NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

COUNTER UNMANNED AERIAL SYSTEM DECISION-AID LOGIC PROCESS (C-UAS DALP)

by

Allen Bullard, Gregory Ferrell, Laura Gilmour, Jedediah Magda, Mark Rice, and Cheryl Young

March 2018

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE March 2018	3. REPORT TYPE AND DATES COVERED Capstone project report

4. TITLE AND SUBTITLE COUNTER UNMANNED AERIAL SYSTEM DECISION-AID LOGIC PROCESS (C-UAS DALP)	5. FUNDING NUMBERS
6. AUTHOR(S) Allen Bullard, Gregory Ferrell, Laura Gilmour, Jedediah Magda, Mark Rice, and Cheryl Young	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

Small, highly capable, and inexpensive unmanned aerial systems (UASs) are commonplace, easily modified, and being weaponized to aid the enemy in attacking U.S. interests around the world. NAVAIR and other stakeholders have multiple and available sensor and countermeasure capabilities that surveil, detect, track, and attack these UAS threats, but these capabilities lack a decision-aid or logic process that bridges the middle elements of the kill chain between detection to countermeasure response. This capstone project creates the logic for a decision process that transitions from the initial detection, characterization, and threat determination to a recommended response based on available sensor and countermeasure data. This logic process enables an operator to quickly, reliably, consistently, and repeatedly make the optimal tactical decisions in response to a dynamic threat environment.

The products and deliverables include the concept of operations, functional architecture, design reference mission, modeling and simulation, decision-aid logic process, future research considerations, and recommendations. The concept of operations describes conceptual ideas relating to the manner of use, location, general logic process, and reference mission. This is the framework for the IDEF0 functional architecture diagrams, decision-aid diagrams, logic process, and modeling and simulation.

14. SUBJECT TERMS counter-unmanned aerial systems, decision-aid, logic process, systems engineering, kill chain, detect-to-engage	15. NUMBER OF PAGES 125
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

and

MASTER OF SCIENCE IN ENGINEERING SYSTEMS

from the

NAVAL POSTGRADUATE SCHOOL
March 2018

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ABSTRACT

Small, highly capable, and inexpensive unmanned aerial systems (UASs) are commonplace, easily modified, and being weaponized to aid the enemy in attacking U.S. interests around the world. NAVAIR and other stakeholders have multiple and available sensor and countermeasure capabilities that surveil, detect, track, and attack these UAS threats, but these capabilities lack a decision-aid or logic process that bridges the middle elements of the kill chain between detection to countermeasure response. This capstone project creates the logic for a decision process that transitions from the initial detection, characterization, and threat determination to a recommended response based on available sensor and countermeasure data. This logic process enables an operator to quickly, reliably, consistently, and repeatedly make the optimal tactical decisions in response to a dynamic threat environment.

The products and deliverables include the concept of operations, functional architecture, design reference mission, modeling and simulation, decision-aid logic process, future research considerations, and recommendations. The concept of operations describes conceptual ideas relating to the manner of use, location, general logic process, and reference mission. This is the framework for the IDEF0 functional architecture diagrams, decision-aid diagrams, logic process, and modeling and simulation.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFB	Air Force base
AFRL	Air Force Research Lab
AIR 4.1	NAVAIR systems engineering
AIR 5.4	Atlantic Test Range subject matter experts
AMRDEC	U.S. Army Aviation and Missile Research, Development, and Engineering Center (Redford Arsenal)
ASN	Assistant Secretary of the Navy
ATR	Atlantic Test Range
CBDR	constant bearing, decreasing range
CLOS	command line of sight
CM	countermeasure
CONOPS	concept of operations
CPA	closest point of approach
Crs	course
C-UAS	counter unmanned aerial system
DAD	Disciplined Agile Delivery
DALP	decision-aid logic process
DASN	Deputy Assistant Secretary of the Navy
Deg	degree
DFT	data fusion tool
DoD	Department of Defense
DON	Department of the Navy
DRM	design reference mission
EA	electronic attack
ECM	electronic countermeasures
EO	electro-optical
EO/IR	electro-optical/infrared
ESM	electronic support measures
FOB	forward operating base
GHz	gigahertz

GPS	Global Positioning System
GUI	graphical user interface
HPEW	high powered electromagnetic weapon
HPM	high powered microwave
ID	identify
IED	improvised explosive device
IFF	interrogator friend or foe
IPR	in-process review
IR	infrared
IRB	institutional review board
ISAR	inverse synthetic-aperture radar
ISIS	Islamic State in Iraq and Syria
ISM	industrial, scientific, and medical
Kg	kilogram
Km	kilometer
Lb	pound
LCDR	Lieutenant Commander
LSI	lead system integrator
LT	Lieutenant
M	meter
MADS-K	Man Portable Aerial Defense System - Kit
MARS	Man portable airborne radar system
MARS-K	Man Portable Airborne Radar System - Kit
Max	maximum
MBSE	model-based systems engineering
MPH	miles per hour
MS	Microsoft
N/A	not available
N9	Deputy Chief of Naval Operations
N98	Air Warfare Division
NAVAIR	Naval Air Systems Command
NAWCAD	Naval Air Warfare Center Aircraft Division

NAWCWD	Naval Air Warfare Center Weapons Division
NM	nautical mile
NPS	Naval Postgraduate School
OODA	observe, orient, decide, act
OPNAV	Office of the Chief of Naval Operations
P/C/S	Position, course, and speed
PID	positive identification
Radar	radio detection and ranging
RCS	radar cross section
RDT&E	research design test and evaluation
RF	radio frequency
ROE	rules of engagement
SE	systems engineering
Sec	second
SME	subject matter expert
Sonar	sound navigation and ranging
Spd	speed
TMA	target motion analysis
UAS	unmanned aerial system
USN	United States Navy
VID	visual identification

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EXECUTIVE SUMMARY

Enemies of the United States are using small, easily obtained, simply operated, and weaponized unmanned aerial systems (UAS) to exploit a current vulnerability in military and civilian defense systems. The UAS includes the air vehicle, radio communication equipment, possible weapon payloads, and the human operator. Their use potential is wide and includes urban and rural environments for both military and civilian activities.

Stakeholders shared that multiple projects focusing on detection and/or engagement capabilities are in development or have been completed. However, they identified a significant capability gap in the middle of the kill chain where decision-making and data fusion occur. The focus of this capstone project was to derive a solution that assisted in the decision-making process. The decision-aid logic process (DALP) would use fused sensor output data to analyze and provide recommendations for counter-unmanned aerial system (C-UAS) action. The logic is intended to be used for an eventual decision-aid logic tool (DALT) created from the inputs, outputs and interactions of the process.

The objective of this capstone project was to develop the concept of operations (CONOPS), high-level needs, and functional architecture for a process that addresses the capability gap. The CONOPS, high-level needs, and functions of the DALP were developed using assumed or notional sensor, data fusion, and countermeasure capabilities. The DALP was evaluated and refined using simulations of applicable kill-chain scenarios. DALP functions to identify the contact, provide indication and scale of threat posture, and recommend actions to commonly encountered enemy UASs. The primary goal is to assist the operator by reliably and repeatedly making the best tactical decisions.

The threat analysis indicated that the most likely threat is a fixed-wing or quadcopter-style UAS modified either to drop explosives or to crash and explode on impact. These methods of attack require the UASs to have no stand-off distance and to be

present at the target site to deliver their payloads. This was assumed when developing the modeling and simulation portion of this effort.

Fused radar, acoustic, EO/IR, and electronic support measure (ESM) sensor output data was assumed to be available as indicated from stakeholder input and guidance. This data was used to form the inputs that the DALP uses to form solutions. The assumed data fusion capability was accomplished in a tool that was introduced in the Arteche et al. (2017) capstone thesis. This tool is referred to as the Data Fusion Tool (DFT) in this capstone.

Outputs from the DFT provide the DALP with information that is used to identify, characterize, and assess characteristics and threat levels of UASs. The DALP uses this information to generate recommendations and alerts. The recommendations include both attack and employment suggestions.

Multiple detect-to-engage sequencing functions are integral to the C-UAS kill chain. These can be accomplished with a single system or an integrated system of systems with linear and or/parallel functional processes. Functional responsibilities can be allocated to sensors, data fusion tools, decision aids, countermeasure systems, and the human operator. The DALP was designed to mimic and, with a follow-on effort, eventually replace the human role in UAS identification, classification, threat posture determination, and attacking. This is accomplished by the DALP continuously running through a series of logic questions and decision gates. The DALP makes the recommendations, but the operator still provides the final attack authority. The DALP requirements and functional architecture could be adjusted to form a fully autonomous C-UAS system in the future.

The functional architecture of the kill chain sequence was decomposed into detect, characterize, and act. The sensors and DFT were allocated to the detect functions. The DALP was allocated to the functions characterize and act. The operator and countermeasures were allocated to the act function for the authorization and launch, respectively. The DALP-derived sub-functions were based on the human operator’s

analysis responsibility and the reality that he or she has the potential to be overwhelmed, distracted, fatigued, and imperfect in decision-making.

The modeling and simulation efforts focused on a limited but representative set of real-world UAS attack and C-UAS scenarios. The DALP was simulated conceptually, and its functionality was tested. The primary modeling and simulation parameters included UAS heading and flight path profiles as well as range limitations, initial start positioning, and IFF determination.

It was shown that the DALP, as used in this capstone's modeling and simulation efforts, functioned as planned in recognizing potential threatening UASs, escalating the associated threat level, and recommending deployment of countermeasures. Success was also achieved in distinguishing between a UAS that posed a threat, one that did not pose a threat, and a non-manmade object that did not pose a threat. There were decision gates that successfully removed the trackable object from the DALP sequence when it was applicable. The DFT outputs were conceptualized, and the resulting information derivatives were incorporated into the simulation.

The solution, as generated by the team, has successfully demonstrated a potentially unique capability that addresses the stakeholder-identified need of filling an identified kill-chain capability gap. The DALP, in conjunction with the development of a follow-on effort of a DALT and graphical user interface (GUI), would significantly increase the ability and decrease the timing required for a single operator to positively disrupt enemy UAS threats. The DALP also has the potential to be configured to act autonomously in this kill-chain scenario. Future work is required for this functionality; however, this capstone provides the framework for such follow-on efforts.

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ACKNOWLEDGMENTS

First and foremost, we would like to thank our families for the sacrifices they made in support of our program. Without their efforts, we would not have succeeded. They deserve just as much recognition, if not more, than we do. We would also like to thank Tom Moulds and Kurt Rockwell for sharing their time and expertise in this subject matter. Their advice throughout the project was necessary and invaluable. Lastly, thank you to our advisors, Ron Carlson and Rama Gehris, as well as the rest of the NPS staff. We will forever be grateful for the education, personal development, and help throughout the process.

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I. INTRODUCTION

Small group one and group two UASs are inexpensive, simple to operate, and easily obtained. Group one UASs are less than 21 pounds, whereas group two UASs are 21 to 55 pounds (UAS Task Force 2011). These UASs have the capability of being outfitted with a variety of explosive, biological, and nuclear materials, and used as an offensive weapon against various targets. In addition, these UASs are used for enemy reconnaissance and surveillance activities. These offensive-threat UASs have the potential to be used in a variety of enemy attack scenarios, including flying into populated and vulnerable civilian areas, as well as into military compounds or even at active aircraft.

Figure 1 displays the stakeholder-supplied C-UAS kill chain. The red circles in Figure 1 depict the major focus areas associated with the conduct of this capstone project. Multiple sensors and countermeasures are currently in use by the Department of Defense to detect and attack UASs. Efforts to integrate sensors and correlate tracking techniques and technologies are ongoing. However, there are some areas in Figure 1 where additional capabilities are needed, namely in data fusion and decision aids. For example, there is a need for a system that can integrate, correlate, and appropriately organize sensor data to be used as inputs to a decision-aid logic tool. A C-UAS decision-aid logic process (C-UAS DALP) could provide recommended courses of action based on a UAS's derived threat potential. The C-UAS DALP, in conjunction with a future follow-on GUI, would likely and significantly increase the ability and decrease the timing required for a single operator to positively disrupt enemy UAS threats.

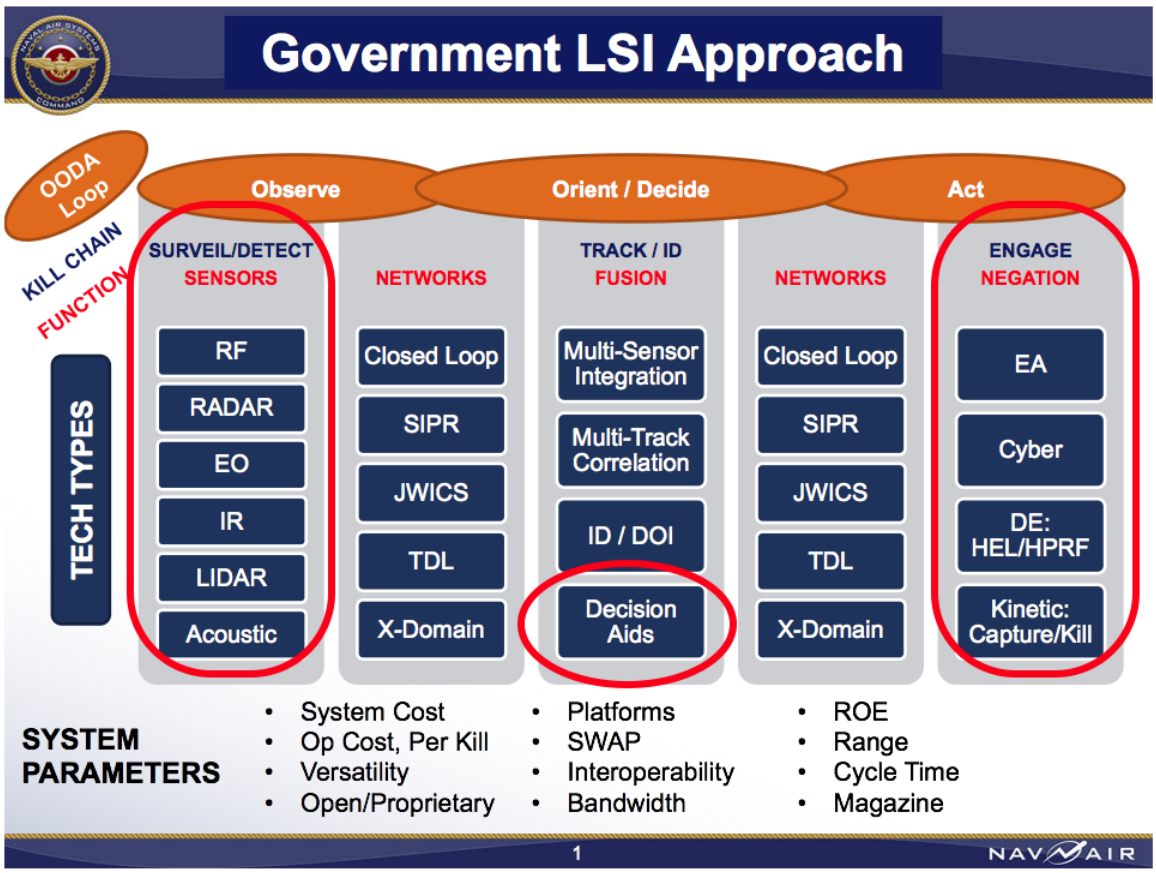

Figure 1. NAVAIR C-UAS Kill Chain/Government LSI Approach. Source: Rockwell (2016).

A. PROBLEM STATEMENT

Small, highly capable, and inexpensive UASs are commonplace, easily modified, and can be weaponized to aid the enemy in attacking U.S. interests. As indicated by the stakeholders, multiple sensor technologies are currently available and utilized to surveil, detect, and track these potential UAS threats. However, a logical progression and associated tool is missing to bridge the gap in transitioning from detection of a potential UAS threat through positive threat identification and characterization to operator determination of a viable and available threat countermeasure response. The DALP in connection with a future implementation into hardware and software (DALT) would enable an operator to make the best tactical decisions reliably and repeatedly in response to a dynamic threat environment based on the sensor data available.

B. LITERATURE REVIEW

Arteche et al. (2017) focused on developing a software system architecture that dealt with command and control, data fusion, threat evaluation, and weapons assignments for middle of the kill chain C-UAS operations. The summary of the Arteche et al. capstone is as follows:

- The project was a high-level C-UAS software system architecture.
- Innoslate was used for the detect, track, identify, and engage modeling and architecting efforts.
- The project focused on the "middle" area of the kill chain, mostly including data fusion and command and control aspects.
- Interfaces between software, hardware, operators, sensors, and countermeasures were identified and discussed.

In addition to the thesis, a SharePoint site (C-UAS n.d.) containing sensor, countermeasure, and other C-UAS topics and data were provided for reference purposes. This information was important in defining the scope, avoiding duplicate efforts, and assisting with the stakeholder analysis. The thesis from Arteche et al. (2017) had high-level focus looking into data fusion and threat assessment software system architecture. That effort indicated that there was an opportunity for a follow-on effort to develop a specific decision-aid process. In other words, that effort dealt with the "whats," and additional work, was needed for the "hows" of the functions. Therefore, the focus for this capstone shifted to development of a specific logic process (DALP) and associated tool (DALT).

C. SCOPE AND OBJECTIVES

The objective of this capstone project was to develop the concept of operations (CONOPS), high-level needs, functional architecture, and logic process that can be used for a future C-UAS decision-aid logic tool (DALT) or as a basis for decision-aid software algorithms. The DALP and DALT architecture was developed to meet the goal of

increasing situational awareness and aid a single operator in making an appropriate decision for threat neutralization against an ever-evolving threat picture.

Note, the scope of the capstone covered both the logic process (DALP) and the functional architecture framework for an eventual tool (DALT). The decision-aid logic was the basis for the process while the interfaces, inputs, outputs, and interactions were the basis for the future tool.

The C-UAS DALP project team reviewed sensor inputs and capabilities to determine what data and information were required to develop the logic process and architecture. Historical, current, and projected UAS capabilities were used for a threat analysis that identified and assessed the threat potential. Sensor and countermeasure technologies were analyzed to identify current C-UAS capabilities. The team also worked with the stakeholders to identify and develop use cases based on anticipated enemy attack targets and methods. This was used to determine the following scope and objectives:

- Assess the current threat.
- Assess current sensor and countermeasure capabilities.
- Develop a design reference mission (DRM).
- Develop a CONOPS.
- Identify top-level needs.
- Conduct a functional analysis.
- Develop the functional architecture for the DALT.
- Develop the logic for the DALP.
- Model the decision logic process with current threat and sensor technologies.

Additionally, the scope was limited due to time, manpower, security classification, and system of systems availability constraints. For example, the DFT

variant from Arteche et al. (2017) is in a software architecture phase, and the hardware and associated functions and interfaces were not yet available. This limited the DALP and DALT to using conceptualized functions and interfaces with the various systems with which it interacts. Follow-on work is needed to integrate the process into a software or hardware tool. The C-UAS DALP project team did not:

- Develop a software application, GUI, or the tool itself.
- Develop any detailed designs for hardware, software, and their associated interfaces.
- Perform a human factors analysis.
- Use any classified data.
- Utilize specific sensor or countermeasure performance against specific UAS threats.

D. ASSUMPTIONS AND CONSTRAINTS

These assumptions are valid throughout the entire capstone unless otherwise noted. The following general assumptions were used:

- The C-UAS DALP and DALT will be a standalone module containing hardware and software.
- All sensor, countermeasure, and UAS data was current at the time the research phase was completed.
- All the sensors were assumed to be energized and searching while the DALP process was active.
- The sensors modeled in this capstone detected the threat.
- Sensor output was required to feed the decision logic process.

- Environmental factors that would degrade sensor performance were not modeled to simplfy modeling sensor performance.
- The DALP was receiving all relevant information from the sensors when the target was within range.
- Malfunctions and failures of sensors and countermeasures were not explored.
- The content and timing of the recommendations differed based on the varying levels of sensor data.
- All the countermeasures were functional and available at the start of the scenario and for any modeling and simulation.
- The DALP did not control Rules of Engagement (ROE) nor decide to launch based on a collateral damage assessment, but rather provided alerts and recommendations.
- Authorization of countermeasure deployment for enemy UAS engagement remains with the human operator.
- The enemy UAS's attack vectors were either a direct hit where the UAS is intentionally crashed into its intended target, or a simple ballistic drop where the UAS overflew its intended target to drop explosives.

E. DATA FUSION TOOL ASSUMPTIONS

The DFT was in the architecture development stages for both hardware and software. System interfaces and interactions were assumed and predicted to facilitate development of the DALT. A conceptualized architecture was used to define the relationship between the DALT and other peripheral systems. While the DALP and DALT were conceptualized as being a standalone hardware and software module that interacts with the operator, DFT, sensors, and countermeasures, future work might use

the tool in a different configuration. However, the decision and logic process should largely remain unchanged. The following assumptions were made:

- The C-UAS DALP and DALT work in conjunction with the DFT.
- The general functions and interfaces are assumed.
- The DALT is linked physically and logically to the DFT.
- The DALT is linked logically to the countermeasures and sensors via the DFT.
- The display and operator workstation are integrated into the DFT.
- DALP is independent of sensor control function.
- The default sensor control is automated, but a manual control override is available.
- The DALP controls sensor tasking and mode selection via the DFT command relays.

