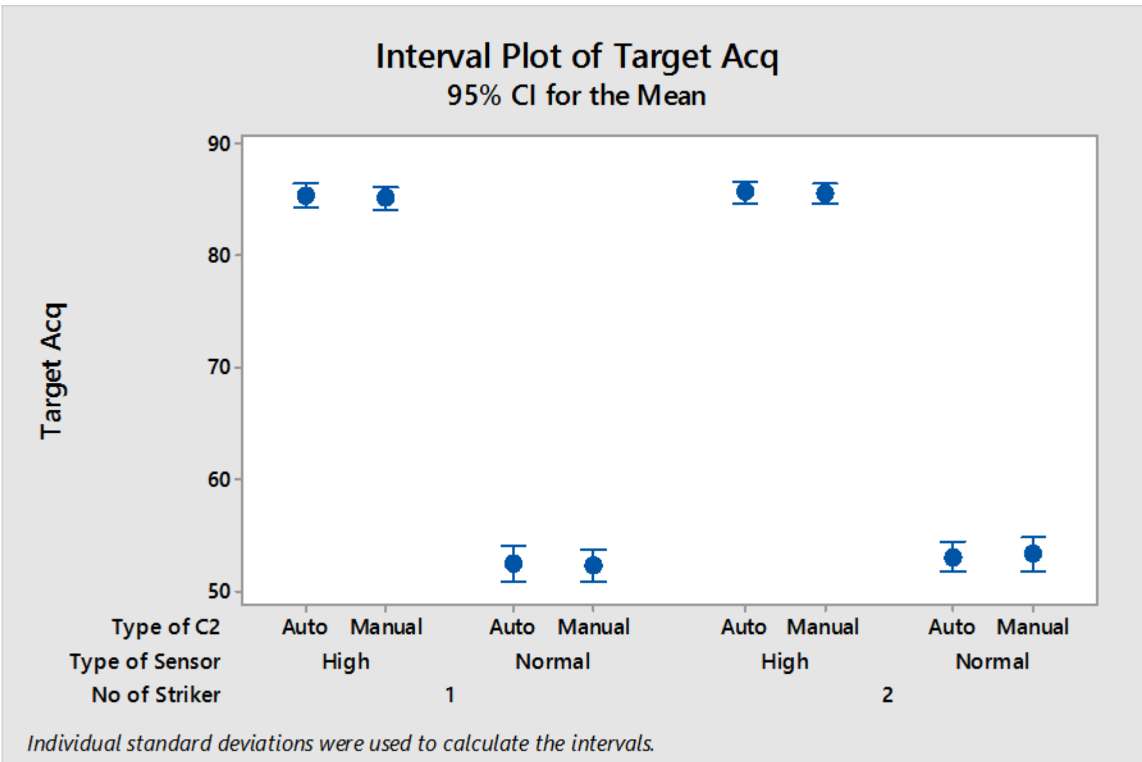


Figure 18: Summary of Target Acquisition MOE with 95% CI

<u>Hypothesis Testing</u>: The one-tail hypothesis is done for both threshold (60%) and objective (80%) value. From the results, it is shown that Scenario 3, 4, 7 and 8 fulfilled both threshold and objective of the MOE, while Scenario 1, 2, 5 and 6 failed to meet the

threshold values. The results are summarized in Table 12 below. From the chart, it is postulated that the Type of Sensor has significant effect on the MOE while Type of C2 and number of Strike UAS has minimal effect.

Table 12: Hypothesis Testing Result

Threshold H_0: The System-under-design has a Target Acquisition Pct equal 60% at 95% CI. H_A: The System-under-design has a Target Acquisition Pct equal or more than 60% at 95% CI								
Z value	-8.919	-10.542	57.957	53.073	-10.817	-9.089	54.355	46.660
Reject HO if Z > 1.645	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True
Objective H_0: The System-under-design has a Target Acquisition Pct equal 80% at 95% CI. H_A: The System-under-design has a Target Acquisition Pct equal or more than 80% at 95% CI								
Z value	-35.864	-41.457	12.678	11.771	-39.208	-33.654	11.079	9.920
Reject HO if Z > 1.645	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True

Evaluation of Design Parameters. To determine the effect of design parameters on the MOE, the Main Effect plot and Interaction Effect plot is charted, as shown in Figure 19 and Figure 20. From the Main Effect chart, it is demonstrated that both Type of C2 and Number of Strike UAS does not have a statistically significant effect on the Target Acquisition Percentage MOE, while the Type of Sensors are statistically significant, with *Normal* sensors resulting in below Threshold value for the MOE, while the *High* sensors resulting in MOEs achieve above Objective Value. This data is further shown in the one-way ANOVA statistic in Table 13.

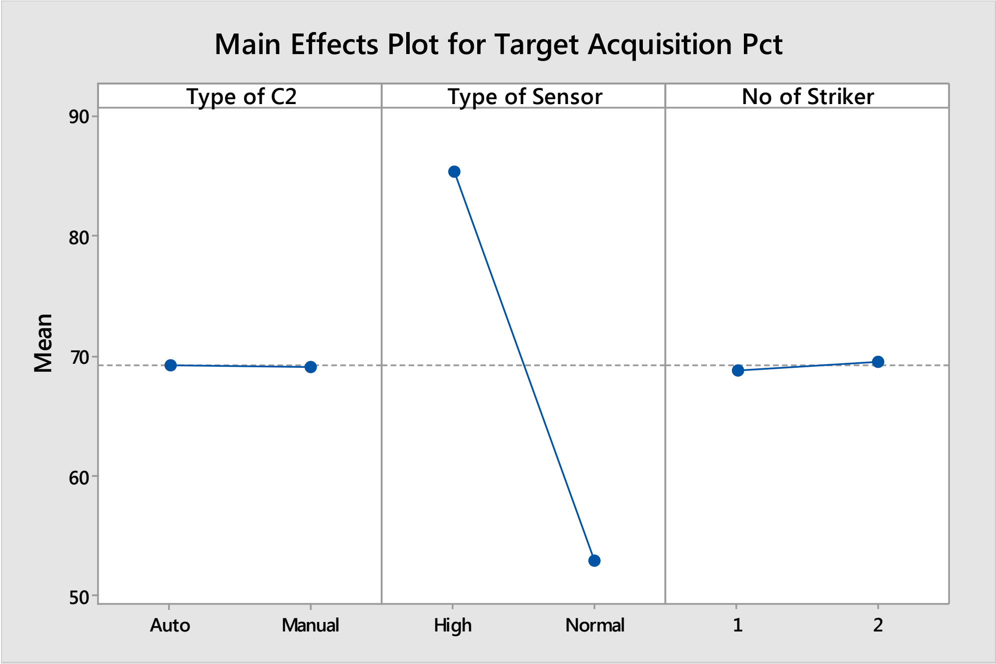


Figure 19: Main Effect Plot for Target Acquisition Percentage MOE

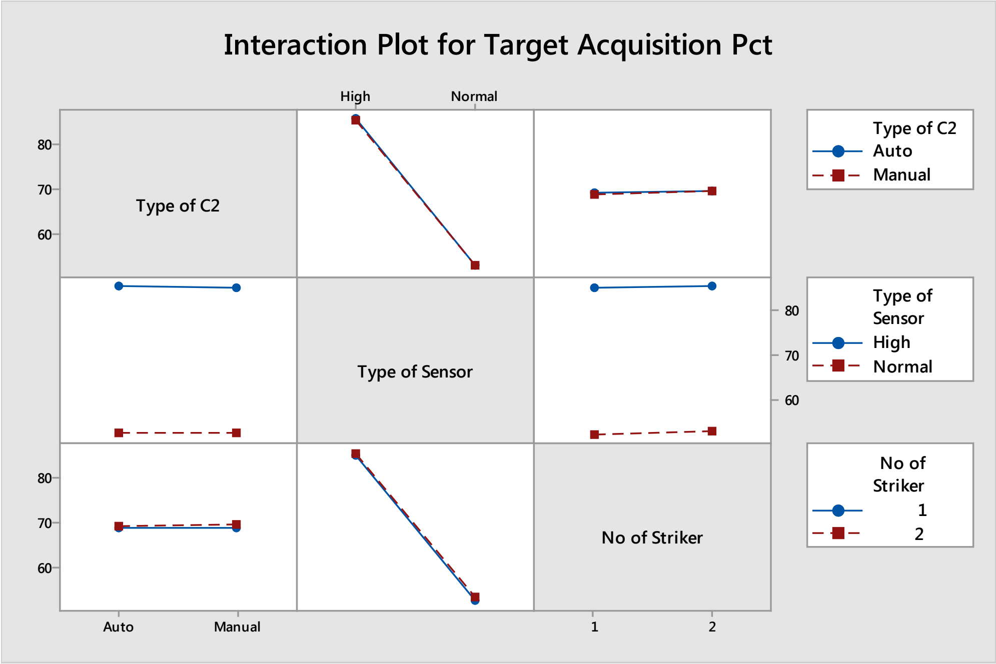


Figure 20: Interaction Effect Plot for Target Acquisition Percentage MOE

The one-way ANOVA results show that there is no significant effect of Type of C2 and Number of Strike UAS on the MOE, with P-values of 0.953 and 0.727 respectively. P-value of <0.05 shows that the Design Parameter is statistically significant on the MOE at 95% CI. Conversely, the Type of Sensor has a P-value of 0.000. The Fisher pairwise analysis also showed significance effect, with a difference of 32.6% on the MOE between Normal and High sensor types. These results are evident from the charts as shown in Figure 21 to Figure 23.

Table 13: One-way ANOVA for Design Parameters

One Way ANOVA					
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
Type-of-C2	1	1	1	0	0.953
Error	398	113639	285.526		
Total	399	113640			
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
Type-of-Sensor	1	106080	106080	5584.7	0
Error	398	7560	19		
Total	399	113640			
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
No-of-Striker	1	35	34.81	0.12	0.727
Error	398	113606	285.44		
Total	399	113640			

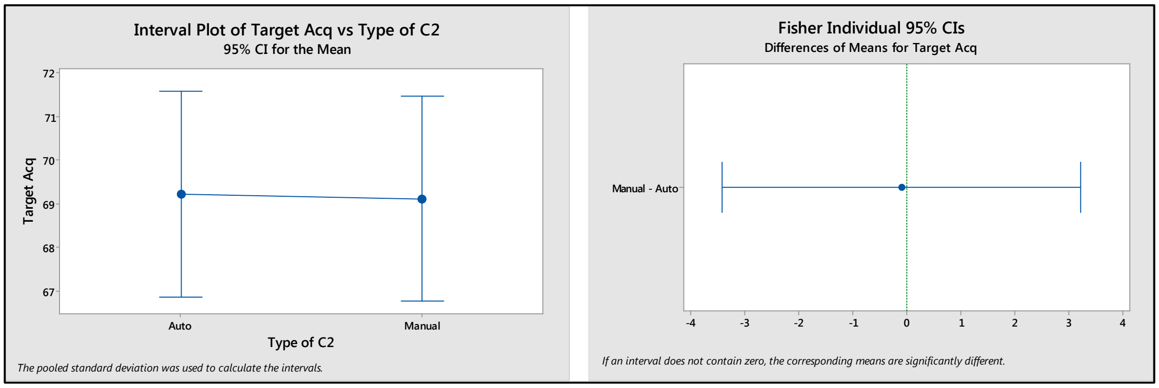


Figure 21: Analysis of Type of C2 on Target Acquisition Percentage MOE

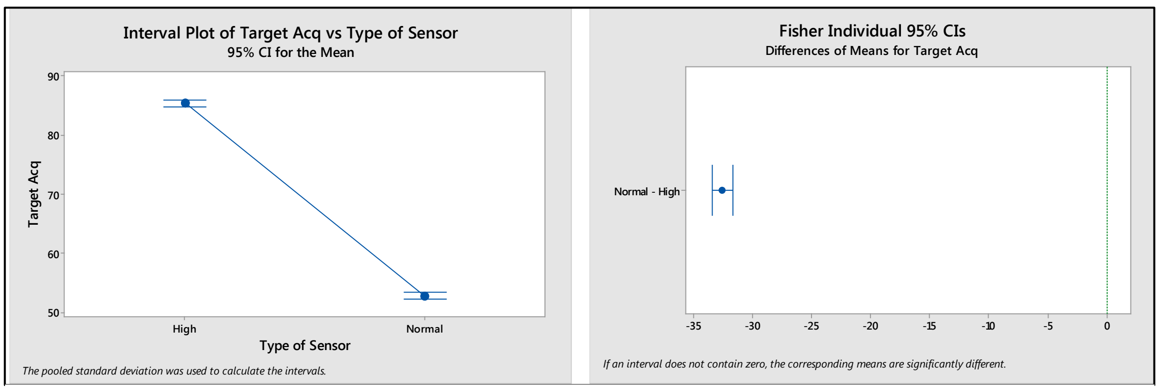


Figure 22: Analysis of Type of Sensor on Target Acquisition Percentage MOE

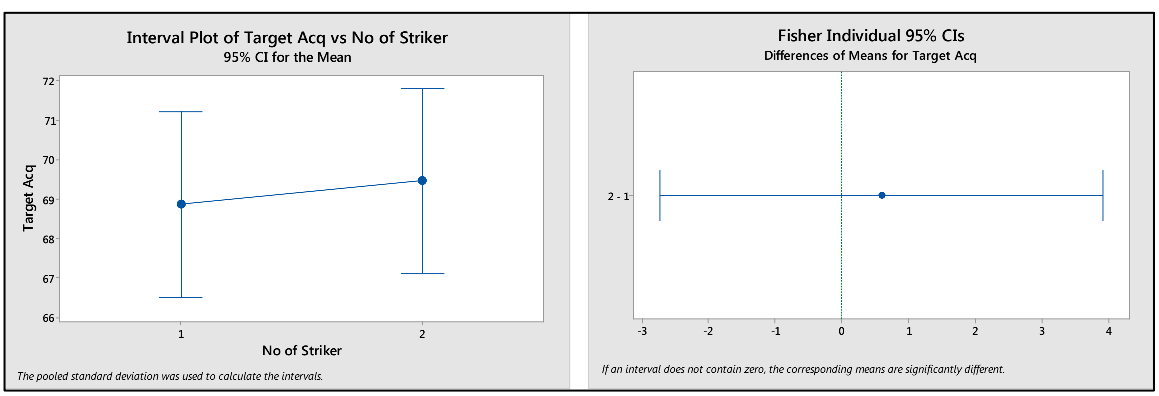


Figure 23: Analysis of Number of Strike UAS on Target Acquisition Percentage MOE

Qualitative Analysis of Results. The statistical analysis of the simulation results across the 8 scenario showed two distinct sets of results on the MOE, with Scenario 3, 4, 7 and 8 showing significantly better performance and achieving both Threshold and Objective values of the MOE, while Scenario 1, 2, 5, and 6 failed to meet Threshold requirement. Further analysis on the respective design parameters shows that the design parameter of Type of Sensor has a significant effect on the system performance on the MOE, while Type of C2 and Number of Strike UAS effects are insignificant.

This result is expected, as the Target Acquisition Percentage MOE depends on the ability of the ISR and Surveillance UAS to pick up and positively identified the targets. Hence, the UAS equipped with higher resolution sensors will improve the Target Acquisition capability of the SoS. The high quality sensors have a positive target percentage of 90% and 95% respectively for ISR UAS and Surveillance UAS, while the normal quality sensor is rated at 70% and 75%. Given that the Target Acquisition Percentage MOE will require both ISR UAS and Surveillance UAS to positively acquire and identify the target, the probability of detection can be calculated to be 85.5% and 52.5% for high quality and normal quality sensors respectively. The simulation results correspond with the expected system design, demonstrating approximately 32.6% improvement in results when using high quality sensor against using normal quality sensor.

