



## DESIGN, ENGINEERING AND ASSESSMENT OF MERCHANT AND MILITARY SEALIFT COMMAND DEFENSE AGAINST UNMANNED VEHICLES

|               |  |
|---------------|--|
| Title         | DESIGN, ENGINEERING AND ASSESSMENT OF MERCHANT AND MILITARY SEALIFT COMMAND DEFENSE AGAINST UNMANNED VEHICLES  |
| Item Type     | Thesis   |
| Authors       | Da Costa Canena, Angeluz;Fairbrother, Jennifer A.  |
| URI           | <a href="https://hdl.handle.net/10945/74756">https://hdl.handle.net/10945/74756</a>  |
| Publisher     | Monterey, CA; Naval Postgraduate School  |
| Date Issued   | 2025-06  |
| Rights        | This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States. |
| Download date | 2026-05-21 05:27:10  |
| Link to Item  | <a href="https://hdl.handle.net/10945/74756">https://hdl.handle.net/10945/74756</a>  |

Downloaded from NPS Archive: Calhoun



# NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

## SYSTEMS ENGINEERING ANALYSIS CAPSTONE REPORT

**DESIGN, ENGINEERING AND ASSESSMENT  
OF MERCHANT AND MILITARY SEALIFT COMMAND  
DEFENSE AGAINST UNMANNED VEHICLES**

by

Angeluz Da Costa Canena and Jennifer A. Fairbrother

June 2025

Advisor:  
Second Reader:

Ronald E. Giachetti  
Hillary Collandra,  
COMPACFLT N3

**Distribution Statement A. Approved for public release: Distribution is unlimited.**

THIS PAGE INTENTIONALLY LEFT BLANK

|  |   |  |   |  |
|--|---|--|---|--|
| <b>REPORT DOCUMENTATION PAGE</b>   |   |  | <i>Form Approved OMB<br/>No. 0704-0188</i>  |  |
| 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.  |   |  |   |  |
| <b>1. AGENCY USE ONLY<br/>(Leave blank)</b>  |   | <b>2. REPORT DATE</b><br>June 2025                             | <b>3. REPORT TYPE AND DATES COVERED</b><br>Systems Engineering Analysis Capstone Report |  |
| <b>4. TITLE AND SUBTITLE</b><br>DESIGN, ENGINEERING AND ASSESSMENT OF MERCHANT AND MILITARY SEALIFT COMMAND DEFENSE AGAINST UNMANNED VEHICLES  |   |  | <b>5. FUNDING NUMBERS</b>   |  |
| <b>6. AUTHOR(S)</b> Angeluz Da Costa Canena and Jennifer A. Fairbrother  |   |  |   |  |
| <b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b><br>Naval Postgraduate School<br>Monterey, CA 93943-5000  |   |  | <b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>   |  |
| <b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b><br>N/A  |   |  | <b>10. SPONSORING / MONITORING AGENCY REPORT NUMBER</b>                                 |  |
| <b>11. SUPPLEMENTARY NOTES</b> 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.  |   |  |   |  |
| <b>12a. DISTRIBUTION / AVAILABILITY STATEMENT</b><br>Distribution Statement A. Approved for public release: Distribution is unlimited.   |   |  | <b>12b. DISTRIBUTION CODE</b><br>A  |  |
| <b>13. ABSTRACT (maximum 200 words)</b><br><br>Advanced warfighting techniques of the modern age consists of a variety of new technology, especially in the field of unmanned systems. Unmanned surface vessels (USVs) and unmanned aerial systems (UASs) are an outstanding problem in current conflict, inflicting damage and destruction to the merchant and Military Sealift Command (MSC) ship fleets. The project proposes alternative solutions for combatting such USV and UAS threats, with a focus on the implementation of a system of systems in threatened areas for defensive purposes. Through a series of research, analysis and design, a two-layered defensive system of systems is proposed as an effective and cost-considered implementation to the fleet. The analysis includes considerations of current and future technology, followed by simulation and modeling of the capabilities, ultimately producing a determination of survivability and effectiveness. The results are included in a thoughtful analysis on alternatives for defense of merchant and MSC ships under attack by unmanned systems. |   |  |   |  |
| <b>14. SUBJECT TERMS</b><br>unmanned, unmanned surface vessel, USV, unmanned aerial system, UAS, unmanned aerial vehicle, UAV, defense, Red Sea, merchant, Military Sealift Command, MSC, drone  |   |  | <b>15. NUMBER OF PAGES</b><br>161   |  |
|  |   |  | <b>16. PRICE CODE</b>   |  |
| <b>17. SECURITY CLASSIFICATION OF REPORT</b><br>Unclassified   | <b>18. SECURITY CLASSIFICATION OF THIS PAGE</b><br>Unclassified | <b>19. SECURITY CLASSIFICATION OF ABSTRACT</b><br>Unclassified | <b>20. LIMITATION OF ABSTRACT</b><br>UU   |  |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)  
Prescribed by ANSI Std. Z39-18

THIS PAGE INTENTIONALLY LEFT BLANK

**Distribution Statement A. Approved for public release: Distribution is unlimited.**

**DESIGN, ENGINEERING AND ASSESSMENT OF MERCHANT AND  
MILITARY SEALIFT COMMAND DEFENSE AGAINST UNMANNED  
VEHICLES**

Angeluz Da Costa Canena and LT Jennifer A. Fairbrother (USN)

with

Jia Jun Ray Ang, Roy Granot, LT Alan J. Hatlestad (USN),  
Zhen Huang Adriel Lam, Wei Zhi Jonathan Lee, Roy Ying Chong Lim,  
Hsih Zheng Ling, LT Alexandre Misenheimer (USN), Steve Kang Sheng Ng,  
Wei Kang Soon, Jin Xing Herman Tan, Joel Rui Qin Tan, and Capt James L. Villanueva  
(USMC)

Submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE IN SYSTEMS ENGINEERING**

from the

**NAVAL POSTGRADUATE SCHOOL  
June 2025**

Lead Author: Jennifer A. Fairbrother  
Lead Editor: Alan J. Hatlestad

Reviewed by:

Ronald E. Giachetti  
Advisor

Hillary Collandra  
Second Reader

Accepted by:

David L. Alderson  
Department Chair, Operations Research

Oleg A. Yakimenko  
Department Chair, Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

## **ABSTRACT**

Advanced warfighting techniques of the modern age consists of a variety of new technology, especially in the field of unmanned systems. Unmanned surface vessels (USVs) and unmanned aerial systems (UASs) are an outstanding problem in current conflict, inflicting damage and destruction to the merchant and Military Sealift Command (MSC) ship fleets. The project proposes alternative solutions for combatting such USV and UAS threats, with a focus on the implementation of a system of systems in threatened areas for defensive purposes. Through a series of research, analysis and design, a two-layered defensive system of systems is proposed as an effective and cost-considered implementation to the fleet. The analysis includes considerations of current and future technology, followed by simulation and modeling of the capabilities, ultimately producing a determination of survivability and effectiveness. The results are included in a thoughtful analysis on alternatives for defense of merchant and MSC ships under attack by unmanned systems.

THIS PAGE INTENTIONALLY LEFT BLANK

---

---

# Table of Contents

---

|          |  |           |
|----------|--|-----------|
| <b>1</b> | <b>Introduction</b>                                    | <b>1</b>  |
| 1.1      | Motivation for Study . . . . .                         | 1         |
| 1.2      | Background . . . . .                                   | 4         |
| 1.3      | Concept of Operations . . . . .                        | 13        |
| 1.4      | Project Objective . . . . .                            | 14        |
| 1.5      | Systems Engineering Process . . . . .                  | 14        |
| 1.6      | Stakeholders . . . . .                                 | 15        |
| 1.7      | Organization of the Capstone Report . . . . .          | 16        |
| <br>     |  |           |
| <b>2</b> | <b>Literature Review</b>                               | <b>17</b> |
| 2.1      | Vulnerability of Merchant Vessels. . . . .             | 17        |
| 2.2      | Counter-Unmanned System Strategies . . . . .           | 22        |
| 2.3      | Radar-Based Detection in Maritime Contexts . . . . .   | 23        |
| 2.4      | Radar Technologies on Ships. . . . .                   | 23        |
| 2.5      | Integration of Detection and Defense Systems . . . . . | 24        |
| 2.6      | Challenges in Maritime Radar Detection . . . . .       | 24        |
| 2.7      | Conclusion. . . . .                                    | 24        |
| <br>     |  |           |
| <b>3</b> | <b>Systems Engineering Methodology</b>                 | <b>25</b> |
| 3.1      | Mission Objectives . . . . .                           | 25        |
| 3.2      | Requirements Definition . . . . .                      | 25        |
| 3.3      | Measures of Performance and Effectiveness . . . . .    | 27        |
| 3.4      | High-Level Operational Concept . . . . .               | 29        |
| 3.5      | System Architecture . . . . .                          | 31        |
| 3.6      | Strategic and Operational Constraints . . . . .        | 41        |
| <br>     |  |           |
| <b>4</b> | <b>Experimental Design</b>                             | <b>43</b> |
| 4.1      | Threat Analysis . . . . .                              | 43        |
| 4.2      | Defensive Layers Definition . . . . .                  | 45        |

|          |  |            |
|----------|--|------------|
| 4.3      | Scenarios . . . . .                                      | 63         |
| 4.4      | Modeling and Simulation Approach . . . . .               | 69         |
| <b>5</b> | <b>Simulation and Analysis</b>                           | <b>71</b>  |
| 5.1      | Simulation Environment . . . . .                         | 71         |
| 5.2      | Analysis of Results . . . . .                            | 78         |
| 5.3      | Cost-Effectiveness Analysis . . . . .                    | 84         |
| 5.4      | Summary . . . . .  | 90         |
| <b>6</b> | <b>Conclusions and Recommendations</b>                   | <b>93</b>  |
| 6.1      | Summary of Report . . . . .                              | 93         |
| 6.2      | Assumptions and Limitations . . . . .                    | 94         |
| 6.3      | Recommendations . . . . .                                | 96         |
| 6.4      | Future Work . . . . .                                    | 98         |
|          | <b>Appendix A Probability of Detection Calculations</b>  | <b>101</b> |
| A.1      | Calculation of Radar Cross-Sections. . . . .             | 101        |
| A.2      | Radar Cross-Section Impacts on Detection Range . . . . . | 109        |
| A.3      | Radar Horizon Limitations to Detection Range . . . . .   | 110        |
| A.4      | Signal-to-Noise Ratio . . . . .                          | 111        |
| A.5      | Probability of Detection. . . . .                        | 113        |
|          | <b>Appendix B Probability of Kill Calculations</b>       | <b>117</b> |
| B.1      | Threat Characteristics . . . . .                         | 117        |
| B.2      | Encounter Conditions . . . . .                           | 117        |
| B.3      | Probability of Fusing . . . . .                          | 119        |
| B.4      | Detonation Zones . . . . .                               | 124        |
|          | <b>List of References</b>                                | <b>127</b> |
|          | <b>Initial Distribution List</b>                         | <b>137</b> |

---



---

## List of Figures

---

|             |   |    |
|-------------|---|----|
| Figure 1.1  | Geographic concentration of Houthi attacks on commercial shipping.                | 3  |
| Figure 1.2  | Department of Defense unmanned aerial systems classification guide.               | 5  |
| Figure 1.3  | Magura unmanned surface vessel technical details. . . . .                         | 7  |
| Figure 1.4  | Ukrainian Sea Baby naval drone. . . . .   | 7  |
| Figure 1.5  | Transit route of oil tankers from the Strait of Hormuz to the Suez Canal. . . . . | 8  |
| Figure 1.6  | Visible decrease in Red Sea vessel traffic due to Houthi attacks. . . . .         | 10 |
| Figure 1.7  | Most targeted vessel type in Houthi attacks. . . . .                              | 10 |
| Figure 1.8  | Maritime traffic density contours. . . . .  | 11 |
| Figure 1.9  | Military base locations in the proximity of the Red Sea conflict. . . . .         | 12 |
| Figure 1.10 | Operational viewpoint for layered defensive system of systems. . . . .            | 13 |
| Figure 2.1  | General approach to counter–unmanned aerial systems. . . . .                      | 19 |
| Figure 3.1  | The survivability onion model. . . . .  | 26 |
| Figure 3.2  | High-level operational concept diagram. . . . .                                   | 30 |
| Figure 3.3  | Counter-unmanned aerial systems defense system block definition diagram. . . . .  | 32 |
| Figure 3.4  | Counter–unmanned aerial systems defense system internal block diagram. . . . .    | 34 |
| Figure 3.5  | Functional hierarchy diagram. . . . .   | 36 |
| Figure 3.6  | Requirement hierarchy diagram. . . . .  | 38 |
| Figure 3.7  | Functional versus requirement traceability matrix. . . . .                        | 40 |

|             |   |    |
|-------------|---|----|
| Figure 4.1  | Arleigh Burke class destroyer (DDG-51), USS Jason Dunham (DDG-109). . . . .   | 46 |
| Figure 4.2  | AN/SPY-6 radar onboard an Arleigh Burke class destroyer. . . .  | 47 |
| Figure 4.3  | Sea Giraffe antenna assembly. . . . .   | 48 |
| Figure 4.4  | Mk-45 Mod 2 firing from a Royal Netherlands Navy De Zeven Provinciën-class frigate. . . . .                                       | 49 |
| Figure 4.5  | BAE Systems hyper velocity projectile five-inch variant. . . . .  | 49 |
| Figure 4.6  | AGM-176 Griffin missile being launched. . . . .   | 53 |
| Figure 4.7  | Opened Mk-208 Griffin Missile Launcher. . . . .   | 54 |
| Figure 4.8  | Griffin B block II missile components. . . . .  | 55 |
| Figure 4.9  | L3Harris Vehicle-Agnostic Modular Palletized ISR Rocket Equipment sensor and rocket launcher. . . . .                             | 56 |
| Figure 4.10 | Advanced Precision Kill Weapon System all-up round major components. . . . .  | 56 |
| Figure 4.11 | LAND-LGR4 laser guided weapon system. . . . .   | 57 |
| Figure 4.12 | M151 and M156 Hydra 70 warheads with an area highlighted in red indicating the length of high explosive filling. . . . .          | 58 |
| Figure 4.13 | Electro Optic Systems Titanis counter drone major sensors. . . .  | 59 |
| Figure 4.14 | Electro Optic Systems R400-M, Titanis on land vehicle and on a container. . . . .   | 60 |
| Figure 4.15 | Mk310 Programmable Air Burst Munition 30 × 173 mm. . . . .  | 61 |
| Figure 4.16 | ABM/KETF air burst 30 × 173 mm munition along its cutaway sample. . . . .   | 62 |
| Figure 4.17 | Activity diagram of group III single unmanned aerial system engagement via naval vessel defense system. . . . .                   | 66 |
| Figure 4.18 | Activity diagram of group III single unmanned aerial system engagement via allied unmanned surface vessel defense system. . . . . | 66 |

|             |   |    |
|-------------|---|----|
| Figure 4.19 | Activity diagram of group III single unmanned aerial system engagement via naval vessel and allied unmanned surface vessel defense systems. . . . . | 67 |
| Figure 4.20 | Activity diagram of group III unmanned aerial system swarm engagement via naval vessel and allied unmanned surface vessel defense systems. . . . .  | 67 |
| Figure 4.21 | Activity diagram of single unmanned surface vessel (threat) engagement via allied unmanned surface vessel defense system. . . . .                   | 68 |
| Figure 5.1  | Threat ring. . . . .  | 72 |
| Figure 5.2  | Simulated merchant traffic with stationary guided missile destroyer. . . . .  | 72 |
| Figure 5.3  | Simulated merchant traffic with escorts. . . . .  | 73 |
| Figure 5.4  | Cumulative probability of detection of each sensor versus an approaching unmanned aerial system with Shahed-136 characteristics. . . . .            | 75 |
| Figure 5.5  | Cumulative probability of detection of each sensor versus an approaching unmanned aerial system with Arash-2 characteristics. . . . .               | 76 |
| Figure 5.6  | Cumulative probability of detection of each sensor versus an approaching unmanned surface vessel with Sea Baby characteristics. . . . .             | 76 |
| Figure 5.7  | Number of ships hit by threats (single group I unmanned aerial system). . . . .   | 79 |
| Figure 5.8  | Number of ships hit by threats (single and swarm Arash-2). . . . .  | 81 |
| Figure 5.9  | Number of ships hit by threats (single and swarm unmanned surface vessels). . . . .   | 81 |
| Figure 5.10 | Threat detections and interceptions (single Shahed-136). . . . .  | 82 |
| Figure 5.11 | Threat detections and interceptions (swarm of Shahed-136). . . . .  | 82 |
| Figure 5.12 | Threat detections and interceptions (single Arash-2). . . . .   | 83 |
| Figure 5.13 | Threat detections and interceptions (single unmanned surface vessel). . . . .   | 83 |
| Figure 5.14 | Threat detections and interceptions (swarm of unmanned surface vessels). . . . .  | 84 |

|             |  |     |
|-------------|--|-----|
| Figure 5.15 | Red Sea traffic. . . . .   | 85  |
| Figure 5.16 | Pareto frontier for all threat configurations. . . . .   | 89  |
| Figure 5.17 | Threat detections and interceptions (swarm of Shahed-136 and un-<br>manned surface vessels). . . . .               | 90  |
| Figure A.1  | Vector network analyzer. . . . .   | 101 |
| Figure A.2  | Shahed-136 shape and main dimensions. . . . .  | 103 |
| Figure A.3  | Arash-2 shape and dimensions. . . . .  | 104 |
| Figure A.4  | Radar cross-section behavior. . . . .  | 105 |
| Figure A.5  | Unmanned aerial system radar cross-section approximations. . .   | 106 |
| Figure B.1  | Weapon envelope and threat position for engagement evaluation.   | 118 |
| Figure B.2  | Miss distance of various launch angles of the chain gun with 30 ×<br>173 mm versus unmanned aerial system. . . . . | 122 |
| Figure B.3  | Uncertainty of launch angle effect on miss distance. . . . .   | 122 |
| Figure B.4  | Detonation zones around the target. . . . .  | 124 |
| Figure B.5  | Propagator path length under detonation zones along respective en-<br>trance and departure points. . . . .         | 125 |
| Figure B.6  | Path lengths inside detonation zones for probability of fusing calcu-<br>lation. . . . .                           | 126 |

---



---

## List of Tables

---

|           |  |     |
|-----------|--|-----|
| Table 1.1 | Relevant stakeholders and their interests. . . . .                                   | 15  |
| Table 2.1 | Counter unmanned above surface vehicles alternatives sensors and mitigators. . . . . | 20  |
| Table 2.2 | Characteristics and limitations of sensors. . . . .                                  | 21  |
| Table 2.3 | Characteristics and limitations of mitigators. . . . .                               | 21  |
| Table 3.1 | Summary of system functions. . . . .   | 37  |
| Table 3.2 | Summary of system requirements. . . . .  | 39  |
| Table 4.1 | Summary of threat unmanned aerial systems. . . . .                                   | 43  |
| Table 4.2 | Summary of threat unmanned surface vehicles. . . . .                                 | 44  |
| Table 4.3 | Calculated radar cross-section values. . . . .                                       | 44  |
| Table 4.4 | Consolidated list of alternative systems. . . . .                                    | 45  |
| Table 4.5 | Mk-45 with hyper velocity projectile performance parameters. . .                     | 51  |
| Table 4.6 | Griffin Missile System performance parameters. . . . .                               | 55  |
| Table 4.7 | Mk-45 with high-velocity projectile performance parameters. . . .                    | 59  |
| Table 4.8 | Mk44S with 30 × 173 mm performance parameters. . . . .                               | 62  |
| Table 5.1 | Probability of kill for each interceptor and threat. . . . .                         | 77  |
| Table 5.2 | Input parameters for calculating the number of escorts required. .                   | 86  |
| Table 5.3 | Cost summary. . . . .  | 87  |
| Table A.1 | Radar cross-section values for group III unmanned aerial systems.                    | 102 |
| Table A.2 | Radar system detection data. . . . .   | 114 |

|           |   |     |
|-----------|---|-----|
| Table B.1 | Threat attributes used in $P_K$ assessment. . . . .   | 117 |
| Table B.2 | Calculated fragment velocities at detonation. . . . .   | 119 |
| Table B.3 | Calculated fragment spray angles. . . . .   | 120 |
| Table B.4 | Geometric parameters for alternatives against the Shahed-136 un-<br>manned aerial system. . . . . | 123 |
| Table B.5 | Geometric parameters for alternatives against the Arash-2 unmanned<br>aerial system. . . . .      | 124 |
| Table B.6 | Geometric parameters for alternatives against the Sea Baby unmanned<br>surface vessel. . . . .    | 124 |

---

---

## List of Acronyms and Abbreviations

---

|                |  |
|----------------|--|
| <b>2D</b>      | two-dimensional                                |
| <b>3D</b>      | three-dimensional                              |
| <b>AGL</b>     | above ground level                             |
| <b>AGS</b>     | Advanced Gun System                            |
| <b>AIS</b>     | automatic identification system                |
| <b>AMDR</b>    | Air and Missile Defense Radar                  |
| <b>AMP</b>     | analytical master plan                         |
| <b>APKWS</b>   | Advanced Precision Kill Weapon System          |
| <b>ASBM</b>    | anti-ship ballistic missile                    |
| <b>ASCM</b>    | anti-ship cruise missile                       |
| <b>BDD</b>     | block definition diagrams                      |
| <b>C2</b>      | command and control                            |
| <b>CENTCOM</b> | U.S. Central Command                           |
| <b>CONOPS</b>  | concept of operations                          |
| <b>CSIS</b>    | Center for Strategic and International Studies |
| <b>CTF</b>     | Combined Task Force                            |
| <b>DDG</b>     | guided missile destroyer                       |
| <b>DoD</b>     | Department of Defense                          |
| <b>DWT</b>     | deadweight tonnage                             |

|             |  |
|-------------|--|
| <b>EMRG</b> | electromagnetic railgun                        |
| <b>EOS</b>  | Electro Optic Systems                          |
| <b>ER</b>   | extended range                                 |
| <b>EW</b>   | electronic warfare                             |
| <b>FSPL</b> | free space path loss                           |
| <b>GMS</b>  | Griffin Missile System                         |
| <b>HDM</b>  | Hypersonic Detection Mode                      |
| <b>HMX</b>  | High Melting eXplosive                         |
| <b>HVP</b>  | high-velocity projectile                       |
| <b>IBD</b>  | internal block diagram                         |
| <b>ISR</b>  | intelligence, surveillance, and reconnaissance |
| <b>MANA</b> | Map Aware Non-Uniform Automata                 |
| <b>MAST</b> | Mission Analysis and Simulation Toolset        |
| <b>MOE</b>  | measure of effectiveness                       |
| <b>MOP</b>  | measure of performance                         |
| <b>MSC</b>  | Military Sealift Command                       |
| <b>MSL</b>  | mean sea level                                 |
| <b>NATO</b> | North Atlantic Treaty Organization             |
| <b>NIF</b>  | Navigation Plan Implementation Framework       |
| <b>NSFS</b> | naval surface fire support                     |
| <b>ODIN</b> | Optical Dazzling Interdictor Navy              |
| <b>OV</b>   | operational viewpoint                          |

|                |  |
|----------------|--|
| <b>PABM</b>    | Programmable Air Burst Munition                                  |
| <b>PBX</b>     | polymer bonded explosive   |
| <b>PESTLE</b>  | political, economic, social, technological, legal, environmental |
| <b>PETN</b>    | Pentaerythritol Tetranitrate                                     |
| <b>PRF</b>     | pulse repetition frequency                                       |
| <b>RCS</b>     | radar cross-section  |
| <b>RDX</b>     | Research Department Explosive                                    |
| <b>RF</b>      | radio frequency  |
| <b>RWS</b>     | Remote Weapon Station  |
| <b>SE</b>      | systems engineering  |
| <b>SEA</b>     | systems engineering analysis                                     |
| <b>SM</b>      | standard missile   |
| <b>SNR</b>     | signal-to-noise ratio  |
| <b>TEU</b>     | twenty-foot equivalent unit                                      |
| <b>TOC</b>     | total ownership cost   |
| <b>TRL</b>     | technology readiness level                                       |
| <b>UAS</b>     | unmanned aerial system   |
| <b>UK</b>      | United Kingdom   |
| <b>ULCC</b>    | ultra large crude carrier  |
| <b>ULCV</b>    | ultra large container vessel                                     |
| <b>USV</b>     | unmanned surface vessel  |
| <b>UUV</b>     | unmanned underwater vehicle                                      |
| <b>VAMPIRE</b> | Vehicle-Agnostic Modular Palletized ISR Rocket Equipment         |

THIS PAGE INTENTIONALLY LEFT BLANK

---

---

## Executive Summary

---

The employment of unmanned systems has historically been an effective method of offense and defense in Naval warfare. Unmanned surface vessels (USVs) and unmanned aerial systems (UASs) have undergone rapid expansion in technological advancements, stealth and speed capability, and tactical employment on a battlefield. As such, these systems are being utilized by enemies to the United States and their allies in both single and swarm warfare to attack merchant container vessels transiting normal shipping routes composed of mainly narrow Straits and contested Seas. The capability gap lies in the effective defenses of these merchants against USVs and UASs that require transit through contested spaces. Without proper defenses, the shipping being redirected will disrupt commerce and trade around the region of concern and increase insurance rates of the merchant marine companies that cannot be redirected.

The background focus of this study was chosen as the Red Sea conflict between the Houthi rebels in Yemen and shipping traffic from the Gulf of Aden, through the Bab Al-Mandeb Strait and into the Red Sea. It was found that the Houthi have an abundance of unmanned systems they have purchased from their allies, mainly Iran, that are very cheap to build and cheap to employ. Defense of the merchants in this area against USVs and UASs, especially those representing allied countries of the U.S., has been limited to help from neighboring Naval ships which house standard missiles (SMs) as their primary weapon system. There lies the true nature of the capability gap, the use of a SM-2 or -6 which costs the Navy upwards of millions of dollars apiece to launch against a swarm of very evasive and extremely cheap UAS ridden with highly explosive material directed at a transiting merchant ship. Though the SMs have a very high success rate of intercepting the UAS systems, it costs a great deal more to defeat one UAS than is feasible for long term unmanned warfare.

The team design effort was conducted under methods introduced in the Systems Engineering processes. This starts with an understanding of the problem including the current state of the Red Sea conflict and the unmanned systems in question, followed by the determination of the systems that may be involved in defense, and finally the design of a systems of systems to act as a layered defense for merchants in transit. During this process, requirements and measures of performance and effectiveness were determined to ensure the designed systems

would be both efficient at ensuring survival of the merchants, and cost effective by way of the ammunition and loadout needed to do so.

Having the design space of defense against unmanned systems being a very real and very current Naval warfare problem in the Red Sea, the architecture of the defense systems was limited to only high technology readiness level (TRL) detection and weapon platforms. The architecture team developed a concept of operations that requires detection of the incoming threat by a Naval ship in the vicinity of the Bab Al-Mandeb Strait, followed by the employment of a long range engagement weapon system from the same Naval ship. Given the interception fails from that, there will be the employment of a smaller short range weapon system from an escort vessel alongside the merchant under attack. Thus, the layers of the systems consist of detection and multiple engagement opportunities.

The design team of this project sought to analyze alternative systems to be used within the defensive layers of the concept of operations. They deduced that the most appropriate systems to study were two full developed and operation radar systems, the AN/SPY-6 and the Sea Giraffe, a comparison of the currently employed SMs to an alternative high-velocity projectile (HVP) suited for U.S. Naval Destroyer employment, followed by the analysis of three different weapons that would be suitable for employment on a very small unmanned surface escort vessel; the Griffin Missile, the VAMPIRE Rocket, and a 30mm x 173mm chain gun based on the EOS Titanis system. This analysis of alternatives took place by way of a simulation formed in Simio technology. By creating various scenarios involving different threat profiles from single USVs up to swarm UASs, the analysis team was able to compare different system results using measures of performance and effectiveness. Each scenario was performed as a 30-day period with 50 runs to obtain probabilistic estimations of these results. The variations of system employment in the defensive layers against the differing threat profiles resulted in 96 scenarios to compare and analyze.

The in-depth analysis of every scenario resulted in the team's determination that there is in fact a layered defensive approach from the systems analyzed that results in an effectiveness of merchant defense comparable to the current SM defenses being employed in the Red Sea. This architecture would also be at a significantly lower cost both in operation and acquisition. The optimal configuration for the systems of systems consisted of the use of the currently employed AN/SPY-6 radar, a salvo operation of HVP missiles from the Naval

ship and an unmanned escort vessel for each merchant integrated with the 30mm x 173mm chain gun.

These results can be translated to conclude several useful aspects regarding the defense of merchants against unmanned systems. It proves that multiple layers of weapon employment are required to match the potential of only the highly capable SM, including the recognition that a salvo of smaller and less advanced missiles may be required but would still perform comparably when paired with the secondary escort layer. This has to be paired with the use of the larger and more capable radar, the AN/SPY or similar, operating with performance specifications like those used in this project. It also infers that the very short-range employment of a chain gun system, like the one used in this study and likely with bursts of munition shot at a time, increases survivability significantly. And last, that the chain gun employment is required as a directly adjacent system with the merchant under attack. This last point infers that the gun is a system integrated onto an escort vessel transiting with the merchant or on the merchant ship itself. Given the escort vessel is chosen, as the Navy would be capable of employing and controlling this, the procurement and acquisition of such should focus on unmanned escorts capable of integration and housing of a gun system. The makeup of this layered defensive system of systems has proven to be a cost effective and highly capable suite for merchant protection against USVs and UASs.

THIS PAGE INTENTIONALLY LEFT BLANK

---

---

# CHAPTER 1: Introduction

---

Unmanned airborne, underwater, and surface vessels have rapidly grown as an effective asset to military warfare tactics and missions. They can range from large, fully autonomous and technologically advanced platforms down to inexpensive, dispensable but highly destructive small crafts. Their missions can consist of a combination of intelligence and surveillance gathering, weapon storage and release, and offensive kamikaze warfare. While unmanned systems development and implementation has been rapidly advanced in the recent decade, research in counter measures to these systems has been much slower and less refined. There is a need for the assessment of possible solutions for countering unmanned vessel attacks with cost effective solutions.

This chapter describes the unmanned threats and establishes the need for considering defensive systems against them. The overview of the threats begins with a description of current day warfare tactics being implemented that utilize unmanned systems as weapons of destruction, including the victims they are most likely to target. With an understanding of the threats performing attacks and the targets to defend, this chapter then defines a proposed concept of operations (CONOPS) for the assumed warfare area of operations and the process the team will implement to determine a systems engineering solution.

## **1.1 Motivation for Study**

Unmanned systems allow military personnel to avoid risk. Historically, unmanned crafts have been used for intelligence, surveillance, and reconnaissance (ISR), precision strikes with loaded munitions, logistics support or communications relays and, in more modern conflicts, in electronic warfare operations. The threats of unmanned vessels in today's warfare are highlighted by the Russo-Ukraine conflict and the ongoing conflict in the Red Sea instigated by Houthi forces in Yemen attacking shipping [1]. These conflicts demonstrate the importance of the size and shape of unmanned systems in their ability to go undetected until very close range to their target, the cost effectiveness of using cheap materials without concern for recovery of the pilots or crafts once expended for a mission, and the difficulty

in defending against them when operated at great speeds or in swarm tactics. This capstone project uses the details and environment from the Red Sea as a backdrop for analysis of a defensive system of systems against unmanned system attacks.

The civil war in Yemen has been ongoing since the 2014 Houthi takeover of the capital, Sanaa. The Iranian-backed Houthi rebels comprise one faction, and the recognized government of Yemen, backed by a Saudi-led international coalition, the other. Following the October 7, 2023 terrorist attacks on Israel and subsequent Israel-Hamas war in Gaza, the Houthis stated their support for the Palestinians and warned the U.S. not to intervene in the conflict, before officially entering the war themselves [2]. In pursuit of a pressure campaign targeting the U.S. and its allies, the Houthis have launched more than 100 drone and missile attacks against merchant ships in the Red Sea with a focus area displayed by red data points in Figure 1.1. Merchant ships have been sunk, seized, and set on fire while several civilian mariners have been killed. As a result, insurance costs have surged from 0.7% to 2% of a vessel's value per voyage with some insurers refusing to underwrite vessels deemed at-risk of attacks [3].

The Red Sea has become a high-risk maritime corridor due to this surge in attacks launched by Houthi rebels from Yemen. Since November 2023, these attacks have concentrated near the Bab al-Mandab Strait, a critical chokepoint for global shipping [4]. Although initially framed as a response to the war in Gaza, investigations have shown that most attacked ships had no links to Israel, indicating a broader disruptive intent.

In April 2024, Secretary of the Navy, the Honorable Carlos Del Toro testified to the Senate Subcommittee on Appropriations that Naval forces operating against threats in the Red Sea has accumulated a cost “approaching \$1 billion in expenditures for munitions” [5]. He specifically cited the employment of standard missiles (SMs) SM-2, SM-6, and SM-3 to counter the variety of anti-ship threats. Open-source analysis from the Center for Strategic and International Studies (CSIS) determined these defense systems are at least twice as costly as the threats they are intercepting [6]. The cost of fighting for defense in the Red Sea currently heavily outweighs the cost of the drones being launched by the Houthi, creating an asymmetry in which nations with low-cost weapon systems can challenge larger and more advanced navies.