F. SYSTEMS ENGINEERING PROCESS

The project team utilized a modified Disciplined Agile Delivery (DAD) process described by Ambler (2013) that also used elements of the systems engineering process described by Benjamin Blanchard (2008). The prioritization for project tasking was determined by the project team with input from the stakeholders. The stakeholders were well informed and able to provide feedback often and without interrupting or delaying the process. The goal was to provide frequent timely and regular process updates. The customized DAD process is illustrated in Figure 2.

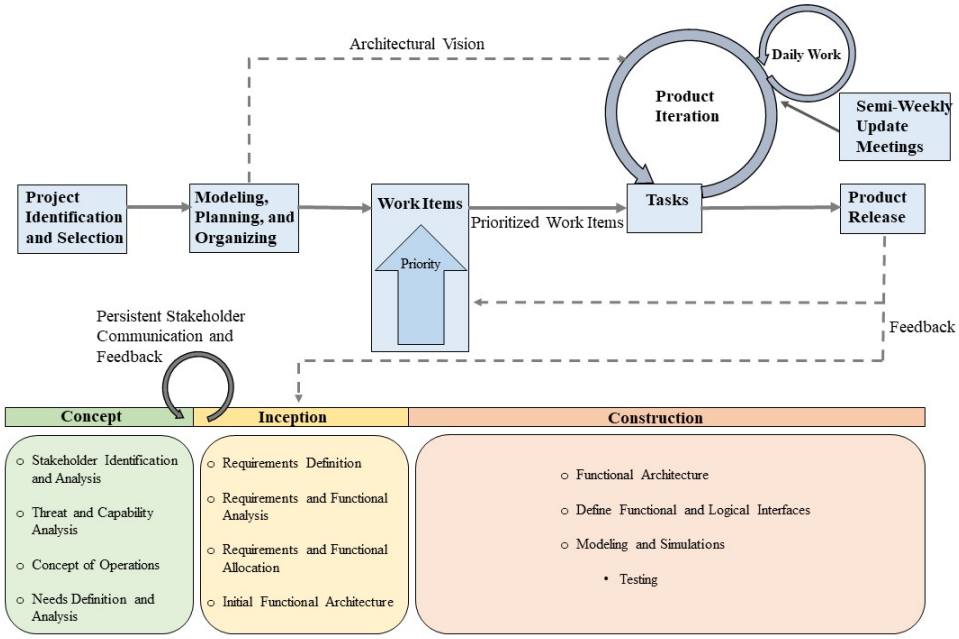

Figure 2. C-UAS DALP Customized DAD SE Process. Adapted from Disciplined Agile Consortium (2013).

1. Concept Phase

Table 1 summarizes the inputs, outputs, and work products of the C-UAS DALP Concept Phase. The C-UAS DALP project began with stakeholder analysis and identification. Stakeholder comments, ideas, and requirements were evaluated to formulate the initial problem definition. Continued research, stakeholder communication, and subject matter expert (SME) inputs assisted with refinement of the problem definition as well as identifying and understanding current threats and capabilities. These activities provided the input required to define and analyze the needs and develop the CONOPS.

Table 1. Concept Phase Summary

Activity	Input from	Output To	Work Product(s)
Stakeholder Identification and Analysis	NPS Advisors, Group Research, Stakeholders	Threat Analysis and Capability Analysis, Concept of Operations, Needs Definition and Analysis	Stakeholder Identification and Communication Plan
Threat and Capability Analysis	Stakeholders, C-UAS SharePoint documentation (C-UAS n.d.)	Concept of Operations and Needs Definition and Analysis	Capabilities and Limitations
Concept of Operations	Stakeholders, C-UAS SharePoint documentation (C-UAS n.d.), Capabilities and Limitations	Needs Definition and Analysis	Operational Diagrams and Concepts, Rules of Engagement (ROE)
Needs Definition and Analysis	Stakeholders, NPS Advisors, C-UAS SharePoint documentation (C-UAS n.d.), Capabilities and Limitations	Inception Phase	Problem Statement and Needs Definition

2. Requirements Analysis (Inception) Phase

Table 2 summarizes the inputs, outputs, and work products of the C-UAS DALP Inception Phase. The inception phase corresponds to the modeling, planning, and organization step in the DAD framework. During this phase, the initial technology strategy, scope, and initial architecture were formulated and developed by the project team and communicated to the stakeholders. The C-UAS DALP system requirements were synthesized from the defined system needs formulated during the concept phase. The system requirements were decomposed and later allocated to functions to meet the system needs as necessary. A concurrent analysis of the system requirement constraints and tradeoffs was performed to develop and prioritize system requirements. The tradeoffs

were determined by stakeholder and project team collaboration to estimate the potential benefits and risks of choosing to use or discard certain requirements.

The assumed functions and required decision-aid logic drove architectural design considerations. These were prioritized to properly allocate the requirements and assign resources for the tasks to be performed in the construction phase. The output of the inception phase was an initial functional architecture that was based on the developed system requirements. This initial functional architecture served as an input to the construction phase.

Table 2. Inception Phase Summary

Activity	Input from	Output To	Work Product(s)
Requirements Definition	Problem Statement and Needs Definition, Stakeholders and Stakeholder Documentation	Requirements and Functional Analysis	High-level Requirements
Requirements and Functional Analysis	High-level Requirements, Stakeholders	Requirements and Functional Allocation	Innoslate or MS PowerPoint Output, List of functions
Requirements and Functional Allocation	Innoslate or MS PowerPoint Output, List of functions	Initial Functional Architecture	Updates to Innoslate or MS PowerPoint Output, List of functions
Initial Functional Architecture	Updates to Innoslate or MS PowerPoint Output, List of functions	Construction Phase	Innoslate or MS PowerPoint Output,

3. Construction Phase

Table 3 summarizes the inputs, outputs, and work products of the C-UAS DALP construction phase. During the construction phase, the project team further defined and decomposed the functional architecture from the requirements and initial functions developed during the previous phase. The construction phase also incorporated the previously derived threat analysis, ROE, and defensive weapons capability to complete

the logic for a decision-aid logic process. A model was created to simulate and validate the required functionality of the C-UAS DALP.

Model-based systems engineering (MBSE) was used throughout the process to aid in organization, design, and communication. Innoslate (2013), MS Visio, and ExtendSim (2013) tools were utilized for modelling and simulation efforts. The outputs of the construction phase were the functional architecture, logical and functional interfaces, and modeling and simulation with its associated testing efforts.

Table 3. Construction Phase Summary

Activity	Input from	Output To	Work Product(s)
Functional Architecture	Innoslate or MS PowerPoint Output, List of functions, ROE	Functional and Logical Interface Definition, Modelling and Simulation, Testing	Innoslate Output, Logic Diagrams, Microsoft Visio IDEF0s, Decision-Aid Logic
Functional and Logical Interface Definition	Functional Architecture, MS Visio IDEF0s, List of functions, ROE	Modelling and Simulation, Functional Architecture Updates	IDEF0 updates, Interfaces, Early Modelling
Modelling and Simulation	Functional architecture, IDEF0 updates, Interfaces, Early Modelling	Functional Architecture Updates	Model of Functions and Behavior
Testing	Requirements Specification Document, Modelling and Simulation	Modeling and Simulation results	Simulation Data

G. SUMMARY

A decision-aid logic process and eventual tool is required to help operators handle complex and dynamic scenarios where threats must be quickly assessed with proper actions taken. Available sensor data can be used to feed predetermined, but configurable decision criteria to aid an operator in identifying and assessing targets. The decision-aid

logic process uses sensor data to continuously monitor and assess contacts throughout a scenario, and the decision logic will recommend engagement of the target to the operator as needed. This capstone project developed the decision-aid logic process and functional architecture that could be used to develop a future DALP software application or tool (DALT).

II. CONCEPT REFINEMENT

The concept refinement phase began with stakeholder analysis and included stakeholder identification and alignment with the needs analysis and requirements. Several stakeholders were identified and narrowed down to include those who were closest to the C-UAS program activities.

A. STAKEHOLDER ANALYSIS

Dr. Harold Kerzner (2013) defines a stakeholder as "individuals, companies, or organizations that may be affected by the outcome of the project or the way in which the project is managed." Stakeholders for this C-UAS DALP project covered multiple tiers of the Department of the Navy (DON), which included Office of the Chief of Naval Operations (OPNAV) N98 Air Warfare Division and NAVAIR. Within NAVAIR, the primary sponsor was Naval Air Warfare Center Weapons Division (NAWCWD) Unmanned & Counter UAS Systems. Additional guidance and collaboration came from AIR 4.1 (Systems Engineering) and AIR 5.4/Atlantic Test Range (ATR) SMEs knowledgeable in C-UAS efforts located at the Naval Air Warfare Center Aircraft Division (NAWCAD) Patuxent River, Maryland. The following stakeholders were collaborated with:

- NAWCWD UxS/C-UxS Director, China Lake, CA (Sponsor)
- NAWCAD AIR 4.1.1.2, Patuxent River, MD
- U.S. Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC)
- NAWCAD, AIR 5.4, ATR, Patuxent River, MD
- Air Force Research Laboratory (AFRL), Wright Patterson Air Force Base, Dayton, OH

Several stakeholder meetings were coordinated and conducted by the project team. The C-UAS kill chain depicted in Figure 3 was the key topic during these

discussions. The Director of NAWCWD UxS/C-UxS program indicated there are many types of sensors available as well as many types of solutions to complete the kill chain. No single sensor or kill chain would be universally effective for all threats, so they adopted a multi-sensor and countermeasure package. However, the kill chain was missing a critical piece—the intelligence and decision-making in the middle, depicted in Figure 3.

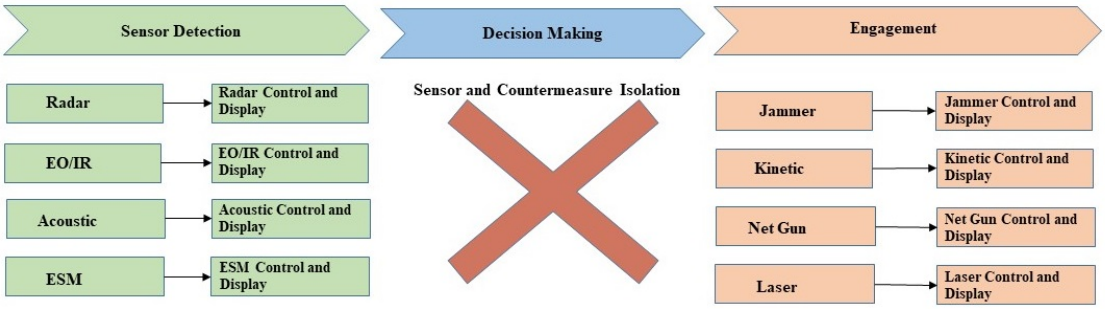

Figure 3. Traditional Kill Chain with Weakness Identified

The stakeholders desired a process that collects and utilizes the fused data inputs to provide the operators with relevant decision logic that will aid them in their decision-making processes for faster and more consistent responses. Multiple project team and stakeholder attended meetings revealed the following:

- Sensors and sensor suites were being used in isolation.
- Countermeasure systems were being used in isolation.
- Isolated sensors and countermeasures offered limited and insufficient solutions.
- Sensor and countermeasure systems utilized diverse output formats and software languages.
- A universal C-UAS solution of “intelligence in the middle” was needed.

- There was a need for a decision-aid logic process that automates an operator's normal decision-making processes for assessing target threat, attempting target identification, and weapons pairing.

- A signal processor and data fusion system were needed to provide relevant information to the decision-aid logic process.

Since multiple organizations were already conducting research on data fusion, the stakeholders and the C-UAS DALP project team decided to focus on a decision-aid logic process. This prevented duplicate efforts and was more appropriate for a nine-month project timeline. Figure 4 illustrates where the data fusion and decision-aid logic process are being implemented in the kill chain with much more sensor and countermeasure integration when compared to the legacy kill chain. Note, the operator and C-UAS DALP share a certain degree of functionality depending on how automated the system is.

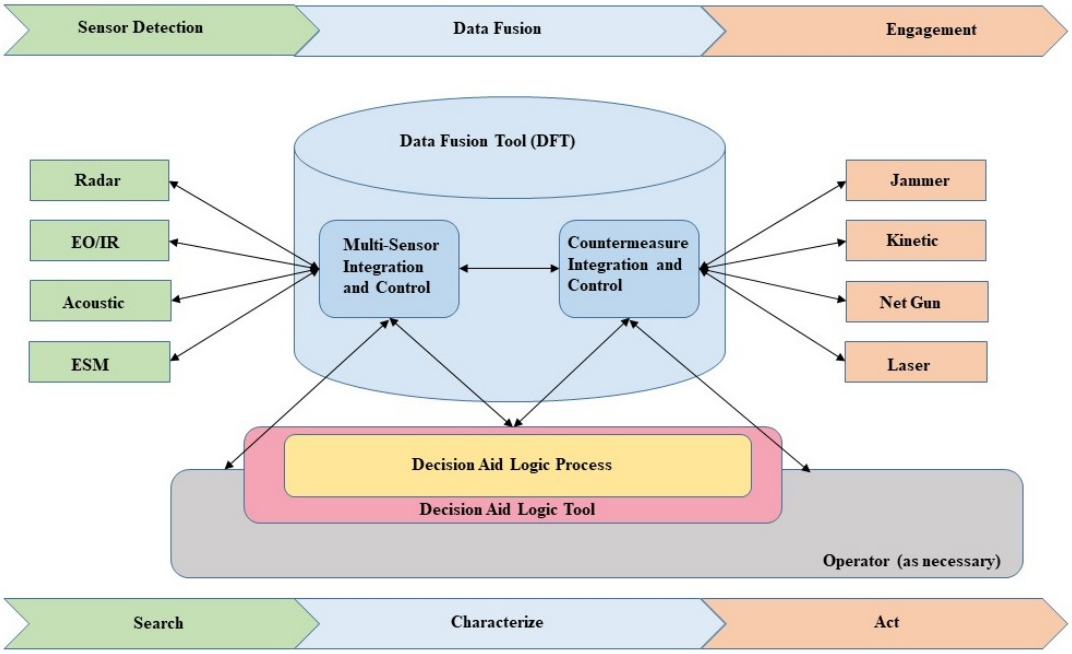

Figure 4. Updated Kill Chain with Data Fusion and Decision-Aid Logic Process

On a separate occasion, members of the project group met with Army stakeholders at the ATR facility in Patuxent River, Maryland, and discussed the Army's perspective on C-UAS. The Army stakeholders shared several concepts of identification for various air contacts, including birds and UASs, but cautioned that a lot of the data is classified at the SECRET level. The team decided to avoid any classified data and consulted the security classification guide to ensure compliance.

After multiple discussions with the stakeholders regarding current kill chain capability limitations and the focus and content of future work, the following determinations and recommendations were made:

- The kill chain already has several sensor and countermeasure solutions that precluded the need to devote additional efforts from the DALP team.
- The kill chain suffers when operators get overwhelmed by large numbers of contacts or become distracted.
- The kill chain suffers when operators are not adequately trained to utilize all the sensors and countermeasures.
- The middle of the kill chain that included data fusion and decision-aid logic process was lacking and would benefit from additional efforts.
- Ongoing research and development of the data fusion capabilities exists but not for decision aids, and any effort to develop a decision-aid logic process would be beneficial.
- The DALP would require a functioning data fusion system to operate effectively.
- The DALP effort would require sensor data, including detection ranges, sensor types, sensor modes, and detection qualities from the existing sensor systems.

- The DALP efforts would require metadata for radar, acoustic, visual, and ESM detection characteristics and any other performance characteristics of existing UAS.
- There are a variety of other C-UAS efforts, and it would benefit the DALP team to leverage and expand upon their researched and published data.
- It was recommended we focus on three or four types of sensor/ countermeasure systems such as radar, acoustic, ESM, and EO/IR to limit the scope.

B. CONCEPT OF OPERATIONS

The overall objective of this work was to provide a decision-aid logic process to bridge the gap in transitioning from detection of potential UAS threat through positive threat identification and characterization to operator determination of a viable and available threat countermeasure response. This decision-aid logic process would enable an operator to reliably and repeatedly make the best tactical decisions in response to a dynamic threat environment based on the sensor data available. The three main functions of the DALP are 1) to provide an indication of what it determines the contact to be, 2) provide a recommendation for the optimal countermeasure employment as needed, and 3) provide an indication and scale of the threat posture with a recommendation to attack. The second function primarily determines and suggests the best available countermeasure as well as the optimal launch characteristics. The third function primarily determines the threat posed by a contact and provides alerts and suggested actions to the operator.

Once a target is detected, the sensors provide additional data to the DALP for analysis. Depending on the information provided, the DALP will provide an indication of what it determines the target to be based on target characteristics. This indication has the capability to facilitate and mature target classification throughout the scenario. For example, the DALP initially indicates an unknown airborne object has been detected. As sensor data builds and UAS attributes are observed, the DALP will recommend that the object be classified as a possible UAS, and then potentially to a probable quad-copter

based on the available sensor data. Due to the limitations of current sensor technology, the ultimate positive visual identification of the both the UAS model and payload, if required, will be done by the operator.

Recommending the best available countermeasure and employment parameters is accomplished by using the available sensor data in conjunction with the available countermeasures. This includes target closure rate, minimum and maximum countermeasure ranges, locations of obstructions, and any other relevant data.

The third function provides the operator an indication of threat-like activity and attack recommendation. The operator can determine what is considered threat-like and can include factors such as ranges, altitudes, closure rates, and swarm characteristics. When the target exhibits threatening behavior, the DALP alerts the operator via the DFT. Additionally, if the targets meet any user specified rules of engagement (ROE) metrics, such as the closest point of approach (CPA) range, the DALP will recommend an attack. Until this system is fully autonomous, the decision to attack is up to the human operator to ensure that collateral damage risk is minimized.

Figure 5 illustrates the notional kill chain logic. When the initial radar detection is determined to be valid, it is forwarded on and analyzed. The DALP attempts to gather more information from other sensors to classify the contact. The DALP is also searching for threatening characteristics, such as a weapon, rapidly closure rate, or swarm-like activity. Once a threat is detected, whether it is from identifying a weapon or from target motion analysis (TMA), the DALP will recommend the ideal countermeasure selection and employment parameters. Once the target has met the predefined ROE, such as crossing a standoff range, the DALP will recommend an engagement. The red arrows represent a feedback loop indicating the DALP will continue to cycle to gain more information as necessary.

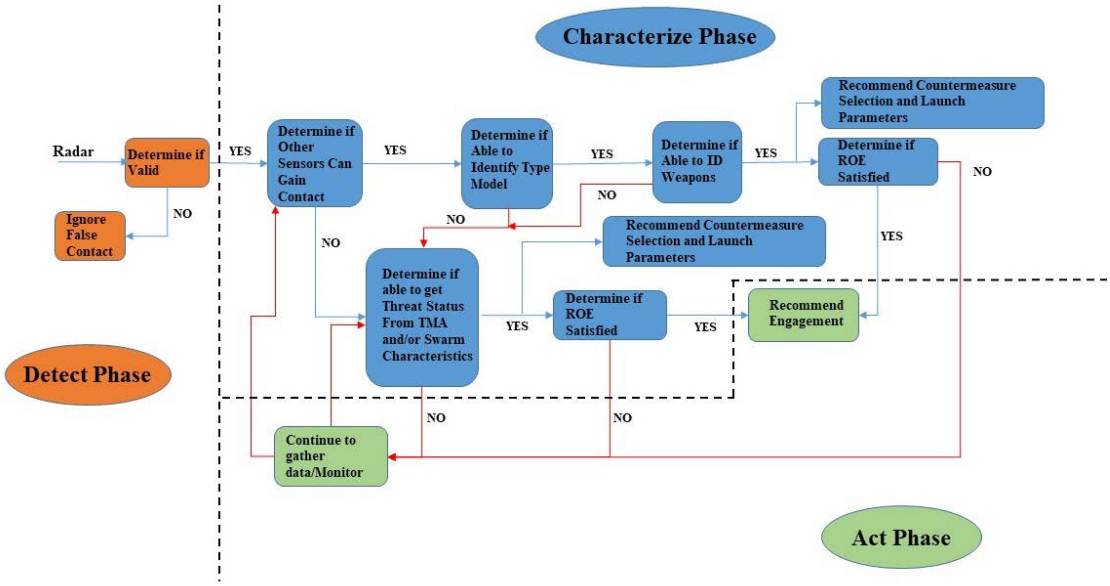

Figure 5. Notional Kill Chain Logic Diagram

The three phases of the kill chain are to detect, characterize, and act. The phases are illustrated in orange, blue, and green, respectively. The detect phase is always occurring, and the remaining two phases only occur when a valid return is present for analysis and decision making.

The concept included an enemy attacking a protected target utilizing a single or swarm of weaponized UASs. All the sensors are energized and in a search mode. As a potential target approaches and is detected by various sensors, the DALP analyzes the available sensor data to provide information and recommendations to the operator. The DALP is analyzing target characteristics such as speed, distance, altitude, size, behavior, emitters, frequencies, and other data that is used in target characterization. The available sensors in this scenario are radar, acoustic, electro-optical/infrared (EO/IR), and electronic support measures (ESM).

The nominal chain of events starts with a valid sensor return, most likely from a broad area sensor such as the radar or acoustic, as illustrated in Figures 6, 7, and 8. Immediately, the other sensors such as EO/IR or ESM will focus their detection ability down that bearing line to provide corroborating data. These sensors continuously feed information into the DALP that, in turn, provides the operator with the most likely

classifications and recommendations, whether the target is a threat, bird, or friendly unit. The sensors will also switch modes as necessary, such as the radar transitioning to inverse synthetic aperture radar (ISAR) mode, to amplify information. The required actions are to continue monitoring, drop the track, or attempt to use countermeasures to destroy the threat. Figures 6, 7, and 8 illustrate this chain of events for a high-speed inbound scenario. Refer to Appendix A for additional diagrams and scenarios.