Analysis of Results: MOE 2—False Alarm Percentage

Overview: The False Alarm Percentage MOE measures the inability of the Multi-tiered UAS SoS to positively distinguish false targets from real ones. The summary of the simulations of the eight scenario are shown in the Box plot in Figure 24.

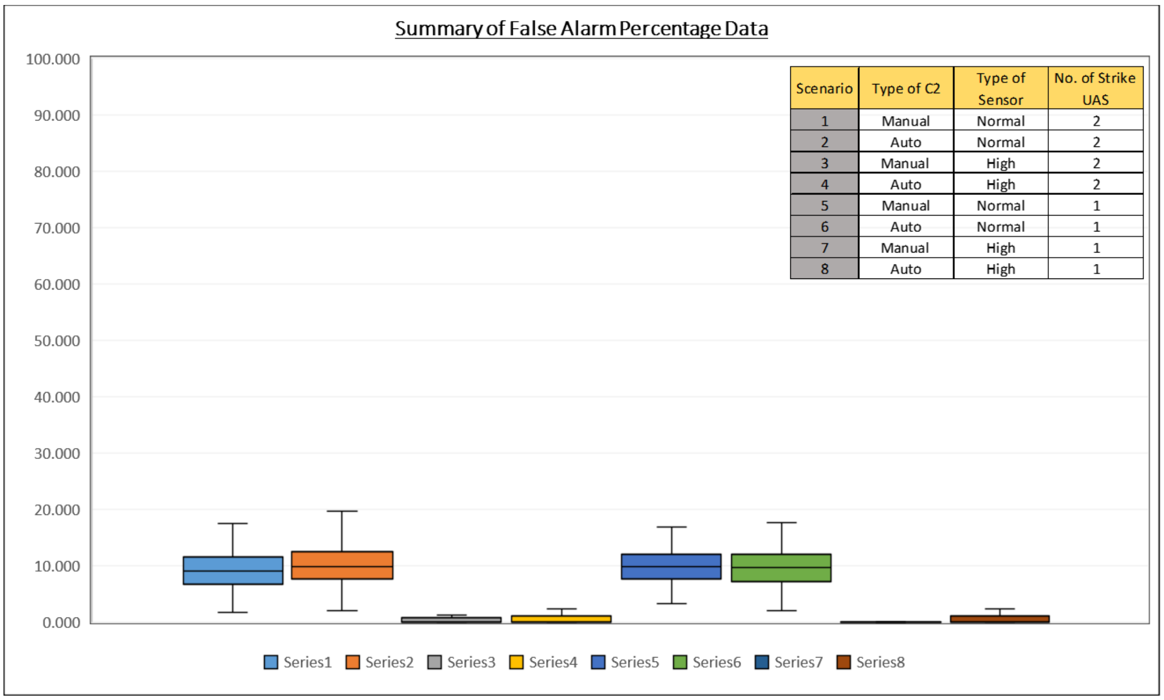


Figure 24: Summary of False Alarm Percentage

From the chart, it can be seen that the MOE performance fall in two distinct categories, in the 5-15% range for Scenario 1, 2, 4 and 5, and in the 0-5% range for Scenario 3, 4, 6 and 7. This grouping of data are further illustrated in Figure 25, the chart of 95% CI for the MOE. It is shown that the results for Scenario 1, 2, 5 and 6 have overlapping results at 95% CI, while Scenario 3, 4, 7 and 8 have overlapping results at

95% CI. Further analysis is done in subsequent sections to determine the effect of design parameters on the MOE.

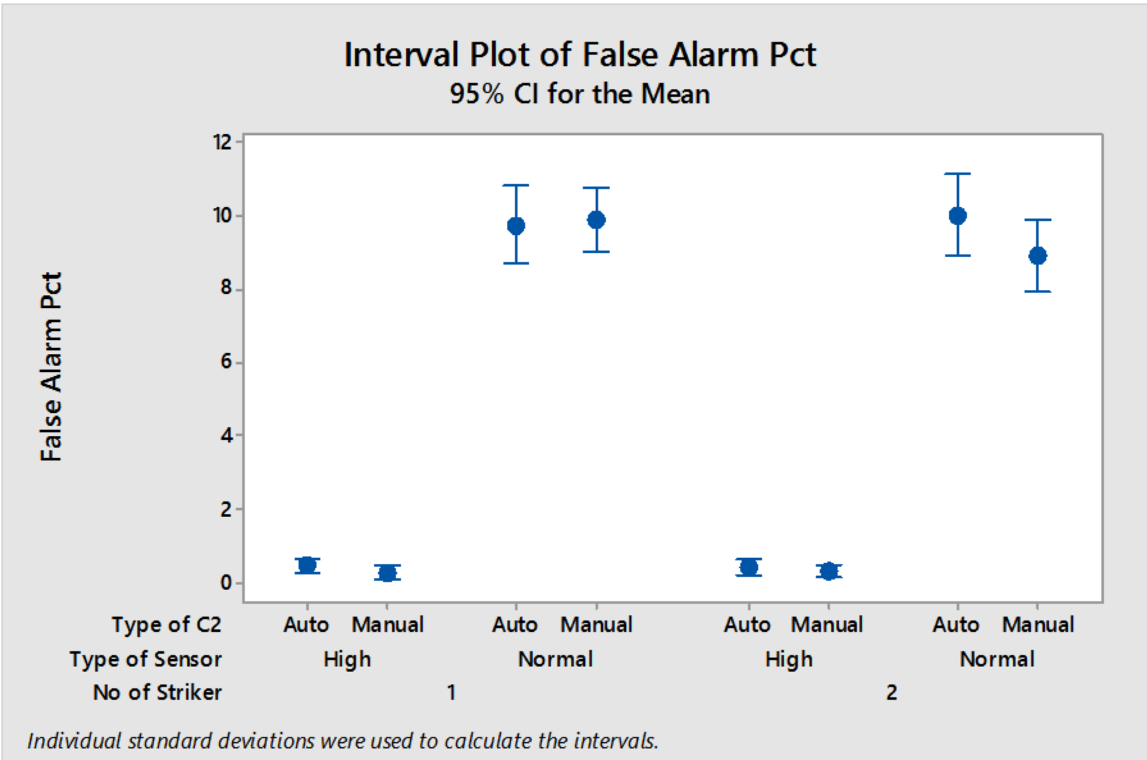


Figure 25: Summary of False Alarm MOE with 95% CI

<u>Hypothesis Testing</u>: The one-tail hypothesis is done for both threshold (10%) and objective (5%) value. From the results, it is shown that Scenario 3, 4, 7 and 8 fulfilled both threshold and objective of the MOE, while Scenario 2, 5 and 6 failed to meet the threshold values. Scenario 1 passed fulfill the threshold requirement while failed to meet the objective value. The results are summarized in Table 14 below. From the chart, it is postulated that the Type of Sensor has significant effect on the MOE while Type of C2 and number of Strike UAS has minimal effect.

Table 14: Hypothesis Testing Results

Threshold H_0: The System-under-design has a False Alarm Pct equal 10% at 95% CI. H_A: The System-under-design has a False Alarm Pct equal or less than 5% at 95% CI								
Z value	-2.234	0.007	-119.859	-90.121	-0.255	-0.510	-107.242	-90.720
Reject HO if z < -1.645	Reject Ho Ha is True	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True
Objective H_0: The System-under-design has a False Alarm Pct equal 5% at 95% CI. H_A: The System-under-design has a False Alarm Pct equal or less than 5% at 95% CI								
Z value	8.063	9.039	-57.938	-43.021	11.318	8.973	-51.955	-43.126
Reject HO if z < -1.645	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True

Evaluation of Design Parameters. To determine the effect of design parameters on the MOE, the Main Effect plot and Interaction Effect plot is charted, as shown in Figure 26 and Figure 27. From the Main Effect chart, it is demonstrated that both Type of C2 and Number of Strike UAS does not have a statistically significant effect on the Target Acquisition Percentage MOE, while the Type of Sensors are statistically significant, with *Normal* sensors resulting in below Threshold value for the MOE, while the *High* sensors resulting in MOEs achieve above Objective Value. This data is further shown in the one-way ANOVA statistic in Table 15.

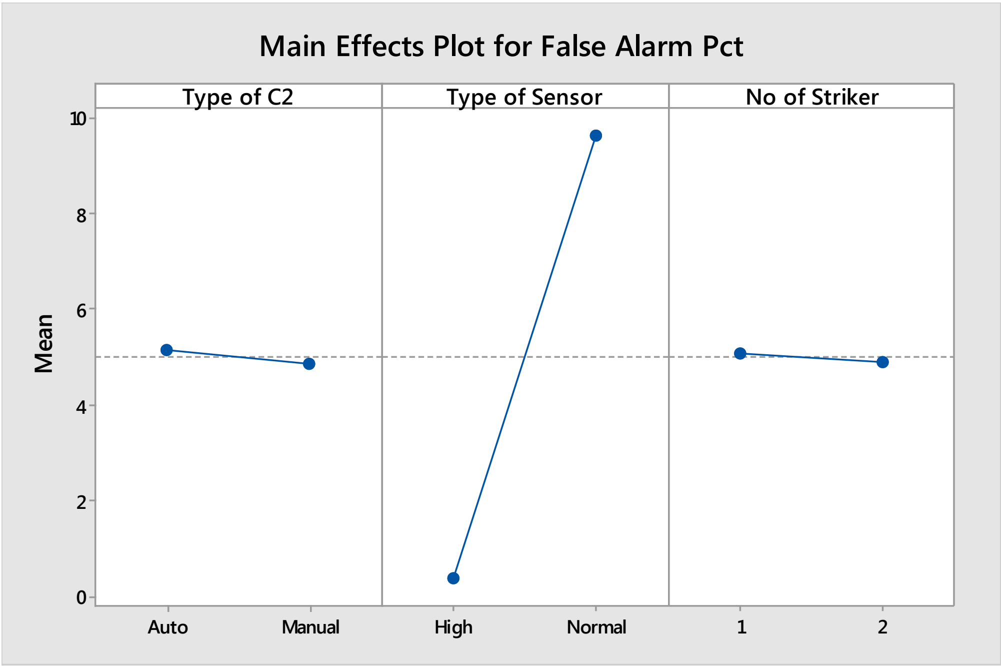


Figure 26: Main Effect Plot for False Alarm Percentage MOE

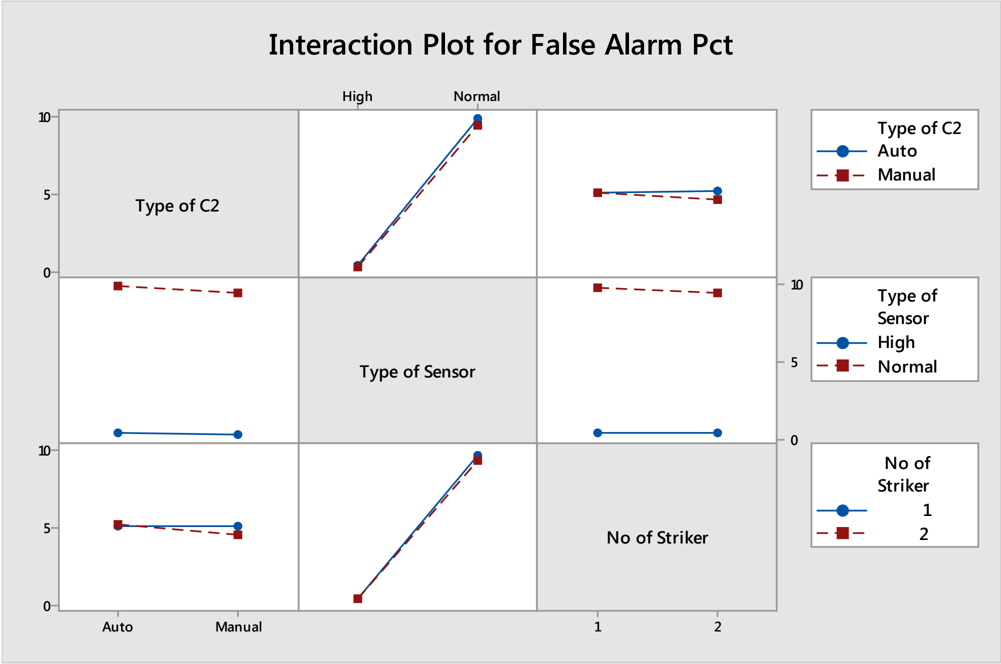


Figure 27: Interaction Effect Plot for False Alarm Percentage MOE

The one-way ANOVA results show that there is no significant effect of Type of C2 and Number of Strike UAS on the MOE, with P-values of 0.568 and 0.735 respectively. P-value of <0.05 shows that the Design Parameter is statistically significant on the MOE at 95% CI. Conversely, the Type of Sensor has a P-value of 0.000. The Fisher pairwise analysis also showed significance effect, with a difference of 9.3% on the MOE between Normal and High sensor types. These results are evident from the charts as shown in Figure 28 to Figure 30.

Table 15: One-way ANOVA for Design Parameters

One Way ANOVA					
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
Type-of-C2	1	9.2	9.151	0.33	0.568
Error	398	11148.8	28.012		
Total	399	11158.0			
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
Type-of-Sensor	1	8563	8563.04	1313.35	0.000
Error	398	2595	6.52		
Total	399	11158.0			
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
No-of-Striker	1	3.2	3.220	0.11	0.735
Error	398	11154.8	28.027		
Total	399	11158.0			