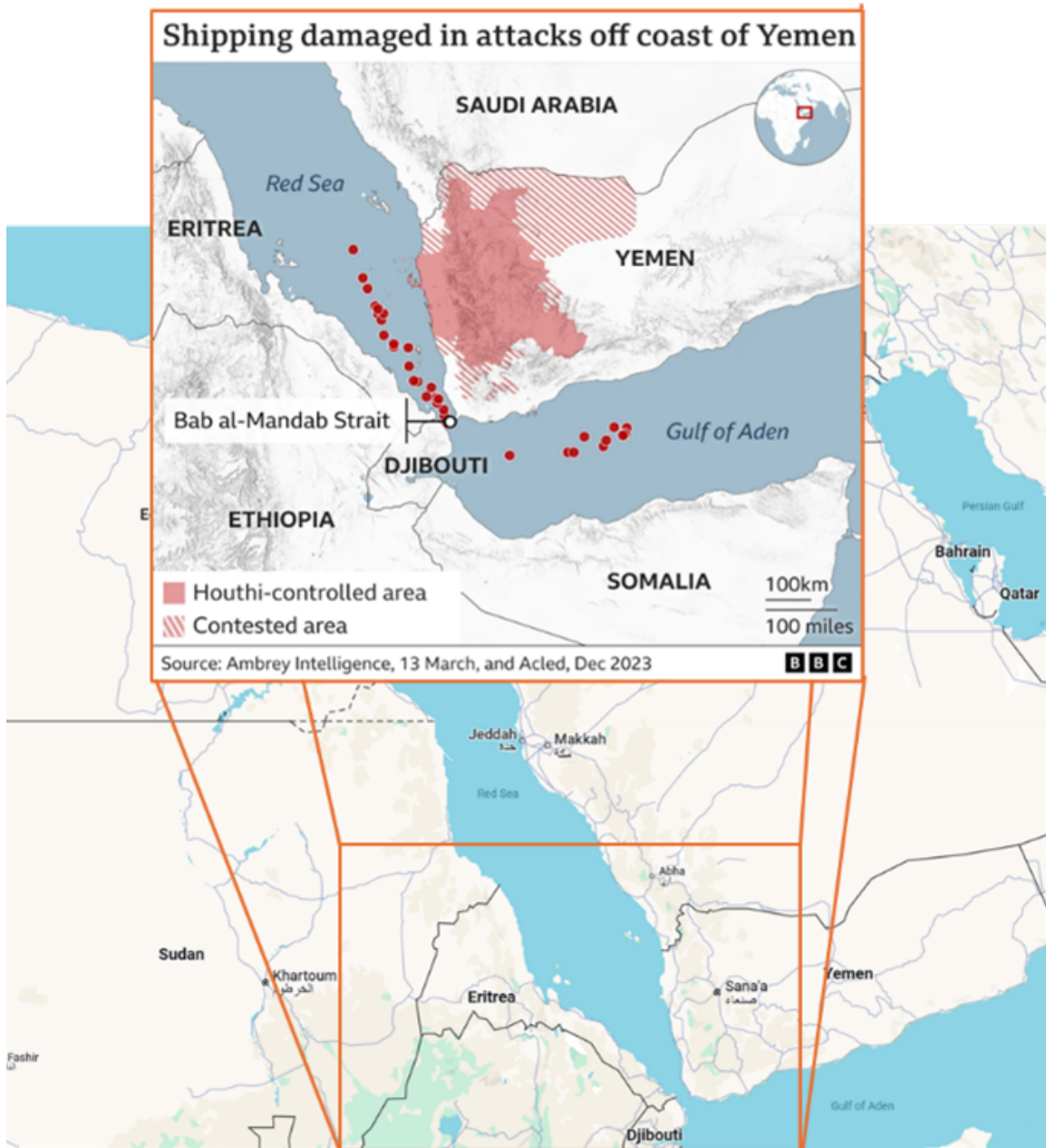


Figure 1.1. Geographic concentration of Houthi attacks on commercial shipping. Source: [7].

### **1.1.1 Problem Description**

The advanced technology of unmanned systems is increasingly threatening in today's warfighting domains. The current tensions in the Red Sea civil war show the use of unmanned aerial and surface vessels as ISR assets, store loaded weapon launch platforms and self-destruction bombs. These vehicles are being used both individually as an attack method or combined with the launch and attack using anti-ship cruise missile (ASCM) and anti-ship ballistic missile (ASBM). In the Red Sea conflict, the unmanned aerial systems (UASs) and unmanned surface vessels (USVs) are targeting merchants and Military Sealift Command (MSC) ships. Current defense measures for the merchant traffic are less than ideally effective and very costly. The Red Sea conflict has highlighted the need for alternative cost-effective solutions against the unmanned system threats.

### **1.1.2 Tasking Orders**

The project team is tasked via the Memorandum for systems engineering analysis (SEA) Cohort 34, focusing on a capability gap provided by the Integrated Warfare (N9I) Office of the Chief of Naval Operations (OPNAV), with the following specific areas:

1. Define the functions and performance of defensive systems against uncrewed air and surface threats.
2. Develop alternative architectures to meet the system functions.
3. Evaluate the alternative architectures for performance and cost effectiveness including acquisition costs, manning estimates and defense effectiveness against varying levels of uncrewed air and surface threats.

## **1.2 Background**

The Red Sea conflict, the assumed environment for the scope of this study, has seen a variety of unmanned vessels being used to threaten merchant traffic. The Department of Defense (DoD) classifies UASs in five groups, as shown in Figure 1.2, [8]. They provide a representative U.S. or U.S. allies' UASs in each group, for reference. For the analysis of attacks in the Red Sea conflict, groups I, II and III are applicable specifications for the technology being implemented by the Houthi. Groups IV and V will not be regarded for the purpose of this project analysis of defense systems, which tend to range in destructive

abilities closer to the ASCM or ASBM weapons being launched. Those higher destruction, more expensively produced weapons, are beyond the scope of determining a defensive system of systems against the more crude, small and cheap designs that pose a threat.


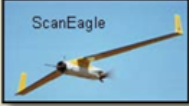
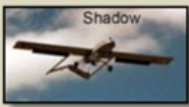

| UAS Groups | Maximum Weight (lbs) (MGTOW) | Normal Operating Altitude (ft)                   | Speed (kts) | Representative UAS              |   |
|------------|------------------------------|--|-------------|---------------------------------|---|
| Group 1    | 0 – 20                       | <1200 AGL  | 100         | Raven (RQ-11), WASP             |    |
| Group 2    | 21 – 55                      | <3500 AGL  | < 250       | ScanEagle                       |    |
| Group 3    | < 1320                       | < FL 180   |             | Shadow (RQ-7B), Tier II / STUAS |    |
| Group 4    | >1320                        |  | > FL 180    | Any Airspeed                    | Fire Scout (MQ-8B, RQ-8B), Predator (MQ-1A/B), Sky Warrior ERMP (MQ-1C)               |
| Group 5    |                              | Reaper (MQ-9A), Global Hawk (RQ-4), BAMS (RQ-4N) |             |                                 |  |

Figure 1.2. DoD UASs classification guide. Source: [9].

There have been varying reports on the methods of UAS attacks by the Houthi in the Red Sea, mainly involving either bomb carrying drones that can drop their payload on a defenseless victim or a kamikaze-like strike of the drone on the victim, also carrying a payload that explodes on contact. For simplicity in this project study, we assume that an incoming threat UAS drone will not use their ability to launch a guided munition and thus, the UAS acts as a missile being launched at the merchant. This simplified assumption is within the scope of Houthi and Ukraine tactics being implemented for kamikaze warfare and allows only one variable to need to be considered. So, upon detection and engagement of the incoming threat UAS, that vessel will be the target of the offensive attack by allied systems.

Along with UASs, the conflict has shown the presence of USV attacks [10]. Reports have noted the USVs operating in a similar one-way mission to the UASs, carrying an explosive payload that is assumed to detonate on contact with the victim vessel or upon command by its controlling station on land. There have also been reports of the USVs carrying personnel who threaten the vessels with boarding and a piracy-like takeover of the merchant crew [11]. Based on the greater USV threats noted in the Black Sea involved with the Russian-Ukraine conflict [4], many assumptions regarding the method of USV employment by Houthi forces will be based on these more conservative, advanced techniques. This assumption lies on the underlying notion that the Houthi, and Middle Eastern warfare in general, will procure access to these advanced USV weapon systems in due time. It also lies on the basis that Ukraine's primary USV for attack, the Magura V-5 shown in Figure 1.3, can be researched in open-source data for specifications and methods of destruction. Notably, the Houthi USVs being used for terrorism are larger with smaller payloads, while the Magura has an extremely low signature, and a larger payload meant to attack a military vessel. This project will use specifications from the Sea Baby shown in Figure 1.4. Of note, the presence of underwater vehicles and warfare has not been as relevant in the Red Sea conflict, thus unmanned underwater vehicle (UUV) threat attacks will not be considered for this project as they have a much more diverse scope of study required.

Though naval vessels, both U.S. ships and allies, have been involved in the conflict and are allegedly targeted, the Houthi party continues to assure that military ships are not their targets for attack. The focus of this project will be on defending the merchant and MSC vessels in the Red Sea, without consideration for the launched drones toward Naval warships. It will be assumed that all attacks are made at the merchants in the vicinity. This introduces another assumption in the study, that applying a self-defense system directly from the merchant poses political and economic questions about the feasibility and lawful operations of weapons systems on civilian manned ships. It is not beyond the scope that merchant companies may access the results of this project and take self-defense into consideration. But as for military applications, the likelihood of self-defense measures being implemented is extremely low. The project makes the assumption the merchant ships do not have onboard self-defense systems against UAS or USV attacks.



Figure 1.3. Magura USV technical details. Source: [12].



Figure 1.4. Ukrainian Sea Baby naval drone. Source: [13].

## 1.2.1 Operating Environment

The geographical features and terrain of the Red Sea form the basis of our backdrop for this project study and are used as the operating environment for the simulation study. This includes the boundaries of where the simulation ends geographically, the locations of potential UAS or USV launch sites and their abilities, and for a determination of factors such as how long it takes a threat to reach a merchant ship traveling through at a certain speed in a given environment.

The Red Sea is a major artery for international maritime traffic. Its north-south length is about 2,300 kilometers (1,430 miles). At its widest point, it has a maximum east-west width of 355 kilometers (220 miles). The depth is variable, with maximum depth of around 3,040 meters (9,970 feet) in the central parts, and shallow waters (less than 200 meters or 660 feet deep) near the coastlines. The narrowest part of the Red Sea is the Bab el-Mandab Strait, at the southern end, which ranges from 18–26 kilometers (11–16 miles). The Suez Canal, at the northern entrance, is a key choke point for global trade, providing a direct link between the Red Sea and the Mediterranean Sea with transit routes shown in Figure 1.5. Its geographic location between three continents makes the Red Sea a strategic maritime route, while congestion within its limited navigable area creates operational risk.



Figure 1.5. Transit route of oil tankers from the Strait of Hormuz to the Suez Canal. Source: [14].

The Red Sea is bordered by nine countries: Egypt, Sudan, Eritrea, Djibouti, Saudi Arabia, Yemen, Jordan, Israel, and Somalia. Egypt controls the Suez Canal, while Saudi Arabia and Yemen dominate the eastern and southern coasts, respectively. Political instability affects several bordering nations, including Yemen, Sudan, and Somalia, where ongoing civil war threatens maritime security. Low-level international conflict persists between Saudi Arabia and Iranian-backed Houthi forces in Yemen. Djibouti hosts military bases from the U.S., China, and France. From Djibouti to the most northern point of the Red Sea is 1,100 nautical miles.

The Sea State is generally calm in the Red Sea, with wave heights averaging 1–2 meters (Beaufort Scale of 4 or less) in the Red Sea and Gulf of Aden. For that reason, high seas are not considered in the simulations.

There is a general problem with dust and persistent haze in the Red Sea area that can affect radar and laser sensor operation onboard military vessels, dependent upon the frequency ranges. This project commences with an optimistic assumption of minimal cloud, haze and dust for optimal sensor operation, but given the capacity limits, degraded conditions are also considered. Good, but not excellent, visibility for flight operations is typical, except during dust storms.

## **1.2.2 Merchant Vessel Traffic Impact**

The escalation in Houthi attacks within the Red Sea region has led to several far-reaching consequences for the global maritime and geopolitical landscape. One of the most immediate impacts has been a sharp surge in global shipping prices. As shipping companies reroute vessels [15] to avoid high-risk areas such as the Bab al-Mandab Strait, longer transit times and increased fuel consumption have driven up operational costs, which in turn are passed on to consumers through higher freight rates and commodity prices. Commercial shipping patterns have undergone significant realignment and reduction, as shown in Figure 1.6. To mitigate exposure to potential missile and drone attacks, a growing number of shipping companies have opted to bypass the Red Sea altogether, instead rerouting vessels around the Cape of Good Hope. While this alternative reduces risk, it also adds considerable time and cost to shipping operations, further exacerbating the global supply chain strain. A report from the International Transport Forum noted that transit through the Bab al-Mandab Strait

dropped by approximately 55% between 1 Nov 2023 and 28 Feb 2024 [16]. This has been particularly evident among bulk carriers, crude oil tankers, and container ships, the vessel types most frequently transiting the region, as shown in Figure 1.7.

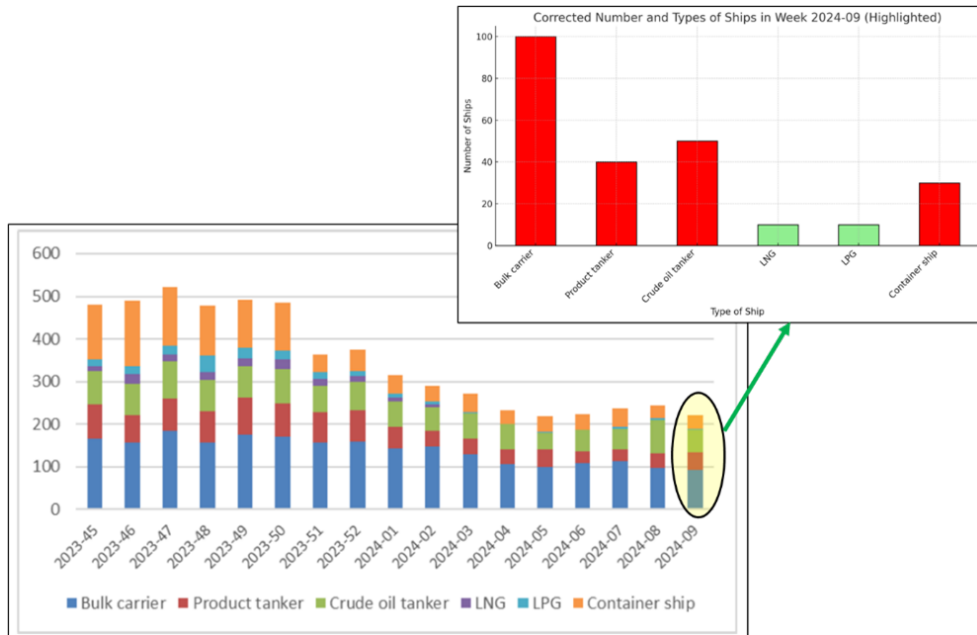


Figure 1.6. Visible decrease in Red Sea vessel traffic due to Houthi attacks. Source: [16].

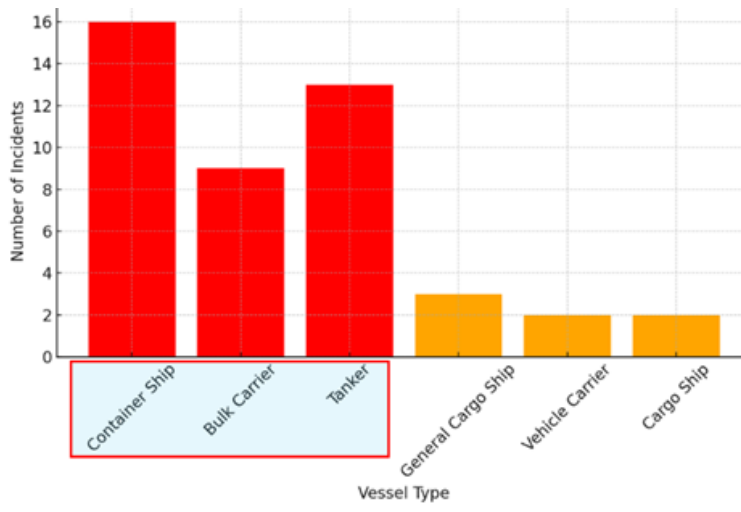


Figure 1.7. Most targeted vessel type in Houthi attacks. Source: [16].

Merchant ships, including container vessels, oil tankers, and general cargo carriers, dominate the maritime landscape of the Red Sea, with traffic patterns through the environment displayed in Figure 1.8. Container ships, ranging from feeder vessels under 1,000 twenty-foot equivalent unit (TEU) to ultra large container vessels (ULCVs) exceeding 20,000 TEU, are vital for moving consumer goods worldwide. Oil tankers, categorized from Handysize—under 50,000 deadweight tonnage (DWT)—to ultra large crude carriers (ULCCs) exceeding 320,000 DWT, are essential for global energy supplies. Bulk carriers, transporting raw materials like coal, iron ore, and grain, represent over half the world’s merchant fleet by capacity.

MSC vessels, critical for logistical and operational support, include prepositioning ships, fleet oilers, and cargo transport vessels. These ships are designed to meet military demands, particularly in high-threat regions like the Red Sea, but remain vulnerable to modern threats such as precision missiles and drone swarms.

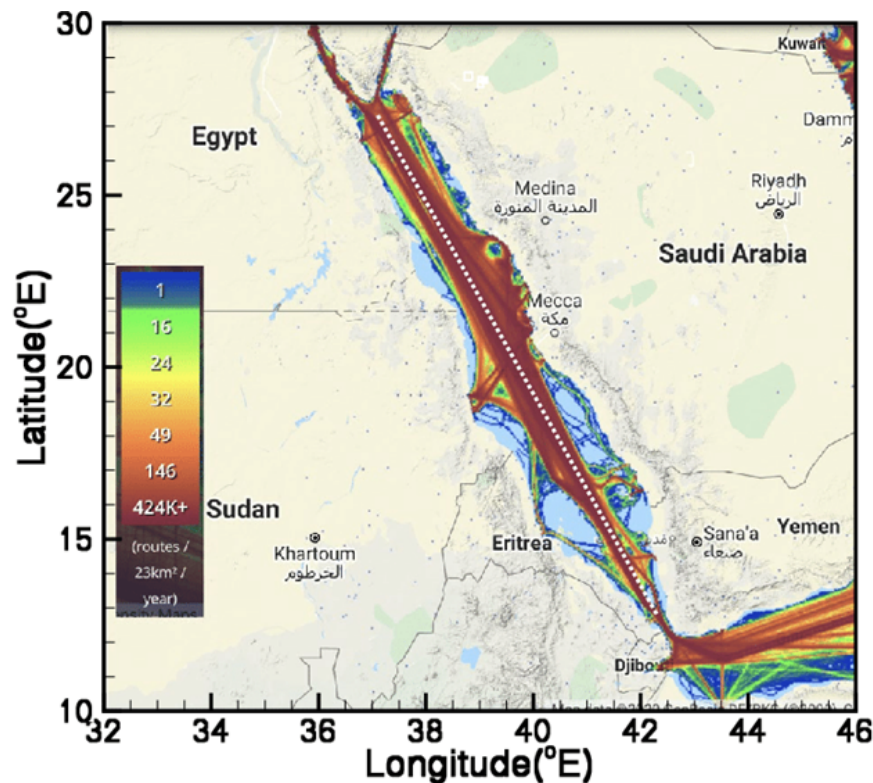


Figure 1.8. Maritime traffic density contours. Source: [17].

### 1.2.3 Port of Djibouti

The primary chokepoint in the Red Sea borders the Gulf Aden and a strategic airfield in Djibouti. This airfield is shared by both the U.S. and French armed forces, with a plethora of manned and unmanned sorties flying in and out daily, as well as regularly scheduled civilian airline flights. Thus, aerial traffic in the region can be quite complex. There is also a Chinese port next to this airfield; however, this port does not have capability to launch or recover aircraft. The figure below, Figure 1.9, summarizes the military base complexities in the Red Sea vicinity. With allied bases within the threat axis, the use of Djibouti as a communication and control node can be considered within the scope of naval assets operating in the Bab Al-Mandeb Strait.



Figure 1.9. Military base locations in the proximity of the Red Sea conflict. Source: [18].

### 1.3 Concept of Operations

Defensive measures shall be implemented to include the ability to employ an offensive kill chain against an incoming threat UASs or USVs directed toward a merchant or MSC vessel. Combat weapons system employment on a direct escort vessel in the form of an allied USV for the merchant ship, or on a neighboring escort Naval vessel, a guided missile destroyer (DDG), in the area of operation, will have the ability to apply their respective systems in a single or layered defensive protection measure. The system of systems among these assets will include communication, detection, tracking, and engagement of the incoming target in motion directly toward the target merchant vessel. The detection will occur on the naval vessel, with a communication link to the escort vessel either directly or via nearby land bases in Djibouti. The naval vessel will determine if it can use its onboard defensive measures against the threat based on range. It will then decide to engage or hand off engagement to the escort vessel closer to the vicinity of the victim merchant. The systems in use shall be responsible for operations against both aerial and surface threats, with an effective range of motion to defend in sufficient time before impact or within a minimum engagement range from the merchant. The operational viewpoint (OV) in Figure 1.10 provides a pictorial representation of the high-level key players and their capabilities needed to ensure mission success.

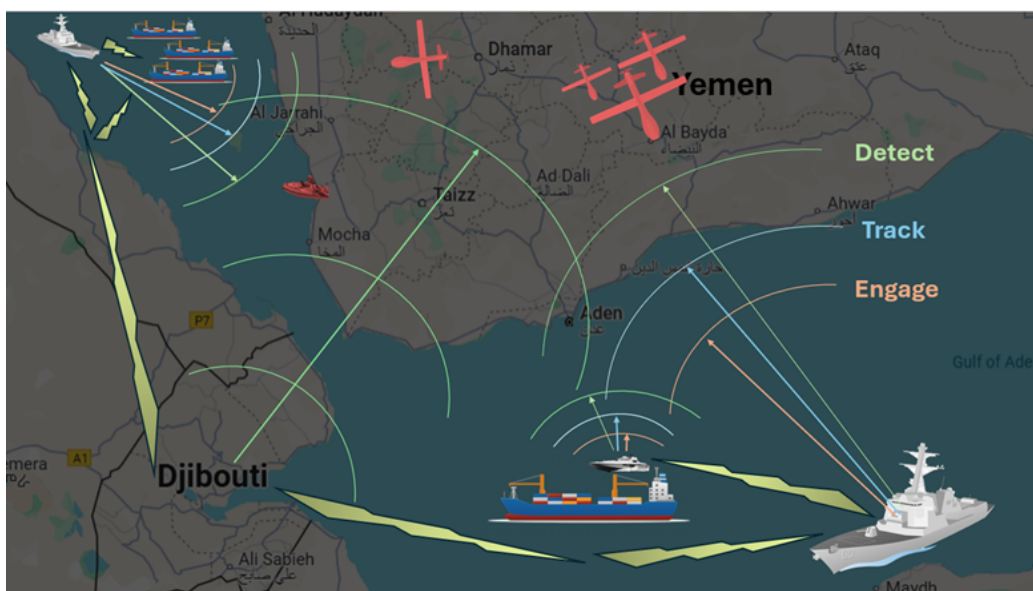


Figure 1.10. OV for layered defensive system of systems.

The CONOPS consists of detection capabilities from the Naval vessel either escorting a merchant convoy directly or alternatively operating as an area defense in the vicinity of the Bab Al-Mandeb Strait with unmanned escorts for each merchant. Based on these alternative viewpoints, engagement of defensive weapons will occur from either the same Naval vessel performing the detection, or from a close in escort allied USV system with the merchant under distress. Enemy UASs may operate as a single vessel or in swarm tactics up to groups of 5, and USVs will be assumed to always operate individually. UASs will be assumed launched from the capital of Yemen, Sana'a, while USVs will be assumed launched from the coastal base of Al Hudaydah on the north side of the West Yemen coast in the Red Sea.

## **1.4 Project Objective**

This project will analyze the structure of a defensive environment that aligns with the analytical master plan (AMP) and within the scope of the Navigation Plan Implementation Framework (NIF). Alternative systems will be identified that meet the specifications of such defensive capabilities on the Naval ships and allied USVs and will be compared using measures of their effectiveness and performance. The conclusion of this project will identify a system of systems defensive structure that optimizes the balance between cost and operational effectiveness for defending merchant vessels using Naval assets.

## **1.5 Systems Engineering Process**

The team followed an agile scrum method of project management, as well as portions of conducting all the activities traditional organized by the Systems Engineering Vee. The agile scrum structure consists of assigning teams of students to tasks, which are documented and tracked using a backlog, over a period called a sprint. Each team worked to complete their task and presents their results during biweekly sprint briefs. A full team presentation was given to stakeholders every six weeks. The project performance loosely followed the Vee model by starting with identifying requirements and determining the concept of operations of the implied system. As this project consisted mainly of an analysis of alternatives, several stages of the Vee model such as design and implementation were not necessary. The team then moved on to an applied simulation modeling stage for verification and validation of the system chosen to meet the requirements.

## 1.6 Stakeholders

Table 1.1 summarizes the key stakeholders for this study. They contributed by providing their needs, capability gaps, and input for our analysis regarding possible solution spaces.

Table 1.1. Relevant stakeholders and their interests.

| Stakeholder                         | Interests and Needs   |
|-------------------------------------|---|
| OPNAV N9I                           | As the sponsor of this project, OPNAV N9I is responsible for warfare integration across multiple domain and is specifically interested in novel solutions to evolving unmanned threats.   |
| MSC                                 | MSC provides logistics support around the world, making it a vital component of national defense. Regional instability coupled with the proliferation of unmanned assets threatens MSC's mission.   |
| Merchant Shipping Community         | Civilian merchant shipping is also affected by this phenomenon and must manage this risk, whether through recruiting or utilization of protective assets.   |
| Surface Warfare Community           | Transport and placement of a new combat weapon system onboard a U.S. Naval vessel, including training of personnel and integration into the ship's structure.   |
| Combatant Commanders                | Open sea lanes are vital for logistics throughput, ensuring local combatant commanders are equipped with the required resources to carry out their missions. Alternatively, possible solutions may include the use of resources already present within these respective areas of responsibility.  |
| Port Authorities                    | Any defensive weapon system may be subject to local regulations when ships are within local ports. These regulations vary drastically throughout the world and may require exemptions for possible systems within our solution space.   |
| Marine Expeditionary Units          | Marine expeditionary units are responsible for rapid response around the world and require transit on amphibious naval ships. Therefore, the ability to transit unstable regions is a direct requirement to accomplish their mission.   |
| International Maritime Organization | A solution to protecting merchant vessels from modern unmanned threats would be of interest to the maritime community worldwide, potentially being adopted or further studied to increase merchant security as they transit unstable regions.   |
| Foreign Navies <sup>†</sup>         | Ensuring the safety of commercial shipping, taking part in the coalition against Houthi attacks "Operation Prosperity Guardian."  |
| Marine Littoral Regiments           | The problem addressed in this project has dynamic implications for the expeditionary advanced base operations concept the Marine Corps is currently preparing to implement. At the edge of this concept are Marine littoral regiments, who have the potential to directly affect and be affected by regional offshore stability, especially in the context of unmanned threats. |
| Defense Technology Sector           | Defense contractors, such as Raytheon and Lockheed Martin, among many others, would likely be interested in further researching and fielding a design for any new technological requirements, especially if they come from a concept that is of interest to the Navy.   |

<sup>†</sup> Bahrain, Canada, France, Italy, Netherlands, Norway, Seychelles, Spain, United Kingdom (UK)

## **1.7 Organization of the Capstone Report**

Chapter 2 of this project will focus on the Literature Review performed for analysis on the history of USV and UAS technology, the Red Sea conflict and the merchant and MSC community. Next, Chapters 3 and 4 will outline the systems engineering (SE) methodology and architecture to define the space used for analysis from start to finish. These chapters will cover the basis of the SE process with requirements, definitions, measures of effectiveness (MOPs), and measures of effectiveness (MOEs) for analysis. They will also outline the threat space and aspects of the defensive system that will need to interact, operate in sequence and coordinate for successful kill chain tactics. An overview of the experiment performed and an analysis of the results will be covered in Chapter 5. Finally, Chapter 6 will cover the conclusion and recommendations for system implementation and future work.

---

## CHAPTER 2: Literature Review

---

The proliferation of UASs and their associated threats has introduced significant security challenges in maritime operations, particularly in the Red Sea region. These systems, ranging from small drones to advanced unmanned platforms, are increasingly utilized by various actors, including pirates, insurgent groups, and state-backed entities. Their affordability, operational flexibility, and ease of acquisition have made them ideal tools for asymmetric warfare [19]. Given the strategic significance of the Red Sea as a global trade artery, the increasing incidents involving UASs for surveillance, reconnaissance, and attacks have raised concerns over maritime security [20]. The Bab-el-Mandeb Strait, a key chokepoint, further amplifies these risks due to the high density of shipping traffic and its geopolitical importance.

This review examines the literature on the threats posed by unmanned systems in the Red Sea, the vulnerabilities of merchant vessels, current detection and defense mechanisms, and the challenges faced in mitigating these threats. The integration of radar detection systems, electronic warfare tools, and point defense strategies for countering unmanned threats will also be explored.

### **2.1 Vulnerability of Merchant Vessels**

Merchant ships, primarily designed for commerce rather than combat, are particularly vulnerable to unmanned threats. Their large size, relatively slow speed, limited maneuverability, and small crew complement reduce their ability to detect, respond to, or evade incoming threats. These inherent characteristics make them easy targets for adversaries using low-cost, agile UASs. A major challenge in countering UASs is their low radar cross-section, making them difficult to detect using conventional radar systems [21]. Small drones, for instance, can fly at low altitudes and speeds, often evading existing detection technologies [19]. The vast operational environment of the maritime domain further complicates early threat identification, with vessels often isolated and far from immediate support. Additionally, UASs have been reported to disrupt ship-to-shore communications, hampering navigation and

security coordination [22]. These vulnerabilities expose merchant ships to various threats, including reconnaissance for future attacks, cyber disruptions, and direct kinetic assaults [21].

With the growing threat of unmanned vehicles against both civilian and military targets, much of the research has focused on countering UASs, while efforts against USVs remain underdeveloped. Notwithstanding, counter UAS and USV solutions share many aspects. In Tiurin et al. [23], a general approach to counter unmanned aerial vehicles is demonstrated, with four critical stages: readiness, detection and decision making, influence, and evaluation (see Figure 2.1).

Focusing on the detection and influence stages—tracking, identification, and neutralization—a survey was conducted to identify current and developing technologies for countering UASs and USVs. A summary of these solutions is provided in Table 2.1, which outlines the sensor and mitigator alternatives for surface and aerial unmanned threats.

Further elaboration on these technologies can be found in Table 2.2 and Table 2.3, which summarize the general characteristics, strengths, and limitations of the various sensor types and mitigation techniques, respectively [24]. These comparisons highlight trade-offs that affect the operational feasibility of counter-UASs at sea.

The Red Sea’s unique security challenges necessitate region-specific countermeasures. Its proximity to land-based threats enables both state and non-state actors to launch drone attacks from relatively short distances, increasing the frequency and unpredictability of such incursions [20]. As a major maritime chokepoint with limited space for maneuverability, the Red Sea further restricts evasive actions by vessels, compounding their vulnerability. Environmental factors, such as high temperatures and humidity, also complicate the deployment and operation of detection and defense systems [19]. These conditions emphasize the need for adaptive, resilient solutions that account for technological, geographical, and environmental variables [21].

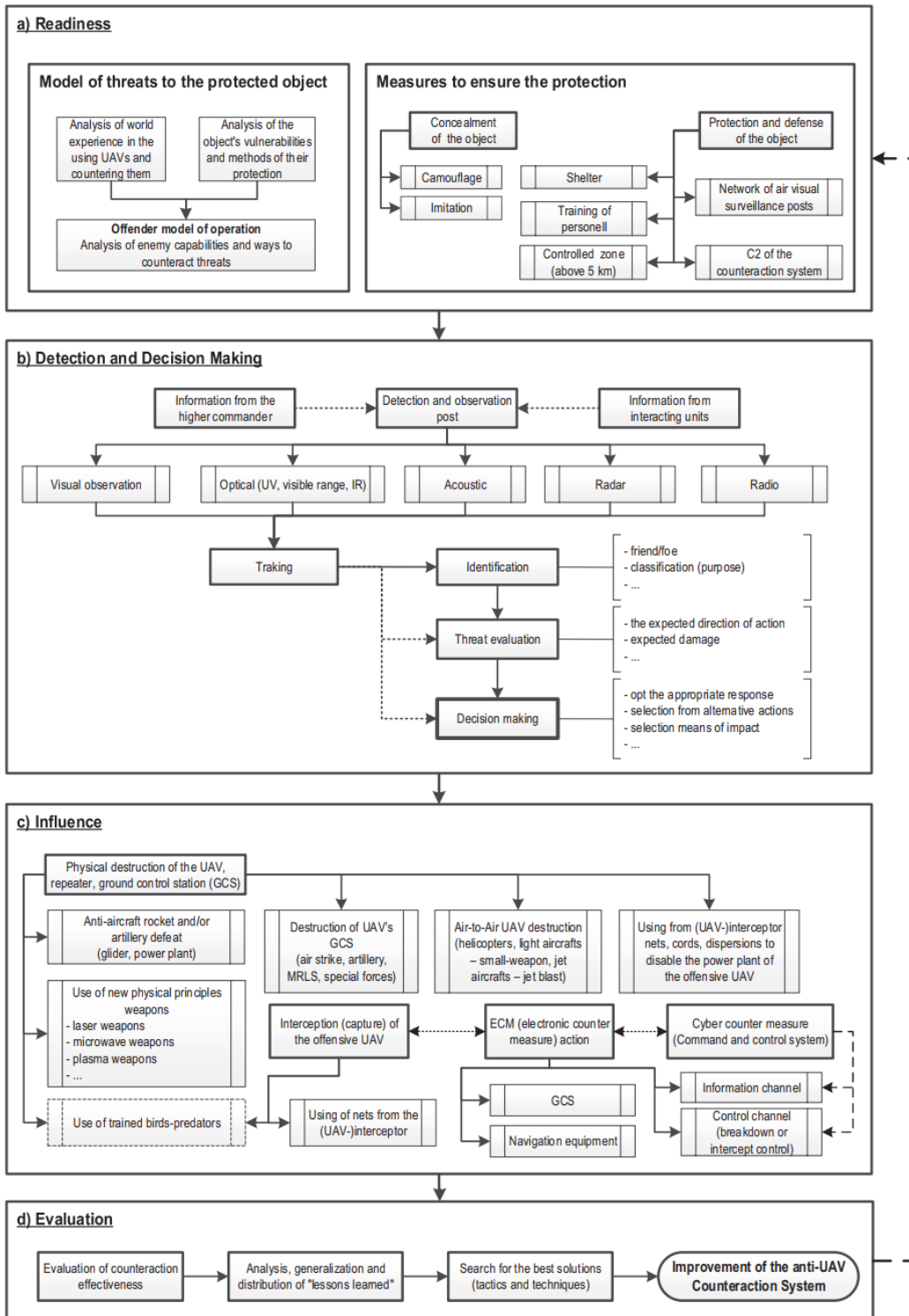


Figure 2.1. General approach to counter-UAS. Source: [23].