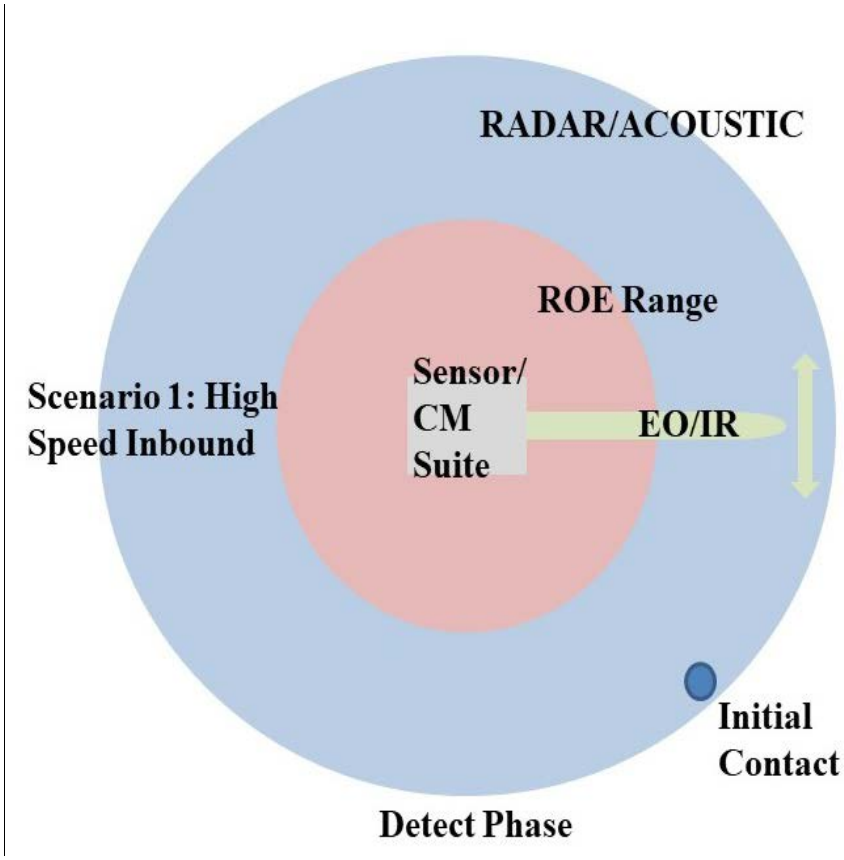

Figure 6. Detect Phase in High-Speed Scenario

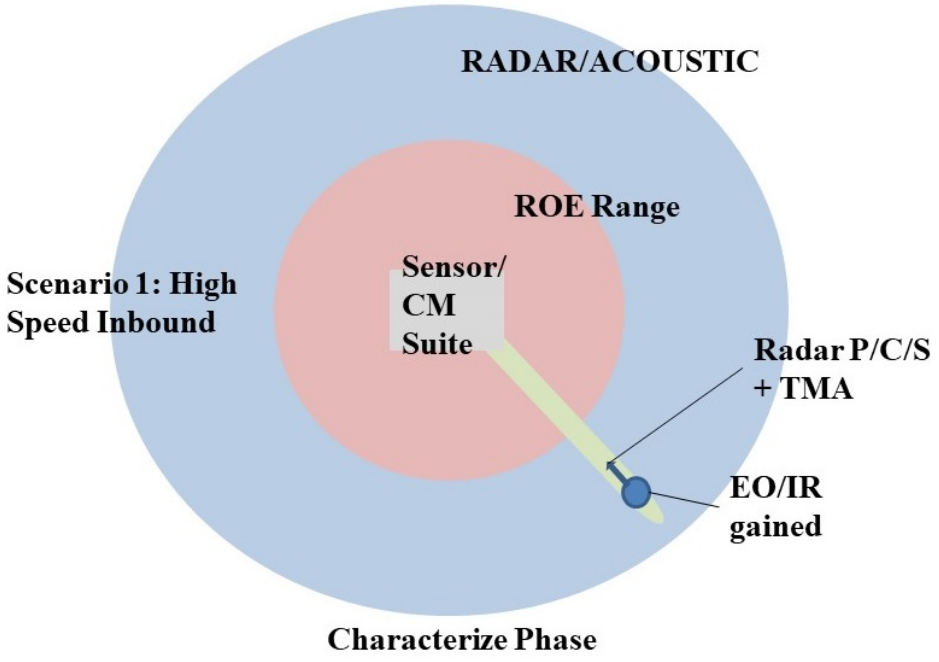

Figure 7. Characterize Phase in High-Speed Scenario

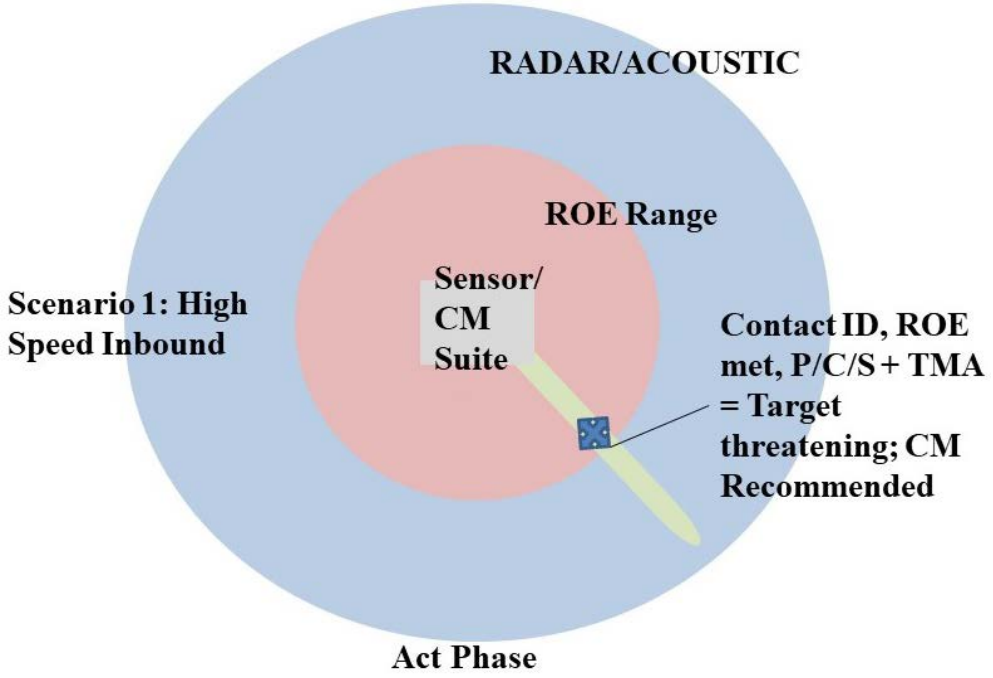

Figure 8. Act Phase in High-Speed Scenario

Depending on how many contacts are in the vicinity, the other sensors may not be available to assist the original detection sensor. It takes time to focus and collect target information with the other sensors, and if there are several contacts, there simply is not sufficient time. In this scenario, the DALP will recommend that the sensors continue to track with the target with the original sensor and allocate the other sensors to the highest threat contact it detects. The threat hierarchy is dictated primarily by closure speed of targets not determined to be friendly, and the DALP assigns the highest threat to whichever contact is on a flight profile that will overfly or crash within the defended perimeter. If there are multiple targets inbound, the DALP will look at whichever one is expected to impact first. If there are no non-friendly targets inbound, the DALP resorts back to utilizing any available sensors to characterize the contacts.

There may never be a 100% positive identification; however, the DALP analyzes and makes recommendations at any point from the initial detection until the target is destroyed, dropped, or has moved out of range of the sensors. The choice to utilize countermeasures is dictated by the ROE, which will vary in how restrictive it may be from location to location. For example, at one location, it may be dictated that the countermeasures shall not be employed until the threat is within one nautical mile (nm) or much closer. In these cases, the underlying decision logic process remains unchanged, but the ROE directed standoff ranges can be updated by the operator through a configurable mission file.

The benefit of the DALP is the ability for an operator to reach the correct decision repeatedly, consistently, and reliably when faced with a dynamic and stressful situation. Moreover, this process aims to reduce operator workload, prevent task saturation, and avoid incorrect decisions. The DALP uses available fused sensor and countermeasure data to analyze and provide recommendations to the operator for decisions in the C-UAS environment.

C. THREAT ANALYSIS

UAS attacks have occurred almost daily over the last year or so. Unmanned aerial system use was estimated at 10 to 15 per day in Islamic State in Iraq and Syria (ISIS)

occupied Mosul but has declined to almost none once allied forces re-established their presence in Mosul (Moore 2017). This is indicative of the intent of ISIS to place more and more reliance on inexpensive UASs as their financial resources are dwindling. Research has revealed the use of both fixed wing and quadcopter style UASs. Weapons delivery methods include the dropping of grenades or other small munitions and a less frequent deceptive tactic of hiding explosives in UAS sub-systems and detonating when they are dismantled, presumably by the enemy. It is expected that ISIS will refine and expand the fly-in and drop technique, but the hiding of explosives may not become an effective tactic (Rassler 2017). The expected style of attack is either a direct impact by the UAS or the UAS maneuvering into a position close enough to drop a weapon. Both expected attack styles require the UAS to be very close. This will be assumed for simulation and analysis purposes.

Captured ISIS documents indicate plans to use fixed wing SkyHunter, Figure 9, and X8 Skywalker UASs, Figure 10, for attack missions (Rassler 2017). The SkyHunter can function up to five miles from radio controller. The X8 Skywalker long range surveillance UAS can function up to 30 miles from radio controller and has a three-hour endurance limit on a single charge. It can also carry a payload of 6.6 pounds. One blog indicated that a recent 62-mile flight was accomplished as identified on the website Conservation Drones (2016). UAS capabilities in terms of endurance, range, and payload are certain to increase significantly in the near future and will be exploited. In general, current mass-produced UASs can reach velocities near 70 MPH and altitudes approaching 10,500 feet with several allowing image transmissions to multiple handheld devices such as iPhones or tablets. Newer quadcopters are capable of 360-degree 4k video output. Operating ranges from radio controller vary depending on equipment, but the mass-produced varieties seem to be about one mile.

Figure 9. Skyhunter Personal UAS. Source: Skyhunter (n.d.).

Figure 10. Skywalker X9 Personal UAS. Source: Skywalker (n.d.).

Quadcopters are known to be in use by both ISIS and Hezbollah. Some are very similar to DJI Phantoms and have been outfitted with a release mechanism to strategically drop explosives. Terrorists are using social media to encourage “Jihadists” to use inexpensive UASs to cause damage wherever people are gathering. The threat to highly populated venues such as sporting events, concerts, and tourist interests are among the most worrisome and hardest to counter. The risk level of collateral damage plays a significant role in the choice of deployable counter weapons.

Threat analysis research produced a huge amount of data for a variety of Group one UASs. The available data includes UAS range, endurance, speed, altitude, and payload as well as UAS weight and the required communications frequencies. Other key pieces of data researched was radar cross section (RCS) and size and performance data (Alexander 2016). RCS data for three of the four A/C used for the man portable airborne radar system (MARS) testing was also made available. RCS at range data for both the man portable airborne radar system kit (MARS-K) and 2026B as well as the Blighter A400 Series surveillance system yielded useful data also. The available data will be used to determine the boundaries for the assumed threats. The assumed UAS threat will consist of random motion, linear direct incoming motion, variable altitude, and single as well as swarm attack scenarios. Table 4 summarizes the capabilities and limitations of the expected UASs to be used.

Table 4. Capabilities and Limitations of UASs. Sources: DJI (2016, 2017a-e), Marcus (2016), Turbo Ace (n.d), Parrot (2017), and Yuneec (2017).

Group One UASs	Range (miles)	Endurance (minutes)	Max Speed (mph)	Max Altitude (feet)	Max Payload (lbs)	Comm Frequencies (GHz)
DJI Phantom 3 Professional	1.24	23	35.7	19,600	2.8	2.4
DJI Phantom 3 Advanced	1.24	23	35.7	19,600	2.8	2.483
DJI Phantom 4	3.1	28	44.7	19,600	3	2.4
Marcus Zypher 2	25	60	90	10,000	5	900
Parrot AR 2.0	1.55	12	24.6	300	0.9	2.4
Turbo Ace X830-D	1.24	25	44.7	19,600	2.4	2.4
MicroPilot MP-Vision Glider	1.55	55	37.2	10,000	6	2.4
Lehmann LA 300	15.5	45	49.7	11,000	1.6	N/A
DJI Inspire 1	1.24	18	49.2	14,700	6.5	5.725 – 5.825 or 2.4 – 2.483
DJI MATRICE 100	3.1	40	49.2	19,600	5.2	5.725 – 5.825 or 2.4 – 2.483
DJI Phantom 3 Standard	0.62	25	35.7	19,600	2.7	5.725 – 5.825 or 2.4 – 2.483

D. SENSOR ANALYSIS

Radar, acoustic, EO/IR, and ESM sensors are commonly used to detect UASs and are the anticipated sensors used in the C-UAS DALP. Each sensor has capabilities and limitations depending on the environment and target characteristics such as size, radar cross section, speed, emissions, communication links, propulsion methods, maneuvering capabilities, and other characteristics. Each of these sensor types could be employed to enhance the ability of the DALP to perform its intended function. A summary of each sensor type for UAS detection and identification is provided. The specific UAS

parameters used in the DALP to add fidelity to identification and threat characterization efforts include but may not be limited to range, bearing, velocity, system type and model, motion, size, control and communication requirements, auditory, and heat signatures.

Recent MARS testing indicted a detection range for flying vehicles with similar RCS as group one UASs is on the order of 1.86 miles. Elevation of the tested system has a 60-degree limit, so altitude of incoming UAS is very relevant. The possibility exists that if a UAS could reach an altitude beyond the capability of radar and do so undetected, it could potentially fly to any target inside that envelope. The detectable velocity for the same RCS is 44.7—89.5 miles per hour (MPH). Table 5 summarizes the MARS capabilities and limitations collected from test results (ELAT 2016). The modeling and simulation efforts did not account for altitude as all simulations were 2-dimensional only.

Table 5. MARS Test Results. Source: ELTA (2016).

#	Test: System tested (If Applicable)	Result
1	Max. Detection Range:	
	DJI Hexacopter S-900	1.49 – 1.74 miles
	DJI Quadcopter Phantom	1.06 – 1.12 miles
	Cessna 152	3.91 – 4.04 miles
	Model Plane	1.73 – 1.99 miles
2	Elevation Coverage	up to 60deg
3	Azimuth Coverage	360
4	Azimuth Accuracy	<1 deg
5	Range Accuracy	<10 m
6	Elevation Accuracy	<0.5 degree
7	Target Velocity:	
	DJI Hexacopter S-900	13.4 – 33.6 MPH
	DJI Quadcopter Phantom	13.4 – 33.6 MPH

#	Test: System tested (If Applicable)	Result
	Cessna 152	89.5 – 134.2 MPH
	Model Plane	44.7 – 89.5 MPH

Acoustic detection and identification systems provide complete spherical coverage, though the maximum range is highly affected by ambient noise levels and obstructions. Typically, a conical dish funnels sound into a microphone to concentrate distant sound and block out ambient noise. Even with a conical dish, the nominal distance for detection and/or identification is in the order of hundreds of yards so this sensor may be limited to short ranges. However, since each UAS emits a unique audible signature that can be cataloged and stored in libraries of UAS models, a distinct advantage of acoustic sensors is the capability to make positive identification possible within just fractions of a second of detected audio. In addition, multiple microphone systems are very effective at pinpointing a range and bearing to the source. Therefore, acoustic sensors are better suited as a secondary sensor that provides additional classification capabilities and amplifying information (Lockheed Martin 2016).

Infrared systems detect heat sources such as jet engines, ground vehicles, and personnel. Some handheld devices state the ability to detect a person out to 1.55 miles. Electric Class I & II UASs do emit a heat signature, though much smaller than internal combustion engines. The Talon 120LE (Class I UAS), for example, can be tracked with a 90% confidence out to approximately 2.17 miles with the Spynel-C IR System. Table 6 summarizes data relating IR systems versus UASs (Shen 2016).

Table 6. IR Systems Max Trackable Range. Source: Shen (2016).

IR System	UAS	% Tracked at Range	Range (miles)
Spynel-C	Talon 120LE (Class I)	89%	2.17
Spynel-S	Talon 120LE (Class I)	82%	0.93
L-3 360HD	Talon 120LE (Class I)	100%	0.31
NVESD 360HD	DJI Phantom Octocopter (Class I)		0.48
NVESD 360HD	Surrey (Class I)		0.80

Optical cameras record an image containing a known number of pixels, with higher-fidelity, military-grade cameras recording the most pixels per picture. Those pixels relate to a specific area of the picture that is directly related to the distance of the object from the sensor. For example, a near field object may have a pixel height in the realm of tenths of an inch. However, a far field object may have a pixel height about a foot. Class I and II UASs are typically less than two feet tall. At multiple-mile distances, the entire UAS may be enveloped within five to eight pixels, which would be difficult to distinguish from background clutter. The camera capability must be matched to and is a function of software that can identify between specific shapes and movements (Jesse Drake, NAVAIR 4.73 Photography Lead, personal communications, October 11, 2017).

E. COUNTERMEASURE ANALYSIS

The DALP will use the inputs from the sensor systems to determine the most logical and effective UAS countermeasure to use to mitigate the threat. There are many different types of countermeasures used today by civilians, police, and military forces. Each type of countermeasure has distinct advantages and disadvantages.

Electronic countermeasures (ECM) are a popular choice for C-UAS efforts as they do not include any physical or kinetic components. ECM is used to “prevent the

successful reception or transmission of data. This may mean simple narrowband jamming (denying the platform the use of the jamming spectrum) or more sophisticated approaches" (Birch, Griffin, and Erdman 2015, 19). Global positioning systems (GPS) used by UASs can be jammed or "spoofed" to make the UAS believe it is in a different location or to force it to move away from its intended target. High-power microwaves (HPM) and high-power electromagnetic weapons (HPEW) are non-kinetic but can cause physical destruction of the UAS's unprotected electronics. Jamming is likely to be used in scenarios where kinetic countermeasures are not a viable option, like crowded public areas. Legacy jamming systems are typically ground based and used for manned aircraft or missile defenses. A jamming system specifically designed for C-UAS applications is the Battelle Drone Defender shown in Figure 11. This is a handheld, highly portable line-of-sight jammer that is well suited for highly populated, public events where law enforcement officers require mobility. The Drone Defender is an attachment for compatible rifles that adds the capability to jam GPS and industrial, scientific, and medical (Industrial, Scientific, and Medical (ISM) band) communication signals.

Figure 11. Battelle Drone Defender. Source: Battelle (2017).

Kinetic countermeasures (such as missiles and guns) are most commonly used in military scenarios where use of deadly force is necessary. Since guided missiles often use Command Line of Sight (CLOS) systems that "require that the system track both the target and the missile," line of sight is a necessary limitation that is a detractor against adopting CLOS systems (Birch, Griffin, and Erdman 2015, 17). "Dumb" weapons, such as machine guns, cannons, and small caliber guns, can also be used as a kinetic countermeasure to bring down a UAS if necessary. However, they are ineffective and inaccurate at long range, and multiple rounds would need to be expended to be an effective countermeasure.

Net systems are becoming more popular for use in urban environments where it could be dangerous for the UAS to become unpredictable and fly out of control and into a densely populated area following a kinetic or jamming engagement. One downside of choosing a net capturing system is that the effective weapon range is relatively limited. There are a few different deployment options for nets as projectiles. The net can be deployed from a ground-based autonomous or human operated system or by another UAS. Net systems are typically a single net per shot and require a manual reload to deploy another net. This significantly hinders its effectiveness against a swarm attack. There are advanced systems that may be more effective, such as the SkyWall 100 anti-UAS gun, which uses a net with embedded ECM capability. Another example is the Michigan Tech Drone Catcher, shown in Figure 12, that uses a UAS that can fire a net and drag another UAS to a safe location (Atherton 2016).

Figure 12. Michigan Tech Drone Catcher. Source: Atherton (2016).

The final countermeasure type identified during research are line-of-sight lasers. Similar to ECM systems, lasers can harm or disrupt electronics by overwhelming EO/IR sensors on the UAS with a low-powered laser. However, there are disadvantages with line-of-sight laser use. Higher power lasers can permanently destroy the sensors and other onboard electronics but do so at an increased risk of collateral damage. Laser effectiveness is influenced by the UAS physical properties and inherent vulnerabilities. Furthermore, they require line of sight and tend to be expensive. The primary advantage, though, is that lasers have longer ranges and higher accuracy than net-based or kinetic countermeasures

In summary, the four viable and available countermeasures chosen for use in the C-UAS DALP capstone are jammers, kinetic weapons, net guns, and lasers. Jamming is useful for short to long-range scenarios where the use of kinetic weapons is not permitted. Kinetic and laser weapons, when authorized and available, are useful for line-of-sight engagements where it is acceptable for the UAS to crash in the vicinity of engagement. Lasers typically have longer range than kinetic weapons. Net guns are useful if a controlled or contained descent is desired but have short ranges and are vulnerable to swarm attacks.