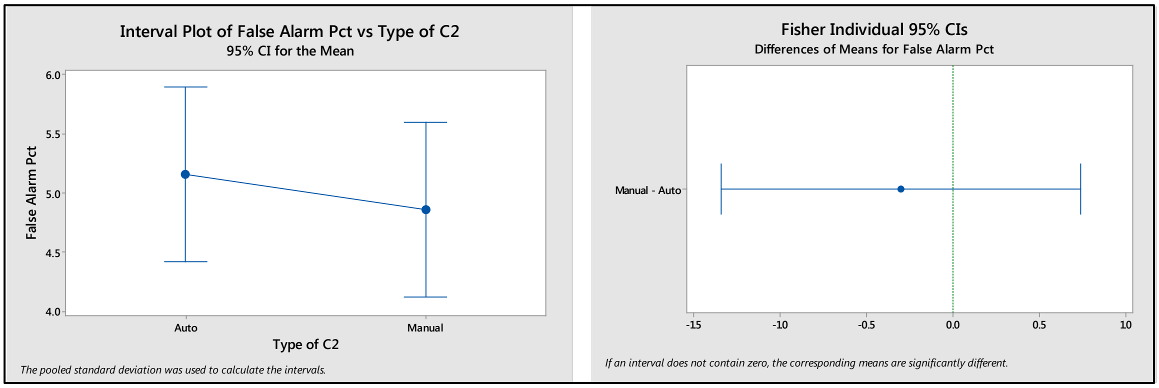


Figure 28: Analysis of Type of C2 on False Alarm Percentage MOE

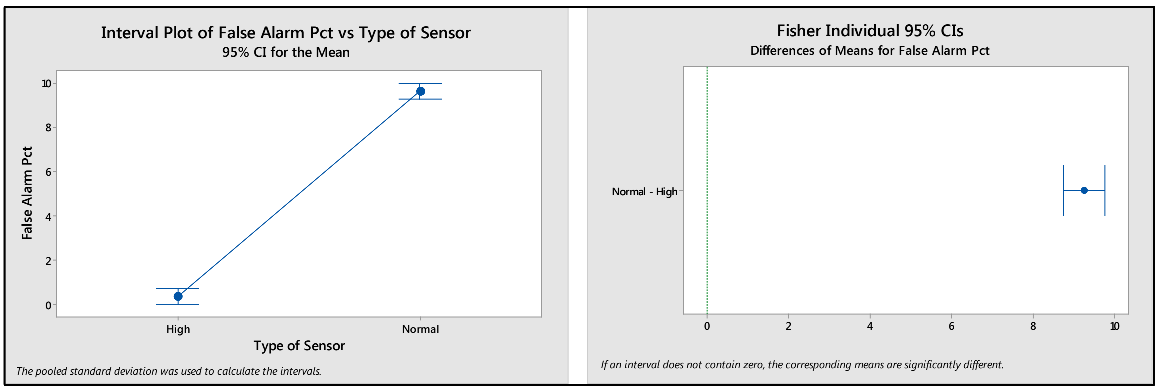


Figure 29: Analysis of Type of Sensor on False Alarm Percentage MOE

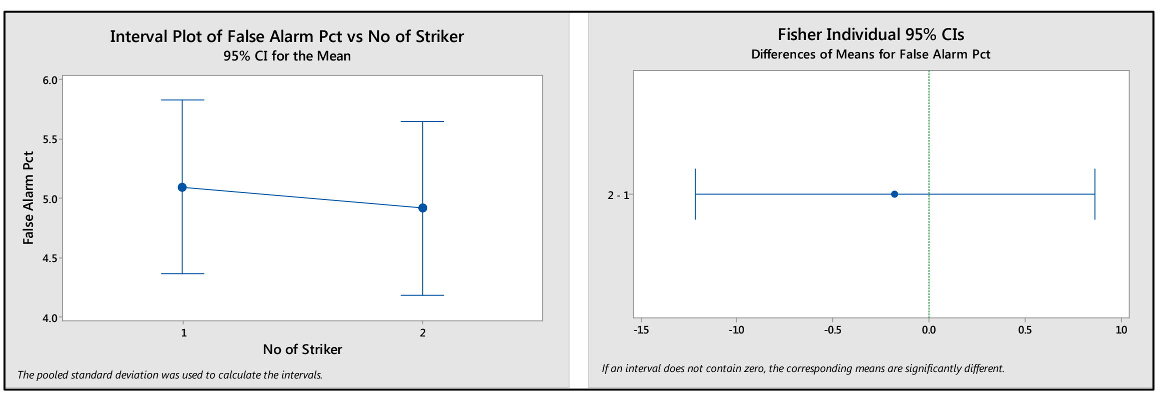


Figure 30: Analysis of Number of Strike UAS on False Alarm Percentage MOE

Qualitative Analysis of Results. Similar to the Target Acquisition Percentage MOE, the statistical analysis of the simulation results for False Alarm Percentage MOE across the 8 scenario showed two distinct set of results, with Scenario 3, 4, 7 and 8 showing significantly better performance and achieving both Threshold and Objective values of the MOE, while Scenario 2, 5, and 6 failed to meet Threshold requirement. Scenario 1 passed the Threshold requirement but failed to meet the Objective. Further analysis on the respective design parameters shows that the design parameter of Type of Sensor has a significant effect on the system performance on the MOE, while Type of C2 and Number of Strike UAS effects are insignificant.

The results of the effect of design parameters on False Alarm Percentage MOE are highly comparable to that on Target Acquisition Percentage MOE. This MOE measures error percentage of the multi-tiered UAS SoS in acquiring the wrong targets. UAS equipped with higher resolution sensors will have a lower false alarm and hence resulting in better performance in this MOE. For the simulation, the high quality sensors have false detection percentage of 10% and 5% respectively for ISR UAS and Surveillance UAS, while the normal quality sensor are rated at 30% and 20%. Given that the False Alarm Percentage MOE measures the total number of false targets against the total number of declaration, the simulation results provide the quantitative assessment of on the effect of different sensor capabilities. The simulation results correspond with the expected system design, demonstrating approximately 9.3% improvement in results when using high quality sensor against using normal quality sensor.

Analysis of Results: MOE 3—Time-to-Strike

Overview: The Time-to-Strike MOE measures the time required between initial target recognition by the Multi-tiered UAS SoS to the launch of missile strike on the TBM. The summary of the simulations of the eight scenario are shown in Figure 31 below.

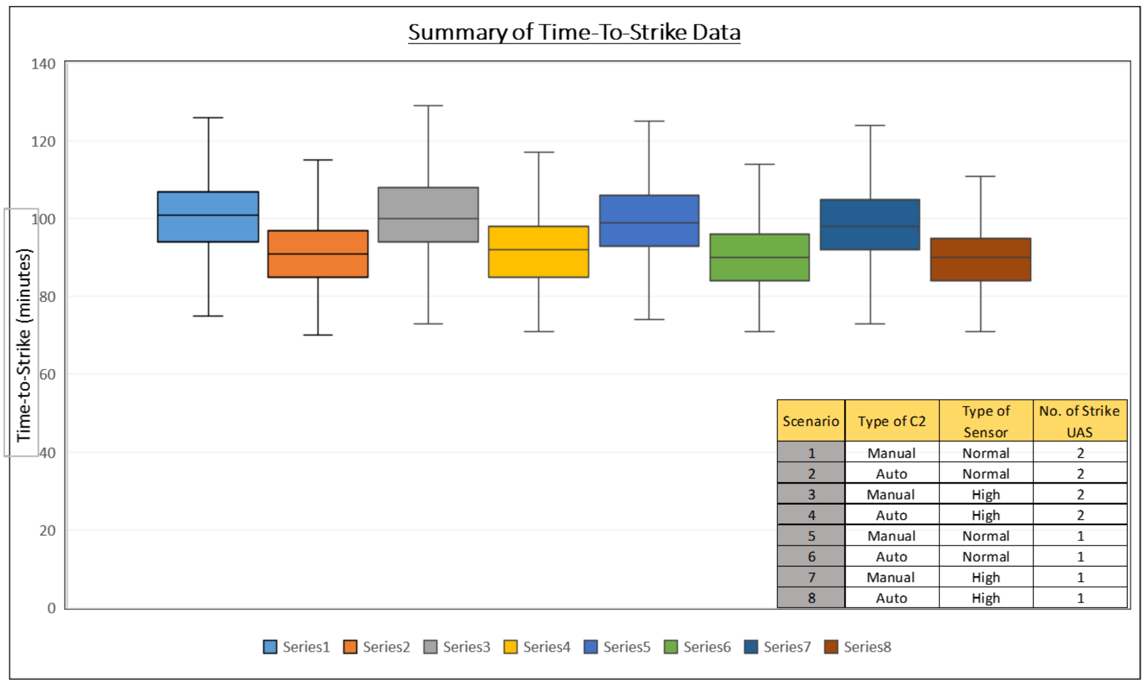


Figure 31: Summary of Time-to-Strike

From Figure 31, it is observed that there appears to be two distinct set of results between the 8 scenarios. Scenario 2, 4, 6 and 8 has better performance with Time-to-Strike ranging 85-100 mins, while Scenario 1, 3, 5 and 7 fare slightly worse with Time-to-Strike ranging from 95-110mins. Further analysis using 95% CI from Figure 32 show that in addition to the larger distinction between Scenario 2, 4, 6 and 8, and Scenario 1, 3, 5 and 7 that can be attributed to the Type of C2 design parameters, there is also a smaller distinction that can be observed between Scenario 1, 2, 3 and 4 and Scenario 5, 6, 7 and 8 that can be attributed to the Number of Strike UAS.

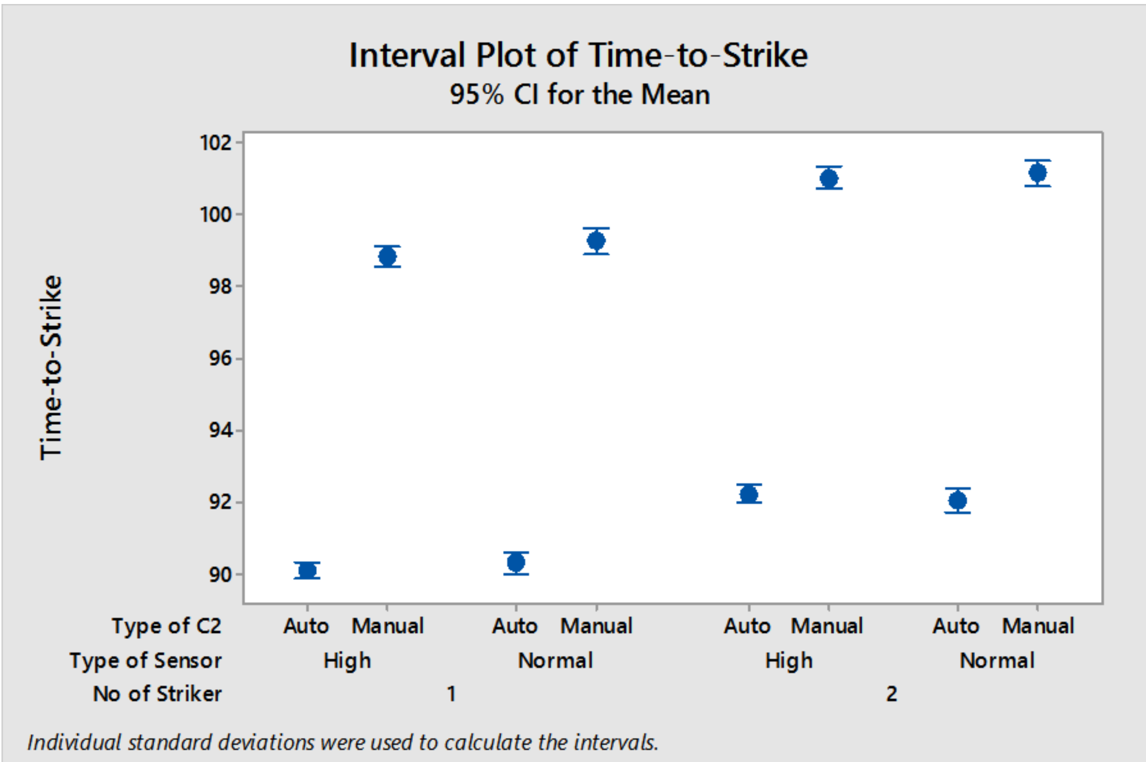


Figure 32: Summary of Time-to-Strike MOE with 95% CI

Hypothesis Testing: The results of the hypothesis testing as shown in Table 16 shows that all 8 scenarios fulfil the Threshold values. However, none of the scenarios meets the Objective requirement.

Table 16: Hypothesis Testing Results

Threshold

H_0: The System-under-design has a Time-to-Strike equal 105min at 95% CI.

H_A: The System-under-design has a Time-to-Strike equal or less than 105min at 95% CI

Z value	-19.840	-73.024	-25.201	-93.760	-31.178	-93.654	-43.666	-126.808
Reject HO if z < -1.645	Reject Ho Ha is True	Reject Ho Ha is True	Reject Ho Ha is True	Reject Ho Ha is True	Reject Ho Ha is True	Reject Ho Ha is True	Reject Ho Ha is True	Reject Ho Ha is True

Objective

H_0: The System-under-design has a Time-to-Strike equal 90min at 95% CI.

H_A: The System-under-design has a Time-to-Strike equal or less than 90min at 95% CI

Z value	58.047	11.629	70.358	16.612	50.810	2.040	63.173	0.845
Reject HO if z < -1.645	Ho Not Rejected	Ho Not Rejected	Ho Not Rejected	Ho Not Rejected	Ho Not Rejected	Ho Not Rejected	Ho Not Rejected	Ho Not Rejected

Evaluation of Design Parameters. To better interpret and explain the observations in the overall results for the Time-to-Strike MOE, further analysis is done on the design parameters. Based on the Main effect and Interaction Effect plot from Figure 33 and Figure 34, it is shown that both Type of C2 and Number of Strike UAS have significant effect on the result of the MOE, while the Type of Sensor does not show significant influence on the overall Time-to-Strike.

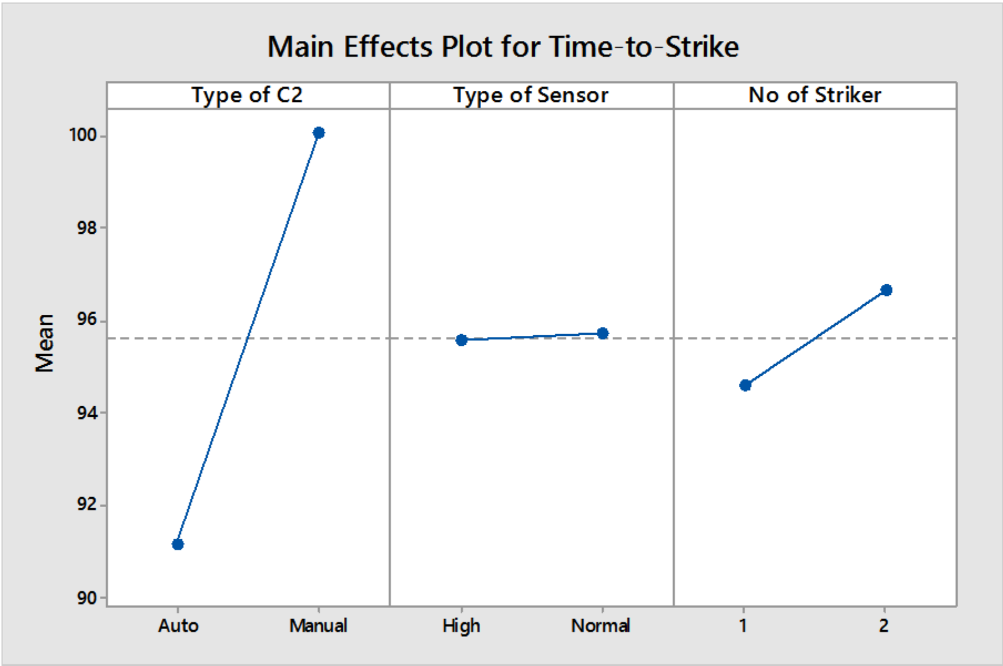


Figure 33: Main Effect Plot for Time-to-Strike MOE

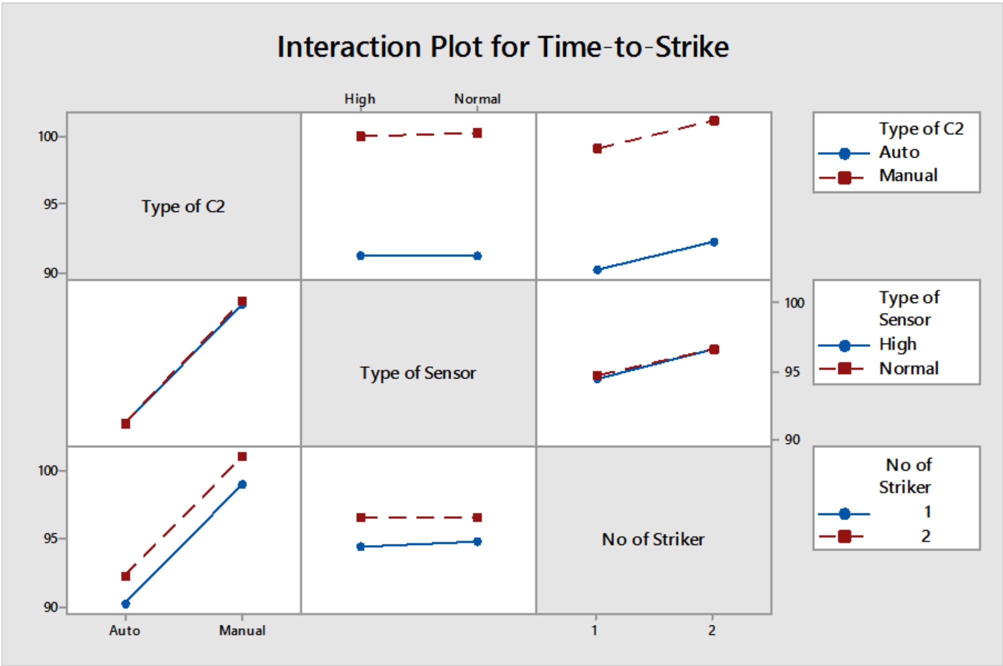


Figure 34: Interaction Effect Plot for Time-to-Strike MOE

The one-way ANOVA results show that there is no significant effect of Type of Sensor on the MOE, with P-values of 0.200. P-value of <0.05 shows that the Design Parameter is statistically significant on the MOE at 95% CI. Conversely, the Type of C2 and Number of Strike UAS both have a P-value of 0.000. The Fisher pairwise analysis also showed significance effect, with a difference of 8.88 minutes on the MOE between Autonomous and Normal C2, and 2.05 minutes between 1 or 2 strike UAS. These results are evident from the charts as shown in Figure 35 to Figure 37.