Table 2.1. Counter unmanned above surface vehicles alternatives sensors and mitigators.

| System                              | Organization  | Sensors     |                    |                   | Mitigators              |                                |
|-------------------------------------|---|-------------|--------------------|-------------------|-------------------------|--------------------------------|
|                                     |   | Sources     | Type               | Active/Passive    | Category                | Subcategory                    |
| Coyote C-UAS                        | Raytheon  | -           | -                  | -                 | Physical                | Collision UAVs                 |
| Roadrunner-M                        | Anduril   | -           | -                  | -                 | Physical                | Collision UAVs                 |
| Hyper Velocity Projectile (HVP)     | BAE Systems   | -           | -                  | -                 | Physical                | Projectiles                    |
| Precision Guidance Kit (PGK)        | Raytheon  | -           | -                  | -                 | Physical                | Projectiles                    |
| DragonFire                          | British Armed Forces  | -           | -                  | -                 | Nonphysical             | Lasers                         |
| Drone Dome w/ NAVAL IRON BEAM™      | Rafael  | Light Waves | EO/IR              | Passive           | Nonphysical             | RF/GNSS Jamming                |
|                                     |   | Radio Waves | RF sensor<br>Radar | Passive<br>Active | Nonphysical             | Lasers                         |
| LOCUST Laser Weapon System (LWS)    | BlueHalo  | -           | -                  | -                 | Nonphysical             | Lasers                         |
| HELMA-P                             | CILAS   | Light Waves | LiDAR              | Active            | Nonphysical             | Lasers                         |
|                                     |   |             |                    |                   | Nonphysical             | RF/GNSS Jamming                |
| Layered Laser Defense (LLD)         | Lockheed Martin   | Light Waves | EO/IR              | Passive           | Nonphysical             | Lasers                         |
| Compact Laser Weapons System (CLWS) | Boeing  | Light Waves | EO/IR              | Passive           | Nonphysical             | Lasers                         |
| SKYctrl Skid C-UAS                  | Advanced Protection Systems (APS) and MSI Defence Systems                         | Radio Waves | Radar              | Active            | Nonphysical             | Lasers                         |
|                                     |   | Light Waves | EO/IR              | Passive           | Nonphysical             | RF/GNSS Jamming                |
|                                     |   |             |                    |                   | Physical                | Projectiles                    |
| D4 C-UAS                            | Defence Research and Development Organisation (DRDO), Adani Defence and Aerospace | Light Waves | EO/IR              | Passive           | Nonphysical             | Lasers                         |
|                                     |   | Radio Waves | RF sensor<br>Radar | Passive<br>Active | Nonphysical             | RF/GNSS Jamming                |
| Titanis C-UAS                       | Electro Optic Systems (EOS)   | Light Waves | EO/IR              | Passive           | Nonphysical             | Lasers                         |
|                                     |   | Radio Waves | RF sensor<br>Radar | Passive<br>Active | Nonphysical<br>Physical | RF/GNSS Jamming<br>Projectiles |
| SPEAR                               | Leonardo DRS  | Light Waves | EO/IR              | Passive           | Nonphysical             | High-Power EM                  |
| MoRFIUS                             | Lockheed Martin   | -           | -                  | -                 | Nonphysical             | High-Power EM                  |
| CERBERUS® XL C-UAS                  | TELEDYNE FLIR   | Light Waves | EO/IR              | Passive           | Nonphysical             | RF/GNSS Jamming                |
|                                     |   | Radio Waves | RF sensor<br>Radar | Passive<br>Active |                         |                                |

Table 2.2. Characteristics and limitations of sensors.

| Sources     | Sensors                     | Act/Pas | Characteristics & Strength   | Limitations & Weakness   |
|-------------|-----------------------------|---------|--|--|
| Sound Waves | Acoustic/ultrasonic sensors | Passive | <ul style="list-style-type: none"> <li>• 20 Hz–20 kHz, Microphones</li> <li>• Acoustic signature library</li> <li>• Supporting other type of sensors</li> </ul>  | <ul style="list-style-type: none"> <li>• Range is limited</li> <li>• Vulnerable to ambient noise</li> <li>• Capacity limits and updating of libraries</li> </ul>   |
|             | RF sensors                  | Passive | <ul style="list-style-type: none"> <li>• Communication spectrum. Capturing commun. signals between mUAVs and operators</li> <li>• Low complexity and easy to implement</li> </ul>  | <ul style="list-style-type: none"> <li>• Knowledge of mUAV communication specifications, such as modulation protocols and MAC addresses, is desired</li> <li>• Poor target detection reliability</li> </ul>                                  |
| Radio Waves | Radar                       | Active  | <ul style="list-style-type: none"> <li>• 3 MHz–300 G Hz (Operate in cloudy weather)</li> <li>• (FM)CW radar, UWB radar, mmWave radar</li> <li>• Micro Doppler signatures (MDS)</li> <li>• Longer range than LiDAR, Velocity info.</li> </ul> | <ul style="list-style-type: none"> <li>• Large radar cross-section (RCS) is desired</li> <li>• Limited performance for low altitudes and speeds</li> <li>• Interference from other small objects</li> <li>• LoS is highly desired</li> </ul> |
|             | EO/IR                       | Passive | <ul style="list-style-type: none"> <li>• 300 GHz–430 THz (visible spectrum)</li> <li>• EO: visual images, IR: thermal images</li> <li>• EO: day light, IR: w/o day light</li> <li>• Assisted by computer-vision technologies</li> </ul>      | <ul style="list-style-type: none"> <li>• Provides 2D images</li> <li>• Limited by weather cond. &amp; background temp.</li> <li>• Susceptible to positions of objects (horizon)</li> <li>• LoS is required</li> </ul>                        |
| Light Waves | LiDAR                       | Active  | <ul style="list-style-type: none"> <li>• 300 THz–500 THz (light pulse)</li> <li>• Providing 3D representation</li> <li>• Detecting an object in a complex background, i.e., high-resolution detection is possible</li> </ul>                 | <ul style="list-style-type: none"> <li>• LoS is required and the detection range is short</li> <li>• Limited usage in nighttime/cloudy weather</li> <li>• Operating altitude: 500–2,000 m</li> <li>• Expensive technology</li> </ul>         |

Table 2.3. Characteristics and limitations of mitigators.

| Category    | Subcategory     | Characteristics & Strength  | Limitations & Weakness  |
|-------------|-----------------|---|---|
| Nonphysical | RF/GNSS Jamming | <ul style="list-style-type: none"> <li>• Interfering with mUAVs to degrade the received SNR</li> <li>• GNSS signals of mUAVs are weak and vulnerable</li> <li>• Increase the possibility of eavesdropping on mUAVs, which is useful when spoofing them</li> </ul> | <ul style="list-style-type: none"> <li>• Ineffective for autonomous mUAVs</li> <li>• Ineffective for GNSS-robust mUAVs with IMU sensors</li> <li>• Ineffective for encrypted GPS in mUAVs</li> <li>• Short distances are desired</li> </ul> |
|             | Spoofing        | <ul style="list-style-type: none"> <li>• Controlling mUAVs and GNSS spoofing are possible</li> <li>• Exploiting the vulnerabilities of various systems in mUAVs</li> </ul>  | <ul style="list-style-type: none"> <li>• Comm. information regarding mUAVs is required</li> <li>• Solid analysis on mUAVs is required</li> </ul>  |
|             | High-power EM   | <ul style="list-style-type: none"> <li>• Impairing electronic systems via high-power EM waves</li> <li>• Narrowband EM waves: high power on a single frequency</li> <li>• Wideband EM waves: short pulses in the time domain</li> </ul>                           | <ul style="list-style-type: none"> <li>• Accurate direction of EM wave is required</li> <li>• Kill assessment may not be possible</li> <li>• There is a chance of a low lethality rate</li> </ul>   |
|             | Lasers          | <ul style="list-style-type: none"> <li>• Low power lasers: dazzlers</li> <li>• High-power lasers: burn and destroy mUAVs</li> <li>• Tracking of the target is required</li> </ul>   | <ul style="list-style-type: none"> <li>• Sensitive to adverse weather conditions</li> <li>• Accurate direction/aiming is required</li> <li>• Lower cost per shot than physical projectiles</li> </ul>                                       |
| Physical    | Projectiles     | <ul style="list-style-type: none"> <li>• Machine guns, munitions, guided missiles, mortars</li> <li>• Traditional mitigator to neutralize enemies</li> <li>• Quick reaction capability is possible</li> </ul>   | <ul style="list-style-type: none"> <li>• Precise aiming is required considering gravity/wind</li> <li>• High cost per shot</li> <li>• Crashed mUAVs may cause the collateral damages</li> </ul>   |
|             | Collision UAVs  | <ul style="list-style-type: none"> <li>• Collision drones with detecting and tracking capabilities</li> <li>• Hybrid of projectiles and small UAVs</li> <li>• Effective for contiguous small mUAVs</li> </ul>   | <ul style="list-style-type: none"> <li>• Approaching and tracking mUAVs are required</li> <li>• Chasing with low velocity causes mitigation delays</li> <li>• Crashed mUAVs may cause collateral damage</li> </ul>                          |
|             | Nets            | <ul style="list-style-type: none"> <li>• Net cannons and sky platforms carrying nets are possible</li> <li>• Nets equipped with parachutes cause mUAVs to descend safely</li> <li>• Possible to extract info. from an mUAV after capturing it</li> </ul>          | <ul style="list-style-type: none"> <li>• Need to approach mUAVs closely</li> <li>• Effective range for mitigation is short</li> <li>• Accuracy highly depends on environment</li> </ul>   |
|             | Eagles          | <ul style="list-style-type: none"> <li>• Using trained eagles for hunting as mitigators of mUAVs</li> <li>• High technology may not be required</li> <li>• Fewer human resources are required than in other schemes</li> </ul>                                    | <ul style="list-style-type: none"> <li>• Applicable to slower mUAVs and those that are smaller than eagles</li> <li>• Injuries to eagles, ineffective for multiple mUAVs</li> </ul>   |

## 2.2 Counter-Unmanned System Strategies

Recent conflicts have demonstrated the effectiveness of a multi-layered counter-UASs approach combining detection, electronic warfare, directed energy, and kinetic neutralization. Directed energy weapons, particularly high-energy lasers, are among the most promising tools for shipboard defense. The U.S. Navy has successfully tested systems like HELIOS aboard destroyers, demonstrating the ability to neutralize drones with precision and low cost per shot. These weapons offer near-instantaneous engagement and essentially unlimited ammunition constrained only by the ship's power supply [25]. Lasers such as the Optical Dazzling Interdictor Navy (ODIN) are also used to blind or confuse drone sensors, serving as non-lethal deterrents [26].

In parallel, electronic warfare plays a central role in disrupting UASs operations. Ship-based radio frequency (RF) jamming systems such as DroneSentry-X have been demonstrated to detect drones over 2 kilometer away and jam them within 300 meters [27].

These systems serve command-and-control links, forcing drones to crash or return to base, often without collateral damage [27]. These tools are increasingly deployed aboard warships and could be adapted for merchant convoys.

When soft-kill methods fail, ships rely on kinetic interceptors such as surface-to-air missiles (SM-2, ESSM) or close-in weapons like Phalanx CIWS or 5-inch deck guns. In Red Sea operations, U.S. warships have launched hundreds of missiles and gun rounds to intercept drones, though this approach is costly and best reserved for high-priority threats. Accordingly, there is growing interest in low-cost kinetic solutions like interceptor drones and smaller guided munitions.

Modern c-UASs doctrine emphasizes integration. Radar, EW, laser, and kinetic systems must operate cohesively within a ship's combat management system. This layered defense is especially critical for convoys where merchant ships depend on nearby naval escorts and modular defense packages. The DoD's Counter-NEXT program and North Atlantic Treaty Organization (NATO) doctrine both support this holistic, scalable model of defense.

## 2.3 Radar-Based Detection in Maritime Contexts

Radar systems emit electromagnetic waves that reflect off objects, producing echoes used for target identification. The effectiveness of radar depends on key parameters including signal frequency, pulse repetition frequency (PRF), beamwidth, and power output [28]. Radar systems are classified according to their transmission frequencies, with different bands offering distinct advantages. X-band radars provide high precision in detecting small, fast-moving drones, while S-band radars are more resilient to weather interference [29].

A crucial factor in detection is the radar cross-section (RCS) of a target, which determines how much of the radar signal is reflected back to the receiver. Small drones and stealthy boats typically have a low RCS, meaning they reflect only a small fraction of the transmitted energy. This results in weak return signals that are often difficult to distinguish from background noise. Effective detection, therefore, hinges on the system's ability to recognize these low-amplitude signals amidst environmental and electronic noise challenge that often requires advanced signal processing algorithms and enhanced sensitivity [30]. Tactics such as drone swarms or high-speed boats further complicate radar performance by overwhelming or saturating detection systems [31].

## 2.4 Radar Technologies on Ships

Modern ships utilize specialized radar systems to improve situational awareness and threat response. Surface search radars are key for detecting and tracking vessels of varying sizes, crucial in high-threat environments like the Red Sea [32]. Air search radars, equipped with phased-array technology, provide fast and multi-target detection capability against aerial threats like UASs and missiles [33]. Three-dimensional (3Ds) radars further enhance tracking by supplying range, azimuth, and elevation data, improving the ability to respond to both aerial and surface threats simultaneously. Modern naval vessels, including many destroyers and frigates, are equipped with 3D radar systems such as the AN/SPY-1 or AN/SPY-6, which provide comprehensive situational awareness and support integrated air and missile defense operations [34].

## **2.5 Integration of Detection and Defense Systems**

Integration across radar, communication, and weapon systems is essential in modern maritime security. Real-time data sharing between merchant ships and naval escorts enhances overall situational awareness and threat response [35]. Combining radar feeds with automatic identification systems (AISs) enhances vessel tracking by providing both positional and identity data. However, AISs spoofing and exploitation by hostile actors, such as the Houthis in the Red Sea, have raised serious concerns [36]. In response, many commercial vessels transiting the region have begun turning off their AISs transponders to reduce detectability and avoid being targeted—though this tactic can complicate maritime situational awareness and safety. These elements, when unified in a combat system, enable faster, smarter defensive responses.

## **2.6 Challenges in Maritime Radar Detection**

The Red Sea conflict is marked by asymmetric threats, including drone swarms and missile attacks. High-resolution radar and advanced classification algorithms are necessary to differentiate threats and maintain accuracy [9]. Harsh maritime conditions such as salt corrosion, humidity, and sea spray degrade system performance, requiring ruggedized radar equipment and environmental compensation [37]. Additionally, adversaries frequently employ electronic countermeasures like jamming and spoofing, prompting the use of frequency-hopping radars and adaptive signal processing to preserve functionality [38].

## **2.7 Conclusion**

The detection and mitigation of unmanned threats in the Red Sea are critical to maritime security. UASs, whether used for surveillance, disruption, or attack, pose a complex and evolving challenge. The integration of advanced radar systems, collaborative detection networks, electronic warfare, directed energy weapons, and kinetic defenses provides a multi-layered framework for addressing these threats. However, the rapidly changing threat landscape demands ongoing innovation in sensor technology, countermeasure design, and systems integration. Protecting merchant vessels and ensuring the safe flow of global trade in high-risk areas like the Red Sea depends on the strategic deployment of these advanced maritime defense systems.

---

---

## CHAPTER 3: Systems Engineering Methodology

---

The systems engineering process begins with requirements definition from the analysis of the stakeholders need. This chapter begins with that starting block followed by an in-depth description of the connections and integration of the system architecture formed by the system of systems for defense of merchants. With requirements established, performance and effectiveness measures are defined for determining the optimal solution based on the analysis of alternatives. The architecture of the systems then defines the space that this project will utilize for system operations in the simulation.

### 3.1 Mission Objectives

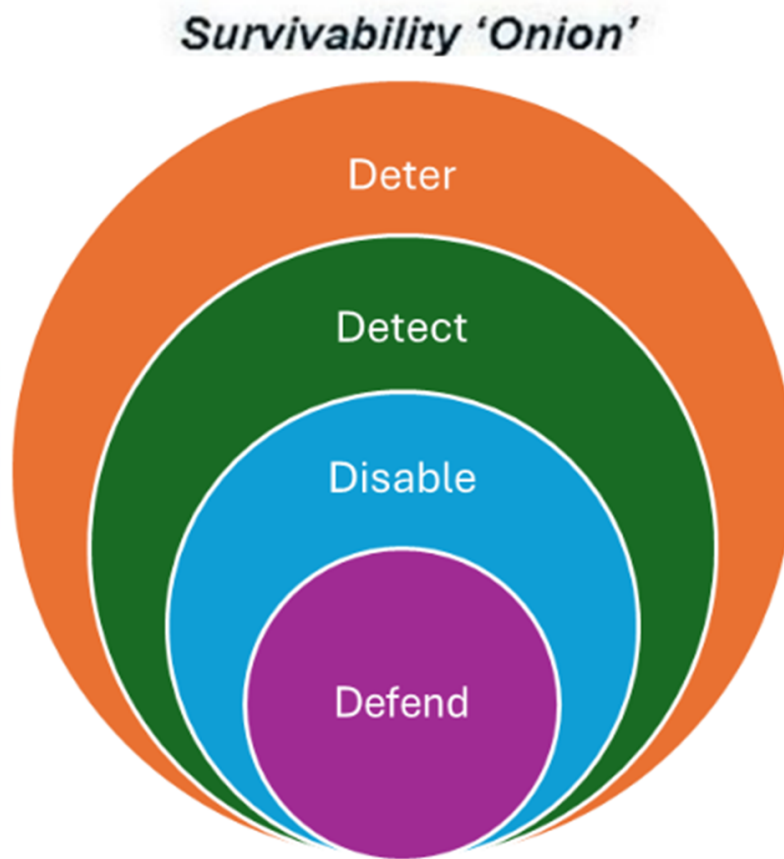
The objective of defending merchant vessels from UASs and USVs threats will be accomplished using a layered defense architecture. The layers will consist of detection capabilities from varying ranges down to alternative analysis of various weapons systems on platforms performing defense from two different postures: area defense in the vicinity of attacks and close direct escort operations with each merchant. Requirements developed are derived from the CONOPS. The key supporting objectives delineated therein include managing user interactions, determining appropriate employment modes, and developing a scheduling and operational cycle. The architectural planning will consider the operational environment defined by physical characteristics as well as threats and hazards. Finally, the system architecture will include interoperability between elements.

### 3.2 Requirements Definition

Due to the increasing threat of unmanned vehicles, the team will be taking a layered approach using the “Survivability Onion” shown in Figure 3.1, comprising of four layers:

1. **Deter:** Protection of ships without firing a single shot.
2. **Detect:** Early detection and warning of potential threats.
3. **Disable:** Soft and hard-kill options to misdirect or eliminate threat.
4. **Defend:** Hardening of ships’ hull to withstand impacts.

Each layer represents a progressive step in the engagement sequence, allowing for escalation as threats become more imminent. For this project, the first and last layer of “Deter” and “Defend” will not be investigated. The first layer, deterrence, would involve attempts to reduce the likelihood of adversaries targeting the ships. This would mostly involve non-materiel solutions that are beyond the scope of the project. The last layer, defend, would require hardening of ships to prevent critical damage to the ship, and would be unfeasible from a cost perspective. Ideally, the earlier layers would be effective in protecting the ships such that the last layer is not needed.



**(a) Survivability onion model**

*Source: ©DEVCOM Ground Systems Vehicle Center.  
Approved for public release.*

Figure 3.1. The survivability onion model. Source: [39].

The second layer, “Detect,” involves the early identification of potential threats through the integration of multi-sensor inputs such as radar and electro-optical/infrared (EO/IR) systems. Effective detection enables situational awareness and provides the necessary reaction time to activate countermeasures.

Following detection, the “Disable” layer is activated to neutralize the threat. This layer includes both soft-kill and hard-kill solutions. Soft-kill measures—such as jamming or spoofing—aim to misdirect or disrupt hostile systems. If these are ineffective or inapplicable, hard-kill responses such as surface-to-air missiles or autocannons are employed to physically intercept and destroy incoming threats.

By implementing a layered defense system structured around the Survivability Onion, maritime forces can provide merchant vessels with comprehensive protection that responds proportionally to threat proximity and severity. This approach improves survivability, minimizes collateral damage, and aligns with the broader strategic, legal, and operational considerations.

### **3.3 Measures of Performance and Effectiveness**

MOPs measure how well a system performs its functions and is capable of meeting requirements. MOEs are the system level measure of overall effectiveness of the system at filling the capability gap. Top level MOEs will be defined based on both effectiveness of the defense system of systems for merchant protection, thus survivability, and based on the cost of the overall operation to do so. Many MOPs will be recognized and analyzed for system level performance within the system of systems.

#### **Measures of Performance**

Operational effectiveness captures the capability of a defensive system to detect, respond to, and neutralize threats before they can impact the protected merchant vessels. The following metrics define these performance measures.

1. **Threat detection range:** The maximum distance at which hostile or uncrewed platforms can be reliably identified by the system. This reflects the system’s early warning capability and influences the time available for defensive action.

2. **Operational coverage area:** The total area surrounding the merchant convoy in which the defensive system can actively detect, track, and engage threats. It indicates the spatial extent of protection.
3. **Response time:** The time elapsed from the initial detection of a threat to the initiation of defensive countermeasures. Lower response times suggest a higher level of system agility and tactical responsiveness.
4. **Engagement success rate:** The proportion of detected threats that are effectively neutralized, deterred, or otherwise rendered non-lethal before reaching the merchant vessels. This is a core indicator of a system's combat utility.
5. **Systems availability:** The availability and endurance of the system's resources (e.g., ammunition, energy, personnel support) throughout the operational scenario. This metric evaluates the system's ability to maintain continuous defense over time.

### Measures of Effectiveness

The primary MOE from each scenario, considering alternative defensive systems and defense postures, is the survival of the merchant ships transiting through the contested environment. In this study, effectiveness is also assessed relative to total ownership costs (TOCs), using an efficiency frontier approach to identify the most viable defensive solutions.

1. Survival is defined as the inverse of the "kill ability" of the enemy [40]. Survivability will be measured as the ratio of merchant vessels that successfully complete their transit without being struck by enemy forces to the total number of vessels entering the scenario. It represents the core performance objective of the defensive systems: ensuring the survivability of merchant shipping assets. A higher survival rate indicates a more successful performance in fulfilling the fundamental mission requirement.
2. Cost efficiency is assessed by measuring operational effectiveness in relation to the TOC of each defensive system configuration. TOC provides a holistic view of the long-term financial burden associated with acquiring, operating, and maintaining a capability [41]. It represents the full lifecycle cost of the defensive system. The key cost components include:
  - **Installation Cost:** The one-time cost of integrating the system onto platforms, including hardware setup, software configuration, and necessary platform modifications. It contributes to the initial deployment phase.

- **Ammunition Usage Cost:** The cumulative cost of all munitions expended during the scenario, calculated by the quantity used multiplied by their respective unit costs.
- **Platform Utilization Cost:** The operational cost of deploying and sustaining platforms such as escort ships, UASs, and other assets integrated into the defensive posture.
- **Support and Sustainment Costs:** Additional costs that may include training, personnel, maintenance, software upgrades, logistics, and eventual decommissioning.

Efficiency Frontier Assessment: Each defensive configuration is evaluated by plotting its operational effectiveness against its TOC. Configurations that lie on or near the efficiency frontier represent the most cost-effective options—delivering maximum mission value per unit cost. This method allows for the comparison of alternative systems not just in terms of capability, but in their practical, scalable application under constrained resources.

### 3.4 High-Level Operational Concept

To convey the integrated nature of the proposed layered defense system, an OV-1 diagram was developed, shown in Figure 3.2, to illustrate the operational flow between surveillance, command, and engagement assets in a maritime defense context. In this concept, hostile threats—specifically UASs and USVs—are detected by crewed DDG-51-class naval escorts equipped with onboard air and surface search radar, electronic surveillance, and optical systems. These platforms serve as primary sensor nodes, scanning the air and sea domain for anomalous signatures or approaching threats. Once a threat is detected, real-time tracking information is relayed to a centralized command and control (C2) node located on either land or the DDG itself. This node fuses data from all sensor platforms and generates actionable directives. The C2 function coordinates the dynamic positioning of escorts, manages engagement decisions, and ensures tactical synchronization across all assets involved in the escort operation.

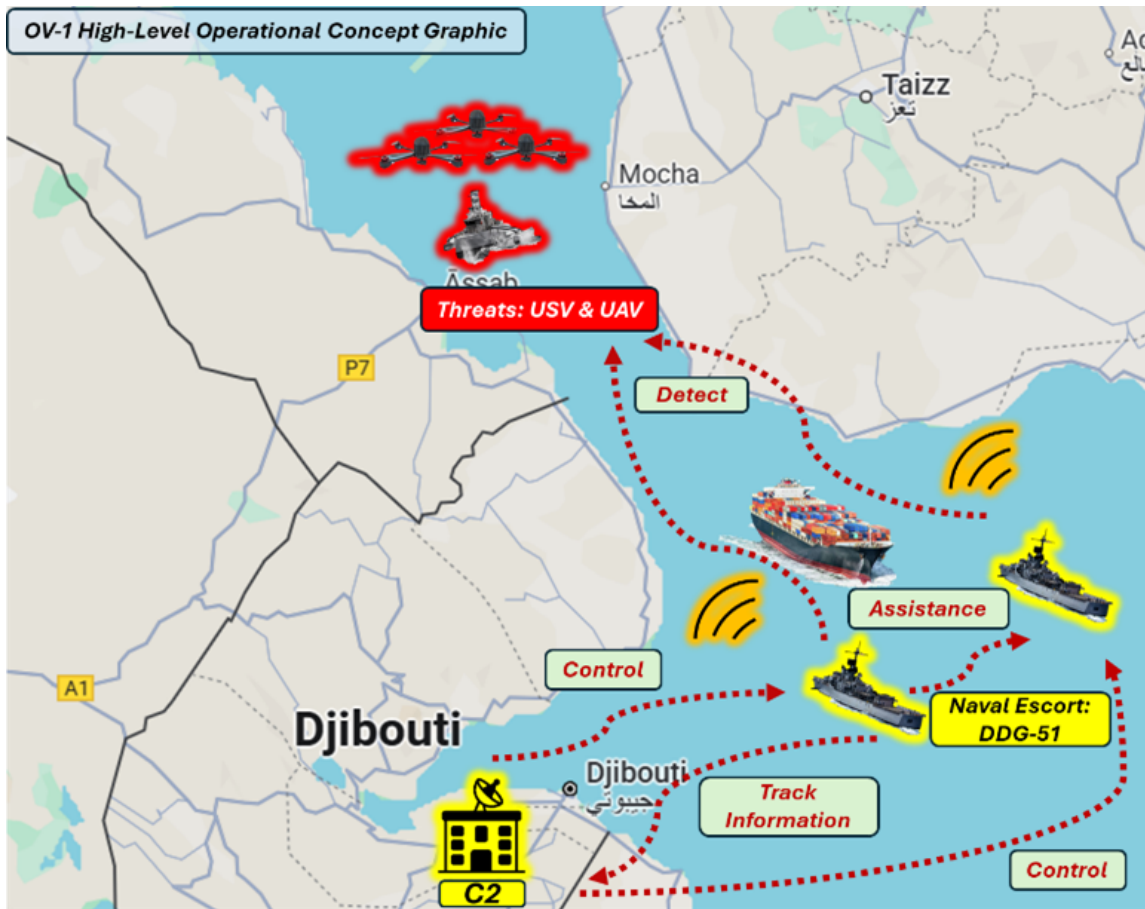


Figure 3.2. High-level operational concept diagram.

The merchant vessel, located at the center of this defensive construct, receives protection from multiple directions by the flanking naval escorts. In the event of a confirmed threat, the escorts can engage using organic hard-kill or soft-kill measures based on C2 authorization. Control and communication loops remain active throughout the mission, enabling continuous threat updates, re-tasking platforms, and responsive maneuvering. This high-level OV highlights the distributed yet coordinated architecture of the defense system. It emphasizes rapid detection, centralized coordination, and decentralized execution as key enablers of survivability. The diagram demonstrates how naval escorts and C2 elements jointly shield vulnerable merchant vessels by forming a mobile and adaptive defense perimeter.

## **3.5 System Architecture**

The concept of operations was synthesized into a system architecture to help conceptualize our design. Included in this architecture are six key components, each representing its own layer of the solution space, as well as a traceability matrix to track cohesion across the architecture. Together, these help visualize the problem as well as the flow and functionality of our design.

### **3.5.1 Block Definition Diagram**

The block definition diagrams (BDD) shown in Figure 3.3 illustrates the logical decomposition of the c-UAS Defense System as presented in the OV-1 operational concept. It breaks down the major subsystems and their internal elements that collectively support threat detection, decision-making, and response in a Red Sea maritime defense scenario involving hostile USVs and UASs.

A naval convoy—led by a DDG-51 destroyer and supported by a shore-based C2 node—is tasked with protecting merchant vessels transiting through a high-threat area. The dotted arrows represent the flow of detection, control, assistance, and information between actors, while the BDD specifies the system components that enable these actions.

At the core of the system is the Detection & Surveillance System, which serves as the initial interface with the threat environment. It is responsible for sensing and detecting incoming unmanned threats—such as UASs or USVs—and transmitting the resulting threat data to the Tracking & Reporting System. This tracking system then processes and refines the incoming sensor data, producing track information and target data that are forwarded to the C2 node.

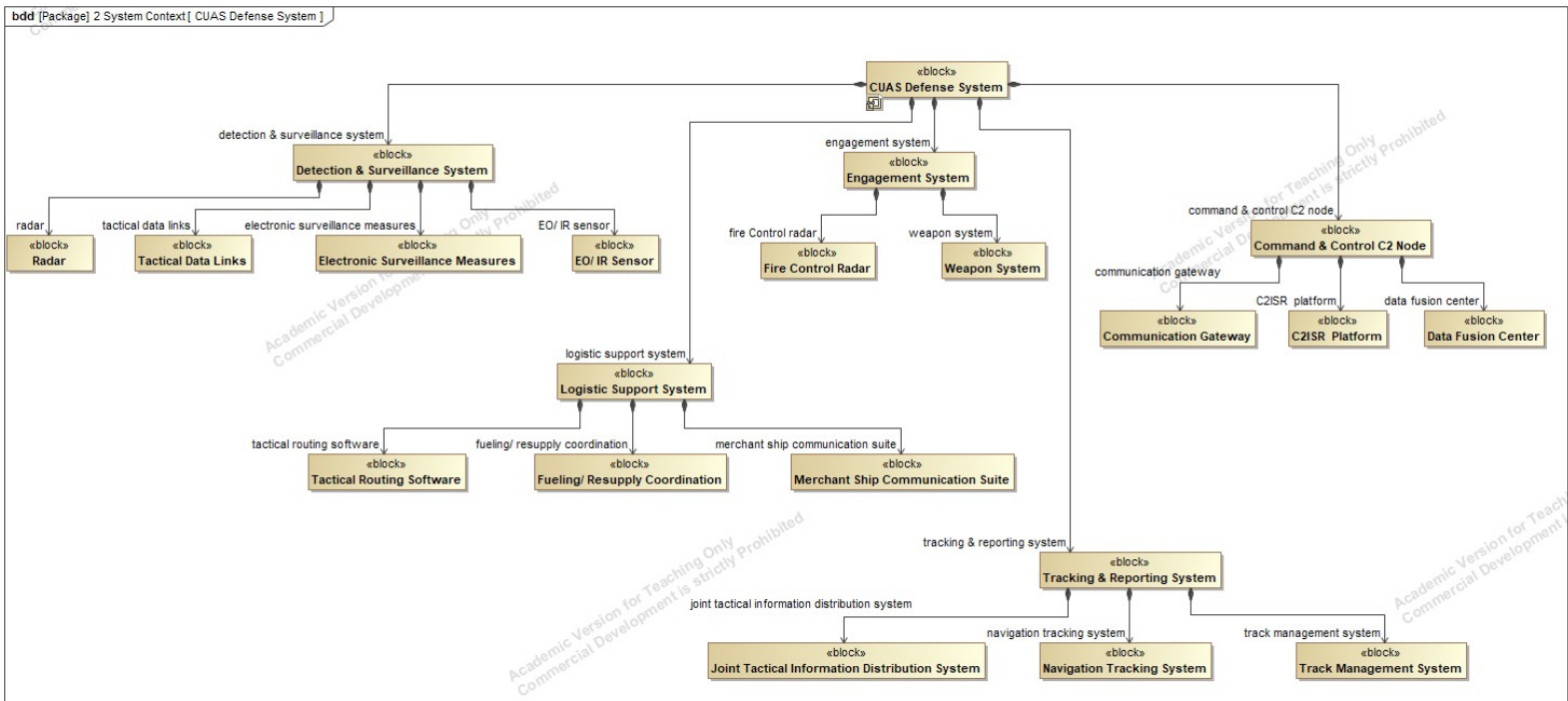


Figure 3.3. Counter-unmanned aerial systems defense system block definition diagram.

The C2 node fuses situational data and making operational decisions. It receives the processed target data from the tracking system, assesses the threat context, and issues engagement authorization and control signals to the Engagement System. Simultaneously, it coordinates with the Logistic Support System, providing routing information and support tasking necessary for sustained operations, convoy management, and tactical maneuvering.

Once engagement commands are received, the Engagement System acts upon them by initiating the appropriate countermeasures—whether kinetic or non-kinetic. Upon completion, it sends the engagement result and battle damage assessment back to the Tracking & Reporting System. This feedback loop ensures that the system continuously updates the threat picture and adapts to changes in the operational environment.