F. C-UAS KILL CHAIN LOGIC

The DALP will function in the space defined by enemy UASs being detected and characterized by sensor technologies and the decision to engage with appropriate weapons. The kill chain design for this project will end at the point where the C-UAS DALP provides a suitable response recommendation based on sensor data indicating target threat and the available weapons capabilities. The C-UAS kill chain design will utilize currently available sensor technology outputs to establish an incoming threat detection capabilities window. Figure 13 and Figure 14 depict notional sensors and countermeasures interacting with the DALP and working through C-UAS kill chain logic. The alerts and display layouts used are for illustrative purposes and have not been optimized based on human-machine interface considerations.

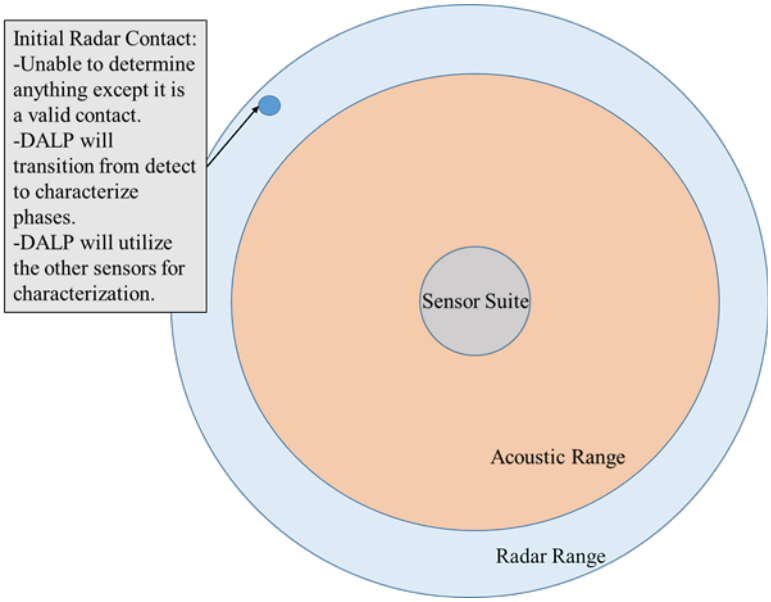

Figure 13. Detect Phase of C-UAS Kill Chain Logic

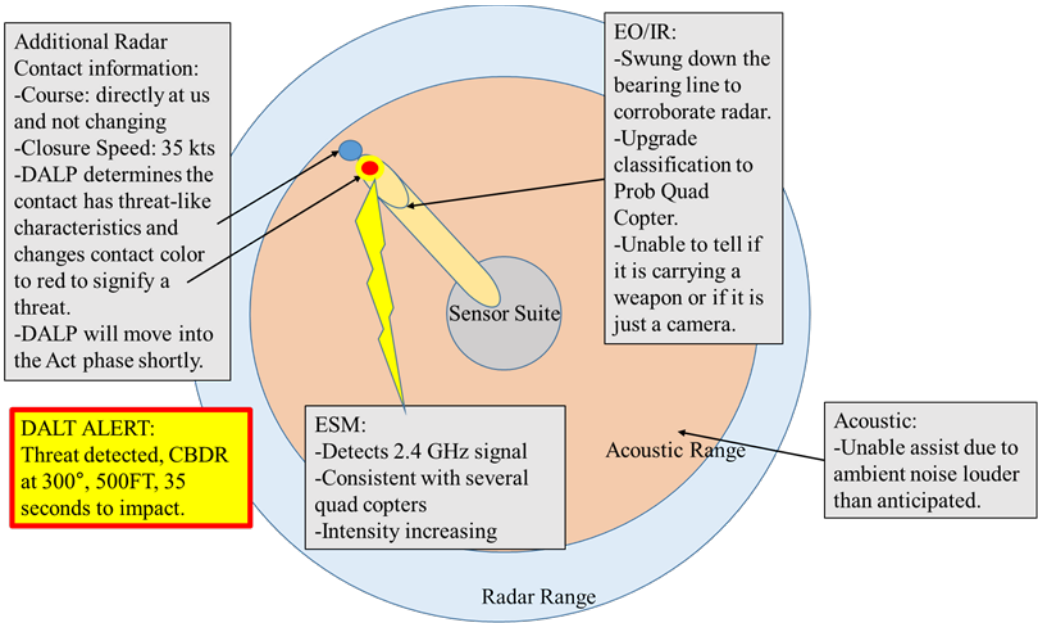

Figure 14. Characterization Phase of C-UAS Kill Chain Logic

The kill chain begins during the detect phase (Figure 13) with a valid sensor contact (i.e., radar indication of an unknown airborne object). The sensors detect the contact and sends it to the DFT to fuse and relay the data. The DALP and operator receive the fused data and transition to the characterization phase (Figure 14). The DALP attempts to identify the UAS based on ESM, acoustic, EO/IR, radar, and IFF sensor data provided by the DFT. The intent is to observe target characteristics that determine whether the contact is a friend, neutral, or enemy threat. The DALP accomplishes this by observing the target's position, course, speed, if it is closing or opening, sound profile, emitter data, and if it is traveling with a swarm. Once the DALP is able to make a threat determination, it transitions to the action phase (Figure 15). The DALP will recommend attacking, continue monitoring, or dropping the track (Figure 16), thereby completing the kill chain. If it is recommending an attack, it will also recommend a countermeasure selection and employment characteristics (Figure 15). Recommendations and alerts that result from the execution of the decision-aid logic process are outputted from the DALT and sent to the DFT for display to the operator.

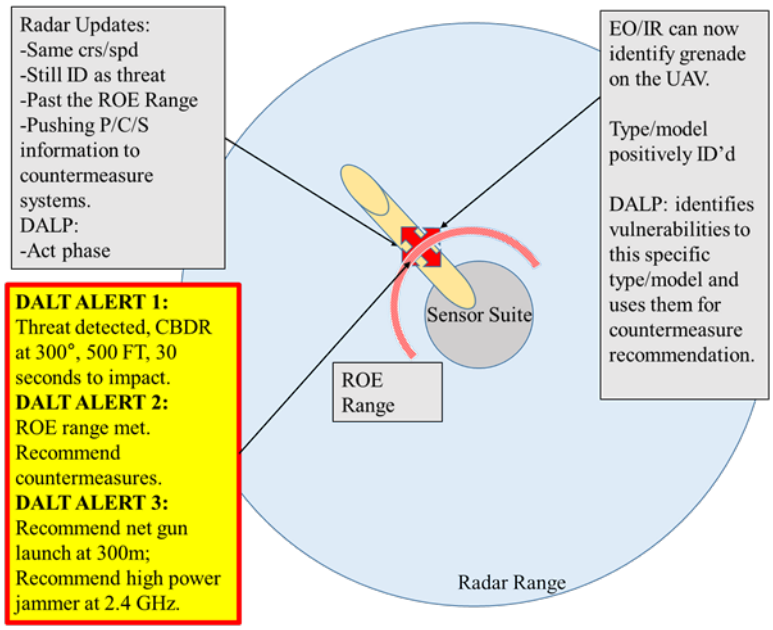

Figure 15. Act Phase of C-UAS Kill Chain Logic

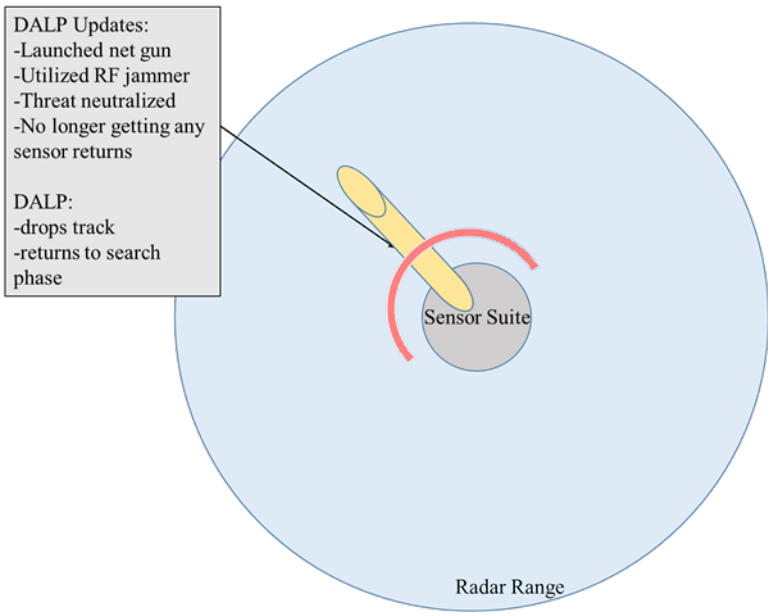

Figure 16. Drop Track and Return to Detect Phase of the C-UAS Kill Chain Logic

The window of opportunity to neutralize threats is dynamic. It shrinks as a threat approaches, dependent on the UASs' speed. It is also affected by weapon choice in that each neutralization choice has capabilities and limitations such as minimum and

maximum ranges, intercept speeds, employment envelopes, time to intercept, max flight time, reloading time, and time required to arm. The reaction window is further limited by the time it takes for the operator to decide and then to act. The intent of the DALP is to make the human decision-making process as simple as an authorization after the DALP has determined the incoming UAS is a threat and recommended an engagement. The operator only needs to verify ROE and collateral damage mitigation and then execute the engagement.

G. KILL CHAIN CAPABILITY GAP

A primary capability gap in the kill chain is the lack of a decision-aid logic process. This process would allow an operator to reliably and repeatedly assess available data in order to assess threats correctly and quickly, and then respond with the appropriate countermeasures. Moreover, the stakeholders have also indicated operators get overwhelmed when there are large amounts of contacts, and they lose their tactical situational awareness resulting in decreased kill chain effectiveness and increased vulnerability.

H. SUMMARY

A broad range of small unmanned air system threats exist and are in use today. Countering those threats are challenging based on current sensor capabilities and UAS characteristics. A decision-aid logic process will aid an operator in the process of characterizing and defeating UAS threats. This DALP may also form the basis for an automated logic that can be used by an operator to defeat a large swarm or saturation type UAS attack. The next section of this report will refine the threat and define requirements for a decision-aid logic process.

The key concept refinement takeaways:

- There are plenty of sensors and sensor and countermeasure options, but they typically operate in isolation and would benefit if they were integrated.

- There is a need for decision-aid and data fusion capability in the middle of the kill chain.
- The logic structure does not change due to varying target data or rules of engagement.
- The quantity and quality of the information provided by the sensors will dictate when and what the DALP recommends.
- The DALP does not currently have the autonomy to attack, but rather gives the recommendation to attack when it detects a threat.
- It is up to the human operator authorize the engagement.
- There are user configurable parameters that the DALP will alert the operator for if any of those parameter thresholds are met.
- The initial recommended parameters set is closure speed, minimum anticipated closest point of approach, range, and swarm characteristics, which are covered by the DALP logic.

The capability gap analysis resulted in the following determinations:

- The DALP will use target data from the DFT and countermeasure data to provide alerts and engagement recommendations to the operator.
- DALP will reduce the operator's workload, chance of being overwhelmed, and chance for error.
- DALP will improve combat effectiveness and reduce vulnerability to single or swarm UAS attacks.
- DALP will effectively address the middle of the kill chain and the orient and decide portion of the OODA loop.

- DALP will reliably, repeatedly, consistently, and correctly recommend a choice for the operator in all phases of C-UAS.
- DALP will be accurately modeled to provide important data for follow-on research.

III. FUNCTIONAL ANALYSIS

The kill chain sequence consists of the detect, characterize, and act functions. These functions can be allocated to the five primary sub-systems—sensors, DFT, DALT, countermeasures, and operator. The following sub-system's functions, interfaces, inputs, outputs, and interactions were identified and used to form the architecture:

- Sensor(s): might be radar, EO/IR, ESM, acoustic.
- DFT: combines sensor inputs and is the primary interface between the operator, DALT, and sensors.
- Operator(s) and DALT: attempt to determine target identification and assess threat.
- Countermeasures: could include kinetic, soft-kill, net.

These sub-systems will be used to define and allocate the functions of the detect-to-engage sequence. The DALT is intended to aid the operator in the execution of their functions, and therefore an accurate understanding of operator functions is needed to define the requirements for the DALT. In the list of functions, the DALT and operator are listed as the same sub-system based on the presumed commonality and overlap of their functions. In the next section, the DALT and operator will be assessed independently to confirm what functions may be performed by each sub-system.

A. DETECT TO ENGAGE FUNCTIONS

The functional allocation is decomposed into five main actors—sensors, DFT, countermeasures, operator, and the DALT. Note, the decision-aid logic process is intended to reduce the workload of the operator and therefore shares many of the same functions as the operator. As a result, the DALT shall be designed to perform as many of the functions allocated to the human operator as possible. Table 7 summarizes the sub-system functions.

Table 7. Sub-system Functions

Nomenclature	Function	Quantity
Sensors (Multiple) **Radar** **EO/IR** **ESM** **Acoustic** **Camera**	**Detect Targets** (ESM, acoustic, Doppler, ISAR characteristics as a bearing or range) **Track Targets** (position, course, speed, altitude, and azimuth) **Transmit Data** to Data Fusion Tool (DFT) **Process Commands from DFT** (sensor mode, sensor scale, sensor sensitivities, threat library inquiries)	Multiple
Data Fusion Tool (DFT)	**Receive Sensor Data** **Correlate Sensor Data** (track data from multiple sensors) **Resolve Ambiguity** (in sensor data) **Display Target Track Data** **Receive Countermeasures Health/Stores Status** **Display Countermeasures Health/Stores Status** **Control Sensors** (sensor mode, sensor scale, sensor sensitivities, threat library inquiries) **Transmit Data** to DALT and countermeasures (position, course, speed, altitude, azimuth, ESM, acoustic, Doppler, ISARE characteristics) **Process Operator Commands via the DALT**(sensor mode, sensor scale, sensor sensitivities, threat library inquiries)	1
Countermeasures (kinetic, soft-kill, net, etc.)	**Process DFT Target Data** (position, course, speed, altitude, and azimuth) **Transmit Health/Stores Status to DALT** (BIT, Stores Inventory, Stores State, Countermeasures Mode (manual, automatic, on, off, standby) **Process Operator Commands** via the DALT (query stores status, track target, launch stores) **Engage Target**	Multiple

Nomenclature	Function	Quantity
Operator	**Monitor DFT Target Tracks** **Command Sensors via DFT** **Characterize Target** • Assess Target Signature • Conduct Target Motion Analysis • Evaluate Threat • Classify Target • Identify Target **Report Target Tracks** (position, course, speed, altitude/azimuth, and track identification, track behavior) **Apply Rules of Engagement** (based on mission, target behavior and signature, environment, population, etc.) **Select Countermeasure** (based on target motion, stores status, ROE, collateral damage assessment) **<u>Make Decision</u>** • Monitor • Drop Track • Release Countermeasures	1
Decision-aid Logic Process and Tool	**Monitor DFT Target Tracks** **Command Sensors** via the DFT **Characterize Target** • Assess Target Signature • Conduct Target Motion Analysis • Evaluate Threat • Classify Target • Identify Target **Prioritize Target** **Report Target Tracks** (position, course, speed, altitude/azimuth, and track identification, track behavior) **Apply Rules of Engagement** (based on mission, target behavior and signature, environment, population, etc.) **Recommend Countermeasure Pairing** (based on target motion, stores status, ROE, collateral damage assessment) **<u>Recommend Decision to operator</u>** • Monitor • Drop Track • Release Countermeasures	1

B. FUNCTIONAL ARCHITECTURE

The functional architecture was used to depict, analyze, and provide feedback on the inputs, outputs, functions, interfaces, and data flow. Four IDEF0 diagrams were used to depict the functional architecture of the kill chain sequence and illustrate the role of DALT. These various levels of decomposition show the functional interactions, inputs, and outputs between the five sub-systems: operator, sensors, DFT, DALT, and countermeasures. It should be noted that in this architecture the DFT will serve as the primary interface between the DALT and the operator, as well as, the DALT and the sensors.

The detect, characterize, and act functions of the kill chain were allocated to the components. The sensors and DFT perform the detect functions, which includes the target detection and data fusion. The DALT performs the characterize function. The DALT, operator, and countermeasures perform the act function. The DALT makes the recommendations, the operator authorizes launches, and the countermeasures perform the launch.

Figure 17 represents the top-level interactions of the main components that form the kill chain sequence. This diagram depicts the flow of data and commands that are passed between the functions. Note, the italics in this section represent the inputs, outputs, controls, and corresponding information flow depicted in the IDEF0s. For instance, *Sensor Stimuli* is detected by a sensor and passed on to the fuse function performed by the DFT as *Sensor Data*. The *Fused Sensor Data* is an input to the analyze and recommend function of the DALT and is the information needed to execute the decision logic. The DALT analyzes target behavior, makes recommendations, and generates alerts. These *Alerts* and *Recommendations* are sent back to the DFT as an input that is in turn relayed to the operator as a *Video and Sound Output*. In its current implementation, the DALT can only recommend an attack. The operator is required to provide an *attack authorization* to execute the attack function. This is based on critical nature of the attack function and the need for the operator to confirm ROE prior to countermeasures employment.

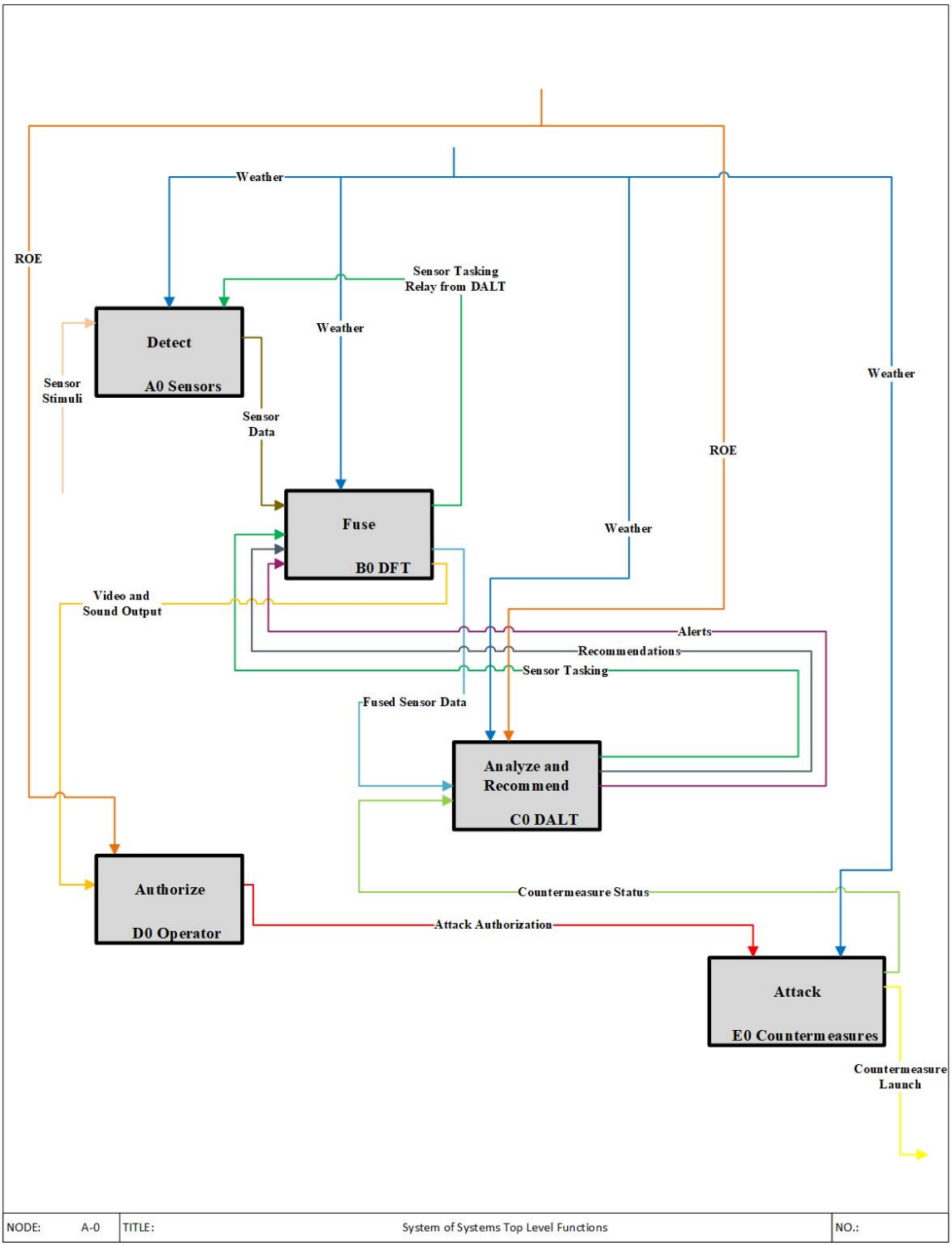

Figure 17. Top-Level Kill Chain IDEF0

The next IDEF0 in Figure 18 decomposes the top-level functions of the DALT. *Fused Sensor Data* enters the characterize function where it analyzes and outputs *Characterized Data*. This is forwarded to the act function where the DALT is computing *Alerts* and *Recommendations* based off the *Characterized Data*. The characterize phase also has a *Sensor Tasking* output that is ultimately relayed through the DFT to the sensors for its autonomous control.