Table 17: One-way ANOVA for Design Parameters

One Way ANOVA					
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
Type-of-C2	1	545652	545652	6529.68	0.000
Error	27648	2310402	84		
Total	27649	2856054			
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
Type-of-Sensor	1	170	169.8	1.64	0.200
Error	27648	2855884	103.3		
Total	27649	2856054			
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
No-of-Striker	1	28966	28966.3	283.28	0.000
Error	27648	2827088	102.3		
Total	27649	2856054			

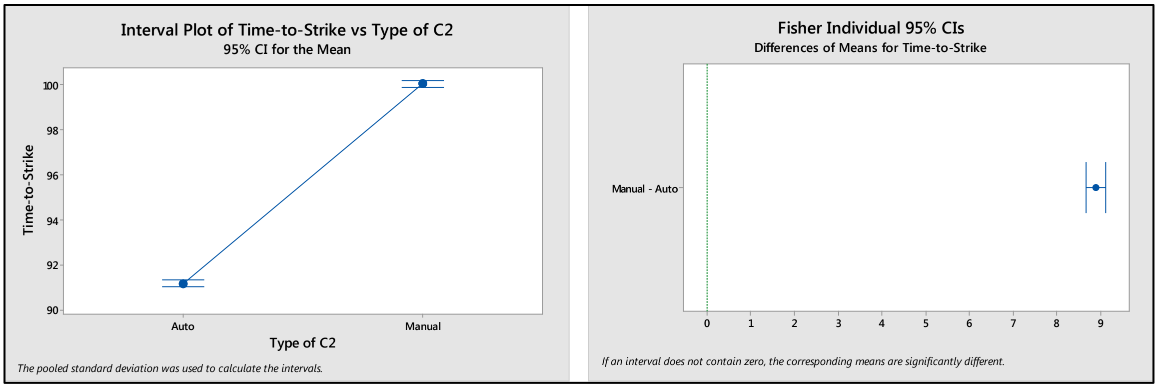


Figure 35: Analysis of Type of C2 on Time-to-Strike MOE

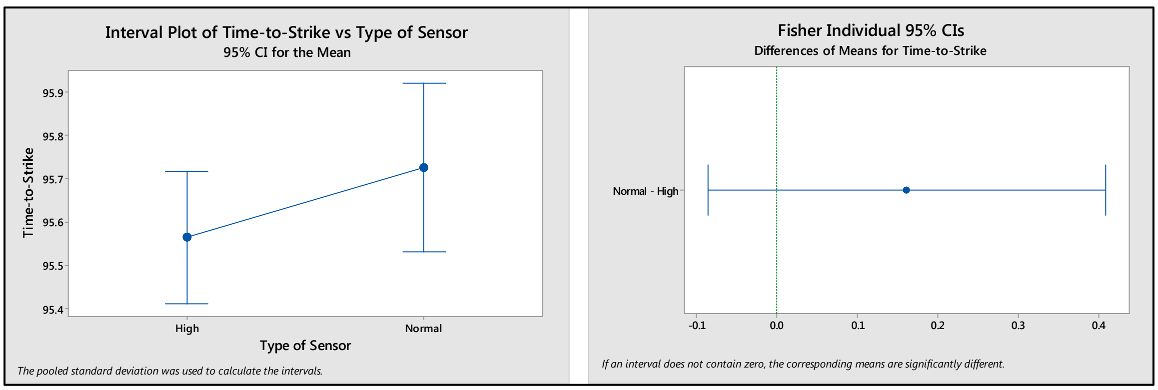


Figure 36: Analysis of Type of Sensor on Time-to--Strike MOE

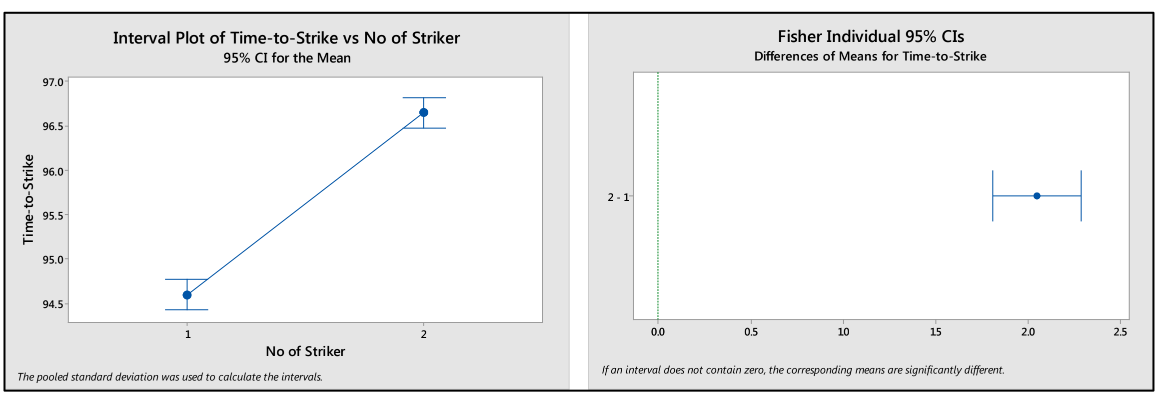


Figure 37: Analysis of Number of Strike UAS on Time-to-Strike MOE

Qualitative Analysis of Results. While initial assessment of the simulation results for Time-to-Strike MOE shows two set of results for Scenarios 1, 3, 5 and 7 and Scenarios 2, 4, 6 and 8, further analysis shows a subtle difference noted between Scenarios 1, 2, 3 and 4 and Scenarios 5, 6, 7 and 8. The first difference can be attributed to effect of Type of C2 on the system, while the smaller difference can be attributed to the Number of Strike UAS. It is observed that all Scenarios fulfilled the threshold requirement but failed to meet the objective.

The assessment is further confirmed by the analysis of design parameters, with both Type of C2 and Number of Strike UAS showing significant effects on MOE performance. In particular, the Type of C2 has a higher impact on the system with 8.88 minutes shorter for Autonomous C2 against Manual C2, while the Number of Strike UAS has a smaller impact with 2.05 minutes faster for 1 x Strike UAS against 2 x Strike UAS.

By system design, the Type of C2 will affect the time required to make a decision, and the quality of decision, affecting the time of deployment of each UAS. The Autonomous C2 has a shorter decision making time but a lower probability in making a good decision as compared to the Manual C2. Through the simulation, it is shown that shorter decision making time has a higher effect on the overall system performance as compared to the quality of decision making, as evident from the shorter duration between Autonomous and Manual C2.

The Number of Strike UAS also affects the Time-to-Strike MOE with 2 x Strike UAS requiring more time. This is because the MOE is measured based on the time difference between initial target recognition and the last missile launched. In this case, with 2 x Strike UAS, it is expected that the duration will be longer due to the time required for the second Strike UAS to launch its missile. Due to the probability of kill of the Strike UAS, not all attacks require a second strike. As such, the delay in duration between 2 x Strike UAS and 1 x Strike UAS is lower at 2.05 minutes, as compared to the 10 minutes required based on the simulation.

The Type of Sensor design parameter does not show a significant difference in the statistical analysis although the UAS SoS with a Normal sensor will result in delays due to the need to verify the false targets. However, it is shown that the difference in Type of Sensor is not sufficiently significant to result in an impact on the MOE.

Analysis of Results: MOE 4—Target Destruction Percentage

Overview: The Target Destruction Percentage MOE measures the ability of the Multi-tiered UAS SoS in positively acquiring and destruction of the targets to positively distinguish false targets from real ones. The summary of the simulations of the eight scenario are shown in Figure 38 below.

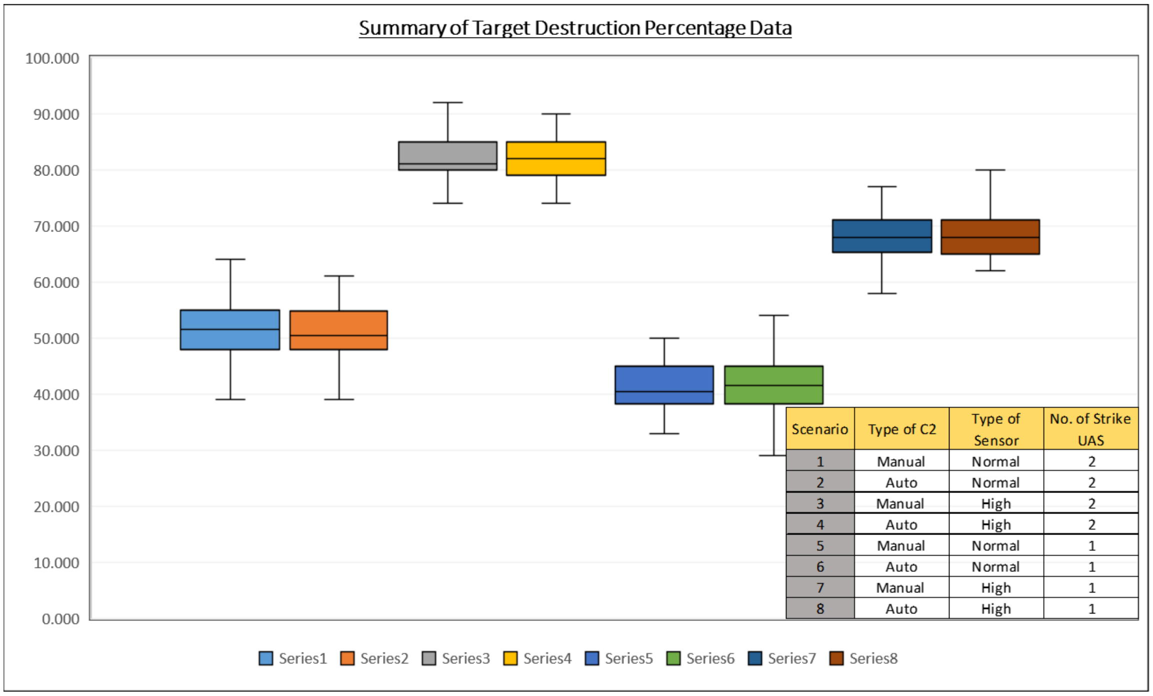


Figure 38: Summary of Target Destruction Percentage MOE

From Figure 38 and 39, it can be observed that there are four distinct set of results, with Scenarios 3 and 4 showing the best performance score at 80-85%, followed by Scenario 7 and 8 with score ranging 65-70%, and Scenario 1 and 2 with score ranging 48-55%. Scenario 5 and 6 yield the lowest performance score from 38-45%.

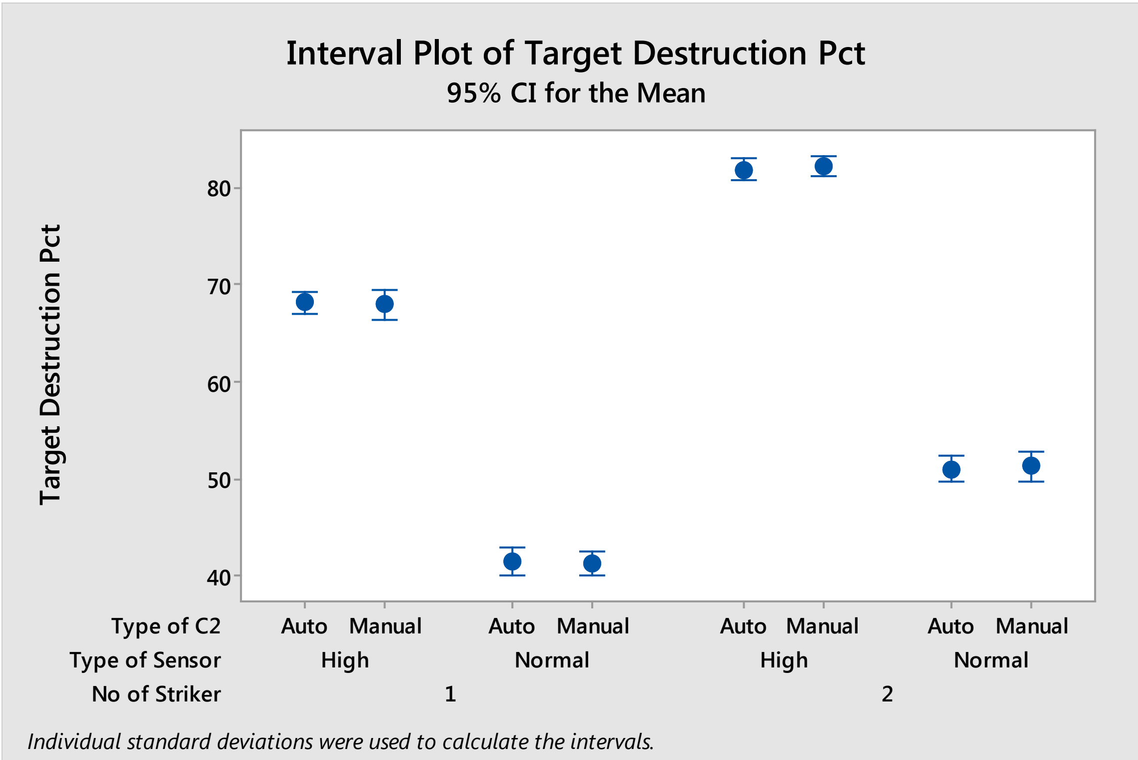


Figure 39: Summary of Target Destruction MOE with 95% CI

Hypothesis Testing: From the results, it is shown that Scenarios 3, 4, 7 and 8 fulfilled the threshold value, while only Scenario 7 and 8 fulfilled the objective value. In addition, Scenario 1, 2, 5 and 6 failed to meet both the threshold and objective values. The results are summarized in Table 18 below. In addition, from the groupings of the results from the different scenarios, it is postulated that both design parameters of Type of Sensor and Number of Strike UAS has significant effect on the MOE while Type of C2 has minimal effect.

Table 18: Hypothesis Testing Results

Threshold H_0: The System-under-design has a Target Destruction Pct equal 60% at 95% CI. H_A: The System-under-design has a Target Acquisition Pct equal or more than 60% at 95% CI								
Z value	-11.319	-13.421	40.617	38.185	-30.489	-26.356	10.698	14.246
Reject HO if Z > 1.645	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True
Objective H_0: The System-under-design has a Target Acquisition Pct equal 80% at 95% CI. H_A: The System-under-design has a Target Acquisition Pct equal or more than 80% at 95% CI								
Z value	-37.520	-43.380	4.189	3.376	-63.027	-54.881	-15.847	-20.248
Reject HO if Z > 1.645	Ho Not Rejected	Ho Not Rejected	Reject Ho Ha is True	Reject Ho Ha is True	Ho Not Rejected	Ho Not Rejected	Ho Not Rejected	Ho Not Rejected

Evaluation of Design Parameters. Further analysis on the effect of design parameters through the use of Main and Interaction plots (shown in Figure 40 and 41), as well as ANOVA and Fischer pairwise analysis confirmed that both Type of Sensor and Number of Strike UAS have statistically significant effect on the Target Destruction Percentage MOE. High resolution sensors coupled with 2 Strike UAS achieved the best results, as shown in Scenario 3 and 4, while normal resolutions with 1 Strike UAS achieved the worst results, as shown in Scenario 5 and 6. From Figure 38, it is shown that the Type of Sensor has a greater effect on the result as compared to the Number of Strike UAS. The Interaction plot shows that there are minimal interaction effects between the different design parameters.