The Logistic Support System, while not directly engaged in combat, plays a vital supporting role by ensuring that platform maneuverability, communication with merchant vessels, and mission resupply are sustained. It supports the overall system by responding to C2's coordination directives, thereby contributing to the endurance and effectiveness of the defense operation.

### **3.5.2 Internal Block Diagram**

The Figure 3.4 internal block diagram (IBD) presents the key subsystem components and their internal item flows, which collectively support the detection, decision-making, engagement, and support functions necessary to counter UASs or USVs threats. The diagram illustrates how these subsystems interact in real time, forming a responsive and layered defense system during operations.

At the core of the system is the Detection & Surveillance System, which serves as the initial interface with the threat environment. It is responsible for sensing and detecting incoming unmanned threats—such as UASs or USVs—and transmitting the resulting threat data to the Tracking & Reporting System. This tracking system then processes and refines the incoming sensor data, producing track information and target data that are forwarded to the C2 node.

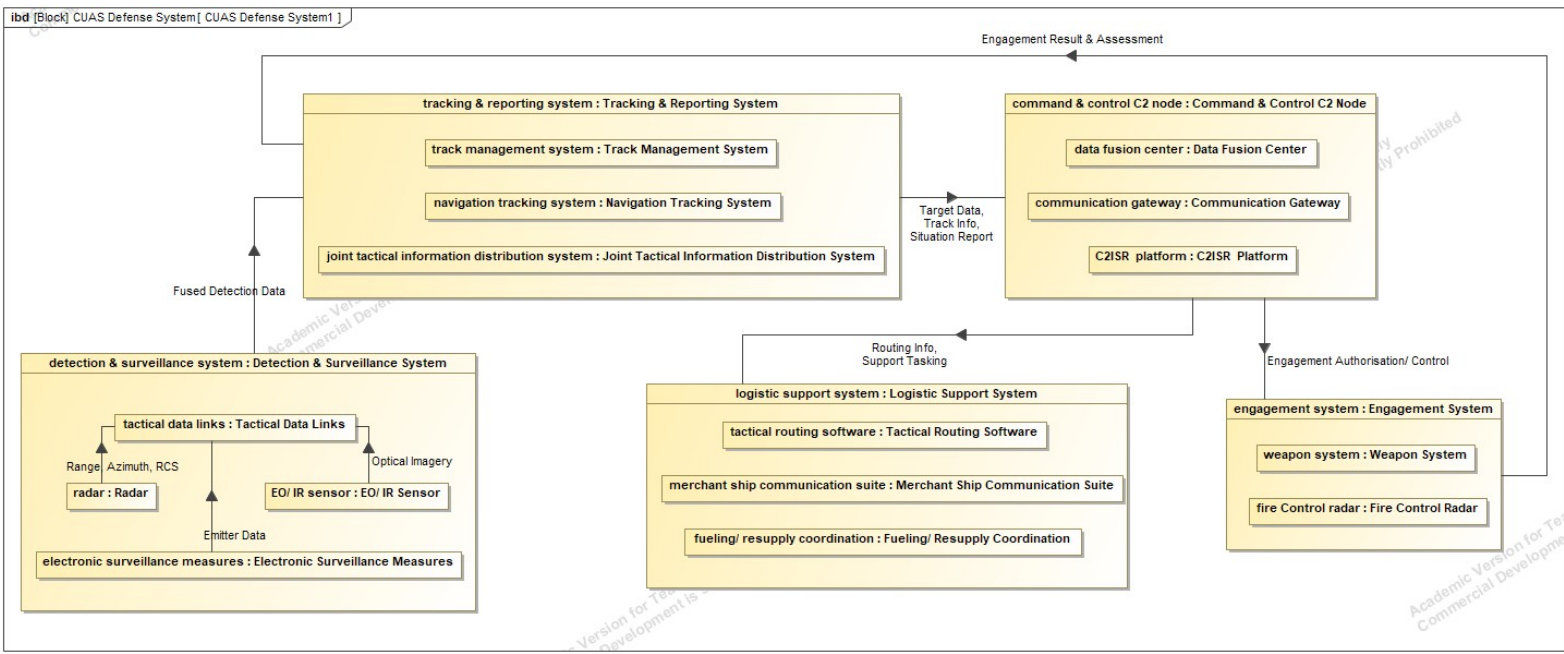


Figure 3.4. C-UAS defense system internal block diagram.

The C2 node fuses situational data and making operational decisions. It receives the processed target data from the tracking system, assesses the threat context, and issues engagement authorization and control signals to the Engagement System. Simultaneously, it coordinates with the Logistic Support System, providing routing information and support tasking necessary for sustained operations, convoy management, and tactical maneuvering.

Once engagement commands are received, the Engagement System acts upon them by initiating the appropriate countermeasures—whether kinetic or non-kinetic. Upon completion, it sends the engagement result and battle damage assessment back to the Tracking & Reporting System. This feedback loop ensures that the system continuously updates the threat picture and adapts to changes in the operational environment.

The Logistic Support System, while not directly engaged in combat, plays a vital supporting role by ensuring that platform maneuverability, communication with merchant vessels, and mission resupply are sustained. It supports the overall system by responding to C2's coordination directives, thereby contributing to the endurance and effectiveness of the defense operation.

To effectively detect, classify, track, and neutralize aerial threats, particularly UASs, a well-integrated system architecture is essential. The c-UAS Defense System consists of a suite of interconnected systems of systems, each performing specialized roles. These subsystems shall communicate through standardized interfaces to enable real-time decision-making, threat engagement, and post-action assessment. The following asset diagram illustrates the architectural layout of these components and the interaction to achieve mission objectives.

### **3.5.3 System Function Diagram**

Following the delineation of the system architecture in the Asset Diagram, which illustrates the structural composition and interfacing of subsystems within the c-UAS Defense System, this section focuses on the functional perspective of the architecture. While the asset diagram highlights the physical and logical interconnections between systems, the Functional Definition outlines how each component operates in support of mission objectives. This includes the decomposition of high-level functions into sub-functions (see Figure 3.5). The system functions table (Table 3.1) illustrates the tasks performed by each subsystem and how they contribute collectively to threat detection, engagement, and system sustainability.

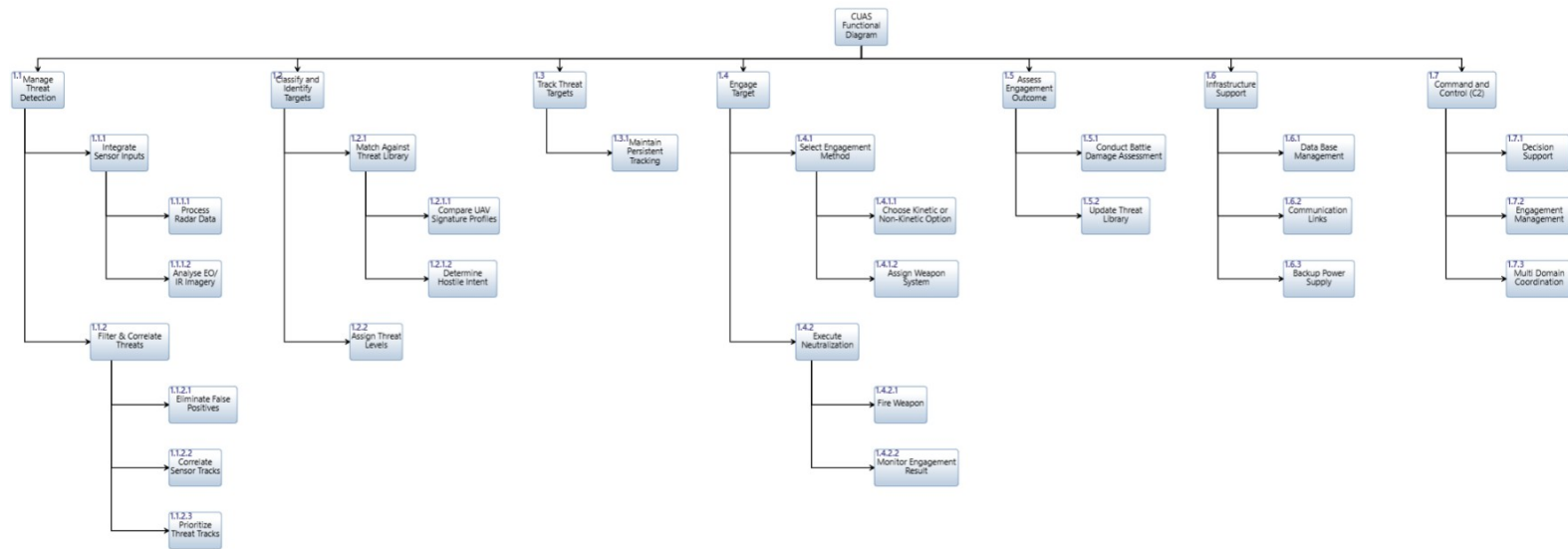


Figure 3.5. Functional hierarchy diagram.

Table 3.1. Summary of system functions.

| Functions (Level 2)               | Sub-Functions (Level 3)                | Sub-Functions (Level 4)                      | Definition  |
|-----------------------------------|--|--|---|
| 1.1 Manage Threat Detection       | 1.1.1 Integrate Sensor Inputs          | 1.1.1.1 Process Radar Data                   | Collect and process multi-sensor data to detect potential threats   |
|                                   |  | 1.1.1.2 Analyze EO/IR Imagery                |   |
|                                   | 1.1.2 Filter & Correlate Threats       | 1.1.2.1 Eliminate False Positives            | Refine and validate detected tracks by removing false alarms, fusing multiple sensor inputs, and prioritizing threats based on risk |
|                                   |  | 1.1.2.2 Correlate Sensor Tracks              |   |
| 1.1.2.3 Prioritize Threat Tracks  |  |  |   |
| 1.2 Classify and Identify Targets | 1.2.1 Match Against Threat Library     | 1.2.1.1 Compare UAV Signature Profiles       | Identify UAV types and threat levels using known profiles and behavior analysis   |
|                                   |  | 1.2.1.2 Determine Hostile Intent             |   |
|                                   | 1.2.2 Assign Threat Level              | Nil  |   |
| 1.3 Track Threat targets          | 1.3.1 Maintain Persistent Tracking     | Nil  | Ensure continuous and accurate tracking of identified threats   |
| 1.4 Engage Target                 | 1.4.1 Select Engagement Method         | 1.4.1.1 Choose Kinetic or Non-Kinetic Option | Determine engagement strategy and initiate threat neutralization  |
|                                   |  | 1.4.1.2 Assign Weapon System                 |   |
|                                   | 1.4.2 Execute Neutralization           | 1.4.2.1 Fire Weapon                          | Carry out the physical or electronic neutralization of the identified threat and monitor the effectiveness of the engagement        |
|                                   |  | 1.4.2.2 Monitor Engagement Result            |   |
| 1.5 Assess Engagement Outcome     | 1.5.1 Conduct Battle Damage Assessment | Nil  | Evaluate results of engagements to confirm neutralization and inform future threat  |
|                                   | 1.5.2 Update Threat Library            | Nil  | Incorporate post-engagement insights and new threat behaviors into the system's knowledge base                                      |
| 1.6 Infrastructure Support        | 1.6.1 Data Base Management             | Nil  | Manage and maintain operational databases supporting detection, tracking, and engagement  |
|                                   | 1.6.2 Communication Links              | Nil  | Establish and maintain secure communication links between subsystems and external C2 nodes  |
|                                   | 1.6.3 Backup Power Supply              | Nil  | Ensure continuous operation through power redundancy and backup sources   |
| 1.7 Command and Control (C2)      | 1.7.1 Decision Support                 | Nil  | Support operators with decision-making tools, threat ranking, and engagement recommendations  |
|                                   | 1.7.2 Engagement Management            | Nil  | Oversee and synchronize the entire engagement process from detection to neutralization  |
|                                   | 1.7.3 Multi Domain Coordination        | Nil  | Coordinate actions across domains (air, sea, cyber) and platforms for integrated defense  |

### 3.5.4 System Requirement Hierarchy

Building upon the system architecture and functional definitions, this section outlines the key requirements listed in the Table 3.2 that the c-UAS Defense System must fulfill to ensure mission effectiveness, resilience, and operator usability. These requirements are categorized into logical groups including Threat Management, c-UAS Capabilities, User Interaction, and Availability as shown in Figure 3.6. Each requirement addresses a specific performance or capability objective that contributes to the overall system’s ability to detect, classify, engage, and assess UAS threats in real time.

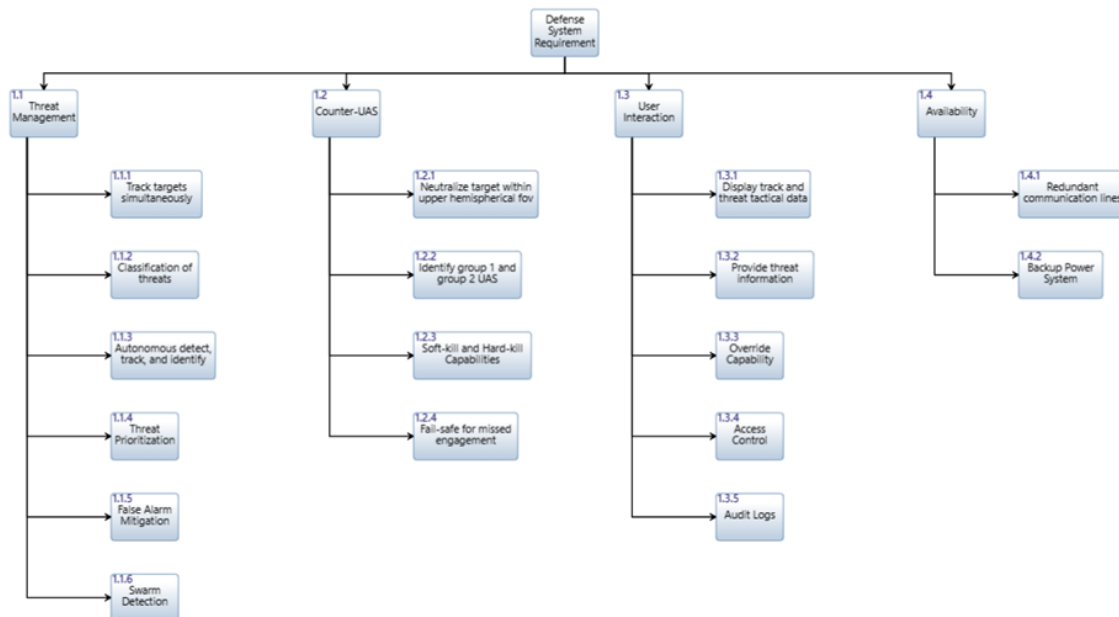


Figure 3.6. Requirement hierarchy diagram.

Table 3.2. Summary of system requirements.

| Requirement Group |  | Definition  |
|-------------------|--|---|
| Level 2           | Level 3  |   |
| Threat Management | Track targets simultaneously                             | System must be capable of tracking multiple aerial threats concurrently                         |
|                   | Classification of threats                                | System must classify detected threats by type, size, and behavior                               |
|                   | Autonomously detect, track, and identify                 | System must detect, track, and identify threats autonomously without continuous operator input  |
|                   | Threat prioritization                                    | System must assign threat priorities based on lethality, proximity, and intent                  |
|                   | False alarm mitigation                                   | System must minimize false positive to prevent unnecessary engagement                           |
|                   | Swarm detection  | System must detect and recognize swarm tactics and behaviors                                    |
| C-UAS             | Neutralize target within upper hemispheric field of view | System must be able to engage targets within a designated upper field of view                   |
|                   | Identification of UAS                                    | System must distinguish between different classes of drones based on operational profiles       |
|                   | Soft-kill and hard-kill capabilities                     | System must support both non-kinetic (e.g., jamming) and kinetic (e.g., missile) neutralization |
|                   | Fail-safe for missed engagement                          | System must include fallback mechanisms if primary engagement fails                             |
| User interaction  | Display track and threat tactical data                   | System must display real-time threat and tracking data to operators                             |
|                   | Provide threat information                               | System must provide actionable threat information to aid decision-making                        |
|                   | Override capability                                      | System must allow human override of automated decisions when needed                             |
|                   | Access control   | System must restrict access based on roles and security protocols                               |
|                   | Audit logs   | System must log all operator and system actions for accountability and review                   |
| Availability      | Redundant communication lines                            | System must use redundant communication pathways to ensure availability                         |
|                   | Backup power system                                      | System must include power backup to maintain uptime during outages                              |

### 3.5.5 Traceability Matrix

The traceability matrix presented in Figure 3.7 illustrates the alignment between the defined system requirements and their corresponding functional implementations within the c-UAS Defense System. Each row represents a system requirement categorized under major capability areas, while the columns list the functional blocks from the c-UAS functional hierarchy. The presence of an “X” indicates a direct functional contribution to the fulfillment of a specific requirement. This matrix ensures that every requirement is traceable to at least one implemented function, validating completeness and coverage across the system.

| Defense System Requirement                | C-UAS Functional Diagram | 1.1 Integrate Sensor Inputs | 1.1.1 Process Radar Data | 1.1.1.1 Analyze EO/IR Imag... | 1.1.2.1 Eliminate False Post... | 1.1.2.2 Correlate Sensor Tra... | 1.2.1.1 Prioritize Threat Trac... | 1.2.1.2 Compare UAS Signa... | 1.2.2 Determine Hostile In... | 1.3.1 Maintain Threat Levels | 1.4.1.1 Select Engagement Tr... | 1.4.1.2 Choose Kinetic or N... | 1.4.2.1 Assign Weapon Syst... | 1.4.2.2 Monitor Engagement... | 1.5.1 Conduct Battle Damag... | 1.6.1 Update Threat Library | 1.6.2 Base Management | 1.7.1 Communications Links | 1.7.1 Decision Support | 1.7.1 Engagement Support | 1.7.2 Multi Domain Coordin... |
|---|--------------------------|-----------------------------|--------------------------|-------------------------------|---------------------------------|---------------------------------|-----------------------------------|------------------------------|-------------------------------|------------------------------|---------------------------------|--------------------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------|-----------------------|----------------------------|------------------------|--------------------------|-------------------------------|
| <b>1.1 Threat Management</b>              |                          |                             |                          |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.1.1 Track targets simultaneously        | X                        |                             |                          | X                             |                                 |                                 |                                   |                              | X                             |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.1.2 Classification of threats           |                          | X                           | X                        | X                             |                                 | X                               |                                   |                              |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.1.3 Autonomous detect, track, an...     |                          | X                           | X                        | X                             |                                 |                                 |                                   |                              | X                             |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.1.4 Threat Prioritization               |                          |                             | X                        |                               | X                               |                                 | X                                 | X                            |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.1.5 False Alarm Mitigation              |                          | X                           | X                        | X                             |                                 |                                 | X                                 |                              |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.1.6 Swarm Detection                     |                          | X                           | X                        |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               | X                             |                             |                       |                            |                        |                          |                               |
| <b>1.2 Counter-UAS</b>                    |                          |                             |                          |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.2.1 Neutralize target within upper ...  |                          |                             |                          |                               |                                 |                                 |                                   |                              |                               |                              | X                               | X                              | X                             | X                             |                               |                             |                       |                            |                        |                          |                               |
| 1.2.2 Identify group 1 and group 2 ...    | X                        | X                           |                          |                               |                                 | X                               |                                   |                              |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.2.3 Soft-kill and Hard-kill Capabili... |                          |                             |                          |                               |                                 |                                 |                                   |                              | X                             | X                            |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.2.4 Fail-safe for missed engagem...     |                          | X                           |                          |                               | X                               |                                 |                                   |                              |                               |                              |                                 | X                              | X                             | X                             |                               |                             |                       |                            |                        |                          |                               |
| <b>1.3 User Interaction</b>               |                          |                             |                          |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.3.1 Display track and threat tactic...  |                          | X                           | X                        |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.3.2 Provide threat information          |                          | X                           | X                        |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        | X                        |                               |
| 1.3.3 Override Capability                 |                          |                             |                          |                               |                                 |                                 |                                   |                              | X                             |                              |                                 |                                |                               |                               |                               |                             |                       | X                          | X                      | X                        |                               |
| 1.3.4 Access Control                      |                          |                             |                          |                               |                                 |                                 |                                   |                              | X                             | X                            |                                 |                                |                               |                               | X                             |                             | X                     | X                          | X                      |                          |                               |
| 1.3.5 Audit Logs                          |                          |                             |                          |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               | X                             |                             |                       |                            |                        | X                        |                               |
| <b>1.4 Availability</b>                   |                          |                             |                          |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               |                               |                             |                       |                            |                        |                          |                               |
| 1.4.1 Redundant communication lin...      |                          |                             |                          |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               |                               | X                           |                       |                            |                        |                          |                               |
| 1.4.2 Backup Power System                 |                          |                             |                          |                               |                                 |                                 |                                   |                              |                               |                              |                                 |                                |                               |                               |                               |                             | X                     |                            |                        |                          |                               |

Figure 3.7. Functional versus requirement traceability matrix.

### **3.6 Strategic and Operational Constraints**

Political, economic, social, technological, legal, environmental (PESTLE) analysis was conducted to define the external constraints shaping system design and deployment in the Red Sea operating environment.

Politically, the region remains highly volatile. Direct targeting of land targets before they can fire upon vessels in international waters raises significant political considerations that are outside the scope of this project. As a result, this project focuses on engagements in international waters.

Economically, the proposed solution is designed to minimize the operational burden on commercial shipping entities. No defensive systems are installed on merchant vessels; all protection is externally provided by dedicated naval escorts. As such, there are no acquisition or integration costs imposed on commercial operators—only their routine operational expenses remain. This approach ensures compliance with commercial norms while delivering layered security through military assets optimized for threat detection and neutralization.

From a social perspective, civilian crew safety is paramount. Instead of integrating defensive systems directly on to merchant vessels, which is operationally undesirable and outside the scope of current doctrine, the concept of operations prioritizes protection through dedicated naval escorts. Ships such as DDG-51-class destroyers and smaller support craft provide the necessary surveillance, threat engagement, and close-range support, allowing merchant crews to focus on navigation and cargo operations without the burden of tactical defense responsibilities.

Technologically, the system must achieve a high technology readiness level (TRL) and incorporate advanced tracking, classification, and engagement capabilities. Given the rapid maneuverability and low radar cross-section of UAS and USV, response systems must be fast, accurate, and reliable in maritime conditions.

Legally, all operations must conform to international maritime law, particularly rules on the use of force and proportionality. Any unintended harm to civilian vessels or infrastructure can incur liability and compromise operational legitimacy. The design must incorporate safeguards to minimize misidentification and collateral damage.

Environmentally, defense systems must limit ecological impact. Intercepted threats, particularly those carrying fuel or electronics, pose risks of marine pollution. The architecture must therefore aim for both operational effectiveness and environmental responsibility.

Ultimately, success depends not only on tactical performance but on its alignment with wider geopolitical, legal, and economic realities, each a critical determinant in the safe and sustainable defense of maritime assets.

---

---

## CHAPTER 4: Experimental Design

---

For this project to obtain usable output information and recommendations for a system of systems capable of merchant defense against unmanned vessels, several variables need to be defined. The use of a simulation will take place with alternative scenarios comprised of those variables to compare and analyze for meeting the MOEs and MOPs. This chapter provides specific threat vessels, and the specific allied systems used as inputs for simulation values. Given the UASs and USVs threats defined in this chapter, and the defensive detection and engagement systems listed and described, several scenarios are defined to outline the variations assumed in the threat environment. The alternative postures combined with the alternative systems being implemented into the system of systems design will allow the team to determine the most effective and efficient solution space for merchant defense in an environment similar to the Red Sea conflict.

### 4.1 Threat Analysis

An analysis of threats in the Red Sea was performed for this project analysis. Tables 4.1 and 4.2 are consolidated tables of UASs and USVs threats with characteristics that define them by group and are used in the calculations of RCS.

Table 4.1. Summary of threat UAS. Adapted from [42], [43], [44], [45], [46].

| <b>Group</b> | <b>Name</b> | <b>Range<br/>(km)</b> | <b>Endurance<br/>(hr)</b> | <b>Speed<br/>(km/hr)</b> | <b>Max. Alt.<br/>(m)</b> | <b>Payload<br/>(kg)</b> |
|--------------|-------------|-----------------------|---------------------------|--------------------------|--------------------------|-------------------------|
| III          | Samad-3     | 1,500                 | 8                         | 250                      | 500                      | 18                      |
| III          | Mohajer-6   | 200                   | 12                        | 200                      | 5,486                    | 40                      |
| II           | Qasef-1     | 120                   | 2                         | 370                      | 3,000                    | 30                      |
| III          | Shahed-136  | 2,500                 | 13                        | 185                      | 4,000                    | 50                      |
| III          | Arash-2     | 1,000                 | 5                         | 400                      | 5,500                    | 30                      |

Table 4.2. Summary of threat USVs. Adapted from [47], [48], [49], [50], [51], [52].

| <b>Name</b> | <b>Speed (km/hr)</b> | <b>Payload (kg)</b> | <b>Size (m<sup>2</sup>)</b> |
|-------------|----------------------|---------------------|-----------------------------|
| Toofan-1    | 35                   | 150                 | 23                          |
| Toofan-2    | 41                   | 400                 | 13                          |
| Toofan-3    | 52                   | 500                 | 21                          |
| Magura V5   | 77.8                 | 320                 | 8.25                        |
| Sea Baby    | 90                   | 850                 | 12                          |

The RCS calculations were completed utilizing chosen UASs and USVs threats from these tables that were determined to be representative unmanned systems in the Houthi attacks. Appendix A shows the details of the calculations, with the chosen threats being the Shahed-136 UAS, Arash-2 UAS and Sea Baby USV, a Ukrainian design. The Shahed and Arash are both later variants of Houthi UAS designs used in their attacks and thus represent the most advanced and likely size characteristic aerial threat in the environment. Open-source data has limited information regarding Houthi attacks using USVs, and thus as a representation for this threat, a Ukrainian drone, was analyzed as it is known to have been employed in a separate modern conflict. Analyzing a Ukrainian USV will provide results that are conservative to future threat encounters, with an assumption that if the Houthi were to employ a USV in this project’s assumed environment, the vessels would be advanced and as capable as those being used in parallel conflict. Table 4.3 summarizes the results. These RCS calculated values for each of these three threats allow the team to determine simulation inputs for the alternative systems used for analysis. With the RCS of a given threat, we can determine the unique probability of detection or probability of engagement and kill of system listed in Section 4.2.

Table 4.3. Calculated RCS values.

| <b>Threat</b> | <b>RCS (m<sup>2</sup>)</b> |
|---------------|----------------------------|
| Shahed-136    | 0.0428                     |
| Arash-2       | 0.139                      |
| Sea Baby      | 0.25                       |

## 4.2 Defensive Layers Definition

The approach for this project is an analysis of alternative systems involved in a layered defensive system of systems approach. The first and outermost layer to consider is the detection, consisting of a radar on the Naval Destroyer (DDG) operating in the vicinity of the threat area. There may be options to increase the range and probability of detecting threats given an additional system can be incorporated into the theater of operation, such as aircraft launched from Djibouti, or an ally UAS launched from a naval asset. This project will only implement the detection capability of the DDG but allows for future analysis of increased detection capabilities with more complex simulation. As part of this outermost layer, the DDG will also have a long-range engagement weapons system onboard which will be an alternative to the SM, the highly effective but expensive current defensive measures in the Red Sea. Following the DDG engagement layer is an optional close-in escort vessel for each merchant. The escort is an unmanned surface vessel carrying a weapon payload for intercepting incoming enemy UASs and USVs. There are a range of unmanned vessels to consider as this close escort and equally, a range of weapons systems that can operate on the escort which will provide additionally alternative architectures to the system of systems. The project team does not address specific capabilities of the escort vessel, nor analyze for integration of the alternative escort weapons systems onto a USV. The analysis assumes integration is possible and the escort is simulated as being directly attached to the merchant in duress, with a  $P_k$  of the weapon systems that can be loaded onto a USV. Table 4.4 provides a consolidated view of the systems being analyzed for inputs of the alternative detection and engagement options.

Table 4.4. Consolidated list of alternative systems.

| System  | Usage Type | Associated Platform |
|---|------------|---------------------|
| A/N SPY Radar                                 | Detection  | DDG                 |
| Sea Giraffe                                   | Detection  | DDG                 |
| Standard Missile                              | Engagement | DDG                 |
| Hyper-Velocity Projectile                     | Engagement | DDG                 |
| Shadow Fox                                    | Escort USV | Escort              |
| Griffin Missile System                        | Engagement | Escort/DDG          |
| VAMPIRE Rocket                                | Engagement | Escort              |
| Chain Gun with 30 mm×173 mm Airburst Munition | Engagement | Escort              |

### 4.2.1 DDG Detection Systems

Arleigh Burke Class Destroyers (DDG-51) are contributing to the protection of maritime traffic in the Red Sea, as part of the Combined Task Force (CTF) 153 [53]. Since ship commissioning, three design classifications are identified, Flight I/II, Flight IIA and Flight III [54]. According to the same report, DDG-51s “are multi-mission destroyers with an emphasis on air defense (which the Navy refers to as anti-air warfare, or AAW) and blue-water (mid-ocean) operations,” sometimes called Aegis ships, in reference to their equipped combat system. An aerial view of DDG-51 Flight IIA is presented in Figure 4.1. A DDG is capable of housing several radar detection systems.



Figure 4.1. Arleigh Burke class destroyer (DDG-51), USS Jason Dunham (DDG-109). Source: [55].

## AN/SPY

The AN/SPY electronically scanned radar is a series of radars employed by many surface ships in the United States and its allies. Further [56], the AN/SPY-1 variant is claimed to be capable of detecting a golf ball sized target at ranges above 165 kilometers (89.1 nautical miles). The earlier versions of these radars were limited to operating in the S-band, whereas the AN/SPY-6, also known as the Air and Missile Defense Radar (AMDR), has the capability to operate in both the S-band and X-band [57]. An illustration of the AN/SPY-6 is depicted in Figure 4.2.

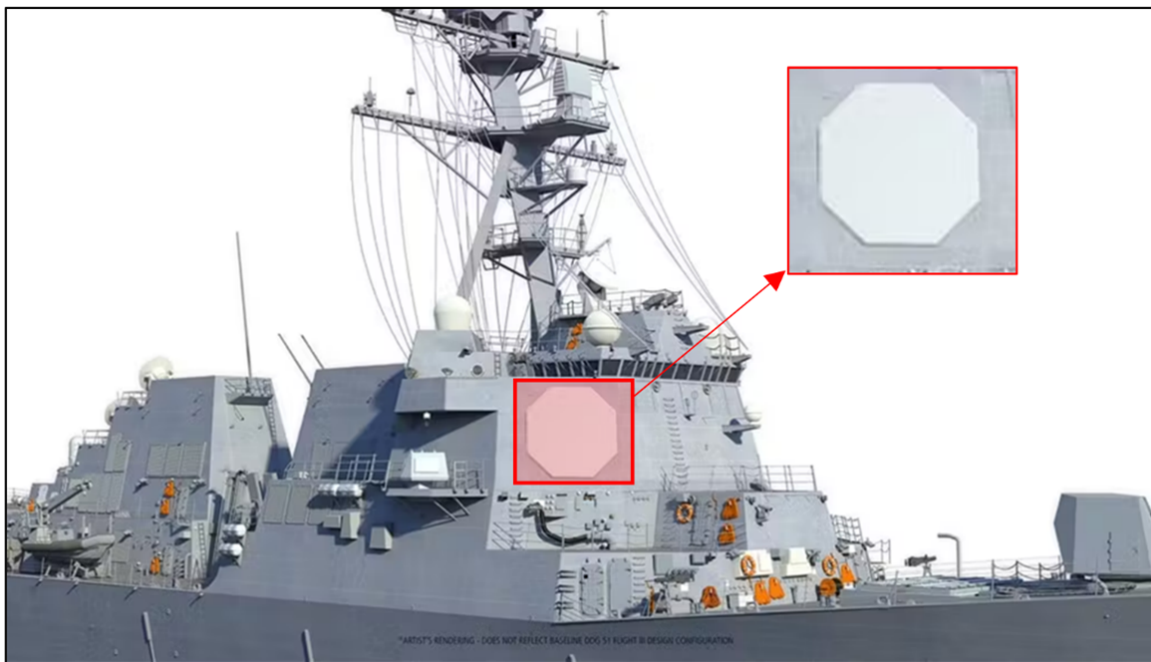


Figure 4.2. AN/SPY-6 radar onboard an Arleigh Burke class destroyer. Adapted from [58].

## Sea Giraffe

Saab's Sea Giraffe is a suite of radars which operates in the C-band, which is employed by the navies of at least 13 countries. There are two-dimensional (2D) and 3D variants. The Sea Giraffe's Hypersonic Detection Mode (HDM) is said to be capable of significantly improving performance against hypersonic threats (specifically against threats traveling at

speeds greater than Mach 5). The high refresh rate and sensing capability is optimized for detection of small, fast targets [59]. Sea Giraffe's antenna assembly is seen in Figure 4.3.

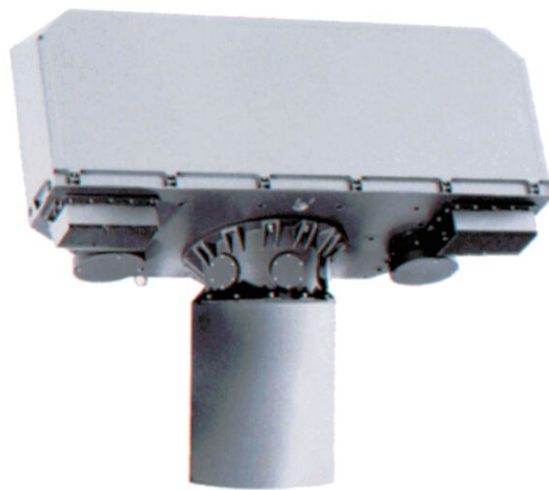


Figure 4.3. Sea Giraffe antenna assembly. Source: [59].

## 4.2.2 DDG Engagement Systems

### SM

The baseline engagement system used for analysis is the Standard Missile ranging from SM-2, -3 and -6. Based on an analysis of data provided by U.S. Central Command (CENTCOM) between October 2022 until May 2023 [60], when unmanned vessels were used as the method of attack on merchant vessels, the area naval assets utilizing SMs for protection had a defensive Pk against the threats of 0.9505. The use of the SMs is clearly very effective as a defensive measure and as the current open-source information provides, is the only weapon being utilized in the current conflict. This will therefore stand as the weapon in the outermost layer of the baseline scenario for the DDG system as a defensive layer.