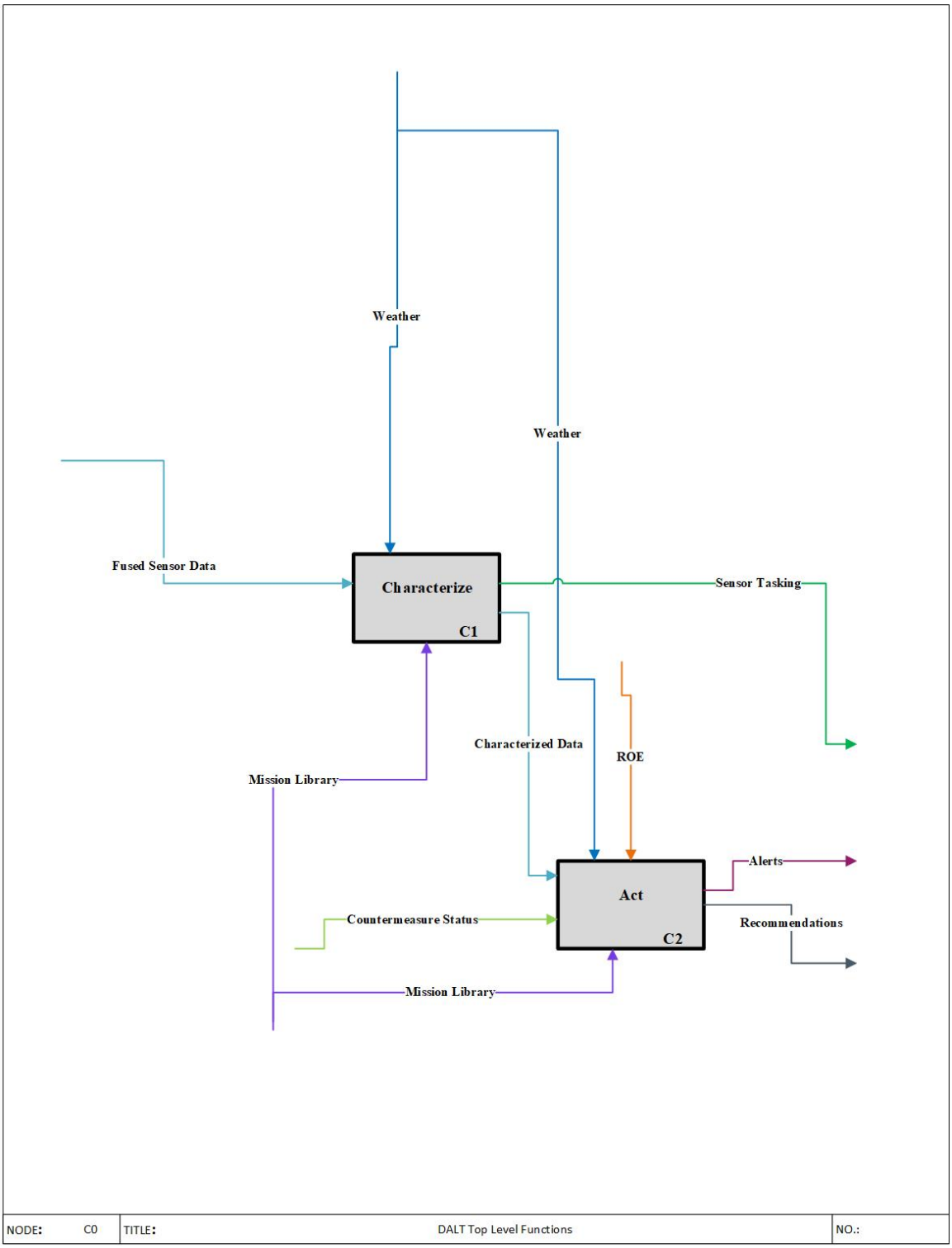

Figure 18. DALT Top-Level Functions IDEF0

Each of the two main functions that comprise the DALT is decomposed in the final two diagrams. The characterize phase shown in Figure 19 is where the DALT begins to use the decision logic to analyze the sensor data and make determinations in classification and threat. The Fused Sensor Data is continuously forwarded to the perform TMA, classify, and determine threat sub-functions. Target motion analysis is used as one of the primary means of determining threat level. It is a simple determination—the faster a contact is approaching or the more direct of an impact course, the higher the threat level determination.

The classify function is determining what the contact is and its associated confidence. This is completely dependent on the fidelity of the sensor data inputs, and as such, classify function generates Sensor Tasking requests to get more information. The prioritize function takes in Threat Data and Sensor Tasking requests and establishes a hierarchy. In concept, the contact that will impact the earliest will likely get the highest priority. The prioritize function uses this hierarchy to update the Sensor Tasking to ensure sensor data is collected on the highest priority contact.

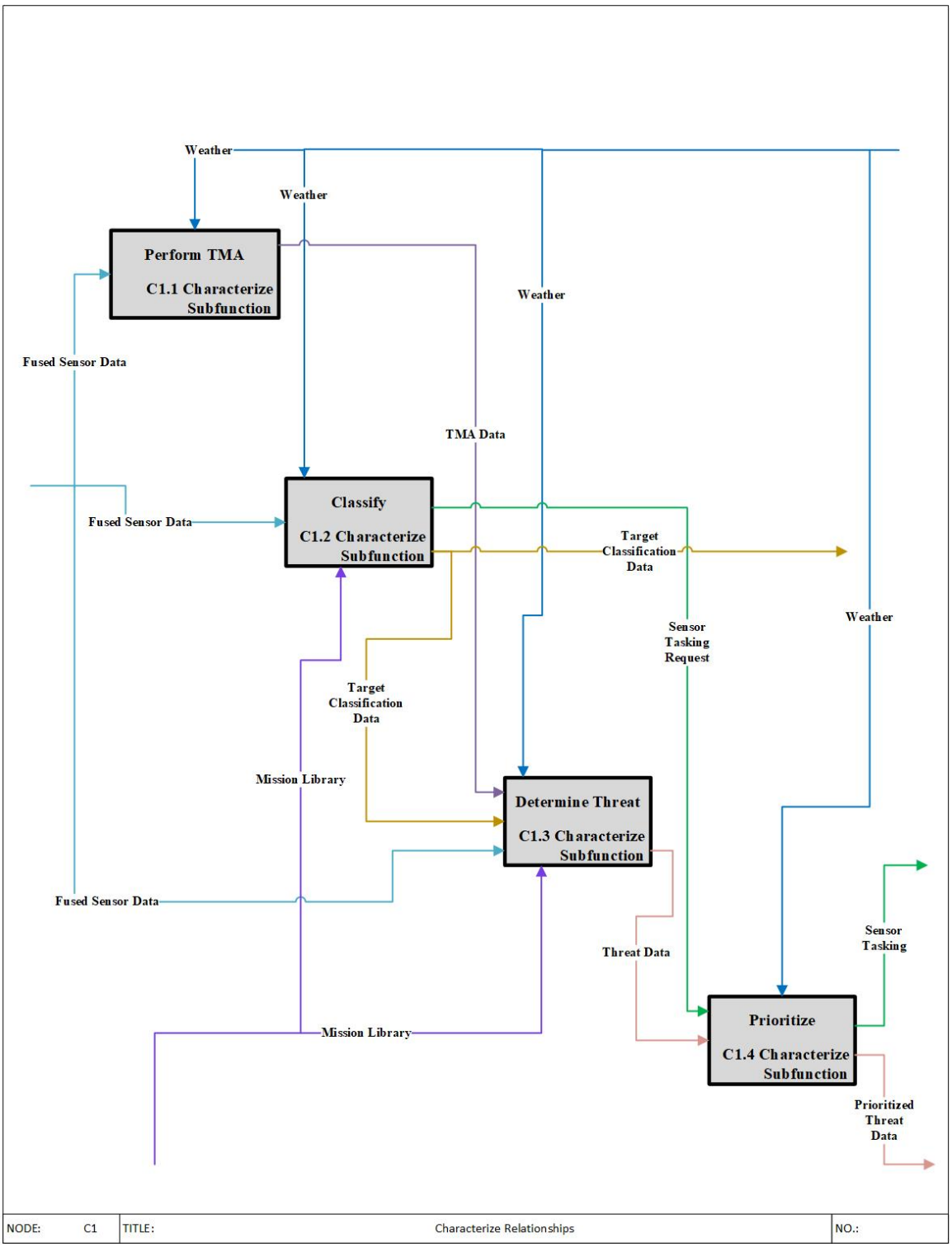

Figure 19. C1 Characterize IDEF0

The last IDEF0 in Figure 20 decomposes the act function. In order to make an accurate *Recommendations* and *Alerts*, the functions need *Countermeasure Status*, system *Health/Stores Status*, *Target Classification Data*, and *Threat Prioritization*. ROE governs the recommend actions sub-function. The DALT utilizing the decision logic will still determine the best countermeasure pairing and deployment recommendations, but it will not recommend an attack until it determines ROE is satisfied. In concept, this most likely is at a specified range and that any unknown or enemy contact within it will get an attack recommendation.

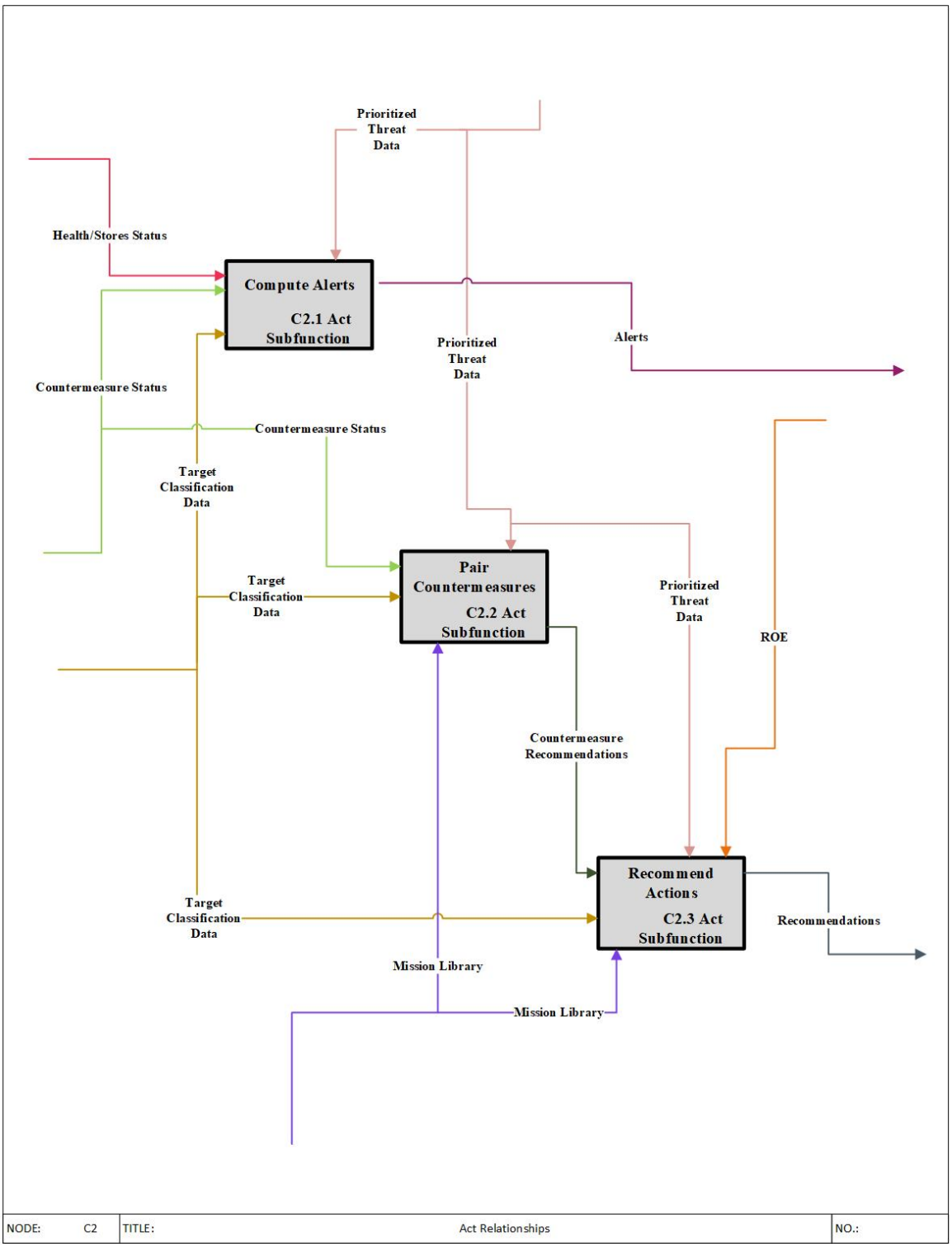

Figure 20. C2 Act IDEF0

C. DECISION-AID LOGIC ARCHITECTURE

The logic process that the DALT utilizes is the DALP. The functional architecture described the inputs, outputs, interactions, and interfaces of the DALT and peripheral systems. The decision-aid logic architecture describes the logic process that is utilized by the DALT to characterize targets and provide recommendations and alerts to the operator. The functional identification and CONOPS described in chapter two form the basis of the decision-aid logic process. The underlying logic process is a series of if-then statements that the DALP continuously cycles through to determine recommendations and other outputs. As the DALP receives information, it is attempting to determine both the classification and threat posture of the unknown contact to formulate weapons pairing, engagement, or other recommendations. Figure 21 depicts a top-level architectural view of the logic process.

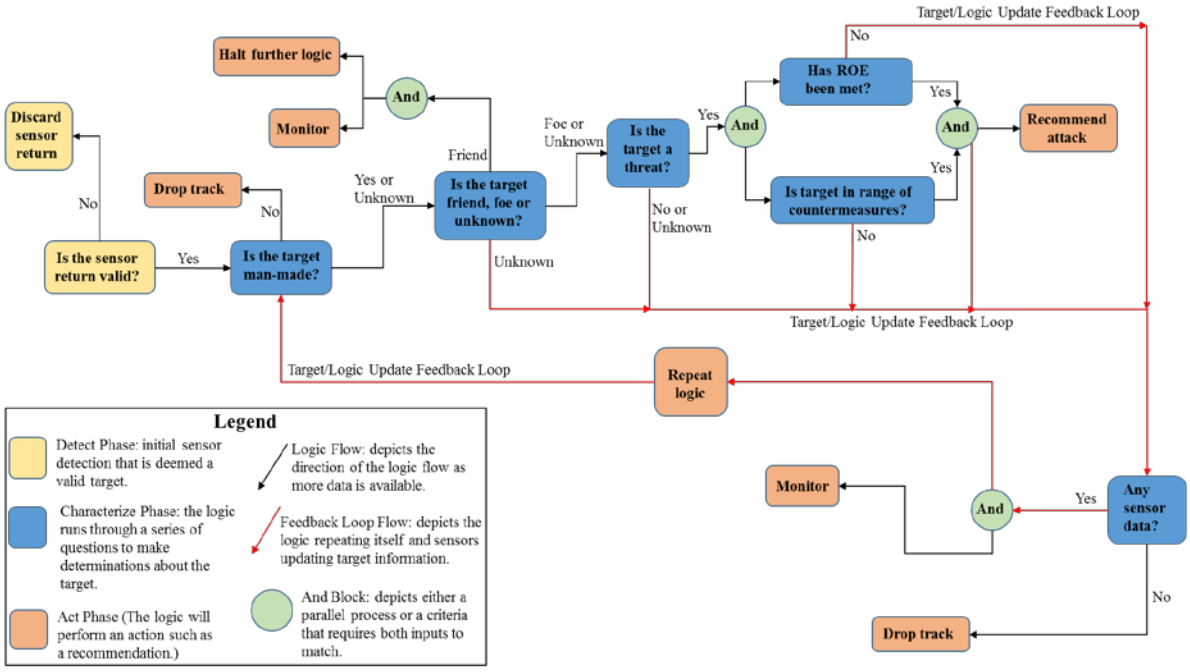

Figure 21. DALP Logic Architecture

D. DALP SYSTEM LOGIC

The DALP continuously runs through a series of questions, which are similar to the thought process that a human operator uses, as it attempts to classify and determine the threat posture. Figures 22 and 23 illustrate the series of questions the DALP is continuously asking to determine classification and threat, respectively. There are varying levels of certainty based off what type of sensor data is available. For instance, during the initial target detection, there is likely only a single sensor in contact with the target, and the DALP will only be able to determine there is an unknown airborne contact based on the limited initial sensor data. If the DALP successfully corroborates the contact with additional sensor data or sensor data from multiple sensors in contact with the target, the confidence in target type can potentially increase. Based off the additional sensor data, the DALP assesses that the target sensor data is consistent with a UAS and determines that the target is a possible UAS. Figure 23 behaves similarly, but it is determining the threat posture rather than the classification. Both of these processes are happening in parallel.

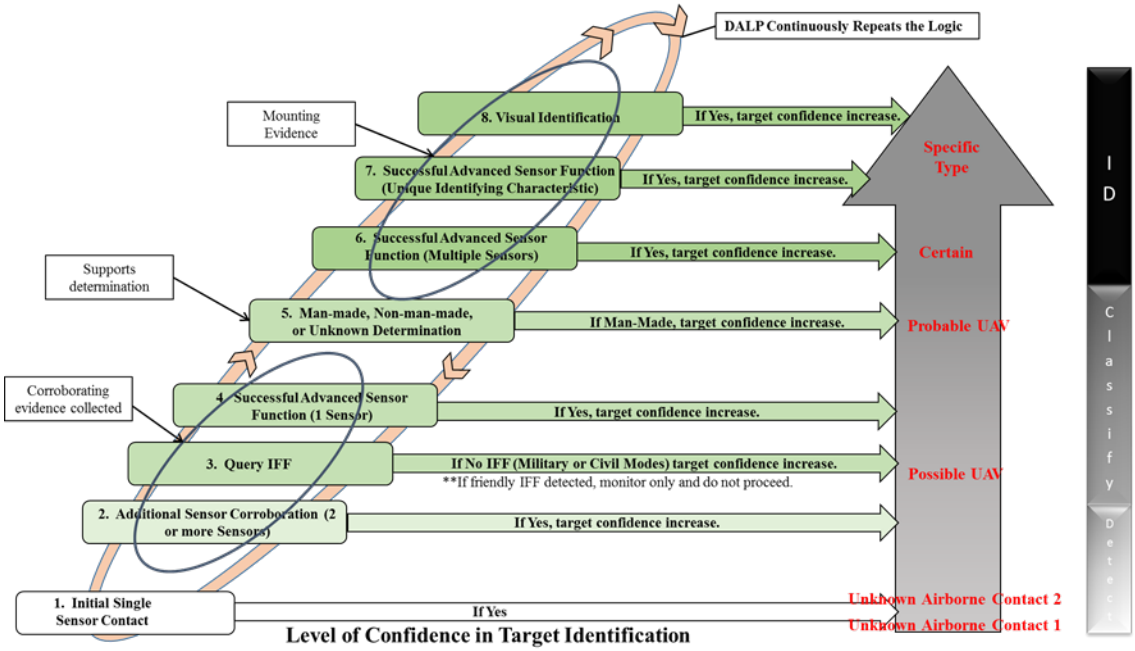

Figure 22. DALP Classification Behavior

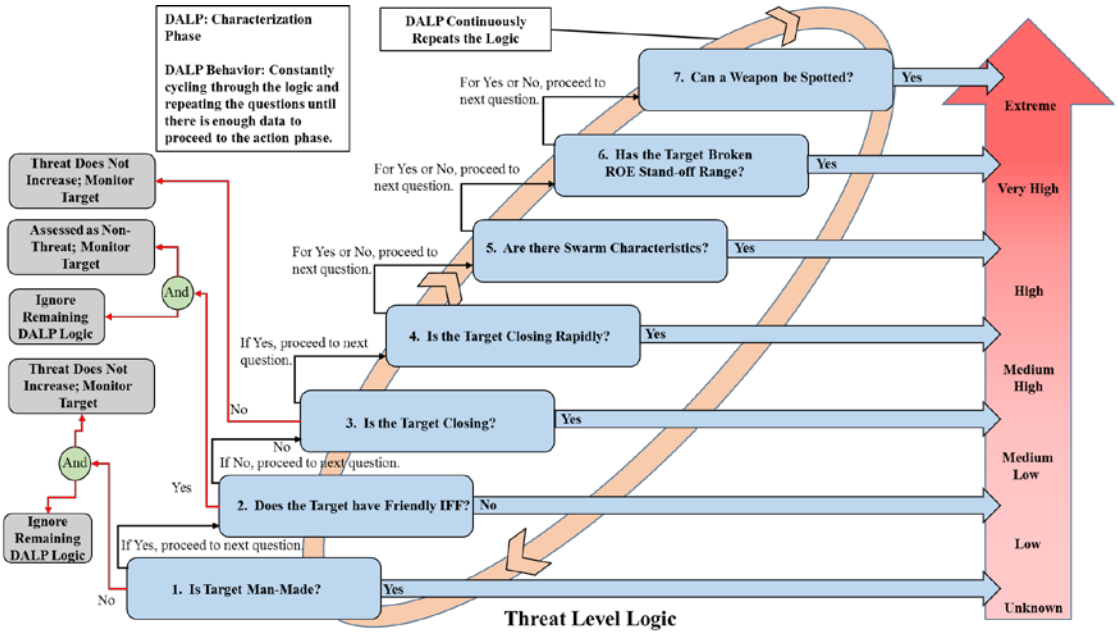

Figure 23. DALP Threat Determination Behavior

Table 8 describes the if-then logic the DALP uses to determine an engagement recommendation, optimal weapon pairing, countermeasures health status, and the risk of collateral damage. Note, the logic depicted in Figures 23 and 24 are resident in the engagement and weapons pairing logic. The input parameters are user configurable, which allows the operator to adjust for things such as collateral damage limits based on location specific factors and theater policies.