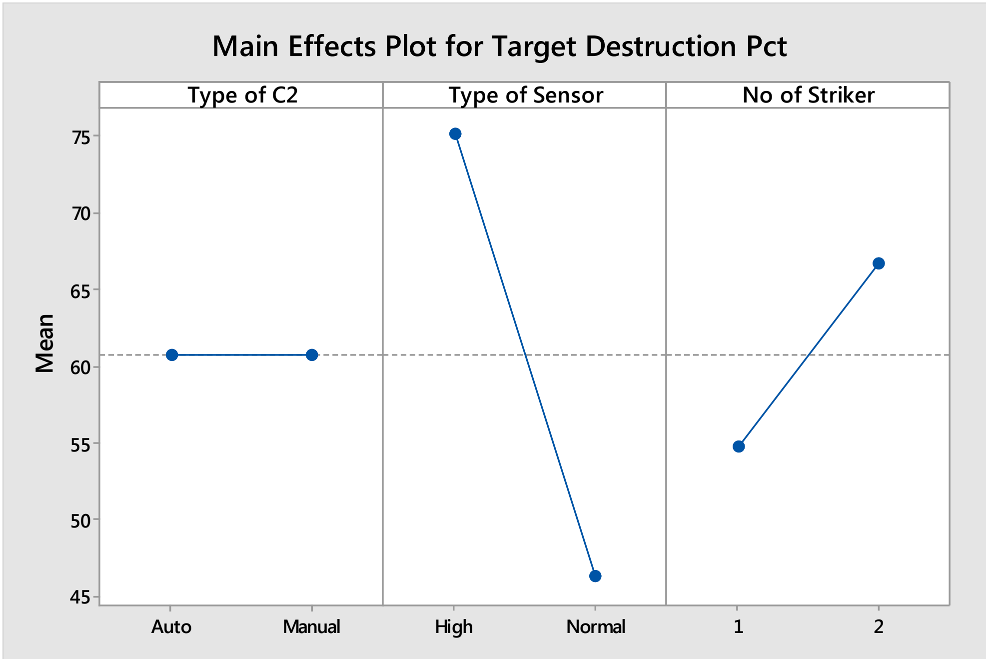


Figure 40: Main Effect Plot for Target Destruction Percentage MOE

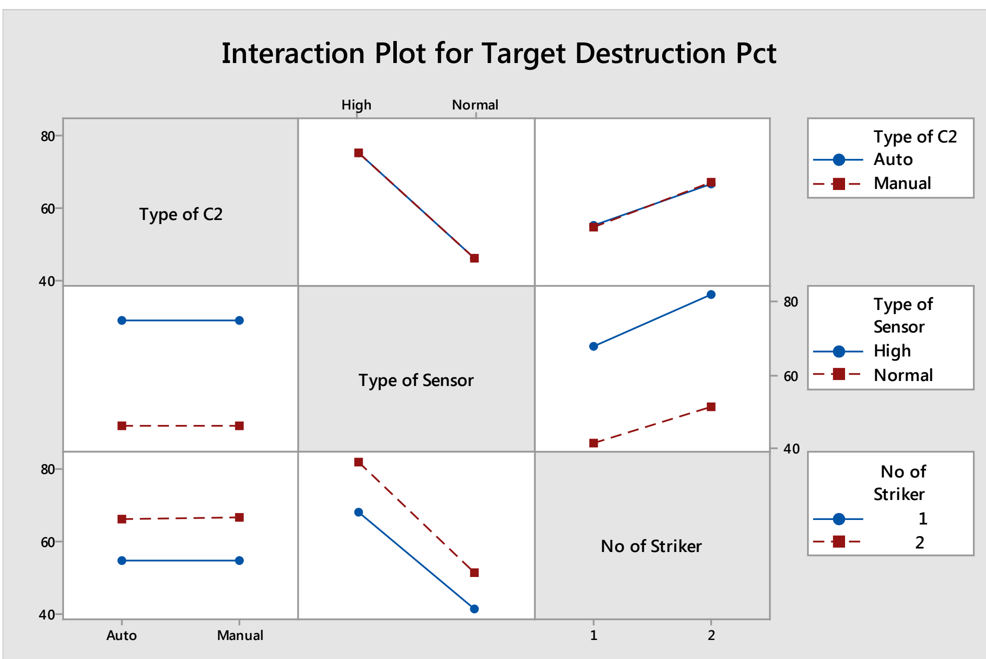


Figure 41: Interaction Effect Plot for Target Destruction Percentage MOE

The one-way ANOVA results on Table 19 show that there is no significant effect of Type of C2 on the MOE, with P-values of 9.73. P-value of <0.05 shows that the Design Parameter is statistically significant on the MOE at 95% CI. Conversely, the Type of Sensor and Number of Strike UAS both have a P-value of 0.000. The Fisher pairwise analysis also showed significance effect, with a difference of 28.8% on the MOE between Normal and High sensor types, and 11.9% between 1 or 2 strike UAS. These results are evident from the charts as shown in Figure 42 to Figure 44.

Table 19: One-way ANOVA for Design Parameters

One Way ANOVA					
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
Type-of-C2	1	0	0.303	0.00	9.73
Error	398	106179	266.781		
Total	399	106179			
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
Type-of-Sensor	1	83203	82303.4	1441.30	0.000
Error	398	22976	57.7		
Total	399	106179			
Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
No-of-Striker	1	14125	14125.3	61.07	0.000
Error	398	92054	231.3		
Total	399	106179			

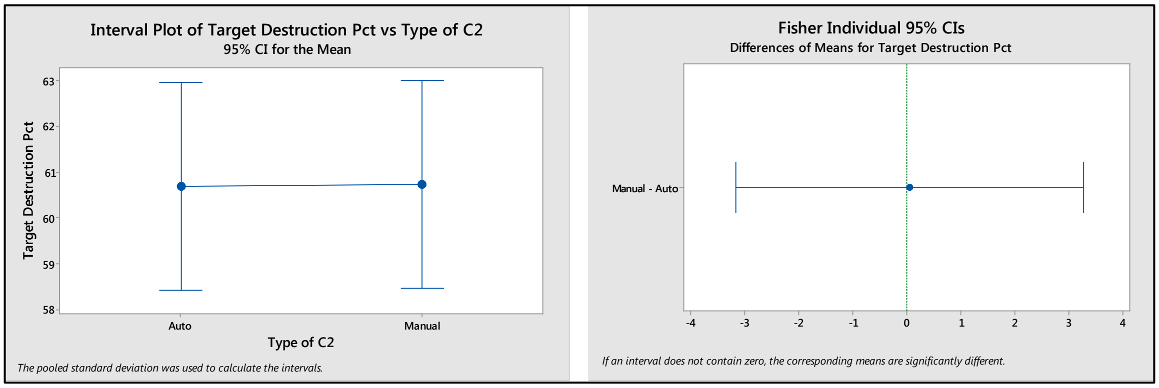


Figure 42: Analysis of Type of C2 on Target Destruction Percentage MOE

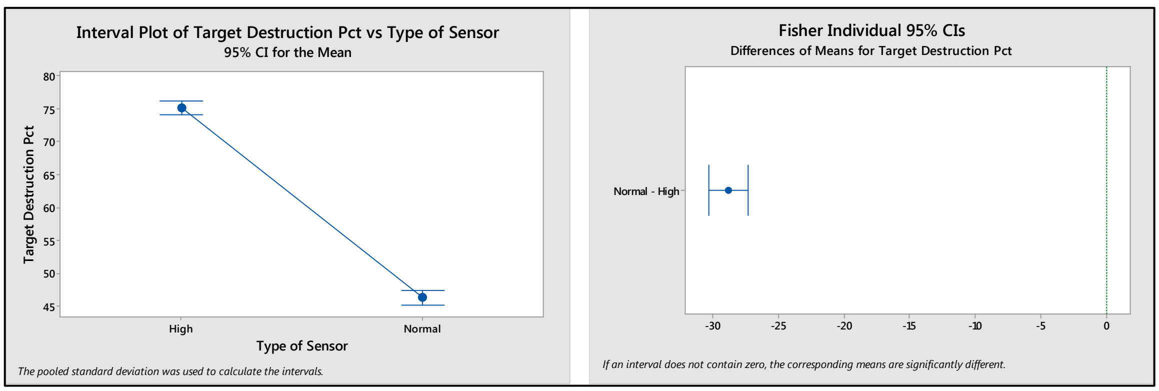


Figure 43: Analysis of Type of Sensor on Target Destruction Percentage MOE

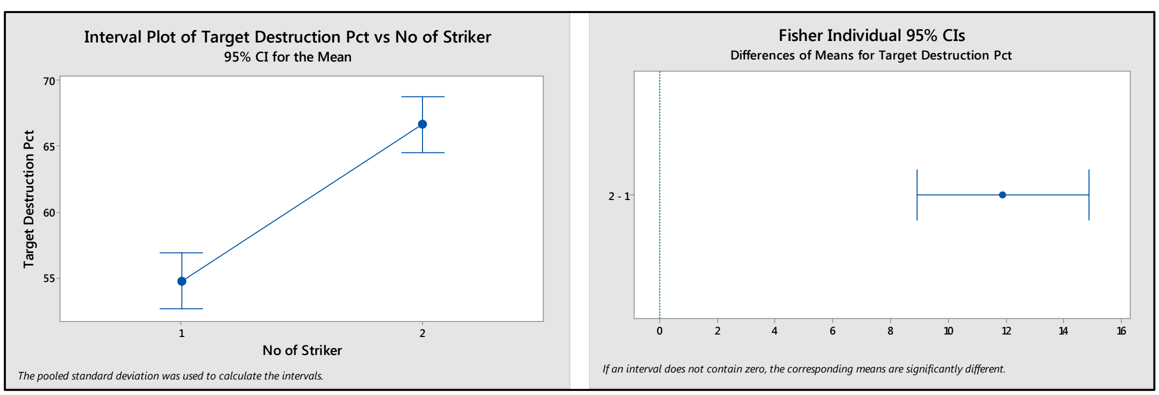


Figure 44: Analysis on Number of Strike UAS on Target Destruction Percentage MOE

Qualitative Analysis of Results. The statistical analysis of the simulation results for Target Destruction Percentage MOE across the 8 scenarios showed four distinct set of results, with Scenario 3 and 4 (High resolution Sensors with 2 Strike UAS) achieving the highest results, followed by Scenarios 7 and 8 (High resolution Sensors with 1 Strike UAS), Scenario 1 and 2 (Normal resolution Sensors with 2 Strike UAS) and Scenarios 5 and 6 (Normal resolution Sensors with 1 Strike UAS). Only Scenarios 3 and 4 achieved the Objective value, while Scenarios 7 and 8 achieved Threshold values. Scenarios 1, 2, 5 and 6 failed to meet Threshold requirement. From this analysis, it is determined that the Type of Sensor must be at high resolution for the system to pass Threshold.

Further analysis on the respective design parameters confirms that the design parameters of Type of Sensor and Number of Strike UAS have a significant effect on the system performance on the MOE, while Type of C2 is insignificant. This is expected as the Target Destruction Percentage MOE will require the Multi-tiered UAS SoS to 1) positively acquire the target and 2) accurately engage and destroy it. To positively acquire, the Type of Sensor has a large impact on the system as demonstrated in MOE 1. In target engagement, a 2 x UAS strike package will have a better probability of kill as compared to a 1 x UAS strike package (provided that the UAS have same system specifications).

The analysis shows that the Type of Sensor has a more significant impact, with an average of 28.8% difference between Normal and High resolution sensor, while the

Number of Strike UAS has lower impact, with an average improvement of 11.9% difference between 1 x Strike UAS and 2 x Strike UAS. This result confirms the earlier observation that the Type of Sensor must be at high resolution for the system to fulfil the threshold criteria.

Objective Hierarchy Process

The OHP is used to provide an overall assessment of the different scenarios on the combined performance of all MOEs. In this assessment, all MOEs have equal weightage, that is 25% of total score. In addition, the scores are awarded as follow: 2 for meeting Objective, 1 for meeting Threshold and 0 for failing. Based on this computation, Scenario 3 and 4 are awarded the high scores, followed by Scenario 7 and 8. Scenario 2, 3,5 and 6 have the lowest score at 0.25 respectively as shown in Table 20 below.

Table 20: OHP Analysis

	Scenario							
	1	2	3	4	5	6	8	8
MOE 1: Target Acquisition Percentage	0	0	2	2	0	0	2	2
MOE 2: False Alarm Percentage	1	0	2	2	0	0	2	2
MOE 3: Time-to-Strike	1	1	1	1	1	1	1	1
MOE 4: Target Destruction Percentage	0	0	2	2	0	0	1	1
Total Score	0.5	0.25	1.75	1.75	0.25	0.25	1.5	1.5

While Scenario 3 and 4 have the highest score, they are also associated with the highest course with High resolution sensors and 2 x Strike UAS. To better compare the results, it is important to include a cost component for a more accurate cost-benefit analysis. However, details of cost components are not included in this thesis research.

Summary

This chapter provides a detailed statistical analysis on the different variants of the Multi-tiered UAS SoS based on the 8 scenarios used in the simulation. From the data, the impact of the design parameters and MOEs can be statistically concluded in Table 21 below.

Table 21: Summary of Design Parameters and MOEs

MOE	Design Parameters	Simulation Results
Target Acquisition Percentage	Type of Sensor	High: **85.5%**
		Normal: **52.9%**
False Alarm Percentage	Type of Sensor	High: **0.4%**
		Normal: **9.6%**
Time-to-Strike	Type of C2	Autonomous: **91.2 mins**
		Manual: **100.1 min**
	Number of Strike UAS	1 x Strike UAS: **94.6 min**
		2 x Strike UAS: **96.9 min**

Target Destruction Percentage	Type of C2	High: **75.1%**
		Normal: **46.3%**
	Number of Strike UAS	1 x Strike UAS: **54.8%**
		2 x Strike UAS: **66.7%**

V. Conclusions and Recommendations

Introduction of Research

This research thesis aimed to implement and assess the suitability of EA in the evaluation of early concepts in the DoD. Specifically, the research focused on the development of EA and dynamic models for a proposed concept of Multi-tiered UAS which was evaluated through the use of executable DoD architectural products. Different configurations of the proposed system were implemented in Innoslate and the effect of different system capabilities, namely 1) Type of C2, 2) Type of Sensors, and 3) Number of Strike UAS, were simulated through EA, and statistical analysis was used to determine their impact on the overall system. Using the results of the simulation and analysis, the four research questions identified in Chapter 1 are answered in the following sections.

Research Question 1: Which views of DoDAF are critical for effective construction of EA?

To answer this question, it is important to understand the System Architecting and System Engineering process, especially in the Concept Development Phase. During early Concept Development, the development team focuses on answering the questions “What will the system do?”, and “How does the system do it?”. To achieve this, the concept development team focuses on high level system operational and functional design and analysis, which forms the foundations of EA. In addition, during the early Concept

Development phase, there are insufficient information in most of the DoDAF products, as summarized in Table 22 below.