### Five-Inch Naval Gun High-Velocity Projectile

The Mk-45 is a five-inch naval gun system, used by frigates and destroyers of the U.S. Navy and allies [55], [61], [62]. Aiming to improve lethality of naval surface fire support (NSFS)

systems, BAE Systems designed the high-velocity projectile (HVP) guided munition. This munition name comes from its high muzzle velocity, up to Mach 7.4 when fired from an electromagnetic railgun (EMRG) [63]. Figure 4.4 displays a Mk-45 naval gun in operation from a Dutch warship [64], followed by a representation of the HVP munition in Figure 4.5 [61].



Figure 4.4. Mk-45 Mod 2 firing from a Royal Netherlands Navy De Zeven Provinciën-class frigate. Source: [64].



Figure 4.5. BAE Systems HVP five-inch variant. Source: [61].

Various performance parameters are related to how likely an engagement system will be able to intercept and deny a threat from reaching a defended vessel. Considering this goal of making the unmanned vehicles threats inoperant before they hit the vessel, it can be noticed that these performance parameters are related to how early it is expected to stop it and for how long the defense system can sustain its activity in various time windows. Therefore, some of the performance parameters identified were the extent of weapon envelope, propagator velocity, magazine capacity, engagement rate and payload characteristics. Each of these performance parameters are influenced by how the systems are operated, the technology employed, and characteristics of their target, assessed as follows.

- **Weapon envelope:** According to BAE Systems [65] the HVP has an effective range of more than 40 NM if fired from a 5"/54 Mk-45 Mod 2 naval gun system. Furthermore, the arc of elevation that can be covered by this gun barrel is limited by the shield that composes the turret, as being from  $-15^{\circ}$  to  $+65^{\circ}$  [55].
- **Propagator velocity:** Three variations of the HVP were developed, for compatibility with the Mk-45, Advanced Gun System (AGS) and 155mm Tube Artillery, and with the EMRG [66]. Each of these rounds has their own design specifications, while operating in different barrels present different ballistic profiles. According to Janes [67], the HVP with this EMRG had a requirement of muzzle velocity on the range of 7,242 to 9,012 km/h. On the other hand, O'Rourke [55] states that when fired from the Mk-45 the compatible variant presented a velocity close to Mach 3 (3,704 km/h) instead. Therefore, for the considered gun and projectile combination the propagator velocity is assumed as 3,704 km/h or 2,000 knots.
- **Magazine capacity:** This is another parameter defined mainly by the manufacturer's datasheets and other online sources. According to Janes [67], the Mk-45 Mod 2 mounting has a drum capable of housing 20 rounds.
- **Engagement rate:** The maximum rate of fire for a Mk-45 when employing HVP as munition is 20 rounds per minute [66]. Nevertheless, the achieved rate would not be this much if any tracking issues occur, as the angular velocity associated with the gun turning speed may be lower than the variations imposed by the target, or if intentional interruptions occur to assess damage on target.
- **Payload characteristics:** The HVP munition has a payload of 15 lbs (6.8 kg) [66]. Further, O'Rourke [55] points that more than 500 three-gram (46.3 grains) tungsten

fragments is expected from this projectile warhead detonation. According to the same report, BAE Systems states that this is a 24 inch long projectile, plus the launch package. If about 70% of this projectile length is the payload, then it would be approximately 17 in long. A cylindrical shape for the payload is assumed, with the same diameter as the projectile, a 5 in width. Moreover, Janes [62] indicates that most of the 5 inch naval gun conventional munitions are filled with a Comp A-3 explosive, which is 91% made of Research Department Explosive (RDX) high explosive. Therefore, from Ball [40] Table 3.9a, a detonation velocity ( $V_D$ ) of 26,800 ft/s and a Gurney constant of 9,300 ft/s would be observed for RDX, then assumed for this payload.

- **Engagement parameters summary:** In summary, the performance parameters considered for the Mk-45 Mod 2 with the 5” HVP are as detailed in Table 4.5.

Table 4.5. Mk-45 with HVP performance parameters. Adapted from [40], [55], [62], [65].

| Parameter                            | Performance |
|--------------------------------------|-------------|
| Effective engagement range (NM)      | 40          |
| Elevation arc (°)                    | -15 to +65  |
| Propagator velocity (knots)          | 2,000       |
| Warhead length (in)                  | 17          |
| Warhead diameter (in)                | 5           |
| Explosive Gurney constant (ft/s)     | 9,300       |
| Explosive detonation velocity (ft/s) | 26,800      |

### 4.2.3 Escort Vessel Systems

#### L3 Harris Shadow Fox Autonomous Surface Vessel

The Shadow Fox is a 13-meter long USV with capabilities of communication via UHF/VHF, Satcom, 4G and Wi-Fi [68]. A setup in the area defense DDG can be established as the C2 for the Shadow Fox, and it can be fitted with a payload. Considerations for the Shadow Fox as a layer in this project’s system include remote control of the vessel and launch

capabilities, integration of the weapons systems analyzed and the USV and the full sensor suite capabilities of the USV autonomously for threat tracking and engagement without DDG support. An additional tactic that can be employed from Shadow Fox is its already integrated ability to launch a UAS from its platform. The UAS could provide further analysis in this project for an increased  $P_d$  for the system, or provide a means to have  $P_d$  fully autonomously, possibly eliminating the need for the DDG in are support. Being a L3 Harris [69] product, this USV has already proved capable of incorporating the VAMPIRE weapon system, discussed in the following section. It has been integrated with various radars including RADA MHR, Elbit MATRX and the Teledyne Raptor but more importantly it will need a cue to slew the EO/IR sensor to, which requires remote operation from a human interface [69]. The consideration for this project will assume the human interaction either occurs from the area DDG, given range of C2 ability, or the merchant self-operating capability given training and equipment can be given to the crew.

#### **4.2.4 Escort Engagement Systems**

##### **Griffin Missile System**

Developed by Raytheon, the AGM-176 Griffin is a lightweight missile system designed to provide low cost and low collateral damage engagements [70], [71], [72]. The whole system known as Mk-60 Griffin Missile System (GMS), comprises not only a battle management system and control panel, but the launcher (Mk-208) and the AGM-176 missile itself [70], [72], [73]. A picture of the Mk-208 launching an AGM-176 missile is shown in Figure 4.6 [72].



Figure 4.6. AGM-176 Griffin missile being launched. Source: [72].

This missile shares components from both the Javelin and the Archer missiles, control and propulsion from the first, while guidance and power from the second [71]. Among variants, three may fit into surface platforms the AGM-176B, AGM-176C and AGM-176C-ER, being the last indicated the most recent, under development [71]. The extended range (ER) on this variant name comes from an extended motor. This section analyzes the performance parameters expected from a missile-based engagement system such as Griffin on the AGM-176C-ER variant.

- **Weapon envelope:** According to Janes [72], an effective range of 15 km (8.1 NM) can be expected from the AGM-176C-ER variant. Further, since the missile maneuvers towards its target, elevation constraints would be tied to the tracking system and are disregarded in this analysis. Thus, maximum elevation of  $90^\circ$  is assumed.
- **Propagator velocity:** With the same propulsion system, the Javelin missile reaches a maximum flight speed of 300 m/s or 583 knots [74]. Given that trajectory and aerodynamics are different in the AGM-176, differences in the speed profile are

expected. Moreover, with a larger motor, the Griffin C-ER may incorporate further changes to this profile. For this missile system under analysis, 650 knots is assumed.

- **Magazine capacity:** A ready to use inventory size of 4 units is assumed for this weapon system, as seen in the opened launcher in Figure 4.7 [75].



Figure 4.7. Opened Mk-208 GMS. Source: [75].

- **Engagement rate:** No restriction to the engagement rate is assumed for the GMS, which according to the Naval Sea Systems Command [73] this system would be capable of performing a multiple salvo.
- **Payload characteristics:** The Griffin system variants all use the same warhead [73]. As published in Global Security [76], according to a presentation from Raytheon on specifications for the AGM-176B, a diameter of 14 cm (5.51 inches) is observed in this warhead. Considering this dimension, from proportions on the image representation of this missile in Figure 4.8, adapted from the same source [76], the warhead length is estimated as 6.24 inches. This warhead filling is a PBXN-110 explosive [71], [72], that according to the standard is 88% made of High Melting eXplosive (HMX) [77] neglecting influence of other present components in this explosive to the detonation velocity and Gurney constant, from data presented in Ball [40] for the HMX, these parameters are assumed as 29,900 ft/s and 10,230 ft/s, respectively.

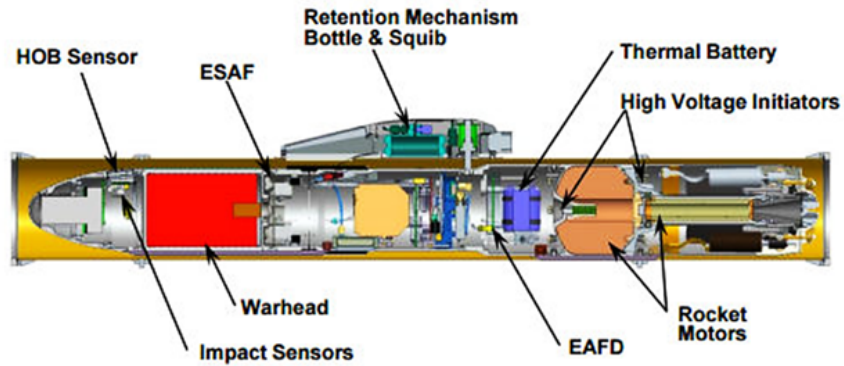


Figure 4.8. Griffin B block II missile components. Source: [76].

- **Engagement parameters summary:** The resulting performance parameters for the Griffin Missile System would then be as summarized in Table 4.6.

Table 4.6. Griffin Missile System performance parameters. Adapted from [40], [71], [72], [73], [74], [76], [77].

| Parameter                            | Performance |
|--------------------------------------|-------------|
| Effective engagement range (NM)      | 0.8         |
| Elevation arc (°)                    | Up to +90   |
| Propagator velocity (knots)          | 650         |
| Warhead length (in)                  | 6.24        |
| Warhead diameter (in)                | 5.51        |
| Explosive Gurney constant (ft/s)     | 10,230      |
| Explosive detonation velocity (ft/s) | 29,900      |

**Vehicle-Agnostic Modular Palletized ISR Rocket Equipment (VAMPIRE) Rocket System with Advanced Precision Kill Weapon System (APKWS)**

Another engagement system alternative that could be suitable for use in the escort vessels is a rocket launching system such as the L3 Harris VAMPIRE. This system comprises a multi-sensor and multi-spectrum unit for tracking and laser designating the target, known as WESCAM MX™-10, a rocket launcher and a control station [74], [78]. This sensor suite and rocket launcher are demonstrated in Figure 4.9, adapted from L3 Harris [70].



Figure 4.9. L3Harris VAMPIRE sensor and rocket launcher. Source: [70].

As stated by L3Harris, this system may employ the APKWS and other munitions that has laser guidance [70]. BAE Systems developed the APKWS, which combines a rocket and warhead of a conventional Hydra 70 rocket (2.75 in wide and 70 mm long) to a guidance kit [76], [79]. Notwithstanding, the APKWS guidance section is available for supply both by itself or with the rocket and warhead as an all-up round. These major components in such an assembly is shown in Figure 4.10 [71].



Figure 4.10. APKWS all-up round major components. Source: [71].

- **Weapon envelope:** The APKWS as an all-up round has different ranges according to the launch platform. On fixed-wing platforms this range can be greater than 12 km (6.48 NM), launched from the Arnold Defense LAU-131 A/A, being more than 5 km (2.7 NM) for rotary-wing from the LAU-68 F/A [80]. Further, Arnold Defense developed a four-cell rocket launcher compatible with the APKWS for ground and sea

vehicles use, the LAND-LGR4 or Fletcher, which can provide precision strike range of up to 6 km (3.24 NM) [80], [81]. The same launcher used by L3Harris VAMPIRE, the Arnold Defense launcher is shown in Figure 4.11. An effective range of 3 NM is assumed, a mid-point between the APKWS on rotary-wing and the Fletcher.



Figure 4.11. LAND-LGR4 laser guided weapon system. Source: [74].

Constraints to the elevation in this rocket system are assumed to be related mainly to the detection or tracking system. L3Harris doesn't state limitations in this regard for the WESCAM MX-10 RSTA [82]. Therefore, in this analysis a maximum elevation of 90° is considered.

- **Propagator velocity:** Once launched the APKWS seeks its target for approximately 1.1 seconds and after 1 second of flight it achieves a maximum speed of Mach 1.2 (800 knots) [80].
- **Magazine capacity:** A magazine capacity of four units is assumed, the rocket capacity of both Arnold Defense LAND-LGR4 and L3Harris VAMPIRE [70], [73].
- **Engagement rate:** The Fletcher can perform single fire or launch on rapid succession (ripple fire) [83], thus restrictions to the launch rate are assumed as negligible for this weapon.
- **Payload characteristics:** Two different fragmentation warheads are available for the APKWS as a complete round, the M151 and M282 [71], [72]. This second warhead is a heavier version, with penetrating and incendiary effects [84]. Figure 4.12, adapted from The Aircav [85], illustrates the M151 and a warhead with similar physical

specifications, the M156. From the figure proportions, given that the length from the base to the fuse is 12.9 inches, it can be surmised that the area with explosive filling is about 11.35 inches in the M156. Considering the similar construction, it's assumed that the M151 also has the same length, which is taken to this analysis. Furthermore, the payload diameter is assumed as specified to the rocket diameter, 2.75 inches [75]. The explosive filling in the M151 warhead is a composition of B-4 [86], a mixture of RDX (60%) and TNT (39.5%) explosives [87]. For the sake of simplicity, it's assumed that it's a RDX filling, thus resulting in a detonation velocity of 26,800 ft/s along a Gurney constant of 9,300 ft/s, according to Ball [40].

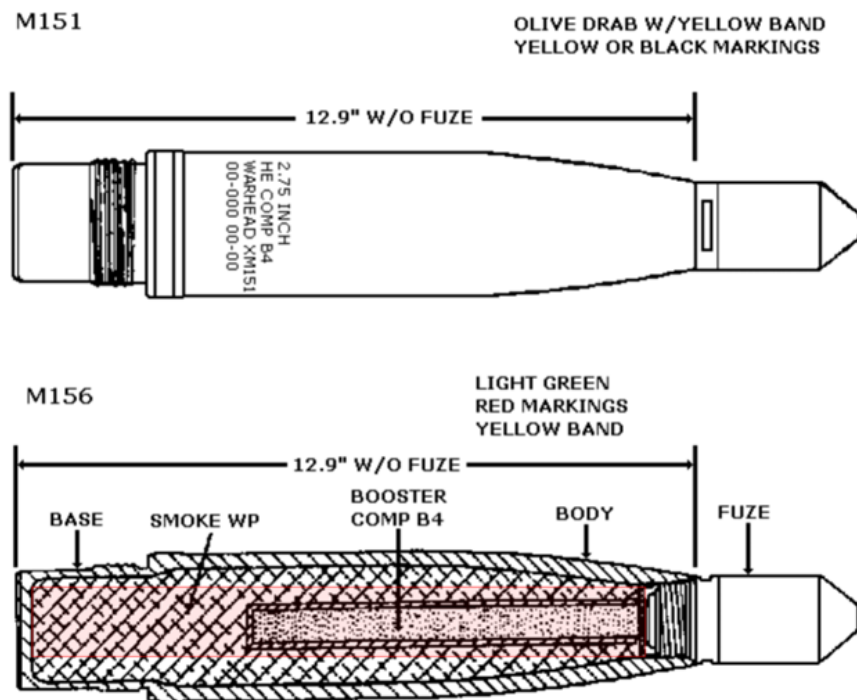


Figure 4.12. M151 and M156 Hydra 70 warheads with an area highlighted in red indicating the length of high explosive filling. Adapted from [85].

- **Engagement parameters summary:** In summary, the performance parameters considered for the rocket launcher such as VAMPIRE with the APKWS are as detailed in Table 4.7.

Table 4.7. Mk-45 with HVP performance parameters.

| Parameter                            | Performance |
|--------------------------------------|-------------|
| Effective engagement range (NM)      | 3           |
| Elevation arc (°)                    | Up to +90   |
| Propagator velocity (knots)          | 800         |
| Warhead length (in)                  | 11.35       |
| Warhead diameter (in)                | 2.75        |
| Explosive Gurney constant (ft/s)     | 9,300       |
| Explosive detonation velocity (ft/s) | 26,800      |

### Chain gun with 30 × 173 mm Airburst Munition

The 30 × 173 mm ammunition family comprises a wide variety of designs each suitable for a different set of mission requirements [88]. Most of modern munitions designed for air-targets use fragments generated by a contact or proximity detonation as the damage mechanism [40]. Systems such as the Electro Optic Systems (EOS) Titanis combine the firing power of this caliber enhanced by the lethality of the airburst munition in a sensor suite to counter unmanned threats. As stated by EOS [89], Titanis is a “fully integrated counter-drone system with soft, hard and directed energy kill capabilities.” This system has a radar, a passive electronic warfare (EW) detector, cameras for both visible and infrared spectrum and also a laser rangefinder as sensors, most of them identified in Figure 4.13 [90].

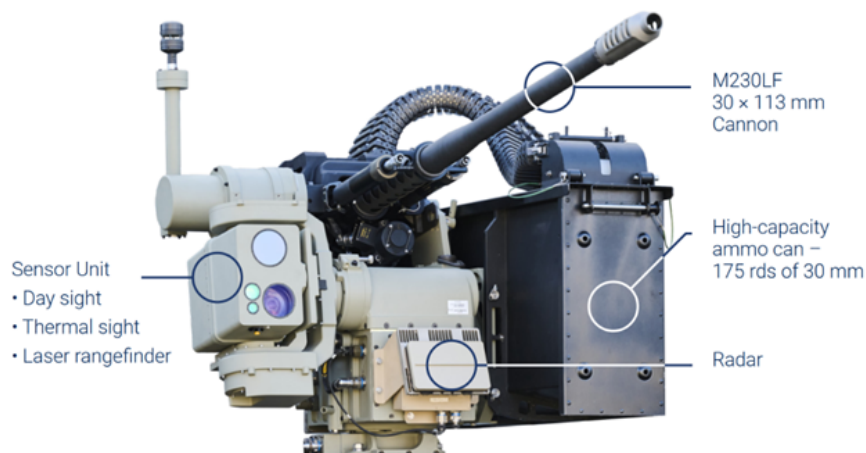


Figure 4.13. EOS Titanis counter drone major sensors. Source: [90].

Among machine guns, cannons, missile and laser, hard-kill effectors can be combined into the turret in multiple ways, according to the product chosen from the family of systems R-Series Remote Weapon Station (RWS) [90]. Maximum firepower is offered in the R800S, which can feature a Bushmaster Mk44S/XM813 (30mm × 173mm), as primary armament, machine guns or a laser dazzler as secondary, plus up to four missiles in two pods, as detailed by EOS [91]. This family of systems has variants that may be installed directly on maritime platforms, on land vehicles or operated from a container. An example of each is illustrated in Figure 4.14 [89].



Figure 4.14. EOS R400-M (top-left), Titanis on land vehicle (top-right) and on a container (bottom). Adapted from [71], [92], [93].

For this analysis, it is considered that a system such as Titanis is installed and fully integrated into the escort vessel, similarly to the up-left system on Figure 4.14. This escort would then maneuver around the ship it was defending, interposing itself between the ship and the threat covering all approaching angles, which requires a very close formation.

- **Weapon envelope:** Besides various guns available as effectors, this analysis will focus on the Mk44S, which is a Northrop Grumman Bushmaster® Chain Gun® [94]. Two effective ranges were informed by EOS when this gun is employed with the Titanis suite, 1.5 km [89] and 3 km [90], with an elevation range from  $-10^{\circ}$  to  $+60^{\circ}$  [71]. For our project, it is assumed that the effective range of this gun is 1.5 km or 0.81 NM.
- **Propagator velocity:** The Mk44S may employ a variety of 30mm  $\times$  173mm munitions, being most appropriate for use against low armored fast moving targets the ones with air burst capability. One such munition is the Mk310 Programmable Air Burst Munition (PABM) with tracer, that presents a 3,182 fps (1,885 knots) muzzle velocity, this ammunition is illustrated in Figure 4.15 [95].



Figure 4.15. Mk310 PABM 30  $\times$  173 mm. Source: [96].

- **Magazine capacity:** The ammunition load of the Mk44S used on Titanis is stored in two containers (boxes) on each side of the cannon, both being able to feed the gun for a total of up to 200 rounds [97].
- **Engagement rate:** This Chain Gun® may be fired in three modes, single shot, burst and fully automatic, with a maximum rate of fire of 200 shots (or rounds) per minute [98].
- **Payload characteristics:** Northrop Grumman [95] does note states the number of fragments and payload weight of the Mk310 PABM. However, a same caliber air burst munition, the ABM/KETF 30 $\times$ 173mm, has a tungsten-alloy payload of 201 g composed of 162 cylindrical fragments with 1.24 g each [99]. This munition is illustrated in Figure 4.16 [99] along its cutaway version [88]. The 30 $\times$ 173mm munition is a 290 mm total length round, with its projectile 173 mm long [88]. Assuming that the payload is 70% of the projectile length, then this dimension would be 121.1 mm (4.77 in). The payload diameter is the same as the projectile, 30 mm (1.18

in). Further, Janes [88] states that the Mk310 PABM munition employs a polymer bonded explosive (PBX) based composite filling. As described by Akhavan [100], these explosives are formulated usually with a high composition of RDX, HMX or Pentaerythritol Tetranitrate (PETN), in this analysis being assumed the first as this ammunition high explosive. Therefore, as previously referred, a detonation velocity of 26,800 ft/s along a Gurney constant of 9,300 ft/s would be observed [40].



Figure 4.16. ABM/KETF air burst 30 × 173 mm munition along its cutaway sample. Source: [101].

- **Engagement parameters summary:** In summary, the performance parameters considered for the Mk44S with the 30 × 173 mm are as detailed in Table 4.8.

Table 4.8. Mk44S with 30 × 173 mm performance parameters. Adapted from [40], [88], [89], [91], [95], [96], [100], [102].

| Parameter                            | Performance |
|--------------------------------------|-------------|
| Effective engagement range (NM)      | 0.81        |
| Elevation arc (°)                    | -10 to +60  |
| Propagator velocity (knots)          | 1,885       |
| Warhead length (in)                  | 4.77        |
| Warhead diameter (in)                | 1.18        |
| Explosive Gurney constant (ft/s)     | 9,300       |
| Explosive detonation velocity (ft/s) | 26,800      |

## 4.3 Scenarios

The outermost layer of the defensive system of systems is detection by the DDG, using one of the listed radars in the previous section. The next layer consists of long-range engagement from the DDG, followed by the innermost layer of shorter range engagement from the escort USV. Using the listed alternative systems in each layer, various scenarios need to be analyzed with different postures of threat and ally vessels. The baseline scenario represents the most realistic model of current posture in the Red Sea, consisting of a UAS attack with only the DDG to detect and defend against it. This scenario, as with each later scenario, will be repeated in the simulation using alternatives for the detection system and the engagement system. From the baseline, the scenarios expand to add the USV escort or remove the DDG as part of the engagement layers. They also include a variation of enemy threat tactics ranging from a single USV or UAS to a swarm of incoming threats for defending against. Based on these five scenarios below with alternative postures by the allies and enemies, the varying weapons systems detection and kill probabilities can be input to analyze for effectiveness. Figures 4.17–4.21 show activity diagrams of the scenarios.

### 4.3.1 Group III Single UAS Attack with DDG Support Only

A group III UAS is launched from Sana'a, the capital city of Yemen controlled by the Houthi militia. The drone flies a straight-line course directly toward a merchant in the Gulf of Aden, as it transits the Bab al-Mandab Strait. A Naval Destroyer (DDG) in the vicinity of the merchant, operating in an area defense posture, detects the approaching vehicle and classifies it as a threat UAS once within a given detection range of the ship's abilities. Engagement combat weapons onboard the naval escort ship operate as defensive measures for the nearby merchant under attack. This hard kill of the UAS shall occur prior to release of additional weapons from the threat store and prior to direct contact kamikaze attack on the merchant. The alternative analysis for this scenario will include the variation of the detection radar on the DDG and the variation of the launched weapon from the DDG munition. This scenario serves as a baseline for the most conventional warfare tactic applied in drone defense historically.

### **4.3.2 Group III Single UAS Attack with Merchant Escort Only**

The same setup as scenario 1 is in place, with a single UAS launched from Sana'a and detected and tracked by a DDG operating in the Red Sea area. The DDG will communicate with the close escort to the merchant in distress, an allied USV, to operate as a defensive system. The USV will engage the incoming threat UAS with the onboard weapon system, launching a single interceptor at the incoming threat. The alternatives for this scenario to analyze will be the USV weapon used to engage the threat.

### **4.3.3 Group III Single UAS Attack with Merchant Escort and Naval Vessel Support**

Again, this scenario is a single UAS launched in a straight line toward a merchant in the Bab Al-Mandeb Strait from the capital Sana'a in Yemen. The DDG will similarly detect and track the threat, and engage the threat given the detection occurs at an appropriate range for the weapon system being operated. Given the DDG does not successfully intercept the threat UAS, communication will occur with the allied close escort USV to engage with its own weapon system as a secondary defensive layer to the DDG. The alternatives for this scenario are the same for scenario 1 for the DDG, are a variation in weapon launched from the escort USV.

### **4.3.4 Group III Swarm UAS Attack with Merchant Escort and Naval Vessel Support**

A 5-drone swarm of group III UASs is launched from Hajjah, a Houthi-controlled city 50 miles northwest of the capital Sana'a. The swarm is headed toward the Bab al-Mandab Strait where the UASs will target transiting merchants into and out of the Red Sea. The DDG in area defense will detect and engage the threat swarm, varying the radar system and engagement weapon onboard for alternative analysis. Given the DDG engagement systems fail to intercept the threat UAS swarm, or there are leaker UASs from the swarm out of range of the DDG systems, communication will occur with the close escort to the merchant under attack. The close escort will be an allied USV carrying a smaller caliber engagement weapon and given the data from the DDG tracking the threat, will launch at the UAS swarm in defense of the merchant it is escorting. The alternatives for this scenario are the same for scenario 1 for the DDG, are a variation in weapon launched from the escort USV and now

can be used to compare a single UAS attack to a swarm UAS attack from Yemen with both a DDG and a close escort for support.

#### **4.3.5 Single USV Attack with Merchant Escort Defense Only**

A threat USV is launched by the Houthi militia from the costal base in Al Hudaydah, Yemen targeting a transiting MSC vessel heading south toward the Bab al-Mandab Strait or North into the Red Sea from the Strait. Due to the low RCS of the stealth USV, the DDG will likely only detect and track the enemy vessel at a short enough range that the escort will have to be the first to engage right away. The DDG will communicate the incoming threat to the allied USV close escort and the engagement system onboard the USV will attempt to intercept the attack toward the merchant it is defending.

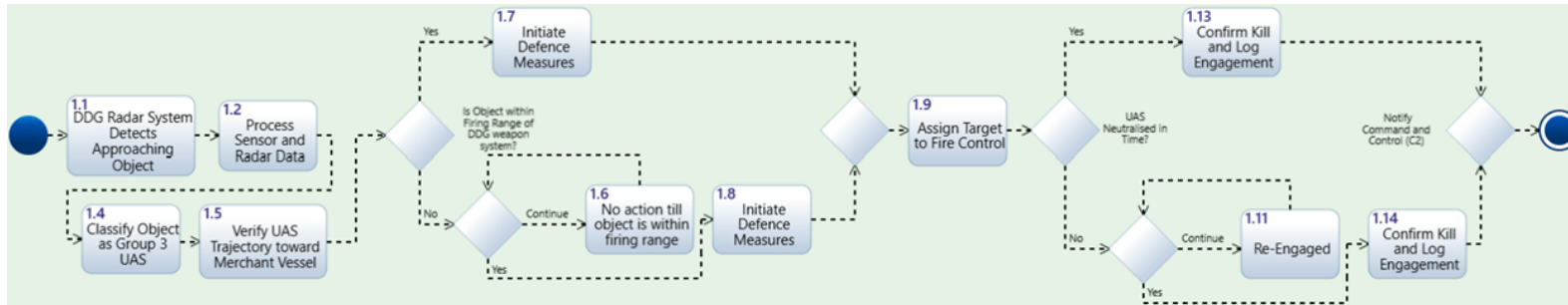


Figure 4.17. Activity diagram of group III single UAS engagement via naval vessel defense system.

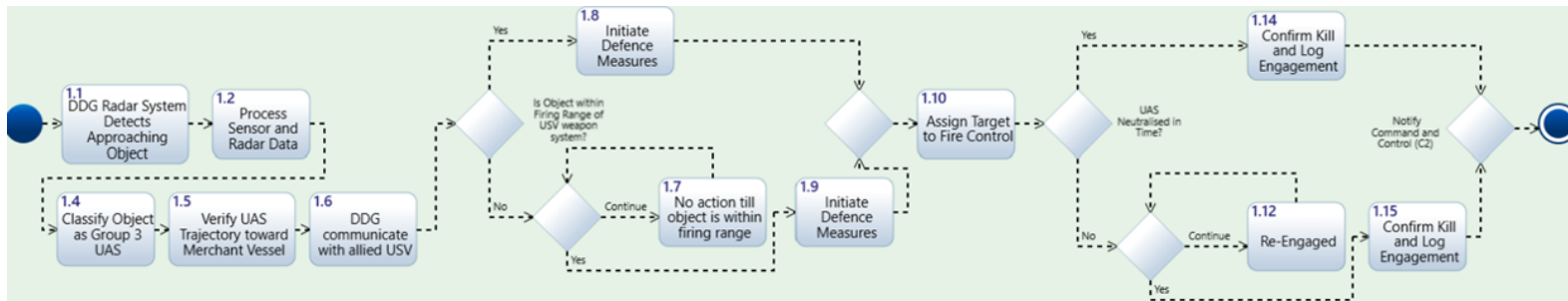


Figure 4.18. Activity diagram of group III single UAS engagement via allied USV defense system.

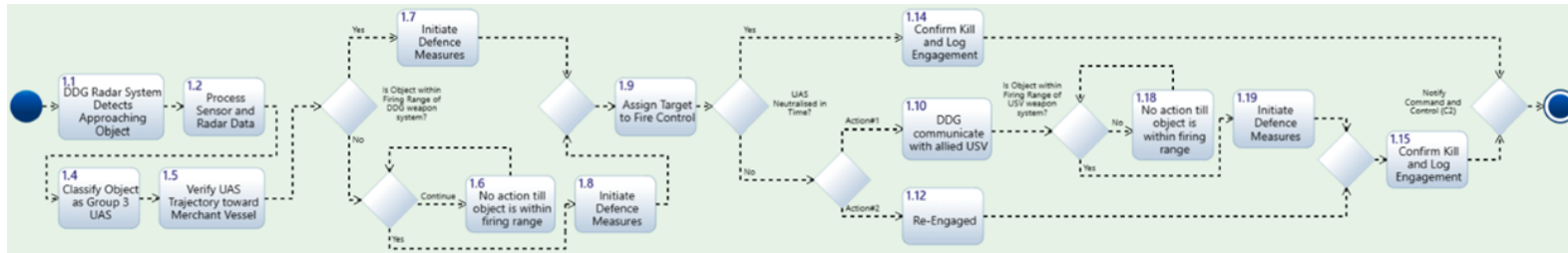


Figure 4.19. Activity diagram of group III single UAS engagement via naval vessel and allied USV defense systems.

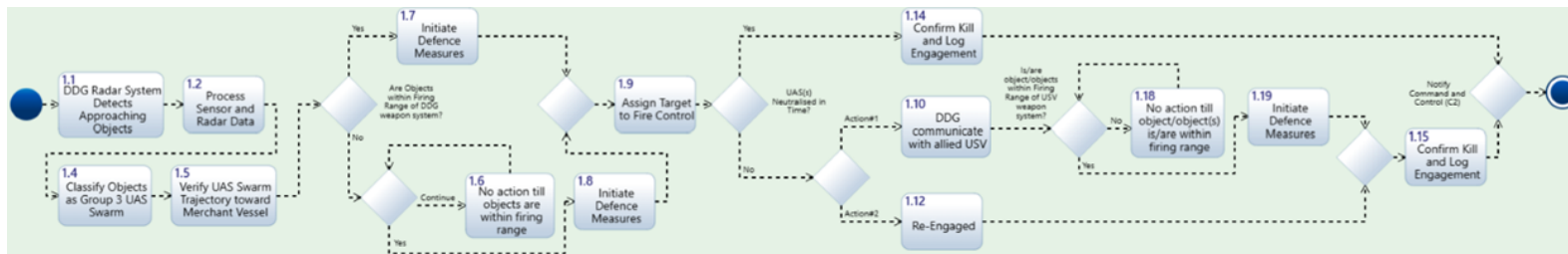


Figure 4.20. Activity diagram of group III UAS swarm engagement via naval vessel and allied USV defense systems.

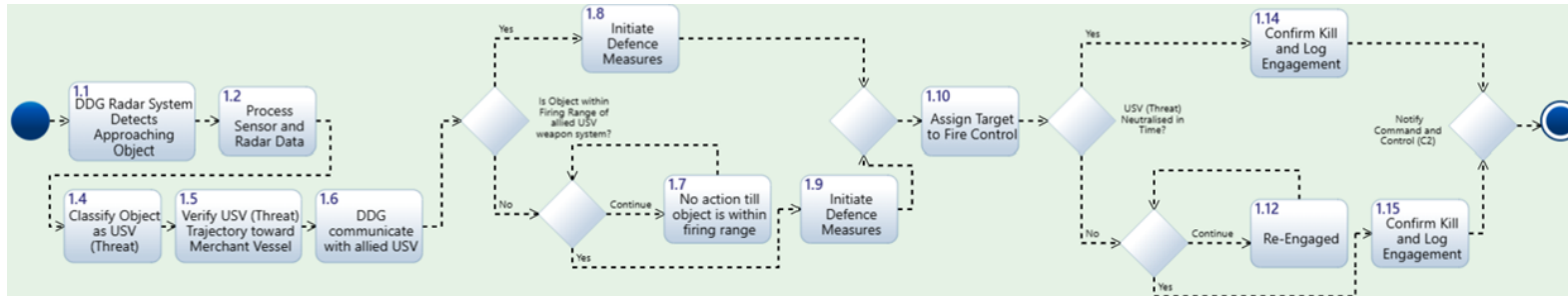


Figure 4.21. Activity diagram of single USV (threat) engagement via allied USV defense system.