Table 8. Engagement, Weapon Pairing, Health, and Collateral Damage Logic

IF	THEN	RATIONALE

Engagement Logic:
 	
• **No Mode IV/V, and**
• **It is man-made and**
  o ***Method of determining if man-made:***
  ▪ **Track has ESM or acoustic return correlated with track, or**
  ▪ **Radar has valid ISAR return**
• **It is unmanned, and**
  o ***Method of determining if unmanned:***
  ▪ **Size is consistent with small UAS, or**
  ▪ **Acoustic signature is consistent with small UAS**
• **Track has crossed ROE boundary,**
  o ***ROE boundary defined as:***
  ▪ **3 dimensional boundary, cylindrical shape over FOB**
	Recommend paired weapon	This logic is attempting to use all the data available to the DALP to prevent a fratricide incident and recommend an engagement to the operator based on threat characteristics. The DALP is unable to visually observe the target and therefore not able to determine if the target is armed or make a VID. The operator still has the ability to attempt VID, and the logic could recommend that the operator attempt to VID.

IF	THEN	RATIONALE

Weapon Pairing Logic:
 	
• **Target is closing, and**
• **Not a FRIEND, and**
  o ***Method of determining if a friend:***
  ▪ **Receive valid Mode IV/V return**
• **Not NEUTRAL, and**
  o ***Method of determining if neutral:***
  ▪ **VID determination, has to be made by operator**
• **Target behavior**
  o **{[Target rate of closure (ROC) >** 100 MPH**] or [track course NOT steady (varies >** +/5 deg**)] } and [target range > =** .5 miles**] and [collateral damage = GOOD] and [missile health status and stores = GOOD]**
  ▪ **Recommend Pair Missile**
  o **{[Target rate of closure (ROC) <** 100 MPH**] or [track course IS steady (varies <** +/5 deg**)] } and [target range <** .5 miles**] and [collateral damage = GOOD] and [net health and Stores = GOOD]**
  ▪ **Recommend Pair Net**
  o **{[Target rate of closure (ROC) <** 100 MPH**] and [track course NOT steady (varies >** +/5 deg**)] and ESM detected} and [target range <** .5 miles**] and [collateral damage = GOOD] and [jammer health and Stores = GOOD]**
  ▪ **Recommend pair jammer**
	Pair weapon = _____	Weapon is paired based on factors that influence probability of hit based on target flight profile, collateral damage concerns, weapons health status information, and weapons stores inventory.
		
		NOTE:
		The values listed in **blue** need to be determined based on the target threat and ROE concerns. These values should be configurable based on a target threat.

IF	THEN	RATIONALE
Health Status Logic: • **Weapon not powered ON, or** • **BIT Failure or,** • **Stores count < 1**	Weapon health and stores logic = BAD	A weapon will not be recommended if it is not powered on, fully operational, and stores are NOT available.

Collateral Damage Logic:
 	
• **Weapon max range splash point not clear, or**
  o ***Method of determining:***
  ▪ **Configuration setting based on land use around base**
• **Friendly target <=** 500 yards **away, or**
• **Neutral track <=** 1000 yards **away, or**
• **Target debris field not clear** ***Method of determining:***
  o **Configuration setting based on land use around base**
  ▪ **Not a real-time assessment of splash point, based on known land use.**
	Collateral damage = BAD	Static collateral damage concerns can be entered based on where the system is deployed.
		
		The operator will have to make a real-time collateral damage assessment based on factors on the ground at that time. The DALP can make recommendations based on weapons characteristics and known land use. This data should be configurable based on system deployment locations.
		
		NOTE:
		The values listed in **blue** need to be determined based on the target threat and ROE concerns. These values should be configurable based on a target threat.

Figure 24 illustrates a notional FOB layout in relation to obstructions or collateral damage concerns. The user can input the locations of buildings, obstructions, or other sensitive areas identified in theater specific policies. In turn, when the DALP identifies a

collateral damage issue, the DALT displays the location and alerts the operator if the countermeasure engagement has collateral damage risks. However, these are just alerts and the operator has the final authority. In this notional example, the DALT is generating an alert for the operator that identifies the collateral damage concerns due to a school and populated building in the vicinity of a potential target.

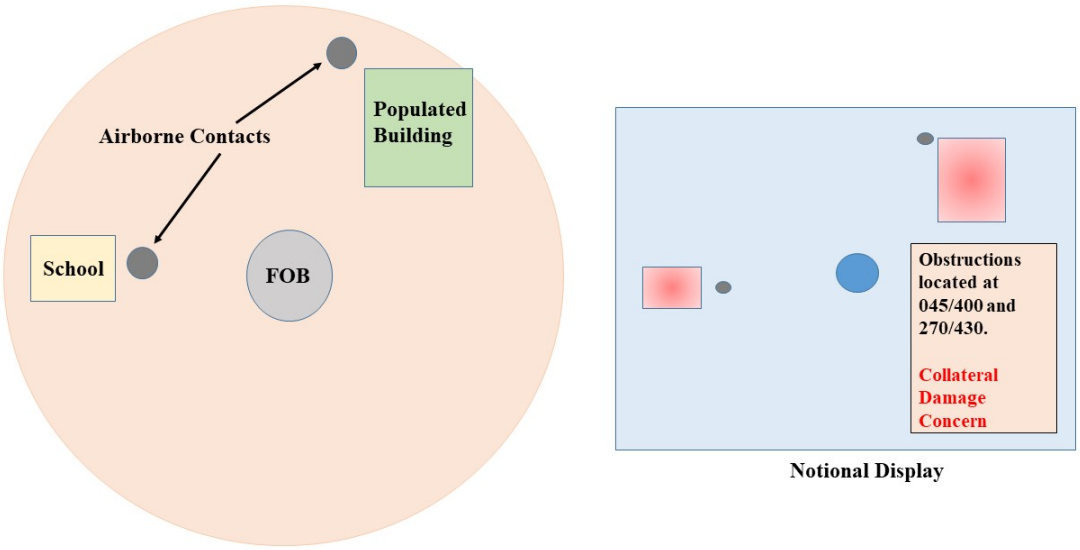

Figure 24. Collateral Damage Alert

E. SUMMARY

The functional analysis developed two important products—the functional architecture of the DALT and logic architecture of the DALP. The functional architecture identified, defined, and analyzed the inputs, outputs, interfaces, interactions, and functions of the logic tool with the other components in the C-UAS kill chain. The logic architecture described the foundation of the logic process.

The functional architecture of the detect-to-engage sequence can be decomposed into five major sub functions: sense, fuse, analyze and recommend, authorize, and attack. The analyze and recommend sub function is further decomposed into the two main

functions performed by the DALT—characterize and act. The DALT functions are intended to replicate the functions performed by the operator and therefore reduce operator workload. The DALT would permit the operator to focus on the critical task of authorizing an attack.

The functions, inputs, outputs, interfaces, and interactions in the detect-to-engage sequence can be allocated to the sensors, countermeasures, data fusion tool, operator, and the DALT. The DALP, which is implemented as part of DALT, shares many of its functions with the operator and is designed to provide more robust, accurate, and timely functionality. A human operator has the potential to get overwhelmed, distracted, or fatigued. The human operator can benefit from a DALT to facilitate faster decisions, a range of autonomy, and consistent results. Requirements were derived and decomposed to provide such functionality.

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IV. MODELLING AND SIMULATION

The research and work documented in this project report were used as the foundation to create a model and simulate a real-world scenario representing a UAS attack and C-UAS effort where the DALP concept is employed. Typical UAS and atypical or "bird like movement" were included in the modelling of three use cases. These were used as inputs to the DALP simulating the threat logic function and flow. Model verification was not a goal of this capstone and has not been completed. However, a verification plan was completed.

A. MODEL ASSUMPTIONS AND LIMITATIONS

The following assumptions and limitations are applicable:

- Each UAS will be launched from positions that keep the UAS operator within visual line of sight of the UAS and the high value location.
- The UAS has been weaponized.
- The UAS approaching high value location will deliver payload as suicide or drop mission
- Sensor degradation is not modeled or accounted for in the simulations.
- Linear motion implies the object is man-made.
- Non-linear motion implies the object is not-man-made.

B. MODEL DEVELOPMENT

The DALP functionality was modelled using ExtendSim (Imagine That Inc. 2013) to incorporate the requirements and logic into a usable and changeable simulation of real-world UAS attack scenarios. Unmanned aerial system and non-UAS flight movement was modelled to test simulation use cases against the logic described in this report. Along with the UAS model, a basic sensor suite was modelled to show how common sensors like radar are used to identify and track an incoming UAS. The remaining part of the

model is the DALP itself, which uses sensor-derived inputs to analyze and make alerts or recommendations on the threat level and classification. While this model is rudimentary, it can easily be expanded upon to more closely match a real-world mission and in the future work section of this report. The model overview is depicted in Figure 25.

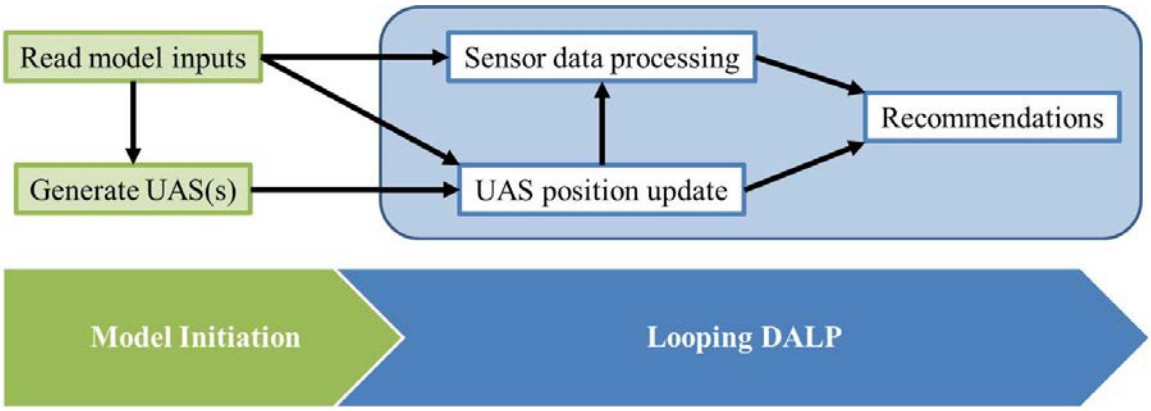

Figure 25. DALP Model Overview

1. UAS Movement, Direction, and Location

Movement can be either linear, semi-random, or fully random. The UAS heading is defined using variable inputs. Linear motion occurs when heading does not change for subsequent time cycles. Random motion occurs when heading varies for each time cycle. Semi-random motion occurs when heading varies for each time cycle, but the general direction of travel is toward a user defined location. The heading is a function of direction of travel.

Direction of travel can vary anywhere between directly at or away from the high value location. This can be a constant or set as a variable. Variable direction is a function of time step and the level of randomness associated to the variability.

The initial location of the UAS is defined using variable user inputs. Many considerations for initial position can be accounted for and can be either random or constant. These include max sensor detection range, max UAS travel distance, tactical

ranges, safe weapons delivery range, unsafe UAS proximity range, and counter-measure weapons range

In the model, the UAS can move in a straight line or a random pattern from a randomly generated initial location toward a user defined destination or without a specific destination. The initial starting distance from the destination, although randomly generated, is defined within a max allowable distance from the high value target. The current model uses a representative UAS max range of approximately two miles as limit for the initial location. Additional movement details are in Appendix D.

2. Sensors

The sensors were modelled to what a sensor suite would do with inputs from the UAS and what useful data the sensors could output to assist with the DALP, rather than modelled to a specific sensor suite (radar, EO/IR, ESM, or acoustic). The model essentially replicates the functionality of the DFT feeding in the data. Refer to Appendix D for additional sensor details.

3. Decision-Aid Logic Process

The actual logic processing was modelled as simple yes/no/unknown decision trees using the logic described previously. Refer to Appendix D for a detailed description and figure of the model.

C. SIMULATION

Using the model, a DALP recommendation for the threat level of a UAS against a fixed high value location can be simulated. Table 9 summarizes the model inputs and outputs that are described in detail in Appendix D.

Table 9. Summary of Model Inputs and Outputs

Model Inputs		Model Outputs	
Motion	Linear	**Identification**	Moving object is a bird
	Random		Moving object is man made
IFF	Friendly	**IFF**	UAS is a friend
	Unknown		UAS is not a friend
Starting Position	Random	**Countermeasure Range**	UAS not within range
	Set		UAS within range
Point moving towards	Random	**Distance to high value target**	UAS is too close to high value target
	High-value location		UAS is not too close to high value target
		Direction object is moving	Object is moving towards the high value target
			Object is not moving towards high value target

1. Use Cases

There are five different use cases of the UAS that the model can simulate to show the different decisions that the DALP makes based on different inputs.

a. Random motion

This is a simulation of a bird to show that the DALP can determine that the object it is tracking is not man-made and therefore not a threat.

b. Linear motion, not moving toward high value location

This is a simulation of a UAS that is likely not an immediate threat to the high value location as it is not travelling straight at the location.

c. Linear motion, moving toward high value location

This is a simulation of a UAS that is perceived as threat and is routed through the DALP logic where countermeasures would be recommended when it comes into range.

d. IFF detected

This simulated a friendly aircraft or UAS showing up on the high value location's radar. The DALP recognizes this IFF signal and recommends de-escalates the threat and only monitors the friendly aircraft.

e. Starting position too close

The final use case is a simulation of an unknown object detected by the sensors at a location within the "no-fly zone" of the high value location. In this case, the DALP would recommend immediate attack to mitigate the threat.

2. Decision-Aid Logic Simulation

The DALP portion of the simulation used decision blocks or "gates" to represent the function of escalating or de-escalating the threat level of the scenario. As described in Appendix E, decision blocks process received information from sensor blocks and either adjust threat level accordingly or continue to monitor the UAS if warranted or drop track if determined a non-threat. DALP routes the object to exit the simulation as a non-threat if IFF is received or random motion is determined. Objects that do not exit simulation can either remain in the DALP processing region of the model or be routed out of DALP back into sensor monitoring for further data gathering and then back into DALP processing region.

D. MODEL VERIFICATION AND OUTPUTS

The model was verified with the use cases previously described by setting inputs to test how the DALP would react and route accordingly. Individual input variables to the model were changed for each scenario, including the motion pattern being linear or random, the starting position of the UAS/object, the location of the fixed high value

location, the direction of movement being either a fixed heading or toward a random location for each motion cycle, and finally if a UAS was sending out an IFF signal. Table 9 shows the inputs for individual use cases and the actions the DALP took in response to the inputs. The model was verified to work as intended per the pre-planned use cases, as shown in the outputs column of Table 9. Verification is described in detail in the Appendix D.

Table 10. Model Inputs with Corresponding DALP Action Outputs

		Inputs			Outputs
		Starting position	**Point moving towards**	**IFF detected?**	**DALP actions**
Use Case	**Random Motion**	Random	Random	No	Assumed a bird, exited simulation
	Linear motion, not moving toward high value location	Random	High-value location	No	continued looping back through model as not a threat until within range and too close
	Linear motion, moving toward high value location	Random	High-value location	No	continued looping through model until within range and too close
	IFF detected	Random	High-value location	Yes	Assumed a friend, exited simulation
	Starting position too close	Set below too close range	High-value location	No	Attack recommendation, too close

E. SUMMARY

The model was useful for the project for displaying equation steps and path, investigating logic basis and providing structure to thought process. ExtendSim allows users to time step through the simulation that showed the path allowing the logic to be

validated and, as necessary, updated. Motion was simulated where each cycle does not necessarily maintain the direction of the previous motion cycle. The general direction of travel toward a specific destination with either linear or random path is an available option and is based on user input variables.

The model was sufficient to demonstrate that the DALP appropriately routed objects through the model and the simulation succeeded in determining threat based on characteristics and eliminating non-threat objects from further sensor processing. The model did not incorporate all coded logic as described in this report but was sufficient in capturing the intent and providing a foundational model that could provide a great resource for future efforts.

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V. CONCLUSIONS AND FUTURE WORK

Small, highly capable, and inexpensive UASs are commonplace, easily modified, and can be weaponized to aid the enemy in attacking U.S. interests. U.S. forces require a robust C-UAS system that satisfies all elements of the kill chain. There are multiple sensor and countermeasure solutions available that support each end of the kill chain, but very few that support the middle of the kill chain. Specifically, a DALP and tool that bridges the gap from detection to action (DALT) was missing. Therefore, the overall objective was to create a DALP and describe the DALT to enable the operator to reliably and repeatedly make the best tactical decisions in response to a dynamic threat environment.

A. CONCLUSIONS

The first product output was the CONOPS. The CONOPS described and illustrated conceptual ideas relating to the manner of use, locations, and general logic process. The CONOPS formed the basis for the functional analysis and modelling development. The functional analysis discovered, analyzed, decomposed, and allocated the various functions and sub-functions to the DALT, DFT, sensors, countermeasures, and operator. A series of IDEF0 diagrams were developed as the functional architecture of the future tool. They described the functions, interactions, and interfaces used in support of the DALT.

The CONOPS, IDEF0s, and various other diagrams were used in the development of the decision-aid logic diagrams and if-then decision statements. This formed the foundation for the decision-aid logic process—reading sensor data, analyzing the data, and providing action recommendations and alerts to the operator. The logic examines target behavior and other characteristics to make a threat determination. Furthermore, the process also utilized autonomous sensor control for rapid sensor tasking as well as prioritized contacts based off their threat determination.

The decision-aid logic and architectural diagrams were used to construct the model. The model was used to run simulations to test and validate the logic. Additionally,

the model was used to analyze the logic process each step of the way. Feedback from the model was used to update the functional architecture.

The modeling and simulation experience gained by the DALP team was a valuable learning tool within the larger project. The model was useful for the project for displaying equation steps and path, investigating logic basis and providing structure to thought process. ExtendSim allows users to time step through the simulation that allowed the logic to be tested and validated. The model was sufficient to demonstrate that the DALP logic was correct.

B. FUTURE WORK CONSIDERATIONS

Due to limited time and personnel, the C-UAS DALP and DALT's scope was narrow. Several research and development needs were identified and would make a good starting point for future work. This includes work on the model, other C-UAS systems, a graphical user interface or software packages, general and detailed hardware design, and automation.

The model needs to expand to be able to test and validate more than just a portion of the DALP. Additional coding, analysis, and testing are needed to improve the robustness and usefulness of the model. A higher fidelity model could also be used to more accurately represent and simulate the timing aspects of the kill chain as well as the limits imposed by the ROE.

As designed, the DALT can task sensors but not launch weapons. DALT provides recommendations to the operator for optimal countermeasure pairing and employment. There are concerns that this semi-autonomous design does not address the timing problems associated with the human's weapons deployment decisions.

The current capability also relies on the operator to verify rules of engagement and collateral damage risks and mitigation prior to making a decision to employ countermeasures. This requirement also increases the timing required for human decision-making.

A future DALT version should include a fully autonomous design that removes these human limitations. Simulations and resultant analyses of this higher fidelity more robust future model should provide data confirming these assumptions and validate the requirement.

It is expected that the C-UAS system would add significant value if it were fully automated. It is likely that the DALT would completely replace the operator function in the C-UAS kill chain.

Further research and additional model improvements should also incorporate sensor degradation, environmental affects, and a variety of threats and target signatures. This would provide a much more accurate representation of a real-world scenario. Also, incorporating multiple location variables to include terrain, climate, wildlife, population and obstacle or structure density would be useful in determining if additional capabilities and limitations would be of value.

Lastly, efforts to transition beyond the conceptual phase and architectural design should include the development of a GUI, software, hardware, and a detailed system-level design. Inevitably, the DALP and DALT will require updates as C-UAS kill chain specific equipment and functionality are added. The most pressing need at present is the DFT.

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APPENDIX A. ADDITIONAL DIAGRAMS

Figure 26 depicts a concept of prioritization logic the DALP could use to determine which of multiple contacts to focus additional sensor tasking, alerts, and recommendations.