Table 22: Assessment of DoDAF View for EA

DoDAF Viewpoints	Assessment	Specific View for EA
All Viewpoint	High level perspective of system-under-design based on CONOPS.	AV-1
Capability Viewpoint	Unable to achieve comprehensive understanding of system capability during early Concept development	None
Data Information Viewpoint	Provide information for data transfer between different system and is required especially for SoS.	DIV-2
Operational Viewpoint	System operation based on CONOPS and Use Case. Form the basis for EA.	OV-1, OV-2, OV-5a, OV-5b, OV-6a.
Project Viewpoint	Insufficient information during early Concept development for Viewpoints to be modeled into EA.	None
Services Viewpoint		
Standards Viewpoint		
Systems Viewpoint		

Based on the above assessment, the following DoDAF products are identified as critical:

1. <u>All-View 1: Overview and Summary Information</u>. AV-1 provides the overarching objectives of the system-under-designed, and hence allows the system architecting team to understand the constraints and the key deliverables for the system. Specifically, AV-1 functions as a broad high-level checklist to ensure that the EA is developed within the scope of the project.

2. Operational View 1: High-level Operational Concept Graphic. OV-1 provides the team with pictorial depiction of the system-under-design, and summarizes the system operations within its operational premises. In addition, the OV-1 represents the system architecting team interpretation of the system-under-design, and serves as an important visual communication tools between the architecting team and the other stakeholders.

3. Operational View 2: Operational Resource Flow Description. OV-2 describes the Resource Flows exchanged between operational nodes and activities. This is critical for the design of EA, as EA operationalizes these information transfer processes through simulation to access the effectiveness of the proposed concept.

4. Operational View 5a: Operational Activity Decomposition Tree. OV-5a details the capabilities and operational activities of the system-under-design, organized in a hierarchal structure. These operational activities are analogous to system functions, and are important in the design of the system's dynamic model. In particular, OV-5a provides different levels of specification, and allows system architects to implement EA at an appropriate level for concept evaluation.

5. Operational View 5b: Operational Activity Model. OV-5b provides the context of capabilities and operational activities. Specifically, OV-5b shows the relationship, processes and sequencing between entities, the operational activities, and the

information input and output between these nodes. OV-5b can be described as the overall system processes and linkages, and serves as the backbone for the dynamic models for EA.

6. Operational View 6a: Operational Rule Model. OV-6a details the operational rules for the key activities nodes in the activity follow diagram. Specifically, OV-6a describes the detailed interaction allowed between activities nodes, the activation and deactivation of each activities and the expected outcome from the different interactions. Hence OV-6a serves as the logic algorithm for effective EA development.

7. Data and Information View 2: Logical Data Model. DIV-2 identifies the data and information flow between different entities within the system-under-design. Specifically, they identify the data types, and how the data are implemented within the system. This is essential as the data model forms the basis for information transfer between different entities in the SoS and are implemented in EA as information linkages.

Research Question 2: What level of Operational or functional hierarchy of component sub-systems is required for EA to be effective?

To effectively answer this question, it is important for the system architecting team to understand the key objectives and requirements of the system-under-design (as represented through the MOEs and MOPs), and the design parameters or configurations to be evaluated. The level of hierarchy must be decomposed to the component sub-systems level whereby the effect of the design parameters can be modeled to each operational or functional node in the EA without overlaps and duplication.

The challenge in determining the right level of hierarchy is in achieving balance. Too many levels of details will result in extensive modelling and system specifics capability. This leads to a longer time and higher cost in development of the EA. At the early conceptual development stage, many of these information, especially system specific capabilities, are not available, and hence modeling such details are impractical and may not provide the necessary value-add to the EA. Conversely, too little details result in an overall simplified system models and the impact of the different configurations are not accurately depicted through the simulation. As such, it is necessary for the EA to sufficient level of hierarchy where the effects of the configurations manifest, but not too many levels of details that result in unnecessary modeling and additional time and development resources. To achieve the right level of hierarchy, the system architect must first answer the following questions:

1. What are the key MOEs to be evaluated through the use of EA?
2. What are the operational activities that affect the MOEs identified in Question 1?
3. What are the configuration or variables to be evaluated?
4. Can these variables be effectively represented in the operational activities stated in Question 2? If not, more layers of hierarchy are required.

The research thesis methodology can be used to illustrate the process. First, the MOEs, namely 1) Target Acquisition Percentage, 2) False Alarm Percentage, 3) Time-to-strike duration, and 4) Target destruction, were determined. Following this, the appropriate level of operational activities was identified. Next, the relationship between the variables, namely 1) Type of C2, 2) Type of Sensors, and 3) Number of Strike UAS, and the operational are established.

For example, as demonstrated in Chapter 4, it was shown that to determine the impact of Type of Sensors on the Target Acquisition Percentage MOE, it was necessary to go into the third level of the Operational Activity Hierarchy as shown in OV-5a. Here the Type of Sensors design parameters specifically affect the Locate TBM(ISR) and Confirm TBM Location Activity node, without affecting other activity nodes.

Research Question 3: How can EA be used to identify and evaluate the impact of design parameters on MOEs and MOPs?

EA uses dynamic modeling as a basis of simulation to evaluate the impact of design parameters on MOEs and MOPs. The EA provides the platform whereby design parameters can be incorporated into the system-under-design and provide operational outcomes based on the inputs to the system. As such, through the use of EA, system architects will be able to identify changes in operational outcomes when different design parameters are implemented. This allows system architects to identify how the system-under-design behaves and operates under different design parameters, and to derive the associated MOEs and MOPs to evaluate these outcomes.

For EA to be effective, the design parameters must be correctly associated with the correct operational activity nodes, and the operational outcome of different design parameters are accurately defined. This is achieved through the analysis of the design parameters and operational activities as stated in Research Question 2 above. Next, these relationships are designed into the dynamic models and simulated to obtain the results for analysis on their impact on MOEs and MOPs.

Citing an example from this research, the design parameters *Type of Sensors* are associated with the operational activities *Locate TBM(ISR)* and *Confirm TBM Location (Surveil)*. The operational outcomes are defined as the *Probabilities of positive detection* and *Probabilities of false detection*. Through the implementation of EA, the design of *Type of Sensors* were determined to affect MOEs of *Target Acquisition Percentage* and *False Alarm Percentage*.

Research Question 4: Which are the key parameters that have significant impact to design and operational cost for the multi-tiered UAV architecture considered herein?

Through the use of EA, the methodology implemented in Chapter 3 and the analysis conducted in Chapter 4 for the proposed multi-tiered UAS SoS, the impact of the design parameters to MOEs can be summarized in the table 23 below:

Table 23: Summary of Design Parameters and MOEs

MOE	Design Parameters	Simulation Results	Percentage Improvement
Target Acquisition Percentage	Type of Sensor	High: **85.5%**	**61.5%** improvement over Normal Sensor
		Normal: **52.9%**	
False Alarm Percentage	Type of Sensor	High: **0.4%**	**95.6%** improvement over Normal Sensor
		Normal: **9.6%**	
Time-to-Strike	Type of C2	Autonomous: **91.2 mins**	**9.8%** improvement over Manual C2
		Manual: **100.1 min**	
	Number of Strike UAS	1 x Strike UAS: **94.6 min**	**2.1%** improvement over 2 x Strike UAS
		2 x Strike UAS: **96.9 min**	
Target Destruction Percentage	Type of C2	High: **75.1%**	**62.2%** improvement over Normal Sensor
		Normal: **46.3%**	
	Number of Strike	1 x Strike UAS: **54.8%**	**21.7%**

	UAS	2 x Strike UAS: **66.7%**	improvement over 2 x Strike UAS

The Percentage Improvement column in Table 23 shows the improvement of the better option for each design parameters, calculated based on the following formula:

$$Percentage\ Improvement =$$

$$\frac{Result\ of\ Better\ Option - Result\ of\ Lessor\ Option}{Result\ of\ Lessor\ Option}\ x\ 100\%$$

The impact of operational costs was not explicitly studied as part of the research, however, it can be noted that in the design parameters: 1) Type of Sensor: High resolution sensor is more costly as compared to Normal Sensor, and 2) Number of Strike UAS: 2 x Strike UAS packages cost more than 1 x Strike UAS package. However, the extensiveness of the cost variation cannot be accurately analyzed without further research, and the cost-benefit relationship cannot be determine based on current results. This is an area where further research can be conducted.

The current level of decomposition is insufficient for accurate cost estimation and further elaboration is necessary for Analogy, Parametric or Engineering cost estimation to be conducted as part of further research. In addition, the further decomposition in hierarchy would enable System Architect to employ the COSYSMO methodology in estimating the System engineering costs.

Effectiveness of Innoslate Software in EA

As part of the thesis research, it is also important that the author provide an evaluation of Innoslate used to develop the dynamic models for implementing EA. Innoslate is a web-based life-cycle system engineering tool developed by SPEC innovation. Specifically, it incorporates DoDAF architectural development tools as part of its software package. The following sections compare the pros and cons of Innoslate for the purpose of EA.

Benefits of Innoslate

1. DoDAF-Ready. Innoslate is equipped with DoDAF dash-board, and maintains Template for key DoDAF architectural products, making it a useful tool for DoDAF-related operation. In addition, the system allows entities to be reused in different diagrams.

2. Simulation-Ready. With its in-built simulation engine, Innoslate is able to generate simulation using the DoDAF products that were developed. In addition, the Simulation enable both discrete-event and Monte Carlo simulations, which is important for statistically significant evaluation of results. In addition, as the simulation is executed directly from the DoDAF view, the system architecting team is able to validate the accuracy of the simulation as well as communicating the results with the key stakeholders.

3. Flexibility of System. The built-in simulation engine allows the user to define the durations required for operational activities. These durations can also be defined using pre-determined statistical functions (such as the Normal distribution) that best represent these operational activities. In addition, Innoslate allows the user to incorporate additional characteristics into each node through the use of Javascript which greatly enhance the flexibility of the software for EA.

Cons of Innoslate

1. Design Limitation—Complexity. One of the key limitations in Innoslate is in the overall complexity that the software is capable of simulating seamlessly. As it is a web-based tool, the efficiency and performance of the software depends on the connectivity to the internet and the overall loading on the servers. As such, a diagram with high level of complexity and many different nodes will result in high latency and the simulation process may be interrupted, resulting in an ineffective run. However, for the purpose of early concept evaluation, this is not a major limitation, since the complexity at the early stages is significantly lower.

Recommendations for Future Research

Due to time and resource limitations, the current research focused on the impact of three different parameters on four identified MOEs. The research can be further expanded to include the following:

1. Expansion of MOEs. Other MOEs critical for Mutli-tiered UAS SoS can be evaluated, such as the 1) Range of Operations, and 2) Endurance of System.

2. Improve resolution in Entities' capabilities. To further evaluate new MOEs, more details can be incorporated during the development of the dynamic models, such as 1) Fuel capacity, and 2) Operational range of each UAS tier. This would further improve the fidelity of the EA.

3. Inclusion of Cost Component. Cost-benefit analysis is a critical part of concept evaluation and especially estimating budgets for project. By including a cost-analysis component as part of the research, the cost for performance can be evaluated and the assessment on the cost benefit be done.

Summary or Significance of Research

This research implements an effective methodology through the use of EA to evaluate the early concept of Multi-tiered UAS SoS. In particular, the research shows that the methodology allows system architects to determine the effect of different design parameters on overall system performance in terms of MOEs and MOPs through the use of dynamic modeling in EA and statistical analysis. In addition, the methodology can be further used to evaluate the following:

1. Determine system performance given sub-system capabilities. The performance of the SoS can be determined when the detail capabilities of the sub-system are available. This is similar to the research methodology, except that the design parameters are replaced with the capabilities of the sub-system, and the results represent the overall performance of the SoS, given the specific sub-system.

2. Determine sub-system requirements given desired System Performance. Conversely, the EA model can be used to determine the system specifications and requirements of the sub-system, given the desired System Performance. In this case, the dynamic models are simulated with different level of sub-system capabilities to determine the sub-system requirement. For example, if the desired performance is for the *Target Acquisition Percentage* MOE to achieve 98%, the model will be simulated with different *Type of Sensor* capability to determine the *Probability of positive detection* required for the sensor sub-system.

From the examples above, it is shown that the EA methodology provide system architects with the tool to 1) evaluate different options, 2) understand the overall system capability given sub-system capabilities, and 3) determine sub-system requirement given desired system performance. These further allow the system architect to proceed with the subsequence stages of the SE process and enable better requirement analysis and system specification processes.

Appendix

Appendix A: Concept of Operations (CONOPS) for Multi-Tiered Unmanned Aircraft System (UAS) in anti-Theater Ballistics Missile (TBM) Launcher operations.

Appendix B: AV-1 Overview and Summary Information

Appendix C: Sample Innoslate Script

Concept of Operations (CONOPS) for Multi-Tiered Unmanned Aircraft System (UAS) in anti-Theater Ballistics Missile (TBM) Launcher operations.

This document articulates the concept of operations in utilizing of multi-tiered UAS system to search, track and destroy Theater Ballistics Missile (TBM) launcher within the Area of Operations. This include the execution of ISR operations to seek, track and confirm the TBM launchers, and the conduct of Dynamic Targeting and Strike to destroy the target.

1. Executive Summary

Theater Ballistics Missiles (TBMs) pose significant threats to our troops, friendly forces and civilian population within the Area of Operations (AO). The long range and lethality of TBMs, as well as the shoot-and-scoot tactics employed by the TBM launcher units, make TBMs an imminent threat within the AO.

To effectively counter this threat, this CONOPS focuses on the holistic use of multi-tier UAS systems to conduct Intelligence, Surveillance and Reconnaissance (ISR) operations to search for and track TBM launchers, and coordinate strike operations to destroy TBM launchers before they can pose a threat to friendly forces.

This CONOPS leverages the rapid development in Unmanned Aircraft System (UAS) technology to provide a comprehensive solution to address the threat presented by TBM systems. Developments in UAS, and the associated sensors and payload technologies, have provided the US military with new capabilities in key mission areas. Specifically, this CONOPS describes the employment of different tiers of UAS within the AO, and how each UAS operates cooperatively with one another to provide target confirmation and activate the kill-chain to destroy threats presented by TBMs. This CONOPS provides a low-cost decision making solution that minimizes risk by pre-emptively destroying TBM launchers through the use of the multi-tiered UAS System-of-Systems (SoS).

2. Purpose

The US's UAS arsenal is comprised of numerous UAS with capabilities that ranges from small man-portable vehicles, to medium “fighter-sized” vehicles, and large “tanker-sized” vehicles, as well as specialized UAS with unique capabilities. These capabilities allow UAS to perform many vital roles in military operations, including:

1) ISR
2) Strike
3) Protection
4) Sustainment
5) Movement and Maneuvering
6) Command and Control

The Multi-tiered UAS architecture aims to deliver a synergistic battlefield effect in the search, track and destroy operations related to TBMs, through using an integrated UAS solution that employs different tiers of UAS, to maximize mission effectiveness, while minimizing operational risks and operating costs. This ISR SoS enables cooperative operations among different groups of UAS within the same AO to identify, confirm targets, and to assign tasks among differing UAS groups to maximize mission effectiveness and efficiency.

3 Background

The proliferation of TBM technology and launcher systems by our adversaries presents a substantial threat to military operations in various regions around the world. Specifically, TBM systems provide our adversary with relatively cheap and accurate stand-off capabilities with a potential for highly lethal munitions. Different warheads (such as high-explosive, nuclear or chemical) within the TBM system provide our adversaries with great degree of versatility during combat, while potentially lowering the effectiveness of friendly forces. To maintain our military edge in contested environments, it is necessary that a low-cost solution with minimal risk be developed to pre-emptively destroy TBM launchers.

4 Future Environment

As TBM components become cheaper to produce and grow more technologically advanced, the threat posed by TBM systems will continue to increase and grow more complex[1]. Current trends indicate that adversary TBM systems are becoming more mobile, survivable, reliable, and accurate while also achieving longer ranges. In addition, pre-launch survivability is also likely to increase as adversaries denial and deception measures improve.