## **4.4 Modeling and Simulation Approach**

The evaluation of simulation tools for this project considered three prominent platforms: Map Aware Non-Uniform Automata (MANA), Mission Analysis and Simulation Toolset (MAST), and Simio. Each tool offered unique strengths aligned with different aspects of modeling and simulation, particularly in naval conflict scenarios such as those in the Red Sea. While MAST was determined to be the most technically suitable tool for this project, Simio was ultimately selected due to the practical constraints posed by the class composition, which included a majority of international students.

### **4.4.1 Evaluation Summary**

MANA is well-suited for agent-based simulations, focusing on dynamic tactical engagements and emergent behaviors. Its ability to simulate interactions between autonomous agents on geographically accurate maps was advantageous. However, its complexity in setting up large-scale scenarios and emphasis on behavioral modeling made it less practical for the operational workflows central to our study.

MAST excels in high-fidelity system-level simulations, providing detailed insights into weapon performance, radar integrations, and mission-specific outcomes. Its precision and ability to model complex system interactions made it the ideal choice for the technical demands of the project. However, the software's restricted availability to U.S. military officers rendered it impractical for a class comprised predominantly of international students. This limitation, combined with the importance of ensuring that all participants could engage meaningfully with the selected tool, necessitated the exploration of alternative options.

As a general-purpose discrete event simulation tool, Simio provides robust 3D visualization, an intuitive interface, and adaptability across various operational scenarios. Although it lacks the military-specific focus of MANA and MAST, Simio's user-friendly design enabled the team to collaboratively develop models while maintaining a balance between technical depth and usability. Its capacity for operational optimization and external data integration further supported its applicability to the project.

#### **4.4.2 Decision Rationale**

The decision to use Simio was driven by practical constraints related to software accessibility. Although MAST offered superior fidelity and was technically the most suitable tool for the project, its restriction to U.S. military personnel made it unavailable for use by the class. Simio, on the other hand, provided a platform that was accessible to all participants, allowing for equitable engagement and active learning opportunities within the class.

In addition to its accessibility, Simio's 3D visualization capabilities enhanced the clarity and communicability of results, enabling the team to present findings effectively to both technical and non-technical stakeholders. This feature was particularly beneficial in a classroom setting, where collaborative learning and comprehension were prioritized alongside technical precision.

---

## CHAPTER 5: Simulation and Analysis

---

To provide sufficient analysis of the detection and engagement systems on our layered defense of platforms, Simio technology was used to create a simulation environment. The Red Sea scenario was built as a map feature providing realistic dimensions and distances. Inputs regarding the threats, allied platforms, and the system of systems on such platforms were created using the previously described specifications. Many assumptions are made within the simulation space to provide consistent and reliable results of the layered defense system. A general description of the simulation environment is described, followed by the specific inputs for each scenario and then the results. Analysis is performed to compare the scenario results using the MOEs and MOPs.

### **5.1 Simulation Environment**

#### **5.1.1 Scope**

For each scenario, a 30-day period is assumed and 50 simulation runs are performed to obtain a probabilistic estimation of the resulting MOEs. The simulation considered real-world locations and distances, system's logic, probabilities of detection and interception for each system's combination (scenario). However, the team descope the simulation for any flight physics and profile of flight data such as speed and elevation of the threat or direction of relative motion of the defense system flight toward the threat. This is due to having too many unknowns to simulate realistic physics, and a physical simulation is over-complicated and out of the team's expertise.

#### **5.1.2 Setup**

The simulation models the Red Sea region with the main shipping route going through it based on public AIS information from civilian merchant traffic. Only one source of enemy threats is input, located in Yemen with a range that approximates the location of hits in real-world Houthi attacks. Figure 5.1 displays the simulation environment, including the radius of the threat attack.

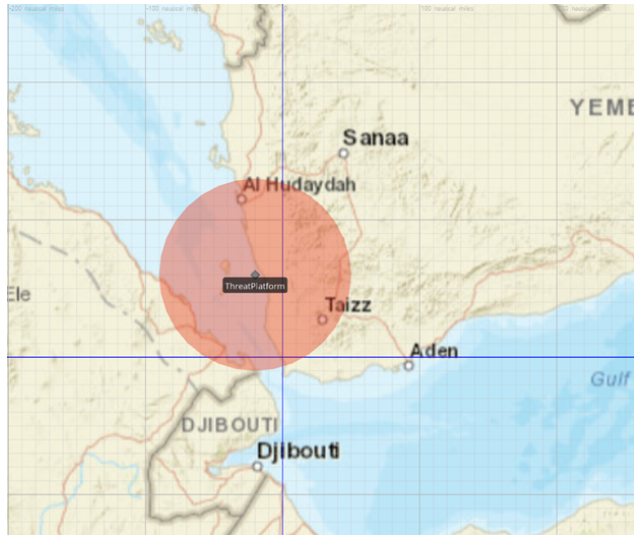


Figure 5.1. Threat ring.

A DDG is simulated in the Bab Al-Mandeb Strait with a Radar detection system and an interception engagement system, varying between scenarios to compare the two analyzed detection capabilities and the two analyzed weapon systems on the DDG. Figure 5.2 shows the merchant traffic simulated, moving in both directions through the Strait and the stationary location of the DDG near the area.

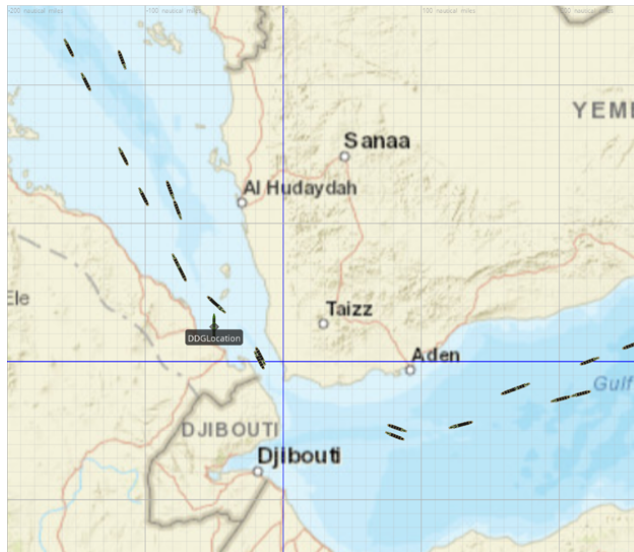


Figure 5.2. Simulated merchant traffic with stationary DDG.

Each commercial ship input to the scenario space is simulated with an accompanied close escort vessel that commences escort duties prior to the threat axis, such as in the Gulf of Aden prior to vessel traffic through the Bab Al-Mandeb Strait, and then turns over to escort a different merchant for the opposite direction of traffic once its initial merchant has left the threat axis region in the North. The close escort varies as well between scenarios to compare its three engagement weapon capabilities and in some scenarios having no capability, as if there was no escort but only the DDG in area for defense. Figure 5.3 shows the same vessel traffic as Figure 5.2 but includes the blue figures for escort interceptors launched at the red threat.



Figure 5.3. Simulated merchant traffic with escorts.

A threat or swarm of threats is launched against a random commercial ship with random exponential inter-arrival time, with a mean rate of 1 launch per day. Every threat can be detected according to a profile of detection probability based on distance from radar, with the highest probability of detection analyzed based on the systems capabilities, as described

in Appendix A. A major assumption for threat detection is that when launching threats in barrages or swarms, one threat detected leads to a detection of all the threats in the barrage. Every detected threat in the simulation enters a logic process as follows:

1. **DDG Engagement, Shoot A:** Based on the scenario, either 1 or 5 engagement weapons are shot at the threat.
2. **Look"** If the threat is not killed based on the DDG's probability of kill, simulation continues to the next step.
3. **Escort Engagement, Shoot B"** Based on the given scenario, the escort is either present with one of three weapon systems or not present. If present, the escort will launch a single shot at the threat.
4. **Fail to Engage:** If both DDG and escort systems fail, or the threat has not been detected, there is an assumed probability of 100% kill of the targeted commercial ship.

The variables which affect the different input parameters that vary between scenarios are as follows:

- **Threat type** (inputs): USV or group III UAS.
- **Threat barrage size** (2): 1 or 5 threats launched at the targeted merchant vessel.
- **Radar type** (2) on the DDG: AN/SPY-6 or Sea Giraffe.
- **DDG interceptor type** (2): One single scenario used as a baseline for real world activity of the in area DDG using SM defenses, and all other simulations involving the DDG with the simulated HVP weapon onboard.
- **DDG interceptors per threat** (2): HVP is launched as either a single shot at each threat or launched as a salvo of 5 shots.
- **Escort interceptor type** (4): Griffin, VAMPIRE, Titanus Mk44S or null values for the escort to simulate its lack of presence in the assumed space.

These variations result in a total of 96 Scenarios, plus one reference scenario for the sole DDG in area with Standard Missiles. The scenario input parameters above affected three different probability values to vary in the simulations. Those different values are the distance at which each threat was detected (probability function determined by threat type and radar type), the probability of interception by each DDG interceptor (probability determined by

threat type and DDG interceptor type), and the probability of interception by each escort interceptor (probability determined by threat type and Escort interceptor type).

### 5.1.3 Input Parameters

As previously described, two conditions were assumed as necessary for a successful engagement, detection of the threat by the radar and its kill by an interceptor. The probabilistic nature of these events is determined as follows. Following the process described in Appendix A, the cumulative probability of detection at various ranges was determined for both sensors described in Chapter 4, the AN/SPY-6 and the Sea Giraffe, according to different weather conditions and threats. During the simulation, the distance between the simulated threats and the DDG at each time-step was used to determine the detection probability based on a predefined lookup table. A random number between zero and one was then generated and compared to this probability to assess whether detection of the threats occurred at that time-step. The probabilities on this table are derived from the cumulative probability of detection versus range demonstrated in Figure 5.4 for a UAS with Shahed-136 characteristics, Figure 5.5 for a UAS with Arash-2 characteristics, and in Figure 5.6 for a USV with characteristics of a Sea Baby.

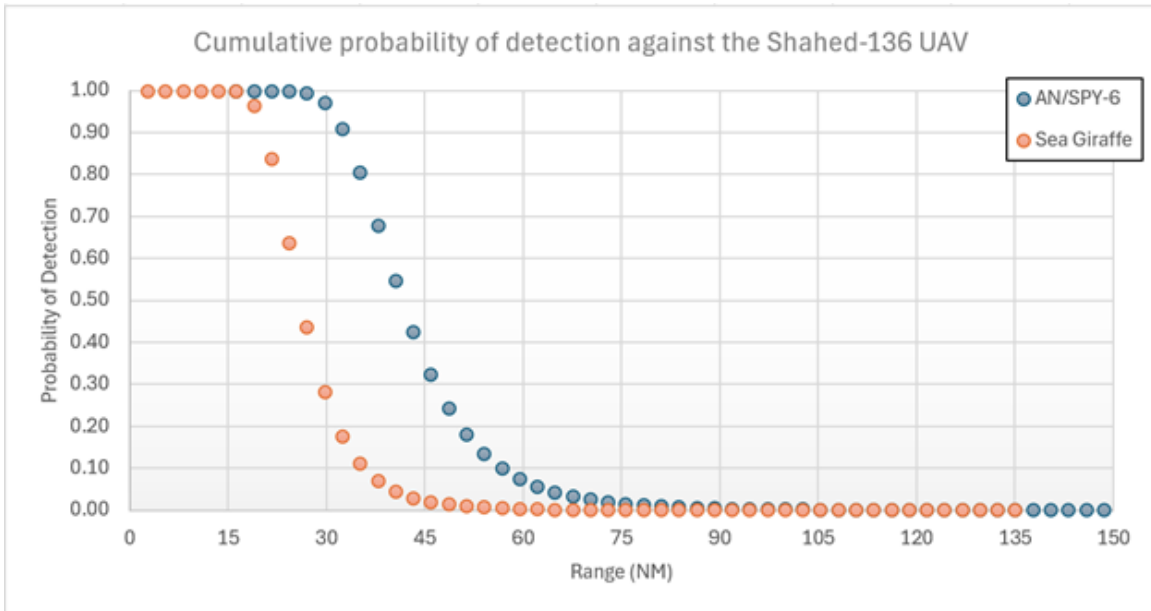


Figure 5.4. Cumulative probability of detection of each sensor versus an approaching UAS with Shahed-136 characteristics.

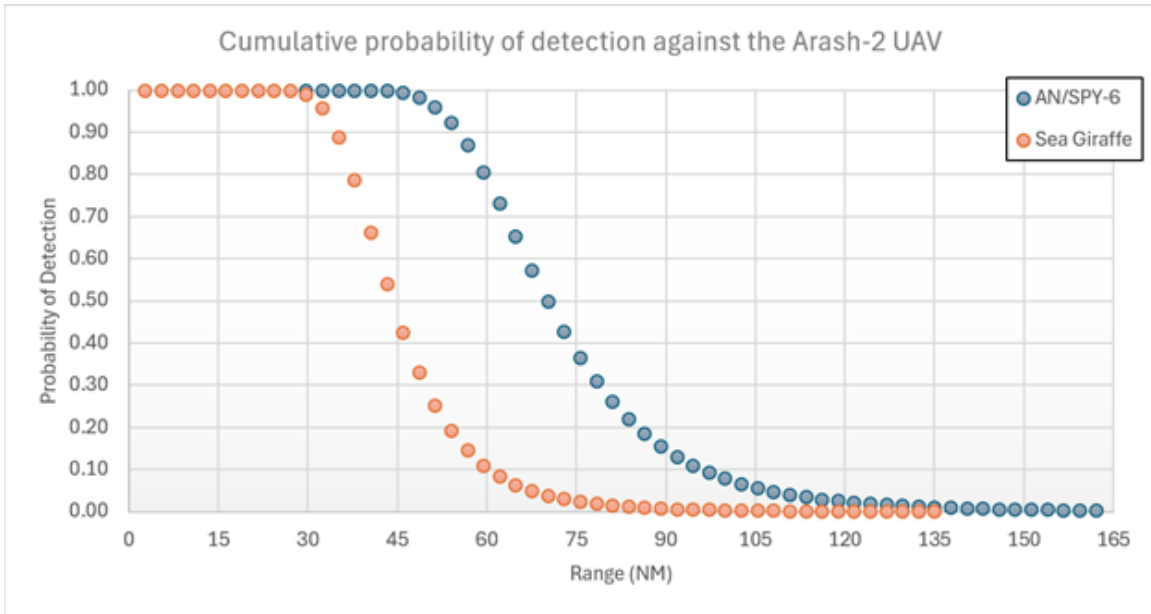


Figure 5.5. Cumulative probability of detection of each sensor versus an approaching UAS with Arash-2 characteristics.

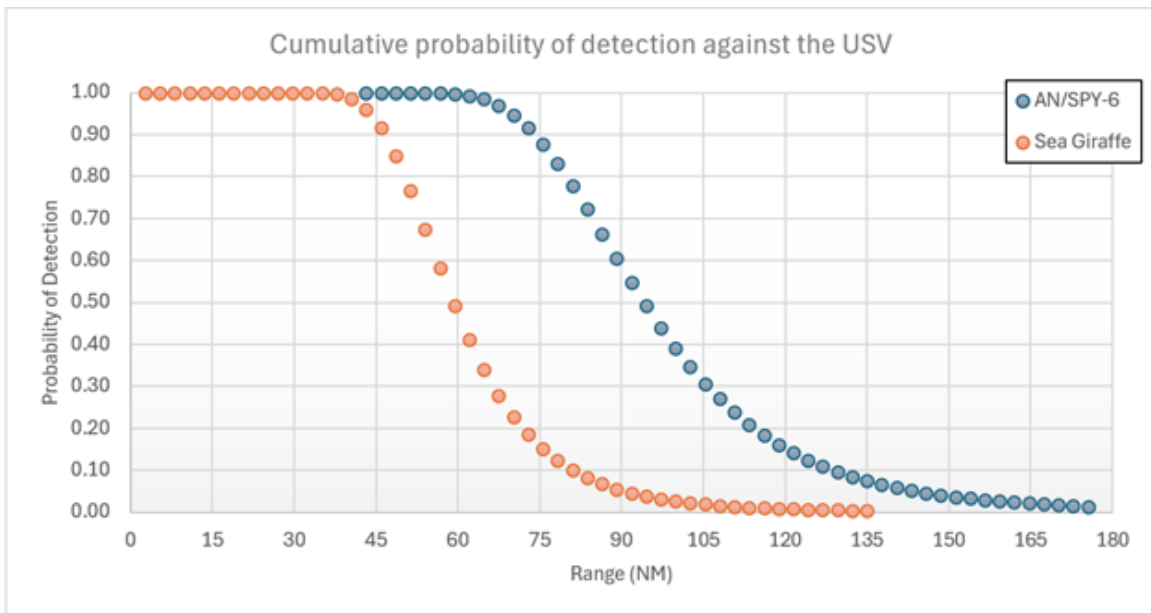


Figure 5.6. Cumulative probability of detection of each sensor versus an approaching USV with Sea Baby characteristics.

After a successful detection, it is assumed that the interceptor launches a propagator which can fuse, fragment and kill the threat or not. As detailed in Appendix B, fragmentation inside the most lethal detonation zones are assumed as a kill in this analysis, and the probabilities of this event happening for each launcher and propagator combination that fed the simulation is summarized in Table 5.1.

Table 5.1. Probability of kill for each interceptor and threat.

| Engagement System                         | Shahed-136 UAS | Arash-2 UAS | USV  |
|---|----------------|-------------|------|
| SM  | 0.95           | 0.95        | 0.95 |
| Mk-45 – 5” HVP                            | 0.16           | 0.17        | 0.63 |
| GMS                                       | 0.67           | 0.26        | 0.90 |
| VAMPIRE – APKWS                           | 0.83           | 0.89        | 0.94 |
| Chain gun with 30×173mm airburst munition | 0.91           | 0.88        | 0.96 |

The SM kill probabilities are based on data provided by CENTCOM for actual statistics on Houthi UAS attacks [60]. The statistics do not include the type of UAS in each situation, nor do they include data for USV attacks, as these are not as likely or released with detail in the Red Sea conflict. With that, it is assumed the SMs are highly capable weapons against all UAS and USV platforms, using one value across all threat types.

The HVP values for each threat are lower than the other weapon systems that would be employed on a USV escort. In the model used to determine probability of kill, the most significant assumed source of error is angular which stems from the launcher. Each increase in radial range is some increase in the propagator miss distance from the target and thus, since the HVP is assumed to launch at the greatest distance between vessel and threat, it has the largest angular error resulting in the lower  $P_k$ . The arbitrary compensation for this error was applied to the guided munitions, and even more to the missile, and due to the long engagement range proposed by the HVP, the compensation is not sufficient to match the miss distance of other alternatives. This trade between engagement range and probability of kill in the model is further observed when contrasting the HVP performance against UAS versus USV which is the only alternative impacted by the radar horizon. The USV is engaged much closer and with a much greater likelihood of success. This approach indicates

that to benefit from an increased engagement range, some loss in probability of kill will be incurred, resting uncertain how much the munition guidance capability would actually be able to close the distance between the warhead and the target at the endgame. Due to this error that causes  $P_k$  to be affected so much from the HVP, the simulation was stressed with up to five HVPs launched in a single salvo against one threat target to determine if the probability of kill can be increased enough to justify utilizing more HVPs.

Similarly, the analysis for each of the three alternative systems employed on a USV escort varied in the assumed range of operation. Seeing as the chain gun is designed as a very close in point defense system, it would engage at a much shorter range than the rocket or missile and thus results in a seemingly very efficient  $P_k$  against the closer threats. The Griffin or APKWS, however, would be more likely to engage as a short-range area defense weapon rather than singular point shot and since this occurs with a longer range than the gun, the angular error is increased resulting in a slightly lower  $P_k$  for these systems.

#### **5.1.4 Significant Scenario Results**

From the total 96 scenarios run, several results can be analyzed by comparing different ones to each other. For example, all scenarios that were run involving the DDG with HVP and no escort as backup should be compared for analyzing the effectiveness of the variation in DDG detection system. Then those same scenario results should be compared to each variation in escort systems present, to determine how much more effective the system of systems can be with the additional layer of engagement. Not all 96 scenarios resulted in useful output and therefore, only those that can be compared against the MOEs and MOPs will be discussed.

### **5.2 Analysis of Results**

Effectiveness is measured as the probability that merchant vessels can safely complete transit. A second goal is minimizing the total lifecycle defensive cost—i.e., the survival-per-dollar effectiveness of the protection suite. Complementing these endpoints are four MOPs that track the system's actions, workloads, and resource consumption.

## 5.2.1 Number of Ships Hit by Threats

This metric is arguably the key determinant of the effectiveness of the said solution. Survivability in each simulation run highlights the number of merchant vessels that sustained mission-ending hits. In each simulation run, the system tracks whether a threat penetrates all defensive engagements and impacts the ship. A summary of the results is shown in Figure 5.7.

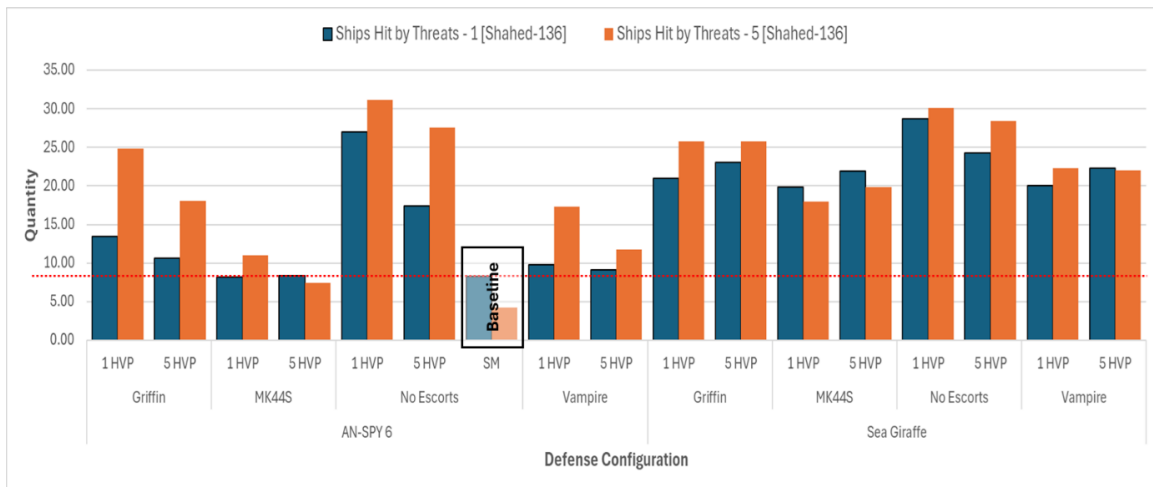


Figure 5.7. Number of ships hit by threats (single group I UAS).

In Figure 5.7, each column represents a unique scenario, with the respective scenario number and defense configuration listed at the bottom. It is important to note that the highlighted scenario in the figure represents the baseline configuration—i.e., what is currently being used in the Red Sea. The simulation aims to stress the defense configuration through high attack frequencies, with a maximum number of threats being five at any given time based on an average of CENTCOM reporting [60]; hence, it is inevitable that some threats may still slip through the system in the simulation environment. Even though the existing defense solution is undoubtedly efficient in deterring threats, it comes at a high cost. Therefore, the performance of this baseline configuration will be used as a basis of comparison with the rest of the defensive suites. The goal being that a layered defensive solution can be identified that is equally efficient or better than the baseline operation in the Red Sea, and at a lower cost. Key observations were made regarding many of the variables:

### **1. Radar Performance Dominates**

The AN-SPY 6 leads to fewer expected hits across every weapon load and mount than its Sea Giraffe counterparts, because of the greater overall detection range, leading to more threats being detected and more intercept attempts. Indicatively, sensor choice and capability may be the biggest driver of vessel survivability. The AN-SPY 6 operates superior to the Sea Giraffe due to its performance capabilities and size, resulting in greater detection ranges as shown in the figures relating cumulative probability of detection of each system. Based on the difference in effectiveness, the cost between the two systems can be compared to determine if the lower effectiveness of one system is worth the monetary savings that could be made for defensive purposes.

### **2. Interceptor Type and Quantity Effects**

The performance of the HVP has a low single-shot kill probability. Simply adding more HVP shots per salvo helps, with the simulation using up to five in one salvo, but lethality remains below the standard missile. Nonetheless, the implementation of additional layered defense, i.e., escort ship, has proven to contribute to lowering the number of ships hit, comparable to that of the baseline scenario. This implies the HVP as a replacement for the SM is feasible but requires more shots per salvo and a layer of defense with the escort addition. Utilizing simple firing solution equations, further work could be done to determine how many HVP shots would be needed to fully replace the SM with the same efficiency [103]. Limiting the simulation to five in a salvo is to show the relevancy of increasing shots, especially with a cost significantly lower than an SM.

### **3. Escort Effects**

Mk44S consistently yields the lowest expected number of ships hit, outperforming Vampire and Griffin when paired with AN-SPY 6. The Mk44S engagement range is a significant contributor to this determination. These results verify that very close-in engagement range using point defense shots is effective and suitable for combating unmanned threats.

### **4. Ideal Defensive Configuration**

Scenarios 3 and 51 (DDG equipped with HVP and AN-SPY 6 capability supported by Mk44S) shows the optimal results of the analysis. This combination of radar, interceptors, and escort drives the key MOE and increases the probability of survival for merchant ships.

This result was further confirmed by exposing the respective defensive suite to varied threat configurations. In every case, AN-SPY 6 outperforms Sea Giraffe by a wide margin, with the Mk44S yielding the fewest ship hits. A summary of the results is shown in Figures 5.8–5.12.

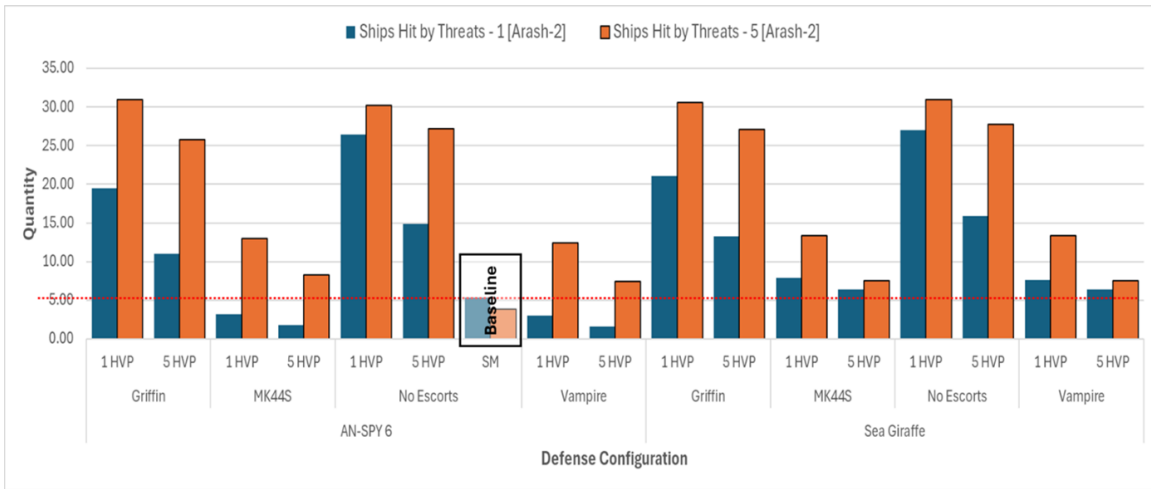


Figure 5.8. Number of ships hit by threats (single and swarm Arash-2).

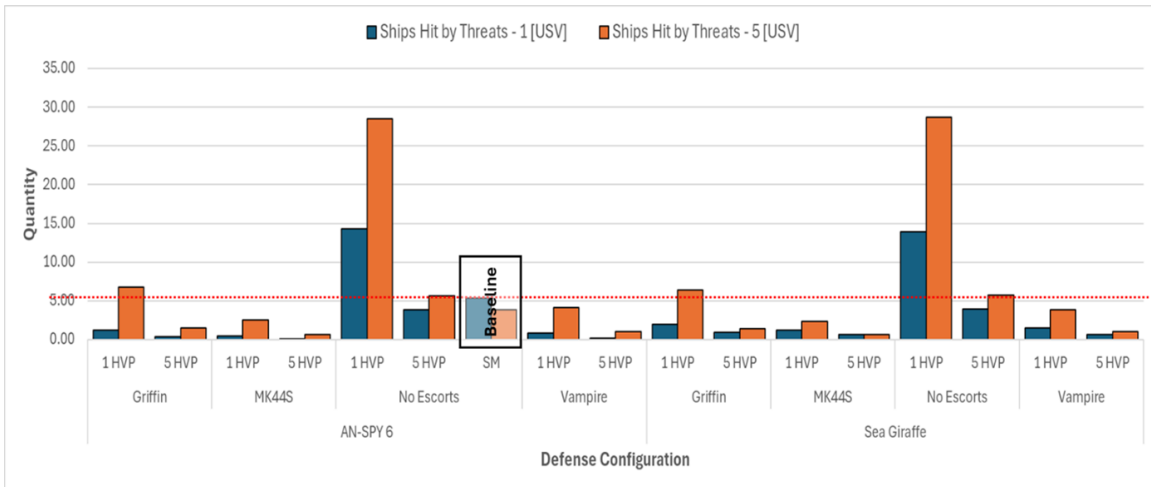


Figure 5.9. Number of ships hit by threats (single and swarm USVs).

## 5.2.2 Threats Detection and Engagement Success Rate

**Threat Detection Ratio** is defined as the ratio of detected threats to total threats launched, this ratio measures how effectively the sensor network acquires incoming targets. A high detection ratio is presumed to be the prerequisite for any successful engagement. **Engagement Success Rate** is defined with detection being the first step to every defensive measure that must lead to a successful neutralization. This metric is crucial to assessing the capability of the defensive suite in engaging incoming threats. A summary is shown in Figures 5.10–5.14.

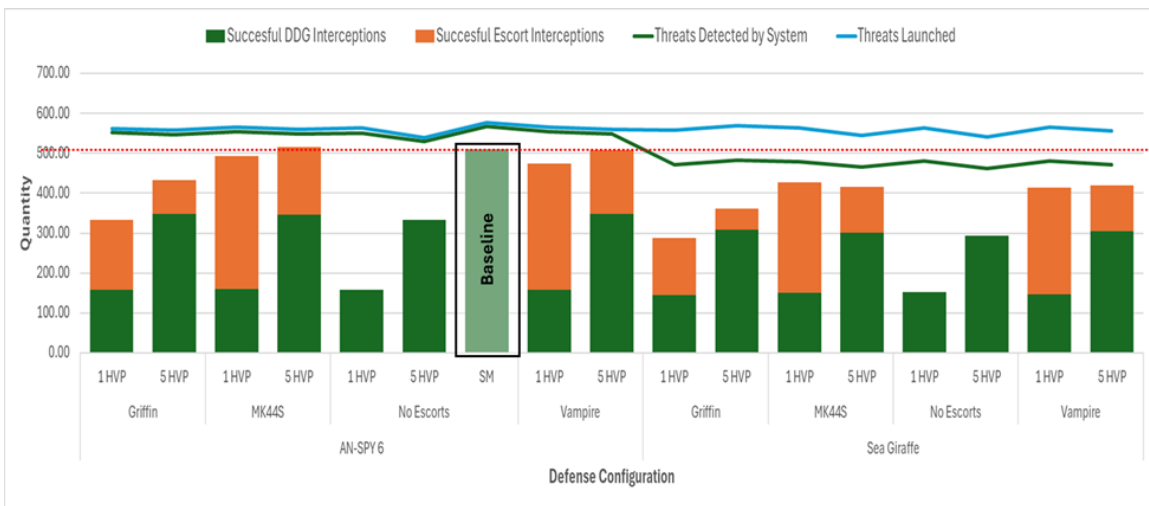


Figure 5.10. Threat detections and interceptions (single Shahed-136).

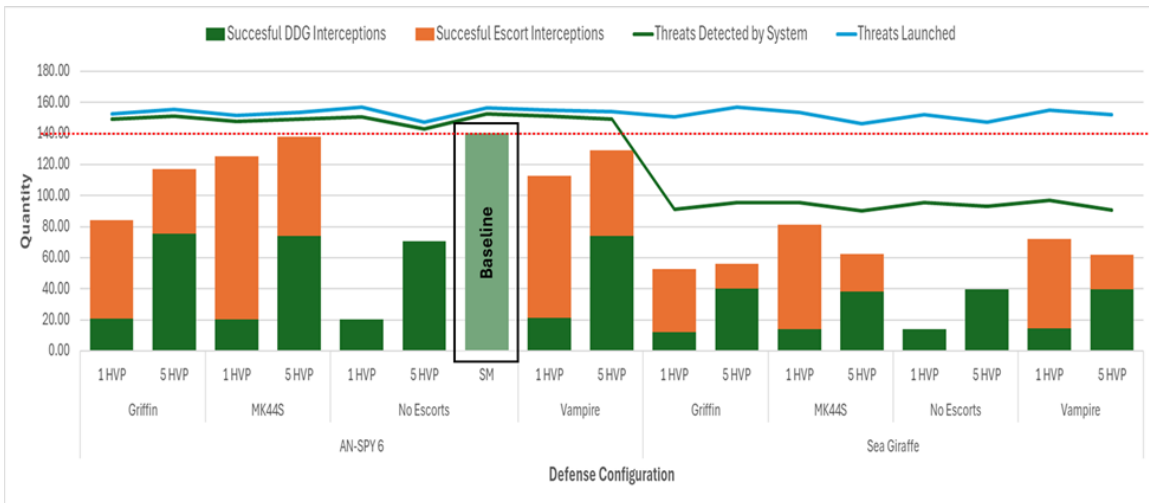


Figure 5.11. Threat detections and interceptions (swarm of Shahed-136).