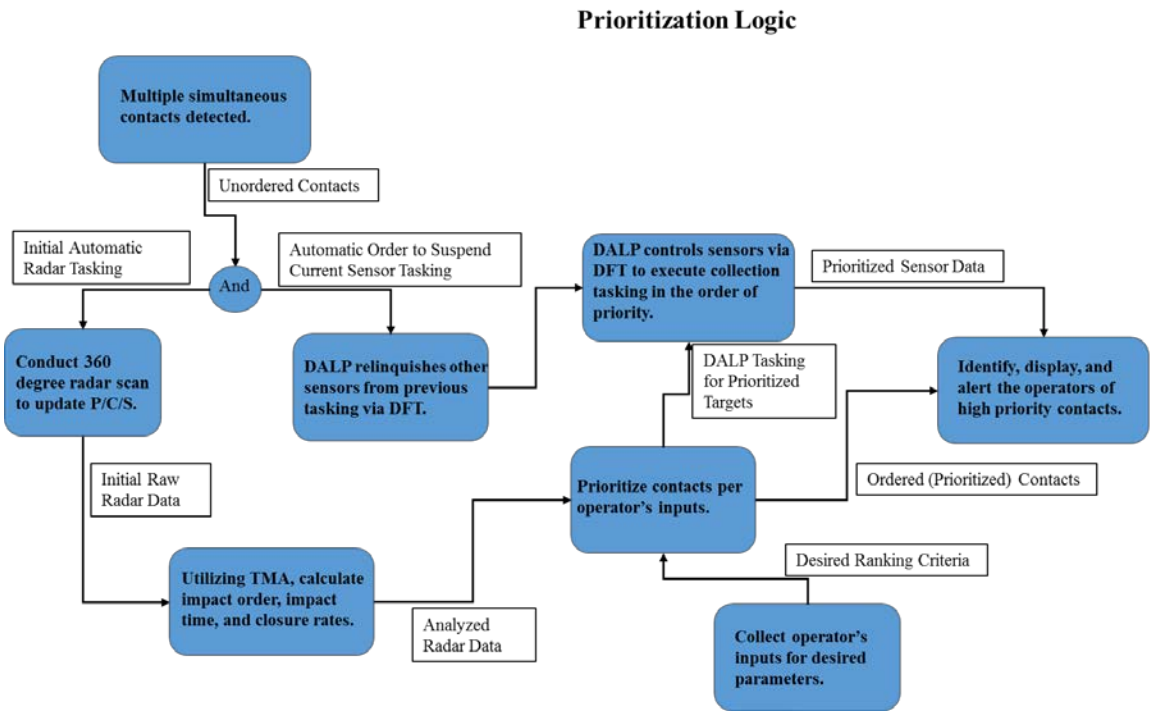

Figure 26. Sensor and Contact Prioritization Logic

Figure 27 provides an alternate diagram of the kill chain logic. Similar to the other diagrams, factors such as closing rate, swarm characteristics, visual weapons, etc., are used to determine the level of threat and appropriate alerts and recommendations. Additionally, this depicts the logic not recommending an attack to an operator until the ROE has been satisfied and an appropriate threat determination made.

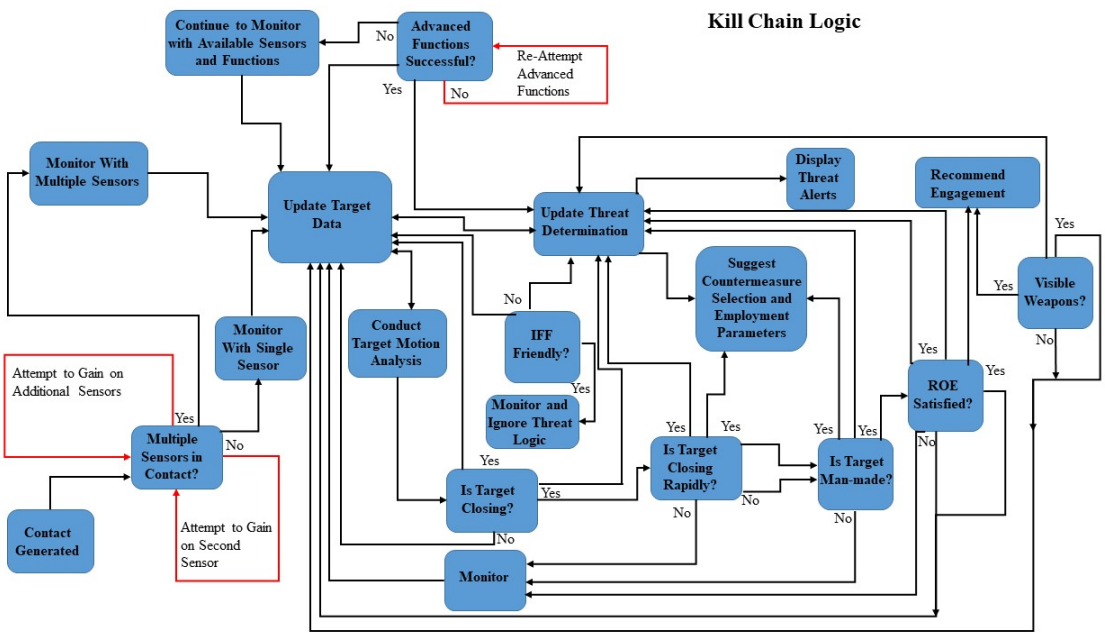

Figure 27. Detailed Kill Chain Logic

Figures 28 and 29 are similar to the diagrams provided in the CONOPS but explore additional scenarios. The first set of illustrations depict a target that is not on an intercept course and is determined not to be a threat. The second set illustrates a swarm attack and appropriate threat determination.

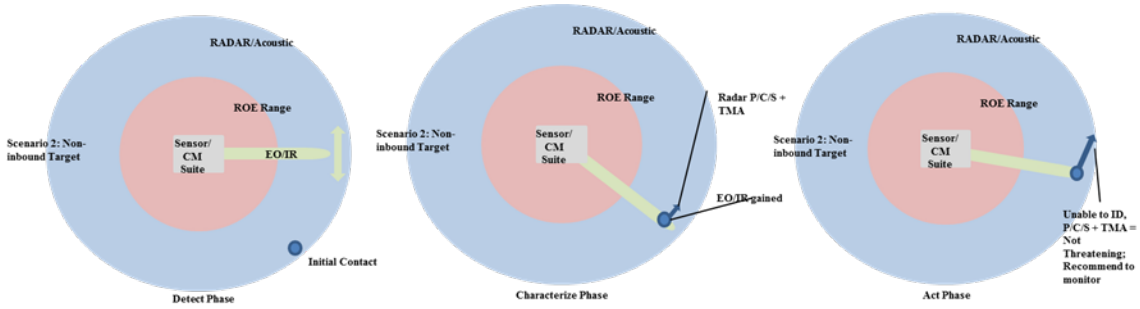

Figure 28. Phases in Non-inbound Scenario

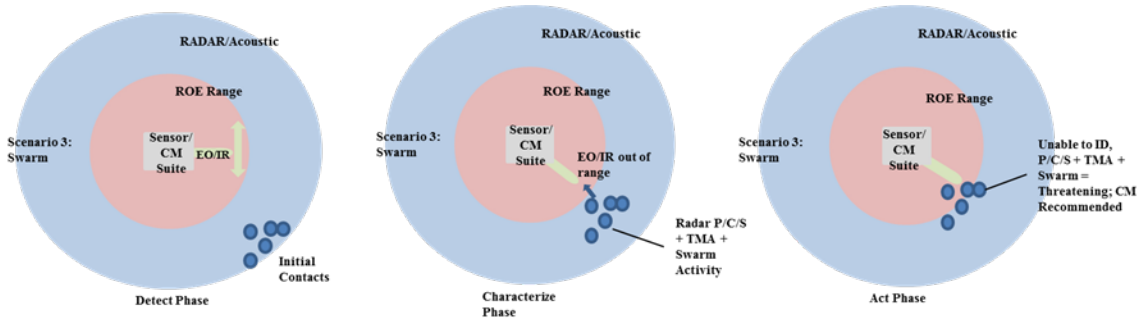

Figure 29. Phases in Swarm Scenario

Figures 30 through 35 were developed with Innoslate and depict the flow of actions, inputs, and outputs of the five major systems in the C-UAS construct—target, sensors, DFT, DALT, countermeasures, and the operator. Figure 30 illustrates a target in motion that is emitting energy and sound, changing its range and bearing in relation to the sensor, and affected by the environment.

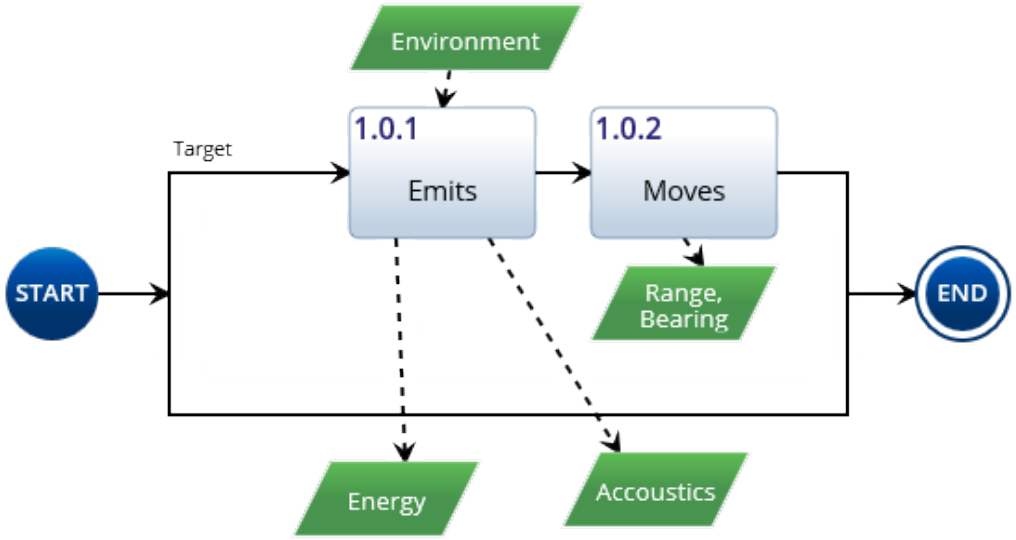

Figure 30. Target Action Diagram

Figure 31 describes the sensor actions as they detect a target, proceed to track, and then process the sensor tasking commands generated by the DALP and relayed through the DFT. Target emissions and relative range and bearing are inputted into the sensor that in turn outputs sensor data. Additional target emissions are used to track the target and provide updates to the altitude, course, speed, etc. Sensor tasking commands are inputted resulting in the sensors changing their modes or target.

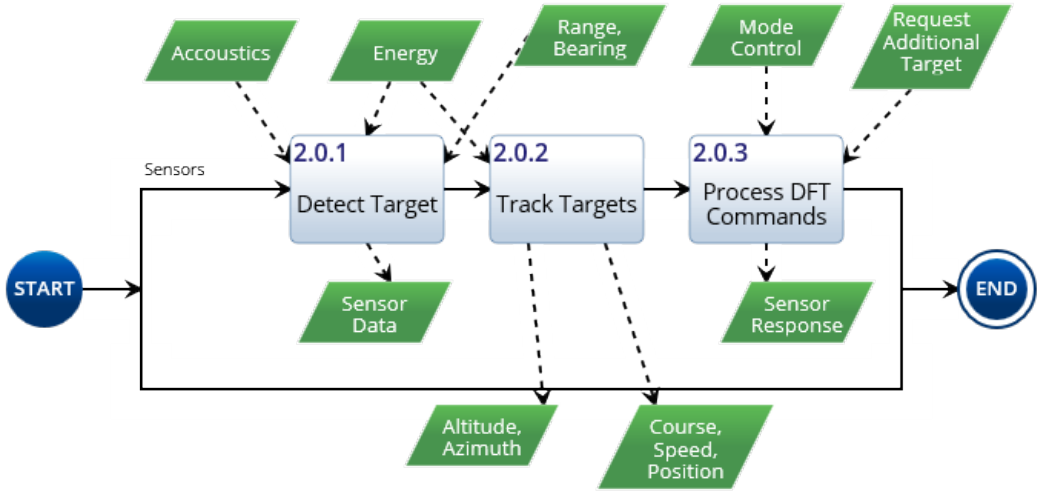

Figure 31. Sensor Action Diagram

Figure 32 describes the flow of actions through the DFT as it collects, fuses, and displays sensor data as well as relaying sensor commands and health and stores statuses.

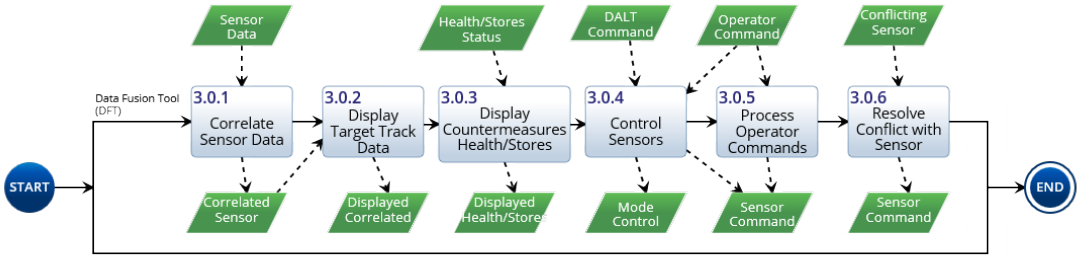

Figure 32. DFT Action Diagram

Figure 33 describes the flow of actions of the DALP as it progresses from the initial input of correlated sensor data from the DFT to a recommended action. Correlated sensor data and target characteristics are continuously used to update the TMA, threat determination, prioritization, alerts, and recommendations. Sensor tasking commands are generated and sent to the DFT. ROE, if used, is a control input for when the DALP recommends an attack.

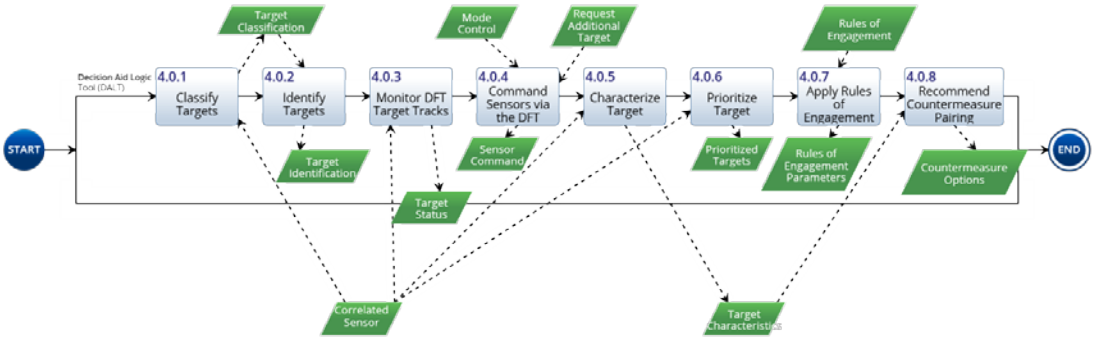

Figure 33. DALP Action Diagram

Figure 34 describes the flow of actions as the operator progresses from noticing the initial target to attacking as necessary. Note, the DALP and operator have similar functions since they both use sensor information to characterize the target, but where they differ is that the DALP provides recommendations and the operator provides the authorization to attack.

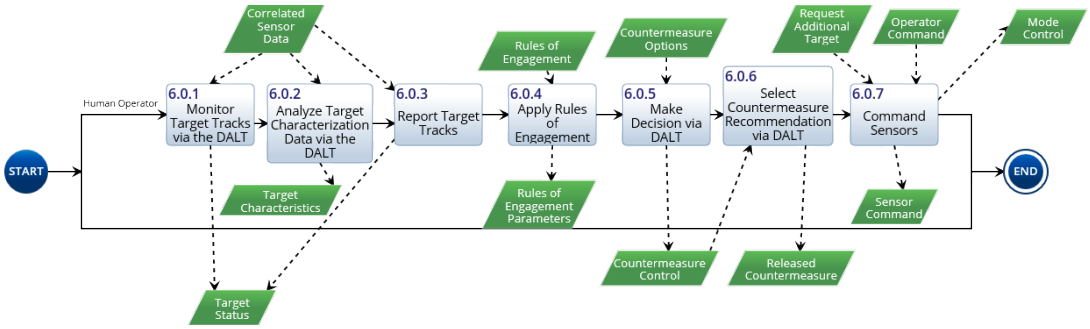

Figure 34. Operator Action Diagram

Figure 35 describes the flow of actions as the countermeasures receive target data, allocate available stores, receive DALP and operator commands, and ultimately engage the target upon authorization. Additionally, the countermeasures are sending out health and stores statuses.

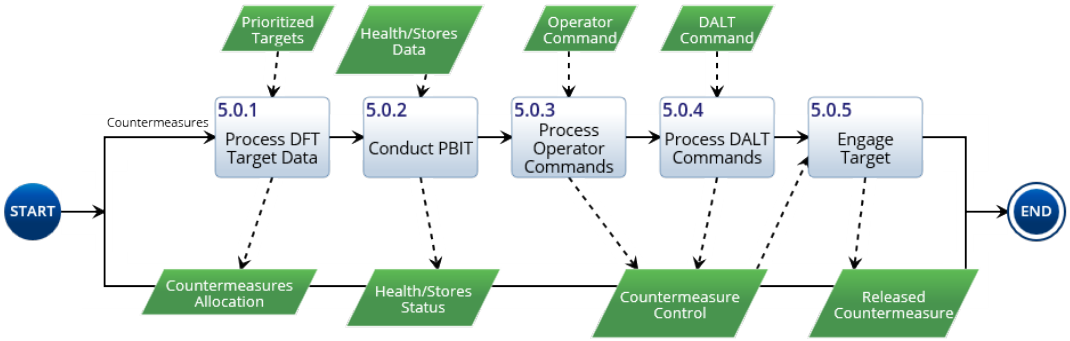

Figure 35. Countermeasure Action Diagram

APPENDIX B. DESIGN REFERENCE MISSION

The decision logic operating scenario analyzed in this project will focus on the defense of a fixed high value location. The high value locations can vary from large urban gatherings such as concerts or sporting events, buildings, power plants to more remote military locations. Two scenarios will be utilized to assess the effectivity of the decision logic design in situations where the rules of engagement (ROE) will differ significantly. The ROE will vary depending on acceptable risk, threat levels, environment and available countermeasures. Scenario one focused on the defense of a military forward operating base (FOB) in a combat environment. Scenario two focused on the defense of a large sporting event in a major metropolitan area.

A. DRM ASSUMPTIONS

The following assumptions apply to both the scenarios:

- Each UAS will be launched from positions that keep the UAS operator within visual line of sight of the UAS and the target location.
- Each UAS is radio controlled.
- Each UAS does not have the ability to autonomously fly to the target location and conduct its attack.
- The operator must maintain control of the UAS throughout the attack.
- For swarm attacks, each enemy UAS is separately controlled by an operator. Radio communication between each operator is used to coordinate the swarm attack mission.
- Each UAS is assumed to have an explosive payload and be flown towards the fixed location with the intent to conduct a suicide attack.
- The same sensors will be utilized for both scenarios.

- Sensor degradation is not modeled or accounted for in the simulations.
- The same countermeasures are available for both scenarios.

B. SCENARIO ONE: MILITARY FORWARD OPERATING BASE (FOB)

In the FOB defense scenario, the environment will be more rural and involve less air traffic compared to the sporting event scenario. The rural environment will present fewer collateral damage concerns based on an uninhabited perimeter surrounding the base. It is assumed the ROE is less restrictive, the area is rural with minimal foot traffic, and there is a smaller collateral damage risk, though there is still the possibility of restrictions and concerns of dropping the UAS on any inhabited area. Fratricide is a primary concern.

The FOB defense scenario is assumed to take place in an environment representing rural Afghanistan. The FOB perimeter environment is uninhabited and foot traffic is considered to have a negligible impact on ROE. The air traffic surrounding the FOB is expected to be tightly controlled where unidentified air vehicle traffic is considered a likely threat. The primary concern effecting ROE determination is fratricide.

C. SCENARIO TWO: LARGE SPORTING EVENT IN METROPOLITAN AREA

In the sporting event scenario, the stadium will be located in a large urban environment. It will be assumed that routine, civilian air traffic will be part of the environment. It will also be assumed that the area in and around the stadium is densely inhabited that will raise collateral damage concerns. It is assumed the ROE is more restrictive, the area is urban with a high density of foot traffic, and there is a high risk of collateral damage. Fratricide is still a concern and there are likely restrictions and concerns about dropping a UAS in a populated area.

The sporting event defense scenario is assumed to take place in a large U.S. city at an open-air stadium. The stadium perimeter environment is densely populated where foot traffic, local businesses, automobile traffic, and human habitation is considered to have a significant impact on ROE. Civil air traffic surrounding the stadium is expected to

be heavy but tightly controlled and monitored. UAS air traffic is assumed not permitted nor thoroughly controlled and is marginally monitored. An identified UAS is a primary threat concern. The primary concern effecting ROE determination in this scenario is collateral damage.

D. SCENARIO ONE AND TWO CASES

In each scenario, the DALP was presented with three attack methods. Additionally, the DALP will address the case where the target is a non-threat. The decision logic will utilize a functional flow that will attempt to detect a target, characterize its behavior, and then take action based on the accumulated threat.

- Case one will involve a single small UAS attempting to mimic the flight profile of a bird (non-mechanical behavior, low, slow flyer).
- Case two will involve a single small UAS being detected at a nominal range of X NM and flying at a speed of 250 kts.
- Case three will involve a simultaneous attack by a swarm of 5–10 UASs conducting a multiple axis attack.

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APPENDIX C. REQUIREMENTS

Although this capstone did not get into any hardware or software development, theoretic system-level requirements were developed. These were developed with the anticipate functions of the DALT and other C-UAS systems. The system-level requirements are allocated into the various system states the DALP can be in—initiation, maintenance, input, and output.

A. INITIATION SEQUENCE REQUIREMENTS

The initiation sequence requirements convey what the DALT needs during a start-up sequence. This includes energizing the system, executing the program, start-up built-in tests (BIT), initial system self-check, and software and mission library health and currency indications.

- The DALT system shall initialize when the DALT system is executed.
- The DALT system shall perform a start-up BIT when the DALT system is executed.
- The DALT system shall check software and mission library versions.
- The DALT system shall provide software and mission library versions to the DFT for display to the operator.

B. MAINTENANCE AND BUILT-IN TEST REQUIREMENTS

The maintenance requirements convey the needs for varying types of maintenance including both planned and unplanned action items. These requirements will accommodate repairs, updates, upgrades, and any other maintenance activities. The built-in test (BIT) requirements work in conjunction with the maintenance requirements by monitoring, identifying, displaying and, if necessary, alerting the DALT or user of the health and system status of all the subsystems.