Similarly, UAS technology will continue to evolve and new capabilities will be developed for UAS operations. In this regard, the USAF Unmanned Aircraft Systems Flight Plan 2009-2047 and the US Army Roadmap for UAS 2010-2035 setup the potential UAS development and employment for the Air Force and Army Respectively. Currently employment of UAS within the US military are executed along stove-piped functional lines, with each operational unit operating specific classes of UAS for their respective mission. It is anticipated that future UAS employment will require a more synergistic deployment of integrated multi-tiered UAS to maximize mission effectiveness while minimizing risks and operating costs.

[1] “Ballistics and Cruise Missiles Threat”, NASIC, 2013

5 Concept Time Frame/ Scope

The successful execution of the CONOPS requires—1) Organizational Structure to vest the Combatant Commander with the Command and Control (C2) authority of different tiers of UAS, 2) Technological Development in Cooperative UAS technology, and 3) UAS sensors and payload systems to deliver the required Capabilities.

The ISR SoS is expected to be fielded in 2026. The timeline goal for the development of this SoS will drive the overall schedule of the program. The Timeline goal for Technological development is expected to be completed within 10 years, by the year 2026, with the respective Organizational Structure approved within the same time-frame. Current UAS sensors and payloads are deemed capable of fulfilling the operational requirements as stipulated by the CONOPS.

6 Military Need Statement

Rapid improvements of TBM technology and increases in weapons proliferation to non-allied nations have resulted in new and constantly changing threats to friendly forces. The high accuracy of many TBM systems allow them to inflict serious damages from significant stand-off distances, even when the missiles are armed with only conventional warheads. To further compound the problem, TBM launchers employ a shoot-and-scoot technique which makes counter-TBM operations challenging. To address this threat, the military needs to have a capability that can preemptively seek and destroy TBM launchers. This multi-tiered UAS SoS provides the capability to maintain persistent situational awareness over a designated area to search and locate possible TBM Launchers, and dynamically target and strike these TBM Launchers with minimal cost, or risk to personnel.

7 Central Idea

The multi-tiered UAS SoS focuses on the efficient employment of different groups of UAS to maintain persistent situational awareness over the AO, to seek and identify possible TBM Launchers, and to dynamically direct targeting and strike operations. It leverages the capabilities of different groups of UAS and sensor systems to achieve a system capable of optimizing UAS employment for mission effectiveness, while minimizing operational cost and risk. Specifically, the multi-tiered UAS SoS will need to employ cooperative control among various UAS groups in the AO to assign roles and plan safe routes for ingress and egress.

a. Larger tiers UASs (Group 4 and 5):

   iii. Persistent ISR. The larger tiers of UASs have greatest range, endurance, airspeed and altitude capabilities in the family of UAS. As such, these UAS are typically employed to conduct persistent ISR over the AO. They will be equipped with the necessary sensors to identify possible Surface-to-Air (SAM) sites and possible TBM Launchers in the AO.

iv. Dynamic Strike. These groups of UAS are also capable of carrying kinetic weapons, and could be loaded with the necessary munitions to provide a dynamic strike capability.

b. Smaller tiers UASs (Group 1 and 2):

iii. Target Verification. The smaller UAS groups have a smaller footprint are used for target verification and can be equipped with Automatic Target Recognition (ATR) software to determine phases of TBM launcher deployment.

iv. Battle Damage Assessment (BDA). These UAS groups will also be used to perform BDA after the conclusion of the dynamic strike to confirm mission success.

8 Users and Stakeholders

Secretary of Defense and Office of Secretary of Defense (OSD): Responsible for determining and approval of UAS policies for UAS employment within the US military.

Chief of Staff: Approval for the Assets to be deployed into the Operational Theater. They are responsible for strategic planning and to balance operational need across different battle fronts to allocate assets to the Combat Commander.

Combatant Commander: The Combat Commander is responsible for the overall mission success in the Operational Theater. He determines and requests assets to be deployed in the Operational Theater and is vested with the authority to designate assets and assign forces for specific missions in theater.

Mission Commander: Operator of multi-tiered UAS SoS who is responsible for all local UAS assets.

Organic UAS Unit: The organic UAS unit is responsible for the tactical execution of launch, recovery and tactical control of the UAS within the AO. They receive orders and taskings from the Combat Commanders in the planning and execution of tactical execution. The organic UAS unit is also responsible for the maintenance and support of the UAS under their responsibility to sustain UAS operations within the AO throughout the mission.

Federal Aviation Administration (FAA): The FAA is responsible for the design of aviation policies that guide the usage of UASs in the National Air Space. In particular, FAA sets air-worthiness criteria for Group 4 and 5 UAS operations and the airspace usage regulations for these UAS. The UASs will be flown within US for training purpose, and AOs are typically out-of-country. In addition, Group 4 and 5 UASs will need to pass the FAA air-worthiness requirement.

SPO: System Program Office – Agency responsible for the long-term sustainment, part revitalization and upgrade programs for a specific MDS.

JFACC: Joint Forces Air Component Commander – Individual in command of the AOC and responsible for all air operations in the AOR.

JFGCC: Joint Forces Ground Component Commander – Individual in command of the and responsible for all air operations in the AOR.This person is responsible for identifying and allocating access to the multi-tiered SoS for all ground forces in the AOR.

9 Policies

Policies governing the use of UAS can be found in the following documents:

a. OSD FY2011-2036 Unmanned Systems Integrated Roadmap, OSD AT&L, 2011

b. OSD Quadrennial Roles and Missions Review UAS ISR Report, USD (I) 2008

c. Joint UAS Center of Excellence (JCOE) Concept of Operation for Unmanned Aircraft Systems, JROCM 229-08, 25 November 2008

d. JP 3-30, Command and Control for Joint Air Operations, 12 January 2010

e. USAF Unmanned Aircraft Flight Plan 2009-2047

f. U.S. Army Unmanned Aircraft Systems Roadmap 2010-2035

10 Mission Operation Scenario

One scenario focusing on the use of different UAS groups consists of a requirement to search, track and destroy TBM Launchers and is elaborated below to illustrate the cooperative nature of the system.

Background: In a conflict between an allied country and its non-allied neighbor over a resource-rich off-shore area. The non-allied country is threatening military response if the AO is not completely vacated by the allied country. The non-allied country is equipped with several SAM sites and TBM launchers.

Mission Operations: The Combatant Commander aims to search, track and destroy the TBMs through the effective use of multiple UAS groups via the multi-tiered UAS SoS.

1. Group 4/5 ISR UAS equipped with Electronic Intelligence (ELINT) sensors and Synthetic Aperture Radar (SAR), patrol along the edge of ally's airspace to classify the SAM sites, build the Electronic Order of Battle (EOB) and perform coherent change detection. These ISR operations are executed over several weeks to detect bunker sites.
2. Group 1 UAS, equipped with EO sensors, monitor the area around bunker sites and are guided by Multi-tiered UAS SoS.
3. Group 1 UAS is also equipped with ATR to determine phases of TBM deployment.
4. Upon detection of a "fueling phase", the SoS is notified.
5. The nearest un-tasked Group 4/5 UAS with appropriate weapon payload is identified and target is assigned to the UAS.
6. Armed Group 4/5 arrives and strike TBM launcher after confirmation by Combat Commander.
7. Group 1 UAS performs BDA via EO sensors and ATR software.

11 Capabilities

The effectiveness of the system depends on the complementary employment of various UAS groups and capabilities. As such the capabilities and characteristics of different tiers of UAS are elaborated below to form the baseline Functional Capabilities of the multi-tiered UAS SoS.

Fig 1: DoD classification of UAS tiers.

In addition, the UASs are designed to be capable of carrying a wide range of sensors and payload to meet different operational needs. The main classes of sensors are descried in Table 1 below:

Table 1: Sensors

No	Sensor Type	Description
1	Electro-Optical (EO)	• EO Sensor is able to detect, classify and identify objects in the visible light spectrum. • Capable of spot coverage or wide area search over a defined area. • Best used on days with clear atmosphere.
2	Infra-Red (IR)	• IR Sensor is able to detect, classify and identify objects in the IR spectrum. • Capable of spot coverage or wide area search over defined area. • Best used on days and nights with clear atmosphere.
3	Communications Intelligence (COMINT)	• COMINT sensor detects personnel or machine-to-machine communications. • Collects frequencies over set ranges. • All-weather capability.

4	Electronic Intelligence (ELINT)	• ELINT sensors detect, classify and identify radar related radio waves. • All-weather capability.
5	Spectral	• Spectral sensor is able to detect, classify and identify materials when target spectral response differs from its surrounding. • Capable of spot mode to survey known location-of-interest to be used in wide area search. • Best used on days with clear atmosphere.
6	Synthetic Aperture Radar (SAR)	• SAR is able to detect and classify targets and provide coherent change detection. • Capable of covering large areas of land using a strip collection mode. • All-weather capability.

12 Risks

Risk to Mission—Asset loss. The risks to the mission due to asset loss are classified in two different categories—1) Non-kinetic Effects, and 2) Kinetic Kills.

1. Non-kinetic Effects: This refers to threats that disrupt the UAS capability within the AO to achieve the desired battlefield effect. Here, the 2 key threats to UAS operations are jamming and loss of communications, resulting in loss of control of the UAS.
1. Kinetic Kills: This refers to the physical destruction of the UAS due to hostile fire. The small UAS groups flying at low altitude are susceptible to small arms fire from ground forces; while larger Group 4 and 5 UAS can be targeted by an enemy's integrated air-defence systems.

Risk to Mission—Mis-identified Target.The risk of Mis-identified target and subsequent destruction of non-hostile personnel or equipment pose a huge risk in the execution of such automated search, track and destroy operations. To address this, it is necessary that the Multi-tiered UAS SoS system include target confirmation algorithms that independently verify target presence and require a human in the loop prior to the sending of the strike command.

13 Summary

The multi-tiered UAS SoS will provide the US military with the new capability to almost completely automate the capability of preemptively addressing threats posed by TBMs. In addition, the system represents a paradigm shift from the current mode of UAS employment whereby UAS are deployed along stove-piped functional lines and enables the synergistic deployment of integrated multi-tiered UAS systems. This will maximize mission effectiveness while minimizing risks and operating costs through the optimal use of different UAS groups to achieve desired battlefield effects.

14 CONOPS Development Team

Capt Andrew Roberts
Ms. Lidia Toscano
MAJ Zhongwang, Chua
Capt Nicholas Gilbert

AV-1 Overview and Summary Information

UAS Multi-Tier Overview and Summary

1 Architecture Description Identification

1.1 Name of Architecture Project

Multi-tiered Unmanned Aircraft System (UAS) System-of-Systems (SoS) for Theater-Ballistics Missile (TBM) Launcher strike.

2.2 Architect Leading Project

Zhongwang Chua is the Chief Architect leading the project development.

2.3 Organization Developing the Architecture

Group 4 Architecting

2.4 Assumptions and Constraints

- The System is able to interact securely with the different tiers of UAS system.
- Mission Commander is vested with the authority to Command and Control UASs deployed within the AO and has the authority to issue Strike command.
- All UAS systems are in the Operations and Sustainment phase of the life-cycle.
- All UAS systems are in working order and have trained personnel to operate them.
- The Group 1 UAS has sufficient camouflage, altitude climbing, or other means of staying hidden from human guards.

2.5 Approval Authority

Lt Col Thomas Ford

2.6 Date Completed

15 March 2016

2.7 Level of Effort and Projected / Actual Cost to Develop the Architecture

The actual cost of this architecture is merely the blood, sweat, and tears of the four members striving to graduate on time with outstanding grades. No additional financial burden is placed on the institution due to the creation of this architecture.

3 Scope: Architecture Viewpoints, Models and Views

3.1 Viewpoints and Models Developed

Various DoDAF viewpoints and models will be utilized in the development of the Multi-tiered UAS SoS architecture. DoDAF viewpoints include:

- AV-1: Overview and Summary Information
- AV-2: Integrated Dictionary
- OV-1: High Level Operational Concept Graphic
- CV-2: Capability Taxonomy
- OV-4: Organizational Relationships Chart
- OV-5a: Operational Activity Decomposition Tree
- CV-6: Capability to Operational Activities Mapping
- OV-5b: Operational Activity Model
- DIV-2: Logical Data Model
- OV-2: Operational Resource Flow Description
- OV-3: Operational Resource Flow Matrix
- OV-6a: Operational Rules Model
- OV-6b: State Transition Description
- OV-6c: Event-Trace Description
- SV-1: Systems Interface Description
- SV-4: Systems Functionality Description

- SV-5a: Operational Activity to Systems Function Traceability Matrix
- SV-7: System Measures Matrix
- Multi-tiered UAS SoS Software Simulation

CONOPS and Use Cases will also be developed to ensure coverage of all major details.

3.2 Time Frames Addressed

The successful execution of the system architecture requires— 1) Organizational Structure to vest the Combatant Commander with the Command and Control (C2) authority of different tiers of UAS, 2) Technological Development in Cooperative UAS technology, and 3) UAS sensors and payload systems to deliver the required Capabilities.

The Multi-tiered UAS SoS is expected to be fielded in 2031. The timeline goal for the development of Multi-tiered UAS SoS will drive the overall schedule of the program. The Timeline goal for Technological development is expected to be completed within 5 years, by the year 2031, with the respective Organizational Structure approved within the same time-frame. Current UAS sensors and payloads are deemed capable of fulfilling the operational requirements as stipulated by the CONOPS.

3.3 Organizations Involved

Secretary of Defense and Office of Secretary of Defense (OSD): Responsible for determining and approval of UAS policies for UAS employment within the US military.

Chief of Staff: Approval for the Assets to be deployed into the Operational Theater. They are responsible for strategic planning and to balance operational need across different battle fronts to allocate assets to the Combat Commander.

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SPO: System Program Office – Agency responsible for the long-term sustainment, part revitalization and upgrade programs for a specific MDS (to include Multi-tiered UAS SoS)

JFACC: Joint Forces Air Component Commander – Individual in command of the AOC and responsible for all air operations in the AOR.

JFGCC: Joint Forces Ground Component Commander – Individual in command of and responsible for all ground operations in the AOR. This person is responsible for identifying and allocating access to the Multi-tiered UAS SoS System for all ground forces in the AOR.

4 Purpose and Perspective

Problem

Rapid improvements of TBM technology and increases in weapons proliferation to non-allied nations have resulted in new and constantly changing threats to friendly forces. The high accuracy of many TBM systems allow them to inflict serious damages from significant stand-off distances, even when the missiles are armed with only conventional warheads. To further compound the problem, TBM launchers employ a shoot-and-scoot technique which makes counter-TBM operations challenging.

Need

To address this threat, the military needs to have a capability that can preemptively seek and destroy TBM launchers. Multi-tiered UAS SoS provides the capability to maintain persistent situational awareness over a designated area to search and locate possible TBM Launchers, and dynamically target and strike these TBM Launchers with minimal cost, or risk to personnel.

Purpose of Multi-tiered UAS SoS

The US's UAS arsenal is comprised of numerous UAS with capabilities that ranges from small man-portable vehicles, to medium “fighter-sized” vehicles, and large “tanker-sized” vehicles, as well as specialized UAS with unique capabilities. These capabilities allow UAS to perform many vital roles in military operations, including:

1) ISR
2) Strike
3) Protection
4) Sustainment
5) Movement and Maneuvering

The system architecture aims to deliver a synergistic battlefield effect in the search, track and destroy operations related to TBMs, through using an integrated UAS solution that employs different tiers of UAS, to maximize mission effectiveness, while minimizing operational risks and operating costs. Multi-tiered UAS SoS enables cooperative operations among different groups of UAS within the same AO to identify, confirm targets, and to assign tasks among differing UAS groups to maximize mission effectiveness and efficiency.