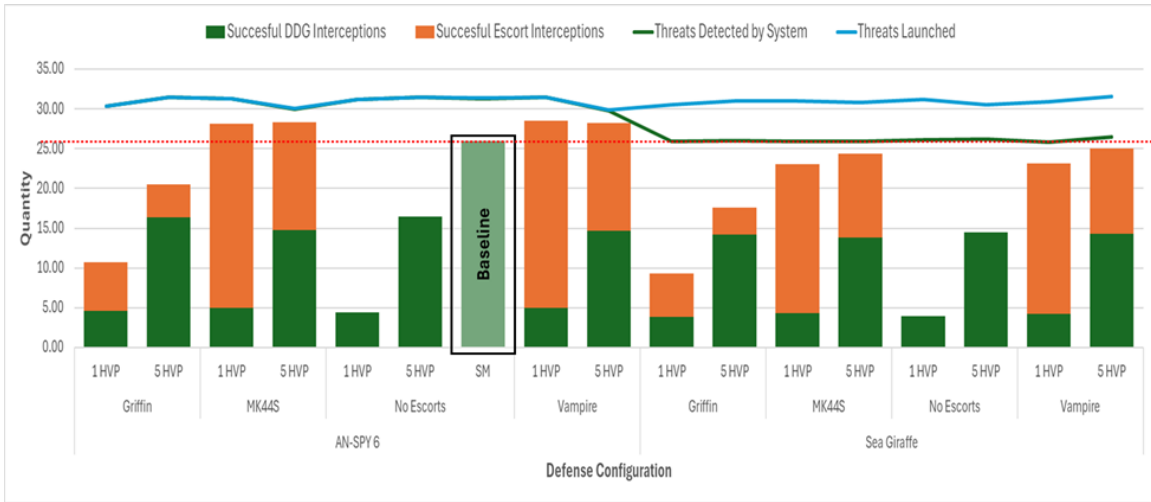


Figure 5.12. Threat detections and interceptions (single Arash-2).

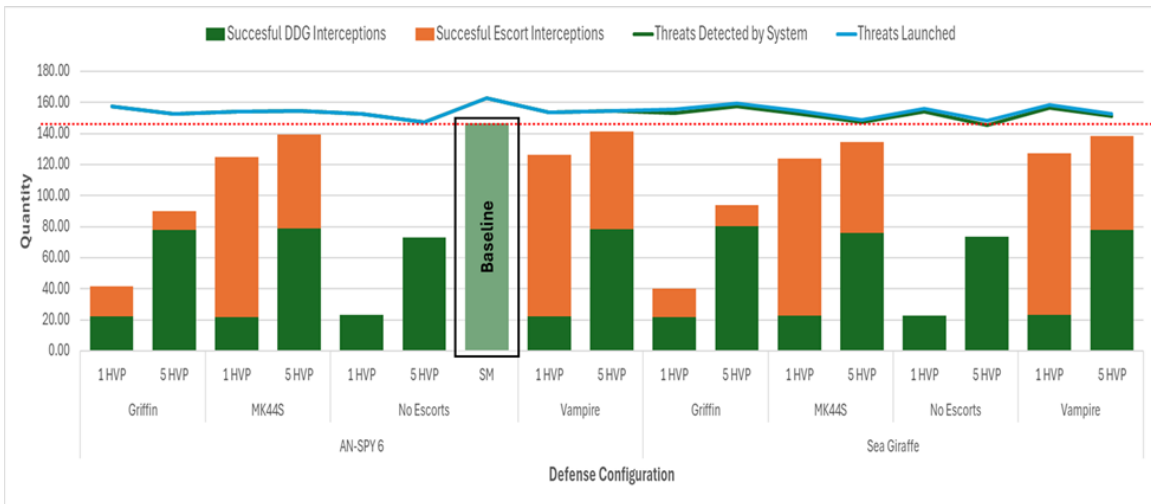


Figure 5.13. Threat detections and interceptions (single USV).

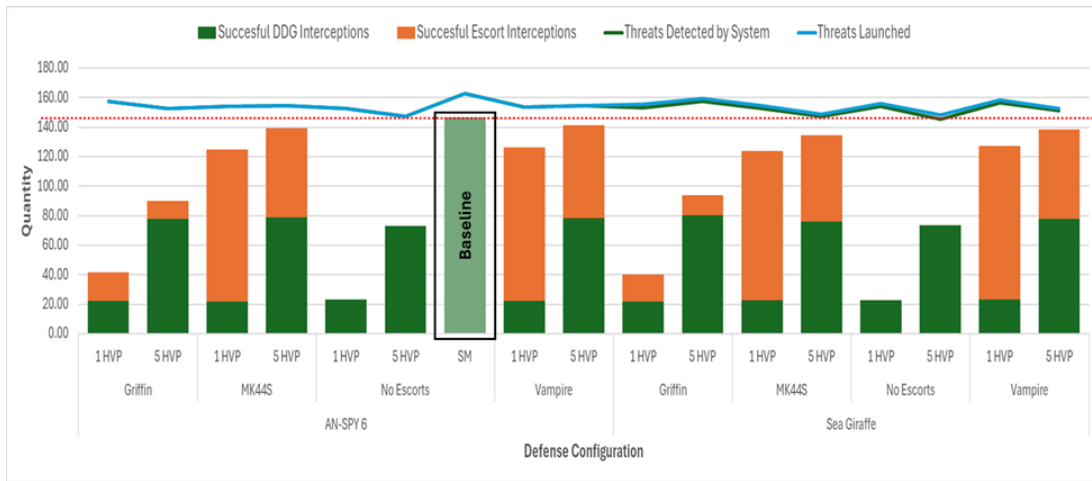


Figure 5.14. Threat detections and interceptions (swarm of USVs).

Figures 5.10–5.14. overlay the total threats launched (blue line) with stacked green bars for successful kills by DDG and orange bars for successful kills by escort across each defense configuration—any gap between a stacked bar and the blue line represents threats that penetrated all defenses. For the AN/SPY-6 configurations, detection rates against single threats are consistently high. By contrast, Sea Giraffe detection is comparatively low given the same threat configuration which also underpins the high vessel-hit rates in Sea Giraffe scenarios. Detection degrades further in swarm scenarios due to target saturation, but AN/SPY-6 retains a high detection rate versus Sea Giraffe. Beyond the baseline DDG + SM architecture, the AN/SPY-6 + HVP + Mk44S escort configuration delivers the highest engagement success rates across all threat environments—exceeding 94% even under swarming assaults.

### 5.3 Cost-Effectiveness Analysis

This report compares the estimated TOC components for key systems in a layered maritime defense. We compare the two radar options, multiple interceptors’ projectiles, and the platform costs along with the defense system mounted on it. We present acquisition and operating costs, and cost-per-shot estimates for each component, then discuss survival-per-dollar effectiveness and methods from the simulation-based analysis. As highlighted in the simulation model, every merchant vessel transiting the threat zone is paired with one

dedicated unmanned escort for the duration of its passage. Figure 5.15 summarizes the merchant-vessel flow through the Bab al-Mandeb strait.

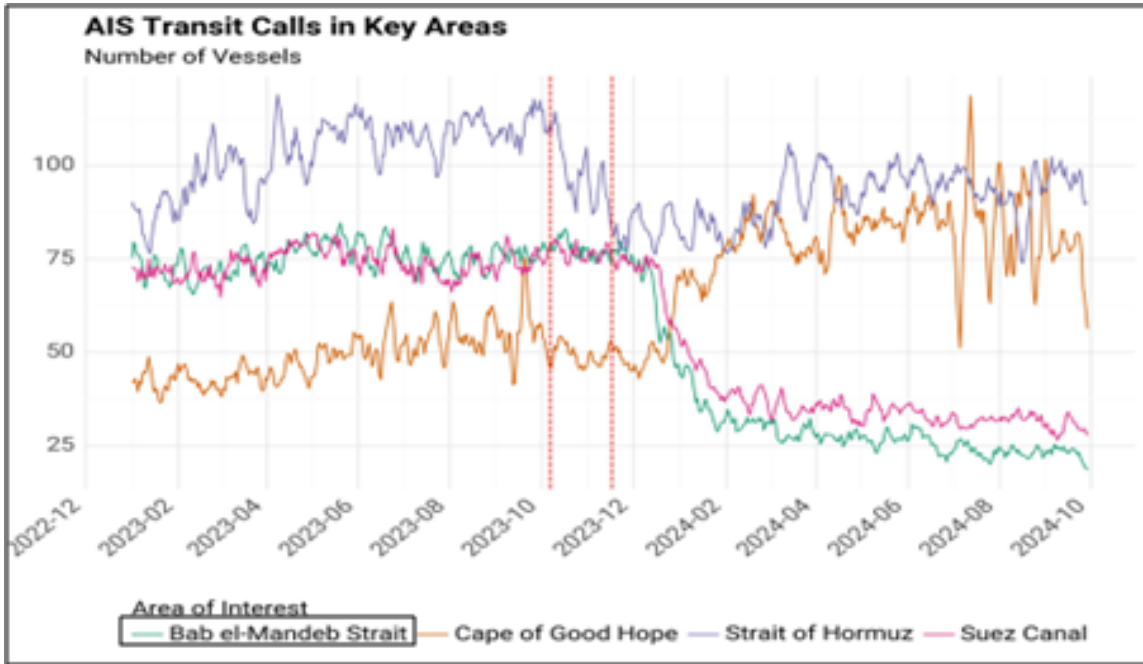


Figure 5.15. Red Sea traffic.

Post-2023, the average traffic dropped to 30 vessels/day in comparison to the 75 vessels/day peak traffic pre-2023. For conservancy, the calculation of the number of vessels required is based on the peak traffic. Through consideration of the unmanned vessel’s technical specification, the turnaround time required as well as the expected mission cycle that the vessel is expected to go through, a total of 78 unmanned vessels are required to sustain the operation in the Red Sea (with buffer of 20%). See Table 5.2 for the derivation.

$$N_{escort} = \frac{(\text{Vessels per day})/2}{(24 \text{ hours})/(\text{Average mission time in hours})} * (1 + \text{Buffer})$$

Table 5.2. Input parameters for calculating the number of escorts required.

| Description                                       | Shadow Fox | GARC    |
|---|------------|---------|
| <b>Technical Data</b>                             |            |         |
| Fuel Capacity (gal)                               | 329.90     | 100.00  |
| Max Speed (knots)                                 | 40.00      | 30.00   |
| Engine Power                                      | 550.00     | 170.00  |
| Num of Engines                                    | 2.00       | 1.00    |
| Total Engine Power (hp)                           | 1100.00    | 170.00  |
| Estimated Speed (knots)                           | 20.00      | 20.00   |
| Power Required (Propulsion Power Theory)          | 0.13       | 0.30    |
| Power Required (hp)                               | 137.50     | 50.37   |
| Typical Marine Diesel Fuel Consumption (lb/hp/hr) | 0.26       | 0.26    |
| Fuel Consumption (gal/hr)                         | 4.94       | 1.81    |
| <b>Operational Setting</b>                        |            |         |
| Speed (knots)                                     | 20.00      | 20.00   |
| Endurance (hr)                                    | 66.80      | 55.28   |
| Endurance (Distance) (nm)                         | 1336.07    | 1105.54 |
| <b>Turnaround Time</b>                            |            |         |
| Refuel/Resupply (hr)                              | 2.00       | 2.00    |
| Maintenance (hr)                                  | 1.00       | 1.00    |
| Buffer (20%) (hr)                                 | 0.60       | 0.60    |
| Total Turnaround Time (hr)                        | 3.60       | 3.60    |
| <b>Escort Cycle Time</b>                          |            |         |
| Number of Trips                                   | 2.00       | 2.00    |
| Number of Missions                                | 1.00       | 1.00    |
| Turnaround Time (hr)                              | 3.60       | 3.60    |
| Total Time (hr)                                   | 41.10      | 41.10   |
| Average Time per Mission (hr)                     | 41.10      | 41.10   |
| <b>Escorts Needed (off-peak) w/ 20% buffer</b>    | 30.83      | 30.83   |
| <b>Escorts Needed (peak) w/ 20% buffer</b>        | 77.06      | 77.06   |

With the estimated total unmanned escorts, we can effectively compare the TOC associated with each defense configuration. While not all the details are available due to the security classification, cost was estimated during the process to generate relative comparison between the alternatives. The values for cost were determined based on normalized ratios of one system to another, ensuring each subordinate weapons system is appropriately scaled to the cost of what is known to be the most expensive weapon, the SM. See Table 5.3 for the

cost summary. With respect to the interceptors, “System Cost” refers to the entire launcher platform while “Cost/Shot” refers to the munitions themselves.

Table 5.3. Cost summary (in \$M). Adapted from [104], [105], [106].

| Description                | Qty | System Cost | Cost/Shot | Operating | Maintenance |
|----------------------------|-----|-------------|-----------|-----------|-------------|
| <b>Radar</b>               |     |             |           |           |             |
| SEA Giraffe                | 2   | 25.00       | –         | 2.50      | 3.00        |
| AN-SPY 6                   | 2   | 100.00      | –         | 12.50     | 13.00       |
| <b>Vessel Comparisons</b>  |     |             |           |           |             |
| DDG                        | 2   | 2200.00     | –         | 255.00    | 200.00      |
| Shadow Fox                 | 78  | 5.00        | –         | 7.00      | 1.00        |
| GARC                       | 78  | 8.00        | –         | 10.00     | 1.50        |
| <b>DDG Interceptors</b>    |     |             |           |           |             |
| SM-6                       | 2   | 50.00       | 4.40      | 0.20      | 0.20        |
| HVP                        | 2   | 14.10       | 0.09      | 0.01      | 0.01        |
| <b>Escort Interceptors</b> |     |             |           |           |             |
| Griffin                    | 78  | 0.20        | 0.13      | 0.01      | 0.01        |
| MK44S                      | 78  | 1.11        | 0.30      | 0.50      | 0.50        |
| Vampire                    | 78  | 2.90        | 0.03      | 0.30      | 0.30        |

Table 5.3 brings together all the procurement, ammunition and sustainment figures for the simulation (in millions).

- **Radar System:** The estimates are based on public contracts and model assumptions as an ANSPY-6 Operations and Support (O&S) cost is likely embedded within the ship cost.
- **Platforms:** The DDG operating cost has a wide range because \$50M/yr reflects direct costs (fuel, crew, maintenance) in Navy budgets, whereas \$200–300M/yr includes full lifecycle and support infrastructure. USV costs assume current prototype data (diesel-powered medium USV). Even if USV costs were underestimated, they remain far lower than a destroyer.

- **Interceptors:** SM-6 drives a large share of the DDG’s magazine cost with cheaper munition such as HVP, Griffin, Mk44S allowing more engagements per dollar, saving high-cost missiles for highest value targets.

The values in Table 5.3 contribute to the input for the TOC model that sums up acquisition, operating, and sustainment costs for a given defense configuration and compares it to the achieved effectiveness. Each alternative’s merchant ship survival rate (effectiveness) is plotted against its estimated TOC, and a Pareto efficiency frontier is identified. Alternatives on or near this frontier deliver the most survival benefit per unit cost, representing optimal trade-offs between performance and cost. A summary of the results is shown in Figure 5.16.

Figure 5.16 plots each defensive configuration as a point, with the horizontal axis showing its estimated TOC (in millions) and the vertical axis showing the corresponding number of merchant ships lost to threats. The red-box Pareto frontier connects configurations that achieve the fewest ship losses for a given cost, highlighting the optimal trade-offs between survivability and expenditure—any point to the upper right of this line is dominated by a solution that is both cheaper and more effective within the plot.

The cost-effectiveness comparison highlighted a few key solutions. Notably, the combination of an AN-SPY-6 radar, HVP interceptors, and a USV escort armed with Mk44S emerged as a top performer. This configuration achieved one of the highest merchant survival rates (fewest ships hit by enemies) while costing roughly half of the baseline solution’s TOC. For example, in the single UAS threat scenarios the AN-SPY-6 + HVP + Mk44S suite yielded comparable or better survivability than the current Red Sea baseline, yet with significantly lower expenditure. In contrast, the current baseline defense (a DDG with high-end interceptors such as Standard Missiles and no unmanned escort) was found to be extremely costly and only marginally more effective in some cases—in fact, it was often not on the efficiency frontier. This indicates that a substantial portion of the baseline’s cost is paying for diminishing returns in protection, especially compared to the novel alternative of pairing cheaper rapid-fire weapons (HVP rounds, autocannons) with advanced sensing.

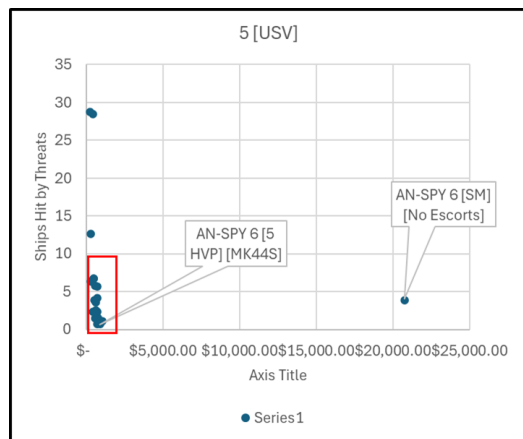
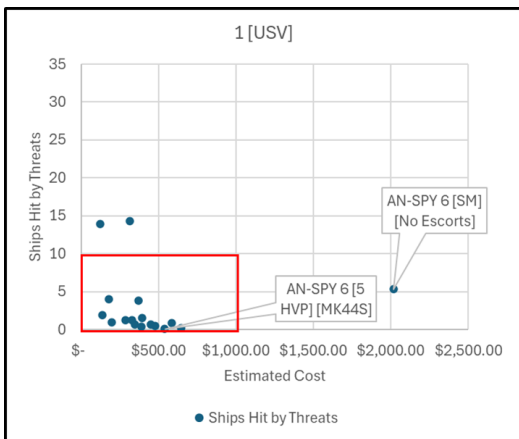
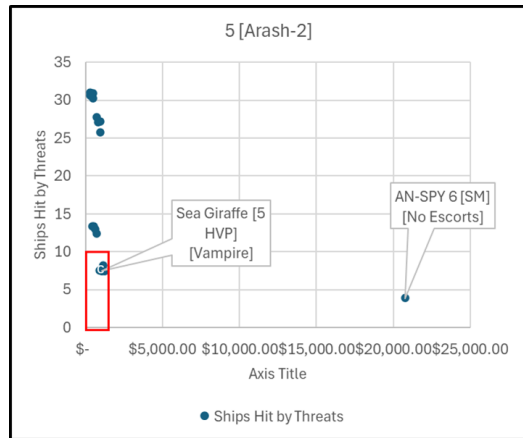
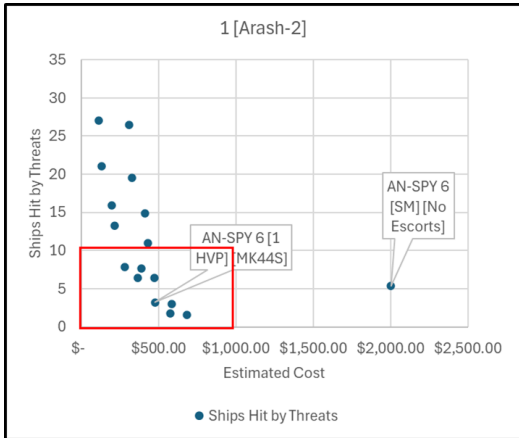
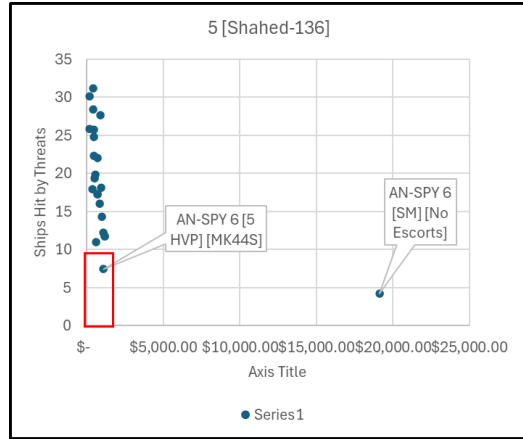
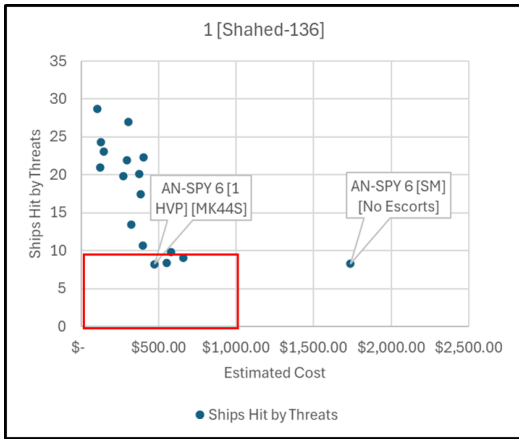


Figure 5.16. Pareto frontier for all threat configurations.

## 5.4 Summary

In evaluating layered defense architectures for merchant vessels in the Red Sea, we found that integrating AN/SPY-6 radar with medium-range HVP interceptors and a close-in Mk44S-armed USV escort dramatically improves protection and cost efficiency compared to legacy all-missile defenses. The AN/SPY-6 consistently doubled threat detection rates and reduced average ship losses by up to 70% versus Sea Giraffe, while the combined HVP + Mk44S escort configuration achieved engagement success rates above 94%—even against five-unit UAS and USV swarms—and cut TOC to roughly half that of a DDG-only SM baseline.

In exploration of future operating concept, a key question arise – could an unmanned vessel provide sufficient protection for the commercial ships? Initial assumptions in this study position the escort vessel as the final layer of defense, clearing threat remnants that the DDG could not. However, what if the unmanned escort served as the first line of defense supported by the DDG, to what extent could an unmanned escort do so? Additional simulations were run subsequently to gain further insight into the threshold at which a single unmanned escort can effectively defend when supported by the DDG. A baseline unmanned escort would be overwhelmed, but on hindsight it could eliminate approximately 80% of the threats launched by the aggressor. A summary of the results is shown in Figure 5.17.

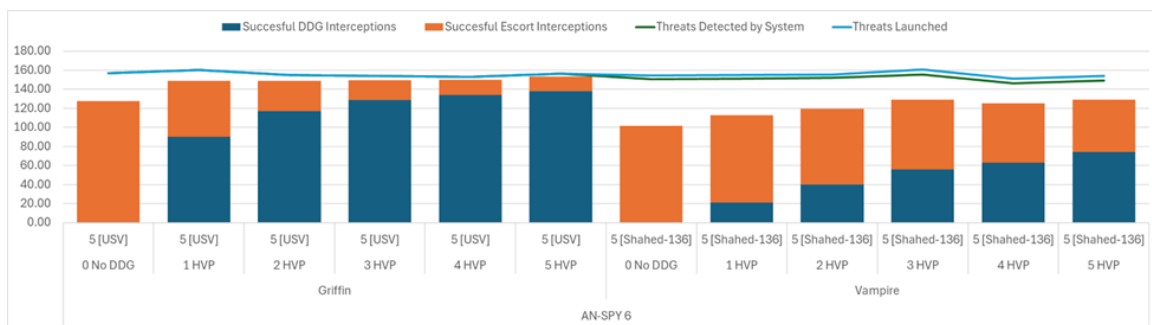


Figure 5.17. Threat detections and interceptions (swarm of Shahed-136 and USVs).

When supported by DDG, it could substantially raise the threshold of defense. It is important to note that the DDG’s support remains critical in these stressed scenarios. The DDG’s advanced sensor (radar) detects and tracks the incoming boats, queuing the escort’s

engagements. This networked approach ensures the unmanned escort is employed to best effect. If the escort were truly “on its own” without the DDG’s radar and coordination, its effective engagement range and reaction time would be far more limited. Thus, the threshold of unmanned escort self-defense is contingent on DDG support: with the DDG handling long-range detection, the unmanned escort could potentially serve as the first line for the DDG to manage residual threats. Within the confines of the simulation, a properly equipped unmanned escort (with MK44S) proved capable of protecting the merchant under attack in swarms up to five, possibly only requiring the DDG to engage the *last* few threats.

THIS PAGE INTENTIONALLY LEFT BLANK

---

## CHAPTER 6: Conclusions and Recommendations

---

Innovative and out-of-the-box solutions are constantly being analyzed to counter modern technological advancements in weapons systems and evolving tactics. Paramount in this endeavor is the ability to protect human lives. The DoD justifies the costly use of highly capable and large missile systems against incoming threats in the Red Sea by explaining that even one Sailor's life onboard the ship is worth the millions of dollars spent. However, as any consumer knows, no matter the extensive cost, no system will operate perfectly all the time and in every situation. Moreover, engagements in conflict lead to the depletion of inventory, which influences not only the cost even more, but also global readiness. The key findings in this report serve to analyze a solution space that will continue to adequately protect the lives of the Sailors and Merchant Marines at sea, while lowering the cost and employment time to do so.

### **6.1 Summary of Report**

Given the problem statement of analyzing alternatives for the protection of merchant and MSC vessels against unmanned threats, the SEA Capstone team scoped the project in the context of the ongoing conflict in the Red Sea. From this background, unmanned surface and aerial threats were acknowledged as problematic, and research was done regarding the environment, the threats, the political structure of the situation, parallel current events within the unmanned threat space, and alternative existing systems that could be useful for answering this problem. From this, the approach of a layered defensive system was established. The team defined a two-layer defensive approach; the outer layer of detection and engagement would be controlled by a DDG and the inner layer would be managed by an unmanned escort surface vehicle. From this approach, several scenarios were established to compare alternative detection and engagement systems operating in varying postures, sometimes with one layer inactive and others with both working together. The results of these scenarios allowed the team to compare these alternative systems for layered effectiveness in protecting merchants and for cost efficiency compared to current real-world operations.

## 6.2 Assumptions and Limitations

Given the scope of the project, many assumptions were made in our modeling and analysis. The following is a list of the most significant assumptions that may have affected the results.

1. The simulation does not include flight physics or characteristics for either threats or allied interceptor weapons. The calculations for  $P_k$  and  $P_d$  utilize empirical data to the maximum extent possible. However, even these heavily relied on generalized assumptions due to the compressed timeline and scope of this project.
2. The project assumes that USV escort vessels can be fully integrated with the analyzed weapon systems, including mechanical and electrical connections and the control and communications systems. The remote control and operation of the unmanned systems was not within the scope of this project and therefore would need further analysis to determine if a land-based operation, such as the base in Djibouti, or a sea-based operation, such as on a DDG in the area or the merchants themselves, would be viable and have appropriate range. Therefore, if this assumption is not met, USV escorts may not be viable alternatives. Further research into the specific USV escort is required to determine the effects of this limitation.
3. Though the threat analysis was focused on the current Red Sea conflict, not everything is directly related to this specific backdrop, as the team used a variety of data from various conflicts to analyze a solution space. The goal of this methodology was to arrive at results which could be used beyond the Houthi conflict. Therefore, the scope of the project is assumed to cover all future situations involving unmanned warfare, but given the timeline needed to have limits placed on it. While there have been reports of swarms as large as 20 at a time, the simulation was limited to five threats engaging a single merchant at once. While this limitation does not stress the defense to the maximum extent possible, it still allows for relative comparison among alternatives in a realistic and broad setting without considering outlier scenarios.
4. Many of the values used in the cost analysis were inferred from ancillary knowledge of other systems and subsequently normalized to the extremes. This normalization, however, is significantly impacted by the open-source costing data provided to the project team. The cost of a single SM, for example, is debated to be anywhere between

the initial procurement cost to a value that is inflated over its lifespan. Other values in the team's normalized cost data were assumed based on comparable systems because data for the desired system was not readily available. The Shadow Fox USV, for example, was valued similar to a USV system produced by Vanguard. The exact value of the Shadow Fox, however, was not available to the project team.

5. The values determined for  $P_k$  of each weapon system are based on the range at which the specific weapon system is likely to engage a threat. Since the longer-range weapons would then incur a larger angular error as they are launched further, the  $P_k$  values trend down. Since the weapons were all analyzed with their assumed operational range and not all with the same range values, the comparison skews the results in favor of the closer engagement systems. For example, a shorter-range weapon like a chain gun seemingly performs very well since the simulation assumes the engagement occurs at a close distance. However, if the range at which the Griffin was simulated, farther out, was employed by the chain gun, the  $P_k$  would be significantly underwhelming.
6. Very early on, the project team shifted away from consideration of directed energy and non-kinetic solutions. The stakeholders directed during the first progress review that with ongoing tensions and the rapid development of technology of enemy nations, only systems that were already developed or in development with a high TRL were of interest for an alternative solution. None of the directed energy weapons or non-kinetic solutions that can be currently researched in an unclassified realm met this criterion.
7. The analysis and research performed for this project was limited to open-source information. Much of the information used for assumptions, especially numerical values, was found or determined from material readily available in the open-source literature. Given future work is performed using the same analysis techniques, the classified values for specific systems can be implemented in a secure environment for more accurate and useful results.

## 6.3 Recommendations

Chapter 5 shows that with a significant margin, the most effective system of systems defense solution against unmanned threats in the assumed environment consists of the following components:

1. A DDG operating in area posture with AN-SPY 6 radar capability and HVP missiles loaded to launch in the maximum practical salvo size against each threat.
2. A USV escort vessel assigned to each merchant that has the capability of housing the Mk44S chain gun system, similar to the Titanus EOS design.

This system of systems implemented in the environment would cost roughly half of what is assumed as the current posture in the Red Sea and yield no significant loss in mission effectiveness as compared to the current SM-6 strategy. The recommendation for the stakeholders regarding unmanned threat protection for merchant and MSC vessels is to incorporate a shorter range, more cost effective missile in the DDG weapon launchers, continue the use of the highly advanced AN-SPY6 radar, and to invest in a series of unmanned vessels that can house a launch system comparable to the Mk44S short range chain gun analyzed in this project. The recommended weapon to be loaded on the DDG is the HVP, as this can already be integrated into the current DDG design and posture. The HVP is a longer-range engagement weapon, capable of defeating unmanned threats launched at an unescorted vessel. The Mk44S gun, however, is a very short-range precise point defense for a last-minute intercept option. It is recommended, therefore, that the Mk44S be placed on an unmanned escort that operates directly in the vicinity of the merchant or even on the merchant itself. The latter option would obviously require that the political and legal restrictions of employing a naval weapon on a civilian craft are accounted for.

Aside from range, another major consideration centers around the logistics involved in reloading these systems, employing them, and storing their munitions. Our recommendation is centered around a salvo defense strategy on the DDG. While a higher number of missiles in each salvo would increase the interception rate, it also comes with tradeoffs. For a given salvo size, the missile housing system would require that number of missiles be ready to fire at any given time. A higher number also increases the reload time and incurs a

higher storage penalty. The highest salvo size tested was in the simulation was five, which yielded the best defense. Based on these tradeoffs, we made a qualitative assessment that this would be the optimal size.

The project analyzed single drone attacks as well as swarms of five attacking simultaneously, with a 30 day simulation window. Since the required number of interceptors is proportional to the number of attacks, the HVPs must be loaded to account for the highest possible number of threats. Without the use of escorts, this number was as high as 150 in our 30 day swarm scenario. With the escort, however, the results are split between needing anywhere from 30 HVPs to 120 HVPs, the difference being the number of threats neutralized by the unmanned escorts. For operational continuity, the escorts themselves also need to be loaded with enough ammunition to sustain a deployment window. Alternatively, additional USVs could be on station and ready to replace a depleted USV or to support underway rearming. Ideally, a DDG would be prepared with 3 months of sustainment, and a backup DDG in the same combatant command would be ready to take over. Our recommendation is to posture 10 fully operational USV escorts, each possessing a single chain gun, to be available to support escort duties at any given time. For heavier merchant traffic patterns or days, the escort posture will need to shift to convoy vice area defense, ensuring sufficient coverage in the threat axis.

All in all, the system of systems that resulted in the highest level of protection and significantly lower cost consists of a large monetary investment in the detection system, a smaller and cheaper missile system for an area defense Naval ship to launch, and the inclusion of vessel-to-vessel escort capabilities. The investment in improved long-range radar detection buys significantly earlier engagement opportunities with less accurate and advanced weapons. This expanded window allows for more shots and better targeting by the missile system that will be used to intercept the threat. With enough additional time, communication abilities can also be extended, and an escort vessel with each merchant can be contacted or employed as needed. These vessels should be small, light, agile and carry a much cheaper interceptor weapon system that can save money and operate as a close-in point defense. The result is a layered defensive system of systems surrounding each merchant in a threat axis, highly capable of detecting and engaging unmanned threats while optimizing cost.

## 6.4 Future Work

Further work can be done to eliminate many of the assumptions listed above as well as to use more precise specifications for a more complex and realistic model. While many of these limitations were due to the nature of an open-source project within a compressed timeline, we recognize that some approaches were more successful than others. Taking these lessons learned onboard, a future team working on a similar project should have improved outcomes. Three primary focus areas are identified for more thorough investigation in the future.

1. This study used multiple different units with various multi-role capabilities. This design choice was implemented to explore a full suite of system capabilities. However, this approach may not always be feasible in a realistic scenario. Additionally, unmanned escorts are a rapidly developing technology. New capabilities may come onboard that could allow them to operate with greater autonomy and without a manned unit in the loop. Even operating under today's technology, where escorts have limited capability, a simulation scenario that examined only the escorts would be a valuable endeavor. Reviewing how the escorts could perform without a manned warship to help cue and coordinate them might produce encouraging results. When a manned warship is added back into the scenario, the observed delta in performance between a fully unmanned and a hybrid system would grant insight into how to strike the appropriate balance between human and machine teaming.
2. Scenarios could be developed in such a way that early detection was performed more holistically at a system level. In other words, the throughput in connectivity between units could maximize early cueing to minimize system response time. Preliminary findings of modeled scenarios show that engaging at maximum range within a quick response time is the key to improving  $P_k$ . A more robust model in the future could push the boundary of networked effects to greatly enhance how the units in the systems move, shoot and communicate together.
3. Finally, neither MSOSA nor Simio is a physics-based model, and this research study did not attempt to model physical interactions. While results of the study are valuable, a future study can corroborate these findings by applying physical modeling

to engagements. Without access to proprietary models and system data, reasonable assumptions were made based on professional experience operating in and around the Red Sea. It is strongly recommended that any follow-up study account for actual physical effects like experimentally determined RCS, atmospheric and weather data, and even sea state.