- The DALT system shall provide an operator initiated Built-In Test.

- The DALT system shall report BIT results to the DFT for display to the operator.

- The DALT system shall run a continuous BIT on the countermeasures and DFT to generate health status.

- The DALT system shall provide a Maintenance mode via operator controls for system software updates and maintenance.

- The DALT system shall perform mission library loading.

  (i) The DALT shall have a physical interface that permits the connection and transfer of data from a mission library loader.

  (ii) The DALT shall have a logical interface that permits the transfer of data from a mission library loader to the DALT.

C. INPUT REQUIREMENTS

The input requirements describe any data, information, user inputs, input interfaces or any other items the DALT needs in order to operate. This includes all of the track and system data generated by the sensors, fused and corroborated in the data fusion tool and sent to the DALT. This also includes all of the BIT data the DALT needs to effectively monitor the health of all the subsystems.

- The DALT system shall accept processed sensor data from the data fusion tool.

  (i) The DALT shall have a physical interface with the DFT that permits the transfer of sensor data from the DFT to the DALT.

  (ii) The DALT shall have a logical interface with the DFT that permits the transfer of sensor data from the DFT to the DALT.

- The DALT system shall accept health status from the countermeasures.

(i) The DALT shall have a physical interface with the sensors and countermeasures, whether directly or through the DFT, that permits the transfer of health status to the DALT.

(ii) The DALT shall have a logical interface with the sensors and countermeasures that permits the transfer of health status to the DALT.

- The DALT system shall accept health status from the DFT.

  (i) The DALT shall have a physical interface with the DFT that permits the transfer of health status to the DALT.

  (ii) The DALT shall have a logical interface with the DFT that permits the transfer of health status to the DALT.

- The DALT system shall accept stores inventory data from the countermeasures.

  (i) The DALT shall have a physical interface with the countermeasures that permits the transfer of stores inventory data to the DALT.

  (ii) The DALT shall have a logical interface with the countermeasures that permits the transfer of stores inventory to the DALT.

- The DALT system shall accept mission configurable input data via operator input from the DFT.

  (i) The DALT shall have the capability to receive and read data input by the operator from an input device, whether directly or through the DFT.

  (ii) The DALT shall process acceptable data input by the operator.

D. OUTPUT REQUIREMENTS

The output requirements convey the majority of the actual decision-aid and logic functionality. This includes all of the analyzed track data, recommendations, alerts, and BIT status sent to a display or speaker as well as all of the output interfaces. This also includes the commands the DALT sends out for sensor operations.

- The DALT system shall send commands to the data fusion tool to command sensor operations.

    (i) The DALT shall have a physical interface with the DFT that permits the DALT to transmit commands to the DFT and all the sensors.

    (ii) The DALT shall have a logical interface with the DFT that permits the DALT to transmit commands to the DFT and all the sensors.

- The DALT system shall output display and auditory data to the DFT or any other display.

    (i) The DALT shall have a physical interface with the DFT or display that permits the transfer of display and auditory signals generated from the DALT.

    (ii) The DALT shall have a logical interface with the DFT or display that permits the transfer of display and auditory data generated from the DALT.

- The tool shall provide recommendations to the operator for characterizing targets via the DFT.

    (i) The DALP shall analyze any received sensor and user input data and utilize the logic to provide a recommendation on target characterization.

    (ii) The DALP shall determine a confidence level based off of the available sensor data.

- The tool shall provide recommendations to the operator on sensor prioritization via the DFT.

(i) The DALP shall prioritize all observed contacts and command the sensor tasking in accordance with the prioritization.

(ii) The DALP shall have an autonomous mode that permits the DALT to command and task sensors based off of the observed contacts and logic.

- The tool shall provide recommendations to the operator on sensor employment via the DFT.

(iii) The DALP shall utilize available sensor data, sensor health status, and decision logic to recommend an optimal sensor employment.

- The tool shall provide recommendations to the operator on contact type via the DFT.

(i) The DALP shall utilize available sensor data and decision logic to provide a recommendation on target type.

- The tool shall provide recommendations to the operator for countermeasure pairing via the DFT.

(i) The DALP shall utilize available sensor data, countermeasure health and system status information, and the decision logic to recommend the optimal type of countermeasure.

- The tool shall provide recommendations to the operator for countermeasure employment via the DFT.

(i) The DALP shall utilize available sensor data, countermeasure health and system status information, and decision logic to recommend the optimal employment of the countermeasure.

(ii) The DALP shall have the capability to determine and list recommendations for all the countermeasures.

- The DALT system shall direct advanced sensor functions (ISAR, Doppler, threat libraries) via the DFT.

(i) The DALT shall have a physical interface, whether directly or through the DFT, that permits the DALT to utilize advanced sensor functions.

(ii) The DALT shall have a logical interface that permits the DALT to utilize advanced sensor functions.

APPENDIX D. ADDITIONAL MODEL INFORMATION

In this model, the sensor logic was coded using two equation blocks. One looked at the flight path to differentiate linear or non-linear/bird-like motion and if mode IV or V was present to determine IFF. The other used that derived motion to determine UAS range and heading. These equation block sensors are shown in Figure 28.

A. SENSOR DATA

The first "sensor" in the sensor processing section of the model used location and time inputs to output data on whether the detected object was moving linearly, likely man-made, or moving randomly, more likely to be a bird or other non-man-made object. Linear flight path was determined using the assumed and calculated distance an object would have traveled over two-time steps in a straight-line flight path this calculated distance was compared to the actual distance the object traveled. If the two distances were equal, the object was determined to be man-made. If the two distances were not equal, the object was determined to be not man-made. This simplified calculation functioned well in this modeling and simulation effort but is likely over-simplified for real-world applications. A more robust and higher fidelity model based from this model could be very beneficial for future efforts. The use of only two-time steps should be a focus of increased model and simulation fidelity.

This modelled sensor processed the "IFFrand" variable that was created at the beginning of the simulation and passed an attribute to the DALP section of the model. This attribute indicated IFF status of the object to be either a friend or undetermined based on the presence of the IFF signal. IFF scanning is incorporated in most air defense radar systems.

Threat determination process also begins in the first sensor. With a simple calculation using location and time step, the sensor block determined whether the object was moving directly or near-directly at the mission target. If the object is moving directly at the target, it is labeled a threat by the sensor.

The second sensor used motion inputs to determine how close the UAS was to the high value location. This is used later in the DALP logic to determine if the UAS was within range of the countermeasures and/or close enough to the high value target that the DALP recommended immediate countermeasures be taken

Cameras: The camera section of the model was built by utilizing an expanded Johnson's Criteria for detect, recognize and identify (DRI). Detection is defined as a computer being able to determine that there is a target of some kind in the field of view. Recognition is the ability for a target to be discerned between one type of object versus another, such as a combatant standing next to a tree versus a truck versus an aircraft.

Recognition also may include the ability to discern a flying aircraft from a bird or between types of aircraft, such as an airplane versus a quadcopter. Identification is the ability to discern a specific person or the model of a specific quadcopter. Identification is in the nearest field of view while detection is in the farthest field of view.

The Johnson's Criteria states that to detect a target, it must be seen by a minimum number of pixels. The same minimum criteria are applied to recognition and identification. Some of the variables that lead up to a camera's ability to see clearly at great distance are: Lens, Sensor Size, and Fidelity of Sensor. Due to this variability, a single camera setup was chosen using a moderate level camera (720P) for the model. This is based off the moderate level camera, a maximum and a minimum distance was established for each of the DRI criteria (Sjaardema, Smith, Birch 2015).

In the model, a Boolean simulation was created to transfer the probability of a criterion into a positive (did detect, recognize, or identify) or a negative (did not detect, recognize, or identify) result. In addition, recognize and identify criteria were set to negative in the event detect was also negative. The thought process is that a computer could not recognize a target if it first did not detect it. The same thought process was applied to the Identify criteria.

B. FLOW

The progress through the DALP processing region of the modeled simulation is as follows:

- Range. The DALP first determines if the UAS is too close to the mission target. If it is, it immediately recommends to attack. If it is not too close, the DALP moves on to the next block.

- Linear track. If the sensor block of the model determines that the object is linear, the DALP increases the threat level and the UAS progresses to the next block. If the object is determined to be a bird, the DALP exits the model.

- IFF. The next block takes input from the sensor on IFF. If no friendly signal is found (unknown friend-or-foe), the DALP routes the object to the next block. If an IFF signal is sensed, the DALP routes the object to exit the model.

- Direction. If the object is determined to be heading directly at the target it is perceived as a threat and routed to the next decision block in DALP processing cycle. If the object is not moving straight at the target, the DALP routes the object to exit the model.

- Attack. If the UAS has been routed through all the DALP processing section and is within countermeasure range, it is recommended that the UAS is attacked by routing through the attack exit block

C. UAS MOVEMENT

In the model, the UAS can move in a straight line or a random pattern from a randomly generated initial location toward a user defined destination or without a specific destination. The initial starting distance from the destination, although randomly generated, is defined within a max allowable distance from the destination and/or FOB.

The current model uses a representative UAS max range as limit for the initial location. The UAS initial location is a user input variable.

Model cycles are based on a user defined delta time (dt). The change in time (dt) is important because most functions and code equations that model the movement of the UAS are based on this time parameter. It made sense to sync this (dt) with the maximum or limiting sensor cycle rate. It is also easily altered as required.

UAS motion is simulated once per cycle (dt). Each cycle produces a linear movement, and the distance traveled is a function of user defined speed and the (dt). The model currently uses representative Type one UAS speeds in the range between 10 to 50 ft/s. The motion was created in the base model as shown in Figure 27. Motion is simulated as entirely random, semi-random where a general direction is defined but the path is highly randomized, and non-random where path and direction are defined by user inputs. The random motion generator can use any of the distributions available in ExtendSim.

The ExtendSim model is coded to determine the type of UAS motion as part of the DALP decision blocks. Model code uses position at the end of specific cycles and derives associated ranges. The difference between ranges and assumed travel distance, based on speed and (dt), is used to estimate direction of travel in relation to assumed location of FOB. This data is used in threat determination. If a UAS has been determined to be coming straight at FOB, it is an indication of a threat. If a UAS has been determined to be traveling away from the FOB, it is not considered a threat. There are infinite directions of travel between these two scenarios and a “tuning” factor (T) has been coded into model to account for this. If a UAS is approaching FOB but not on a direct route, it may still be considered a threatening approach. The tuning factor (T) allows a range of incoming directions to be considered threatening.

D. DECISION-AID LOGIC PROCESS

The actual logic processing was modelled as simple yes/no/unknown decision trees using the logic described previously. This is depicted in Figure 36.

- Blocks 305 and 190 use the range of the object from the mission target and determines if it is too close for further processing through DALP and must be shot down or can continue through DALP and routes accordingly.

- Blocks 139 and 99 use flight path information from the first sensor to determine if the object is man-made or a bird and routes accordingly.

- Blocks 212 and 108 uses IFF sensor data from the first sensor to determine friend or foe status and routes accordingly. Any input that is unknown is assumed to be foe.

- Blocks 217 and 116 uses object heading information from the first sensor to determine whether the threat should be increased or not and routes accordingly.

- If object remains in DALP and enters blocks 222 and 133, it is assumed to be at a high enough threat level to be attacked and determines if the object is within range of the countermeasures and is able to be shot down and routes accordingly.

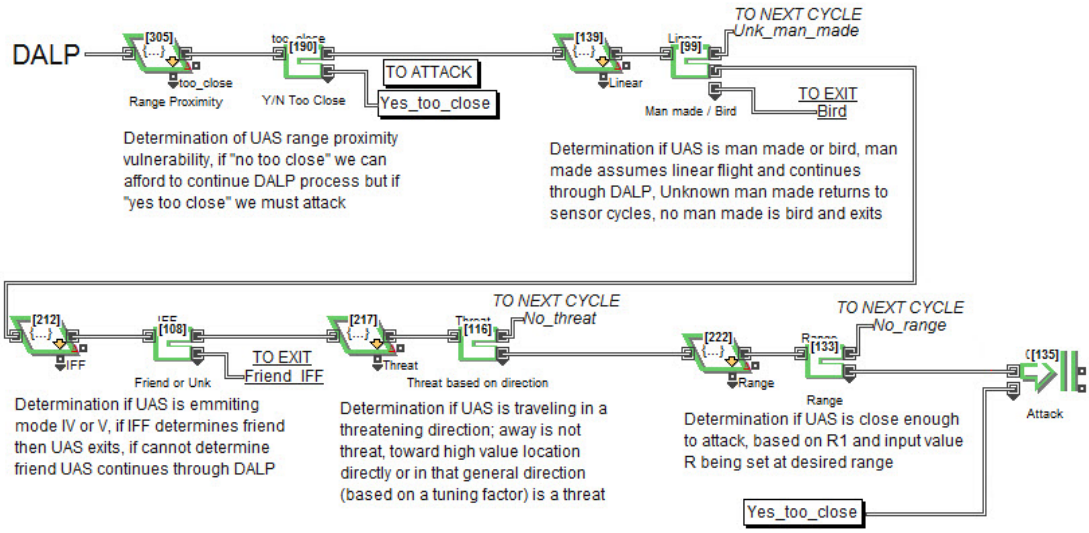

Figure 36. DALP Model

E. VERIFICATION

Figure 37 represents the random motion use case of the simulation. This was meant to simulate how a bird might fly in a random motion unlike a threatening UAS. The DALP monitored the motion through a few cycles, all with the motion far away from the high value location and recognized the motion as random and exited the model.

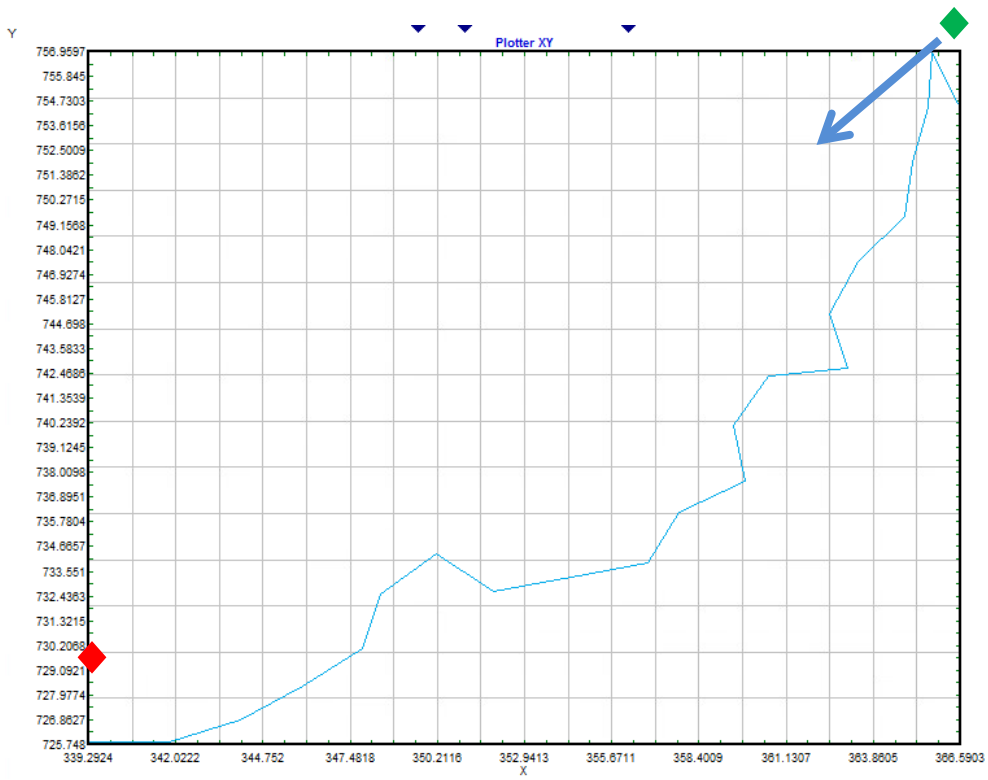

Figure 37. Random Motion Simulating a Bird

In Figure 38, the UAS is moving linearly but it is moving away from the high value location. With these inputs, the DALP model continued cycling through the threat assessment blocks but did not exit or recommend an attack as the threat was never escalated due to the direction of motion of the UAS.

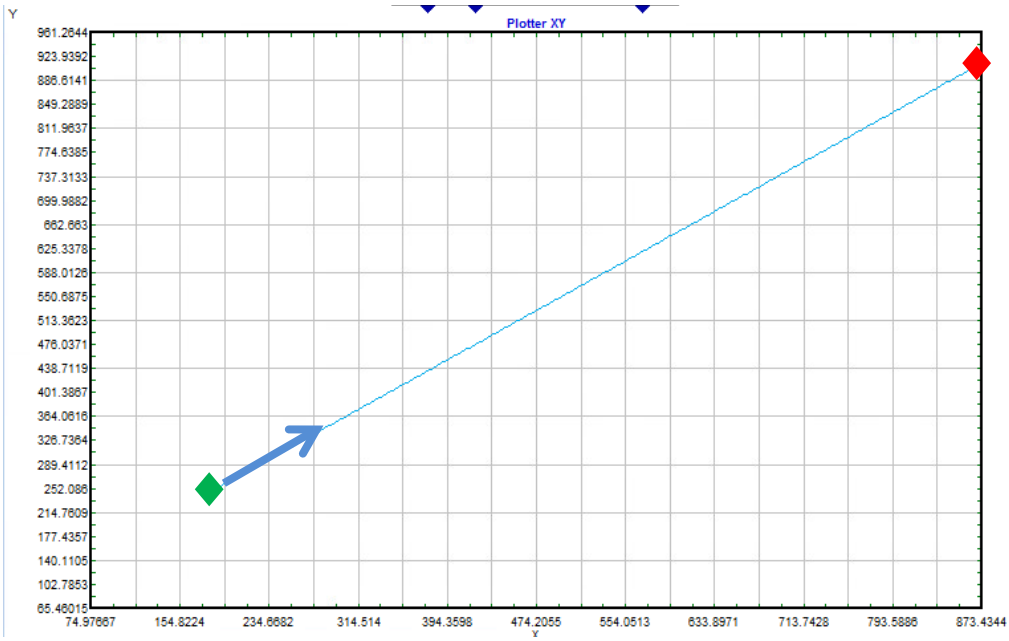

Figure 38. Linear Motion, Not Moving Toward High Value Location

A UAS moving toward the high value location linearly was the intention of this use case and is shown graphically in Figure 39. The DALP recognized the linear motion, recognized that the UAS was moving toward the high value location, and continued to monitor the UAS until it came first within range of the countermeasures. When it moved within the range of the countermeasures, it exited the model and recommending an attack. The UAS is attacked by routing through the attack exit block.

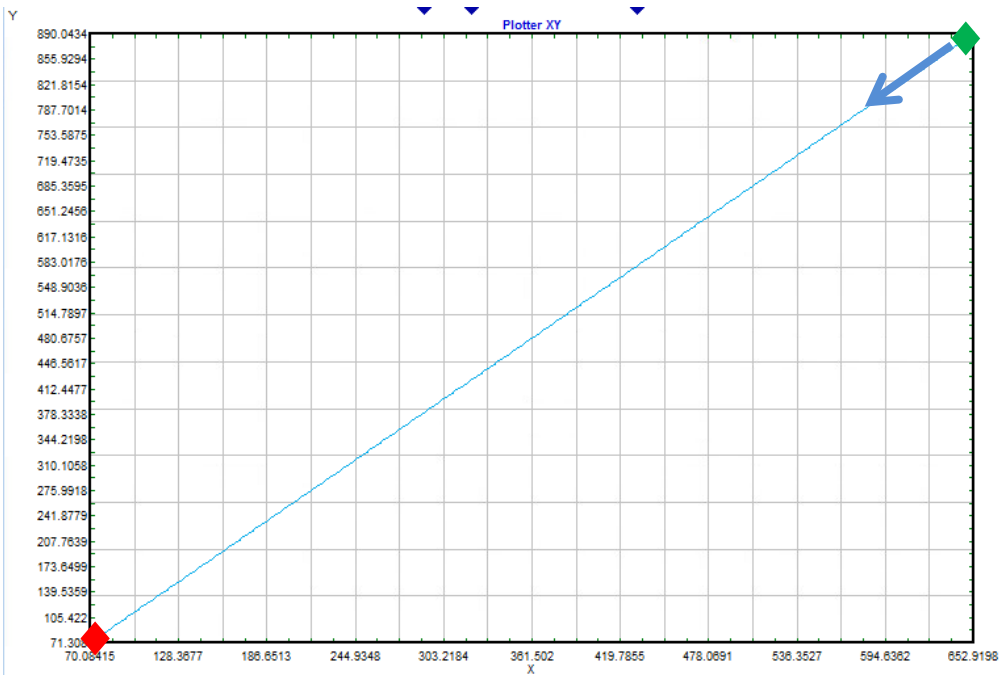

Figure 39. Linear Motion, Moving Toward High Value Location

The final use case validation showed that the DALP can recognize an IFF signal and route object to exit the simulation based on the de-escalated threat. Due to the fact that the model routed the object to exit immediately when DALP recognized the IFF determination, there is no flight path to indicate on a graph.

SUPPLEMENTAL

The ExtendSim model used decision blocks to simulate the DALP to appropriately route a UAV through a threat level determining progression. The model derived threat levels via user input variable characteristics. The result was the removal of non-threatening objects from further sensor processing or an attack recommendation for objects achieving a significant threat level.

The model is in two parts and is catalogued with this report by the Naval Postgraduate School and the Defense Technical Information Center.

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