5 Context

5.1 Mission

Different Tiers of UASs will be deployed within the same AO to achieve the desired battlefield effect and mission success. In theater, UASs will be equipped with different sensors and software so that they can fulfill different mission roles. In particular, this architecture focuses on finding, tracking, and destroying TBMs efficiently and effectively through the use of the Multi-tiered UAS SoS system.

5.2 Doctrine, Goals, and Vision

The System provides the Combat Commander with a full suite of aerial capabilities applied automatically to achieve mission success. In particular, UAS systems:

- Reduce risks to ground troops.
- Reduce command workload while sustaining persistent operations by automating what can be automated.
- Increase capabilities for extended range and stand-off operations.

5.3 Concepts of Operations/Scenarios

The system focuses on the efficient employment of different groups of UAS to maintain persistent situational awareness over the AO, to seek and identify possible TBM Launchers, and to dynamically direct targeting and strike operations. It leverages the capabilities of different groups of UAS and sensor systems to achieve a system capable of optimizing UAS employment for mission effectiveness, while minimizing operational cost and risk. Additionally, the system will be the central node in a system-of-systems employing cooperative control among various UAS groups in the AO to assign roles and plan safe routes for ingress and egress.

a. Larger tiers UASs (Group 4 and 5):

   i. Persistent ISR. The larger tiers of UASs have greatest range, endurance, airspeed and altitude capabilities in the family of UAS. As such, these UAS are typically employed to conduct persistent ISR over the AO. They will be equipped with the necessary sensors to identify possible Surface-to-Air (SAM) sites and possible TBM Launchers in the AO.

ii. Dynamic Strike. These groups of UAS are also capable of carrying kinetic weapons, and could be loaded with the necessary munitions to provide a dynamic strike capability.

b. Smaller tiers UASs (Group 1 and 2):

i. Target Verification. The smaller UAS groups have a smaller footprint are used for target verification and can be equipped with Automatic Target Recognition (ATR) software to determine phases of TBM launcher deployment.

ii. Battle Damage Assessment (BDA). These UAS groups will also be used to perform BDA after the conclusion of the dynamic strike to confirm mission success.

5.4 Information Assurance Context

The same information assurance criteria for individual UAS tiers will apply because there are no new information streams, only new methods for automating them.

5.5 Linkages to Other Architectures

This architecture is linked with the ISR and each UAS group's respective architecture.

6 Architecture Development Schedule

13 Jan 2016 - Overarching CONOPS, Use Cases, AV-1, AV2
20 Jan 2016 - OV-5a, CV-2, OV-1, OV-4
27 Jan 2016 - CV-6, OV5b, DIV-2
17 Feb 2016 - OV-2, OV-3, OV-6a, b, c
24 Feb 2016 - SV-1, SV-4, SV-5a
2 Mar 2016 - SV-7, Multi-tiered UAS SoS Software Simulation

7 Findings

This section will be developed as the architecture development progresses.

7.1 Analysis Results

Ownership and Responsibility

a. Who owns the asset?
   - ***The AOC will own this asset.***
b. Who commands UAS employment?
   - The Multi-tiered UAS SoS shall be supervised by the Mission Commander at all times.
c. Who has the final say in this system?
   - ***Mission Commander.***
d. What level is required for the implementation of proposed architecture?
   - Office Secretary of Defense through JCIDS process
e. Does funding have an impact on employment? (who pays for it?)
   - Yes.

Technical Feasibility

a. What are the technical issues affecting integration between different fleet (such as communication datalink, commonality of software data systems)?
   - Flight Planning Algorithm
   - Strike Target Flight Maneuvers
   - Intelligence Gathering
   - BDA Image Processing
   - Bandwidth
   - Secure Communications
   - Communicate Intelligence feed simultaneously between Mission Commander, AOC, and Ground Forces

Deployment Guidelines

a. What should the Rules of Engagement (ROEs) be?

- The system will have the mission parameters altered by the Mission Commander in order to tailor the guidance parameters in order to maximize flexibility. The Mission Commander is kept in the loop for this reason and to ensure that a human always makes the decision to launch munitions.

Sample Innoslate Script

Some of the main Javascripts used in initialization and rules implementation in the Innoslate Executable Models are provided for references.

System Initialisation Block

```
// The Activity block initializes all the systems parameters in the global arrays.
// Due to the nature of the simulation where it is not possible to pass information between
blocks, Parameters are declared in global.

function onStart()
{
   //intialize global mission status
   globals.put("Run_Count",0);          // To determine which run the simulation is in
   globals.put("Current_Location",0);  // To determine the current location of ISR UAS

   //initialize target counting
   globals.put("Target_Count",0);       // Running tally of total Targets created
   globals.put("Target_confirm",0);    // Running tally of tatal targets confirmed
   globals.put("NonTarget_Count",0);   // Running tally of total non target confirmed
   globals.put("Strike_Count",0);       // Running tally of total Target Struck

   //Set ISR UAS Sensor Probability
   globals.put("ISR_TruePos",0.7);      // Probability for detection given real target
   globals.put("ISR_FalsePos",0.3);     // Probability for detection given non-target

   //Set Surveil UAS Sensor Probability
   globals.put("Surveil_TruePos",0.75);   // Probability for detection given real target
   globals.put("Surveil_FalsePos",0.2);  // Probability for detection given non-target

   //Set Strike UAS hit Probability
   globals.put("Strike_Hit",0);         // Probability for hit by Strike UAS
   globals.put("Strike_Miss",0);        // Probability for miss by Strike UAS

   //Set array for Target count
   for (counter = 1; counter <= 200; counter ++){
      globals.put("Combined_Target_Location["+counter+"]",counter);
         // Target Locationfor each of the 200 targets
         globals.put("Target_Acquired["+counter+"]", 0);         // Flag for target acquire
         globals.put("Target_Strike_Time["+counter+"]", 0);      // Time to strike target
         globals.put("Time_Taken["+counter+"]", 0);              // Time from target acquire
         to target strike
         globals.put("Target_Destroyed["+counter+"]", 0);        // Flag for target destroyed
```

```
    }

    //Variables for simulation control
    globals.put("Surveil_UAS",0);      // For Surveil UAS selection
    globals.put("Sur_UAS_1_Loc",0);                  // Location for Surveil UAS 1
    globals.put("Sur_UAS_2_Loc",0);                  // Location for Surveil UAS 2
    globals.put("Sur_UAS_3_Loc",0);                  // Location for Surveil UAS 3
    globals.put("Sur_UAS_4_Loc",0);     // Location for Surveil UAS 4

    globals.put("Strike_UAS",0);       // For Strike UAS selection
    globals.put("Strike_UAS_1a_Loc",0);    // Location for Strike UAS 1
    globals.put("Strike_UAS_1b_Loc",0);    // Location for Strike UAS 2
    globals.put("Strike_UAS_2a_Loc",0);    // Location for Strike UAS 3
    globals.put("Strike_UAS_2b_Loc",0);    // Location for Strike UAS 4

    globals.put("BDA_UAS",0);          // For BDA UAS selection
    globals.put("BDA_UAS_1_Loc",0);                // Location for BDA UAS 1
    globals.put("BDA_UAS_2_Loc",0);                // Location for BDA UAS 2
}
```

Loop Initialisation Block

```
// This block reinitialize the parameters for each run by:
// 1. Count total number of targets.
// 2. Create 2 x Real targets and 2 x False targets at random position.
// 3. Ensure that the targets are not located within the same location.
// 4. Reset the UAS starting condition.

function onStart(){

    //declare variables
    var target = [0, 0];
    var false_target = [0,0];
    var time_to_strike = [0,0];


    // initialize current search location of ISR UAS
    globals.put("Current_Location",0);

    // initialize Surveil UAS deployment to 0
    globals.put("Surveil_UAS",0);            // For Surveil UAS selection
    globals.put("Sur_UAS_1_Loc",0);          // Location for Surveil UAS 1
    globals.put("Sur_UAS_2_Loc",0);          // Location for Surveil UAS 2
    globals.put("Sur_UAS_3_Loc",0);          // Location for Surveil UAS 3
    globals.put("Sur_UAS_4_Loc",0);          // Location for Surveil UAS 4

    globals.put("Strike_UAS",0);             // For Strike UAS selection
    globals.put("Strike_UAS_1_Loc",0);       // Location for Strike UAS 1
    globals.put("Strike_UAS_2_Loc",0);       // Location for Strike UAS 2
    globals.put("Strike_UAS_3_Loc",0);       // Location for Strike UAS 3
    globals.put("Strike_UAS_4_Loc",0);       // Location for Strike UAS 4

    globals.put("BDA_UAS",0);                // For BDA UAS selection
    globals.put("BDA_UAS_1_Loc",0);          // Location for BDA UAS 1
    globals.put("BDA_UAS_2_Loc",0);          // Location for BDA UAS 2


    //initialize Loop Count
    Current_Run = globals.get("Run_Count") + 1;
    globals.put("Run_Count",Current_Run);
    //print("Run No: "+globals.get("Run_Count"));

    //Initialize target location per run
    target[0] = 0;
    target[1] = 0;
```

```
    while (target[0] === 0){
        target[0] = Math.round(Math.random() * 100 / 2.5);
    }

    //To ensure targets are not located within the same search grid.
    while (target[1] == target[0] || target[1] === 0){
        target[1]= Math.round(Math.random() * 100 / 2.5);
    }

    //Initialize false target location and ensure it does not co-locate with target.
    false_target[0] = Math.round(Math.random() * 100 / 2.5);
    while (false_target[0] == target[0] || false_target[0] == target[1] || false_target[0] ===
0){
        false_target[0] = Math.round(Math.random() * 100 / 2.5);
    }

    //Initialize false target location and ensure it does not co-locate with target or first false
target
    false_target[1] = Math.round(Math.random() * 100 / 2.5);
    while (false_target[1] == target[0] || false_target[1] == target[1] || false_target[1] ==
false_target[0] || false_target[1] === 0){
        false_target[1] = Math.round(Math.random() * 100 / 2.5);
    }


    //Update global targets and false targets variables
    globals.put("Target[0]", target[0]);
    globals.put("Target[1]", target[1]);
    globals.put("False_Target[0]", false_target[0]);
    globals.put("False_Target[1]", false_target[1]);

    //print("Initialization --- Target 1: " +globals.get("Target[0]") +" Target 2: "
+globals.get("Target[1]") +" False Target 1: " +globals.get("False_Target[0]") +" False
Target 2: " +globals.get("False_Target[1]"));

    current_target_number = globals.get("Target_Count");
    if (current_target_number === 0){
        current_target_number = current_target_number + 1;  // 1st run
    }
    else{
        current_target_number = current_target_number + 2;  // 2nd run onwards need to
account for 2 targets per run
    }
```

```
    globals.put("Combined_Target_Location["+ current_target_number +"]",target[0]);
    globals.put("Target_Count",current_target_number);

    current_target_number = globals.get("Target_Count") + 1;
    globals.put("Combined_Target_Location["+ current_target_number +"]",target[1]);
    globals.put("Target_Count",current_target_number);

    //reset the target count to correspond to the 1st target of current run
    current_target_number = globals.get("Target_Count") - 1;
    globals.put("Target_Count",current_target_number);

}
```

TBM Located? Block

```
// This block determine if the ISR UAS locate a TBM launcher within the current search.
// It uses the probability function for Probability of detection of real target and non-target
// to declare if a TBM launcher is located.

function onEnd(){

   // Generate random number for probability comparison
   Rand_Num = Math.random();

   // If target is located at current location
   if (globals.get("Current_Location")==globals.get("Target[0]")){

      // target is located and identified
      if (Rand_Num <= globals.get("ISR_TruePos")){
         target_counter = globals.get("Target_Count");
         globals.put("Target_Acquired["+target_counter+"]",1);

         exitBranchName = "Yes";

      }

      else {
         target_counter = globals.get("Target_Count");
         exitBranchName = "No";
      }

   }


   else if (globals.get("Current_Location")==globals.get("Target[1]")){

      // target is located and identified
      if (Rand_Num <= globals.get("ISR_TruePos")){
         target_counter = globals.get("Target_Count") + 1;
         globals.put("Target_Acquired["+target_counter+"]",1);

         exitBranchName = "Yes";
      }

      else {
         target_counter = globals.get("Target_Count") + 1;
```

```
        exitBranchName = "No";

      }


   }



   // If false target is located at current location
   else if (globals.get("Current_Location")==globals.get("False_Target[0]")||
globals.get("Current_Location")==globals.get("False_Target[1]")){

      // false target is located and wrongly identified
      if (Rand_Num <= globals.get("ISR_FalsePos")){
         exitBranchName = "Yes";

      }

      // false target is not identified
      else {
         exitBranchName = "No";

      }


   }

   // If no target of false target at current location
   else{
      exitBranchName = "No";

   }

   return exitBranchName;

}
```

Assign Surveil UAS Block

```
//This block assigns the next available Surveil UAS after target is identified.
//This control function is similar to other Assign UAS blocks

function onEnd() {

   // Check current UAS Deployment
   UAS_Current = globals.get("Surveil_UAS");

   if (UAS_Current === 0){
      UAS_Current = UAS_Current + 1;
      globals.put("Surveil_UAS",UAS_Current);
      globals.put("Sur_UAS_1_Loc", globals.get("Current_Location"));
      //print ("Surveil UAS 1 deployed to " +globals.get("Sur_UAS_1_Loc"));
      exitBranchName = "UAS 1";

   }

   else if (UAS_Current == 1){
      UAS_Current = UAS_Current + 1;
      globals.put("Surveil_UAS",UAS_Current);
      globals.put("Sur_UAS_2_Loc", globals.get("Current_Location"));
      //print ("Surveil UAS 2 deployed to " +globals.get("Sur_UAS_2_Loc"));
      exitBranchName = "UAS 2";

   }


   else if (UAS_Current == 2){
      UAS_Current = UAS_Current + 1;
      globals.put("Surveil_UAS",UAS_Current);
      globals.put("Sur_UAS_3_Loc", globals.get("Current_Location"));
      //print ("Surveil UAS 3 deployed to " +globals.get("Sur_UAS_3_Loc"));
      exitBranchName = "UAS 3";

   }


   else if (UAS_Current == 3){
      UAS_Current = UAS_Current + 1;
      globals.put("Surveil_UAS",UAS_Current);
      globals.put("Sur_UAS_4_Loc", globals.get("Current_Location"));
      //print ("Surveil UAS 4 deployed to " +globals.get("Sur_UAS_4_Loc"));
      exitBranchName = "UAS 4";
```

```
    }
    return exitBranchName;
}
```

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14. ABSTRACT
The increasing complexity in the development of today's modern warfighting systems demands a systematic evaluation approach in the assessment of the envisaged capability and estimating the cost effectiveness, especially in the early stages of Concept Development. This research focused on the development of early Concept evaluation methodology through the use of Executable Architecture (EA) through the System Architecting process. Particularly, the methodology was applied in the assessment of a proposed Multi-tiered Unmanned Aircraft System System-of-System that is designed provide target acquisition and conduct dynamic strike on Theater Ballistic Missile launchers.

Through the implementation of the evaluation methodology using dynamic modeling of the system-under-design, the research was able to provide quantitative assessment of different design parameters on the overall system effectiveness, as measured using a set of pre-determined Measures-of-Effectiveness. Specifically, Innoslate was used to develop the EA model of a fictitious multi-tier Unmanned Aircraft System System-of-Systems, and provided quantitative assessment of the overall system performance due to changes in the design parameters. Specification, the research showed that the proposed evaluation methodology provides system architects with the tool to 1) evaluate different design parameters, 2) understand the overall system capability given sub-system capabilities, and 3) determine sub-system requirement given desired system performance.

15. SUBJECT TERMS
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