THIS PAGE INTENTIONALLY LEFT BLANK

---

## APPENDIX A: Probability of Detection Calculations

---

### A.1 Calculation of Radar Cross-Sections

#### A.1.1 Method 1: Estimating RCS for UASs using Existing Literature

A NATO study [107] conducted prior research on the RCS of UASs and drones utilizing a far-field transition measurement with a Vector Network Analyser (see Figure A.1).

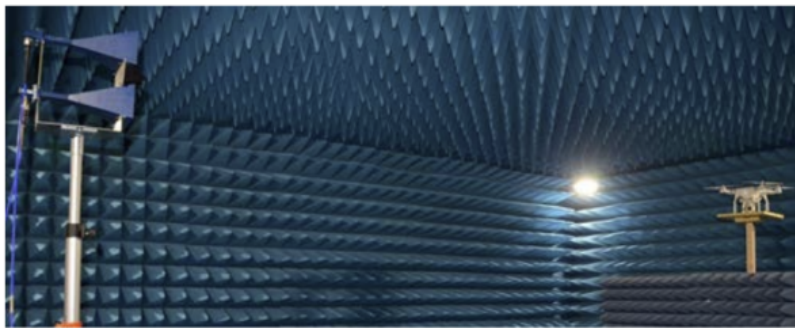


Figure A.1. Vector network analyzer. Source: [107].

In order to find the RCS of group III UASs and USVs, representative craft were selected. Example systems, including the Arash-2, and the Shahed-136, were considered to represent their respective UAS or USV systems. The RCS parameters for both craft were estimated using known parameters and comparing to the nearest representative presented in this paper.

#### **Shahed-136 (Loitering Munition)**

- Wingspan: 2.5 meters
- Length: 3.35 meters
- Construction: Composite materials with some metallic components (engine, warhead casing)
- Profile: Low profile fuselage, Delta wing

### Arash-2 (Long Range Attack Drone)

- Length: 4.5 meters
- Wingspan: 4 meters
- Construction: Composite materials with some metallic components
- Profile: Bulkier, larger fuselage cross-section

This paper published the maximum, minimum, and mean RCS of several UASs. Of note, we selected the UAS that was closest to the UAS that we were modeling, which was the Pelikan GAMA 2100 (fixed-wing). Using the dimensions of the Pelikan, we scaled the RCS values up to the dimensions of the Shahed-136 and Arash-2 to obtain estimations of the RCS of the UASs we were interested in, with additional adjustments based on the particular compositions and shapes. The minimum RCS of the Pelikan GAMA 2100 was taken as  $0.02 m^2$ , maximum RCS of  $0.1 m^2$ , and mean RCS of  $0.02 m^2$ . Starting with those values for the example system presented, the following adjustments were made.

- The value of  $length * wingspan$  for the Shahed-136 is 3.24 times greater than that of the GAMA 2100, and that value for the Arash-2 is 6.97 times greater than that of the GAMA 2100. RCS generally scales with the area increase for simple shapes but this can not be perfectly assumed due to shape and material complexities.
- Considering that both Shahed-136 and Arash-2 are larger and Shahed-136 employs delta wing to reduce RCS, this effect was assumed to cause a 50% reduction from head-on observations. However, this slightly increase the RCS from broadside perspectives.
- The Shahed-136 uses composites to reduce radar visibility, slightly mitigating the RCS.
- The Arash-2's bulkier shape results in a larger consistent radar signature.

Applying all of those adjustments to the figures provided for the GAMA 2100, the following RCS values were estimated (see Table A.1).

Table A.1. RCS values for group III UASs.

| Drone      | Minimum RCS ( $m^2$ ) | Maximum RCS ( $m^2$ ) | Mean RCS ( $m^2$ ) |
|------------|-----------------------|-----------------------|--------------------|
| Shahed-136 | 0.00324               | 0.324                 | 0.0486             |
| Arash-2    | 0.0139                | 0.697                 | 0.139              |

### A.1.2 Method 2: Using RCS Equation with Dimensions of UASs

Assuming a group III UAS with the dimensions and shape as an Iranian Shahed-136 or an Iranian Arash-2, the aircraft would be like those in Figures A.2 and A.3. As mentioned, these aircraft have the following dimensions:  $3.50 \times 2.50$  meters and  $4.50 \times 4.00$  meters in length vs. wingspan. Considering the picture proportions, the nose and other relevant dimensions can also be estimated as highlighted in these figures.

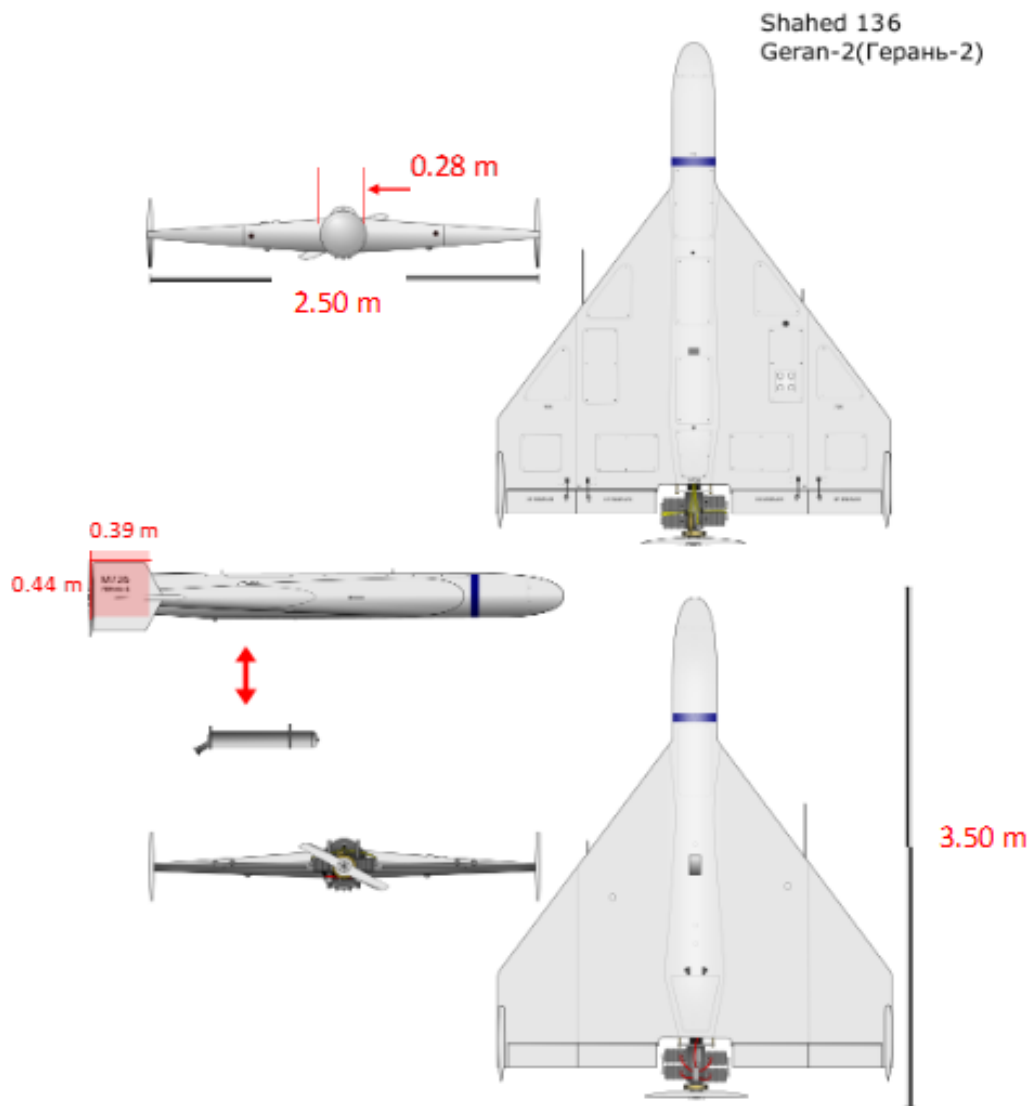


Figure A.2. Shahed-136 shape and main dimensions. Source: [108].



Figure A.3. Arash-2 shape and dimensions. Source: [46].

The RCS of a target is defined by the ratio of power per steradian reflected from it over the incident power per area on it, described by Harney [109].

$$\sigma = \frac{4\pi \frac{\text{Power Reflected Toward Receiver}}{\text{Unit Solid Angle}}}{\frac{\text{Incident Power}}{\text{Unit Area}}} . \quad (\text{A.1})$$

Given that the RCS of a target is per definition related to its incident area, it is expected to also be related to its shape. Nevertheless, due to wave scattering, the area covered by the incident wave and how much shape will be relevant is influenced by the relationships between wavelength size, the targets size, and its conductance. As can be seen in Harney [109], Fig. 2-5 (displayed here in Figure A.4), scattering on a perfectly conducting sphere of radius “a” presents three main different behaviors.

**Figure 2-5.** Radar cross section of a perfectly conducting sphere.

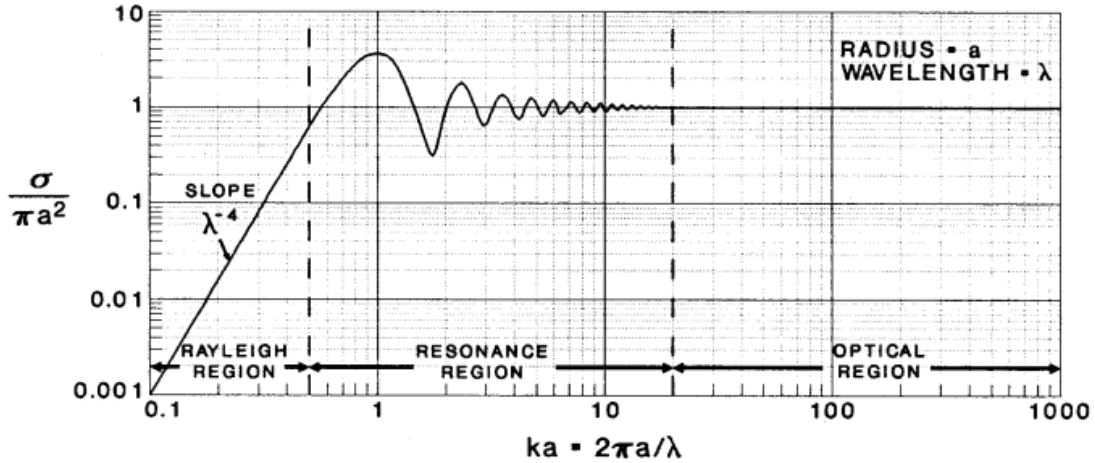


Figure A.4. RCS behavior. Source: [109].

Assuming an operation at maximum frequency (for typical radars, around 12 GHz), the wavelength can be calculated considering the relationship between frequency ( $f$ ) and wavelength ( $\lambda$ ), for a wave propagation velocity in a particular medium ( $v$ ), given by Payne [110], Eq. (2-1),  $\lambda = v/f$ . Combining this equation to Payne [110],  $n = c/v$ , where  $c$  is the speed of light, about  $3 * 10^8 m/s$ , and  $n$  for air is 1.0003, according to Payne [110], Table 2-1.

$$\lambda = \frac{c}{nf} \rightarrow \lambda = \frac{3 * 10^8 m/s}{1.0003 * 12 * 10^9 s^{-1}} = 0.25m . \quad (A.2)$$

For this wavelength, the abscissa of Fig. 2-5 would present the following relations.

$$ka = \frac{2\pi a}{\lambda} = 251.4a . \quad (A.3)$$

Considering the smallest dimension of the nose-on for the group I UAS, as 0.28 meters, we substitute “a” in the previous equation.

$$ka = 251.4 \times 0.28 = 70.39 . \quad (A.4)$$

As from Fig. 2-5, if “ka” is greater than 20, then the optic region should be considered. In this region, the shape is a relevant factor for estimating the radar cross-section [109].

Complex targets like an aircraft can be approximated to simple shapes for the RCS calculation [109] (see Figure A.5). Considering the similar shape of the UAS targets to an aircraft, a UAS can also be approximated to a cylinder and one or more flat plates in the broadside view, and to a cone, ogive, or sphere in the nose-on view.

| TARGET TYPE          | ORIENTATION                      | CROSS SECTION APPROXIMATION  |
|----------------------|----------------------------------|--|
| Airplane             | Broadside<br>Nose-on<br>Top View | Cylinder + one (or more) Flat Plates<br>Cone, Ogive, or Sphere<br>Cylinder + several Flat Plates |
| Ship                 | Broadside                        | Several Flat Plates  |
| Submarine (surfaced) | Nose-on<br>Broadside             | Cylinder + two Flat Plates<br>Two Cylinders + Flat Plates  |
| Ground Vehicle       | Any                              | Several Flat Plates  |
| RF Missile           | Nose-on<br>Broadside             | Ogive<br>Cylinder + several Flat Plates  |
| IR Missile           | Nose-on<br>Broadside             | Sphere<br>Cylinder + several Flat Plates   |
| Reentry Vehicle      | Nose-on<br>Broadside             | Cone or Sphere<br>Cone   |
| Chaff                | Any                              | Cloud of N Randomly oriented dipoles   |
| Decoy                | Any                              | Sphere (balloon), Trihedral (retroreflector)   |
| Complex Target       | Any                              | Flat Plates or Sphere  |

Figure A.5. UAS RCS approximations. Source: [109].

The RCS of a target is directly proportional to the reflected power to the receiver, and so, another important contribution to it comes from its reflectance ( $\rho$ ), as expressed in Harney [109], where  $\zeta$  is a directivity factor:

$$\sigma = A_{TARGET} \times \rho \times \zeta . \tag{A.5}$$

We assume that both the threats fuselages are covered with the same material, and that its reflectivity is 0.45 in the visible spectrum, which would be equivalent to an anodized

aluminum according to Payne [110], Table 7-4. So, as scattering will be predominantly in the optical region, the RCS can be estimated at each aspect.

### Nose-On RCS

Assuming the nose has an ogival shape with  $70^\circ$  of half-angle, its cross section can be estimated by the expression [109]:

$$\sigma_{nose-on} = \frac{\lambda^2 \rho \tan^4 \theta_0}{16\pi} = \frac{(0.025)^2 (0.45) \tan^4(70^\circ)}{16\pi} = 3.19 \times 10^{-4} m . \quad (A.6)$$

Considering  $0^\circ$  ( $\theta$ ) as nose-on for an observer, this expression would then be valid approximately in the following range:  $\theta \ll 20^\circ$ .

### Broadside RCS

On the broadside, we can assume the RCS of the UAS fuselage as being approximately a cylinder and a flat plate. Therefore, its broadside cross section would be:

$$\sigma_{broadside} = \sigma_{cylinder} + \sigma_{flat\ plate} . \quad (A.7)$$

Since the wavelength is approximately 2.5 cm, it can be assumed to have a specular reflection on the UAS surface. Ergo, from Harney [109] Table 2-2, given the referred constraints are met, it is observed that the cross sections approximations can be calculated as below, where  $\theta$  is the angle with respect to normal.

$$\sigma_{cylinder} = \frac{2\pi a L^2 \rho \cos(\theta)}{\lambda} \left[ \frac{\sin(kL \sin(\theta))}{kL \sin(\theta)} \right]^2 , \quad (A.8)$$

$$\sigma_{flat\ plate} = \frac{4\pi A^2 \rho}{\lambda^2} . \quad (A.9)$$

For the Flat Plate cross section, given a characteristic target dimension ( $l$ ), the validity of the above equation is constrained to the following condition:  $\frac{2\pi}{\lambda} \gg l$ , which is satisfied as long as  $l \gg \frac{\lambda}{2\pi} = \frac{0.025m}{2\pi} \approx 0.004m$ .

Holding true, the least flat plate dimension is 390 mm, much greater than 25 mm.

For the Cylinder, with a radius  $a$  and length  $L$ , the constraints are:  $\frac{2\pi a}{\lambda} \gg 1$ , and  $\frac{2\pi L}{\lambda} \gg 1$ .

As can be seen in Figure A.2, for the assumed shape there is an overlap from the broadside view between the flat plate and the cylindrical body. Therefore, the fuselage length  $L$  for the following calculation will be 3.50 m minus the plate length of 0.39 m, so 3.11 m. Considering the length and the average diameter of about 0.28 m (0.14 m of radius), the conditions are also met:

$$\frac{2\pi(3.11m)}{0.025m} > \frac{2\pi(0.14m)}{0.025m} \approx 35 \gg 1 . \quad (\text{A.10})$$

Then, substituting gives the following:

$$\sigma_{broadside} = \frac{2\pi a L^2 \rho \cos(\theta)}{\lambda} \left[ \frac{\sin(kL \sin(\theta))}{kL \sin(\theta)} \right]^2 + \frac{4\pi A^2 \rho}{\lambda^2} . \quad (\text{A.11})$$

Since it is a broadside view,  $\theta = 0$ . Plugging in gives:  $\sigma_{broadside} \approx 419.62m^2$ .

Converting both obtained RCS values to dBsm, the RCS of this UAS would range from  $-34.96$  dBsm (nose-on) to  $26.23$  dBsm (broadside). This gives a geometric mean value of  $-4.365$  dBsm, which is equivalent to  $0.366 m^2$ . This is reasonably consistent with the values obtained in Method 1, adding to their robustness.

### A.1.3 Calculating the RCS of USVs

There are not as many pieces of scholarly literature that study the RCS of USVs compared to UASs. However, most studies agree that USVs suffer from much lower signal-to-noise ratio (SNR) due to the large amount of sea clutter generated from the low angle of the USV with respect to the sea. We will be using the radar equations from Nathanson [111] to calculate the RCS of our USV.

The equation we will be using is shown below, which is used to calculate the 50th percentile of the RCS of a typical USV, where  $f$  is the radar frequency in MHz, and  $D$  is the ship's displacement in kilotons.

$$\sigma = 52f^{1/2}D^{3/2} . \quad (\text{A.12})$$

The USV we are modeling our calculations after is the Ukraine Sea Baby Naval Drone, which has a length of 6 m and a width of 2 m. The dry weight of the drone is 3527 lbs, which will correspond to  $D$ , the ship's displacement. The radar frequency we are assuming in this case is 5.35 GHz.

From the equation, the 50th percentile RCS for our USV is calculated at  $0.25m^2$ .

## A.2 Radar Cross-Section Impacts on Detection Range

For alternatives conducting surveillance through a radar, impacts on the detection range can be estimated from the cross-section ( $\sigma$ ) ratio between the analyzed threats. From the radiometric analysis of radars, Harney [109], Eq. 8.15, models the factors involved in radar detection.

$$CNR = \frac{P}{kTBF} = \frac{P_T L_T A_R G_T \sigma e^{-2\alpha R}}{kTBF (4\pi R^2)^2} . \quad (A.13)$$

In the equation above,  $P_T$  is the source radiated power,  $L_T$  is the loss factor of the transmitter,  $L_R$  is the loss factor of the receiver,  $G_T$  is the source antenna gain,  $A_R$  is the receiver antenna area,  $\lambda$  is the wavelength,  $\alpha$  is the atmospheric attenuation coefficient,  $R$  is the range to the source,  $k$  is Boltzmann's constant,  $T$  is the effective receiver temperature,  $B$  is the receiver bandwidth, and  $F$  is the receiver noise figure.

Considering that we are looking for effects on the detection range, and it is highly dependent on the spreading loss, as this distance is at fourth power, solving for the detection range gives the following.

$$R = \sqrt[4]{\frac{P_T L_T A_R G_T \sigma e^{-2\alpha R}}{CNR * kTBF * (4\pi)^2}} . \quad (A.14)$$

To focus the analysis on the cross-section parameter and detection range, then the previous equation is rearranged:

$$R = \sqrt[4]{\frac{P_T L_T A_R G_T e^{-2\alpha R}}{CNR * kTBF * (4\pi)^2}} \sqrt[4]{\sigma} . \quad (A.15)$$

Therefore, a proportionality relation between detection range and cross-section can be established:

$$R \propto c \sqrt[4]{\sigma} . \quad (\text{A.16})$$

Ergo, the change in detection range from the cross-section of one target to the other would then be proportional to the fourth root of their cross-section ratio.

$$R_2 \propto R_1 \frac{c_2}{c_1} \sqrt[4]{\frac{\sigma_2}{\sigma_1}} . \quad (\text{A.17})$$

### A.3 Radar Horizon Limitations to Detection Range

When “normal” refraction is in place, with modified refractivity between 79 and 157  $km^{-1}$ , detection through electromagnetic wave systems would be limited to the radar horizon. The total distance ( $R_h$ ) at which an object would appear on the horizon is then related to this object’s height ( $H_T$ ), and the observer height ( $H_O$ ), as follows [109]:

$$R_h = A \left( H_T^{1/2} + H_O^{1/2} \right) . \quad (\text{A.18})$$

Here,  $A$  is a numerical coefficient, that varies depending on the metric used for the distance and height, also the electromagnetic spectrum region of the considered wave. Ergo, for height in feet, distance in nautical miles and a radar operating in the microwave region, this parameter would be 1.229 [109]. The same relation was also demonstrated in Ball [40] Eq. 4.4 for distance in nautical miles, taking the following form.

$$R_h = 1.23 \left( H_T^{1/2} + H_O^{1/2} \right) . \quad (\text{A.19})$$

The composition of altitudes in the way an aircraft takes from launch to its target and back home is called mission profile. As described by Ball [40], this profile is a decision influenced at least by what anti-air defenses the aircraft is intended to be exposed to. Moreover, it will also influence aircraft autonomy and radar horizon. Considering the current scenario, the UAS operators are assumed to use them for both searching their targets and then engaging. Therefore, operating at their maximum altitude will benefit them with more autonomy and a less restricted radar horizon.

This way, assuming the radar antennas on the escort ship and in the merchant vessel to be installed at 45 ft., and that the UAS is operating at the maximum altitude for its category, thus 13,000 ft., the radar horizon would be:  $R_h = 1.23(13,000^{1/2} + 45^{1/2}) = 148.5NM$ .

This value is greater than the detection range baselines defined, thus the radar horizon isn't imposing any restriction to this range.

## A.4 Signal-to-Noise Ratio

The SNR was found from the classical radar equation [111], where SL is source level, TL is transmission loss, TS is target strength, and NL is noise level.

$$SNR = SL - TL + TS - NL . \quad (A.20)$$

The SL is equal to the peak power plus gain. Gain is approximated by the equation below, where G is the antenna gain, A is the physical aperture of the antenna,  $\lambda$  is the wavelength, and  $\eta$  is the efficiency (typically in the range of 0.5–0.7).

$$10 \log \left( \frac{4\pi A}{\lambda^2} \eta \right) . \quad (A.21)$$

For the Sea Giraffe [112], operating in the the C-band, a median value of 5.65 GHz is used. Given  $\lambda = c/f$ , the equivalent wavelength is 0.053 m. The radar diameter is estimated to be approximately 0.7 m, which gives an area of  $0.38 m^2$ . A typical efficiency of 0.6 is assumed. Therefore, the gain for Sea Giraffe is approximated:

$$10 \log \left( \frac{4\pi(0.38m^2)}{(0.053m)^2} (0.6) \right) = 30.1dB . \quad (A.22)$$

The peak power for Sea Giraffe is given as 25 kW (equivalent to 44.0 dBW). Therefore, the SL for Sea Giraffe is taken to be 74.1 dBW.

In the case of A/N SPY-6 [113], the system is equivalent to the A/N SPY-1 system with 15 dB of gain, implying a SL of 82.8 dBW.

The TL is the free space path loss (FSPL) that occurs due to spreading plus the losses due to attenuation/extinction. The primary variables which are worth evaluating to determine

their impact to the FSPL for operational radars in the Red Sea are spherical spreading and extinction due to rain or haze [114].

Spherical spreading is straightforward, and is simply given as  $20 \log(R)$ , where  $R$  is range. For radars operating in the C-band and S-band, extinction due to haze is negligible to their very low diameter. Haze particles are significantly smaller than the wavelengths utilized, so generally outside of the scattering/absorption regimes. Rain, however, can be a more severe source of extinction. Spy-6, operating in S-band, is unlikely to be seriously degraded/attenuated even by very heavy rain, since the size of the drops are much smaller than the wavelength of the radar. Sea Giraffe, however, operates where rain attenuation and degradation starts to become significant.

From ITU [114], the attenuation due to rain is given by the following formula:

$$\gamma = \kappa \nu^\alpha , \quad (\text{A.23})$$

where  $\nu$  is the rain rate in mm/hr,  $\gamma$  is the attenuation in dB/km, and  $\kappa$  and  $\alpha$  are empirically derived values. For the reference frequency of 5.65 GHz,  $\kappa = 0.00039$  and  $\alpha = 1.65$ . For good weather ( $\nu = 0$ ), there is no degradation due to rain. For moderate weather ( $\nu = 10$ ), the degradation value is 0.017 dB/km. For severe weather ( $\nu = 50$ ), the degradation value is 0.248 dB/km. For the purposes of this project, good weather simulations were the focus, as is typical of Red Sea conditions.

Combining, the general formula for TL is given:

$$TL = 20 \log(R) + 20 \log(f) + 20 \log\left(\frac{4\pi}{c}\right) + \gamma R . \quad (\text{A.24})$$

This gives the following expressions for TL.

1. A/N SPY-6
  - Weather Independent:  $TL = 20 \log(R) - 42.82$
2. Sea Giraffe
  - Good Weather:  $TL = 20 \log(R) - 47.49$
  - Moderate Weather:  $TL = 20 \log(R) + 0.000017R - 47.49$
  - Severe Weather:  $TL = 20 \log(R) + 0.000248R - 47.49$

The TS is given by the RCS, converted into dBsm.

1. Group I UAS:  $TS = -13.13dBsm$
2. Group II UAS:  $TS = -8.57dBsm$
3. USV:  $TS = -6.02dBsm$

The NL, primarily due to thermal noise, is assumed to be 4.25 dB for both systems.

With all of that information available, it is possible to calculate the SNR for each system.

1. A/N SPY-6
  - Weather Independent:  $SNR = 121.37 - 20 \log(R) + TS$
2. Sea Giraffe
  - Good Weather:  $SNR = 117.34 - 20 \log(R) + TS$
  - Moderate Weather:  $SNR = 117.34 - 20 \log(R) - 0.000017R + TS$
  - Severe Weather:  $SNR = 117.34 - 20 \log(R) - 0.000248R + TS$

## A.5 Probability of Detection

To estimate the probability of detection ( $P_d$ ), from the SNR, receiver operating characteristic curves were used [115], assuming non-coherent detection over a single pulse.

$$P_d = Q\left(Q^{-1}(P_{fa}) - \sqrt{2\gamma}\right). \quad (A.25)$$

In the previous equation,  $Q$  is the cumulative density function (CDF) for a normal distribution,  $P_{fa}$  is the probability of false alarm, assumed to be  $10^{-6}$ , and  $\gamma$  is the SNR expressed linearly, not in dB. The Q function is given:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{t^2/2} dt. \quad (A.26)$$

Converting back to linear gives the following formula for  $P_d$ :

$$P_d = Q\left(4.753 - \sqrt{2 * 10^{SNR/10}}\right). \quad (A.27)$$

A sample of the calculated values are provided in Table A.2.

Table A.2: Radar system detection data.

| System      | Target        | Weather     | Range (km) | SNR     | Q-input | Cumul. $P_d$ |
|-------------|---------------|-------------|------------|---------|---------|--------------|
| AN/SPY-6    | Group III UAS | Independent | 50         | 14.2606 | -2.5507 | 0.9946       |
| AN/SPY-6    | Group III UAS | Independent | 60         | 12.6770 | -1.3334 | 0.9088       |
| AN/SPY-6    | Group III UAS | Independent | 75         | 10.7388 | -0.1162 | 0.5462       |
| AN/SPY-6    | Group III UAS | Independent | 105        | 7.8162  | 1.2750  | 0.1011       |
| AN/SPY-6    | Group III UAS | Independent | 155        | 4.4334  | 2.3970  | 0.0083       |
| AN/SPY-6    | USV           | Independent | 115        | 14.1360 | -2.4467 | 0.9928       |
| AN/SPY-6    | USV           | Independent | 135        | 12.7433 | -1.3801 | 0.9162       |
| AN/SPY-6    | USV           | Independent | 170        | 10.7410 | -0.1174 | 0.5467       |
| AN/SPY-6    | USV           | Independent | 245        | 7.5667  | 1.3735  | 0.0848       |
| AN/SPY-6    | USV           | Independent | 325        | 5.1123  | 2.2054  | 0.0137       |
| Sea Giraffe | Group III UAS | Good        | 30         | 14.6676 | -2.9011 | 0.9981       |
| Sea Giraffe | Group III UAS | Good        | 40         | 12.1688 | -0.9876 | 0.8383       |
| Sea Giraffe | Group III UAS | Good        | 50         | 10.2306 | 0.1605  | 0.4362       |
| Sea Giraffe | Group III UAS | Good        | 70         | 7.3080  | 1.4727  | 0.0704       |
| Sea Giraffe | Group III UAS | Good        | 95         | 4.6555  | 2.3359  | 0.0097       |
| Sea Giraffe | Group III UAS | Moderate    | 30         | 14.1576 | -2.4646 | 0.9931       |
| Sea Giraffe | Group III UAS | Moderate    | 36         | 12.4719 | -1.1915 | 0.8833       |
| Sea Giraffe | Group III UAS | Moderate    | 44         | 10.5929 | -0.0351 | 0.5140       |
| Sea Giraffe | Group III UAS | Moderate    | 60         | 7.6270  | 1.3500  | 0.0885       |
| Sea Giraffe | Group III UAS | Moderate    | 82         | 4.5397  | 2.3679  | 0.0089       |
| Sea Giraffe | Group III UAS | Severe      | 18         | 14.6405 | -2.8773 | 0.9980       |
| Sea Giraffe | Group III UAS | Severe      | 21         | 12.5576 | -1.2504 | 0.8944       |
| Sea Giraffe | Group III UAS | Severe      | 24         | 10.6538 | -0.0687 | 0.5274       |
| Sea Giraffe | Group III UAS | Severe      | 29         | 7.7700  | 1.2935  | 0.0979       |
| Sea Giraffe | Group III UAS | Severe      | 35         | 4.6486  | 2.3378  | 0.0097       |

Continued on next page

Table A.2: Radar system detection data. (Continued)

|             |     |          |     |         |         |        |
|-------------|-----|----------|-----|---------|---------|--------|
| Sea Giraffe | USV | Good     | 70  | 14.4180 | -2.6843 | 0.9964 |
| Sea Giraffe | USV | Good     | 85  | 12.7316 | -1.3719 | 0.9149 |
| Sea Giraffe | USV | Good     | 110 | 10.4921 | 0.0202  | 0.4920 |
| Sea Giraffe | USV | Good     | 150 | 7.7982  | 1.2822  | 0.0999 |
| Sea Giraffe | USV | Good     | 215 | 4.6712  | 2.3315  | 0.0099 |
| Sea Giraffe | USV | Moderate | 60  | 14.7370 | -2.9625 | 0.9985 |
| Sea Giraffe | USV | Moderate | 75  | 12.5438 | -1.2408 | 0.8927 |
| Sea Giraffe | USV | Moderate | 90  | 10.7051 | -0.0973 | 0.5388 |
| Sea Giraffe | USV | Moderate | 120 | 7.6964  | 1.3227  | 0.0930 |
| Sea Giraffe | USV | Moderate | 160 | 4.5176  | 2.3740  | 0.0088 |
| Sea Giraffe | USV | Severe   | 30  | 14.3376 | -2.6157 | 0.9955 |
| Sea Giraffe | USV | Severe   | 34  | 12.2584 | -1.0471 | 0.8525 |
| Sea Giraffe | USV | Severe   | 38  | 10.3003 | 0.1235  | 0.4508 |
| Sea Giraffe | USV | Severe   | 44  | 7.5389  | 1.3843  | 0.0831 |
| Sea Giraffe | USV | Severe   | 52  | 4.1039  | 2.4846  | 0.0065 |

THIS PAGE INTENTIONALLY LEFT BLANK

---

---

## APPENDIX B: Probability of Kill Calculations

---

The engagement performance parameters described in Chapter 4 were used to estimate the probability of a single shot kill for each system considered in this report. This is defined as the joint probability that a threat is neutralized given detection and engagement by a defensive weapon system. The framework for these calculations is mainly taken from [40] and is described in this appendix.

### B.1 Threat Characteristics

Probability of kill,  $P_K$ , was assessed against three threat models: the Iranian Shahed-136 UAS, Arash-2 UAS, and the Ukrainian Sea Baby USV. Three defining attributes from each system were taken into consideration for our calculations: velocity, length, and mean flight path altitude. As further detailed, altitude is considered to account for targeting geometry and detection horizon and is therefore defined in terms as above ground level (AGL). Since we are focused on naval applications, this is equivalent to mean sea level (MSL).

Table B.1. Threat attributes used in  $P_K$  assessment. Adapted from [44], [46], [51], [52], [108].

| Threat         | Velocity (kts) | Length (m) | Altitude (ft) |
|----------------|----------------|------------|---------------|
| Shahed-136 UAS | 99.982         | 3.5        | 13,000        |
| Arash-2 UAS    | 215.983        | 4.5        | 18,045        |
| Sea Baby USV   | 48.596         | 6          | 2             |

### B.2 Encounter Conditions

After launch, the interceptor flies toward the target, and since all analyzed payloads are fragmentation warheads, detonation is based on a proximity fuse, with probability of interception inversely proportional to distance from the target. Therefore, probability of interception is heavily influenced by initial position and velocity at launch. For standardized comparison,

all weapon systems were evaluated at the middle of the engagement envelope. Air threats were evaluated at  $30^\circ$  elevation from the launcher horizon, which corresponds to approximately half of the maximum elevation arc for guns. Surface threats were evaluated at  $0^\circ$ , discounting any slight difference between the launcher and threat elevation. This is illustrated in Figure B.1, with the light blue crosshair representing surface threats and the darker crosshair representing air threats.

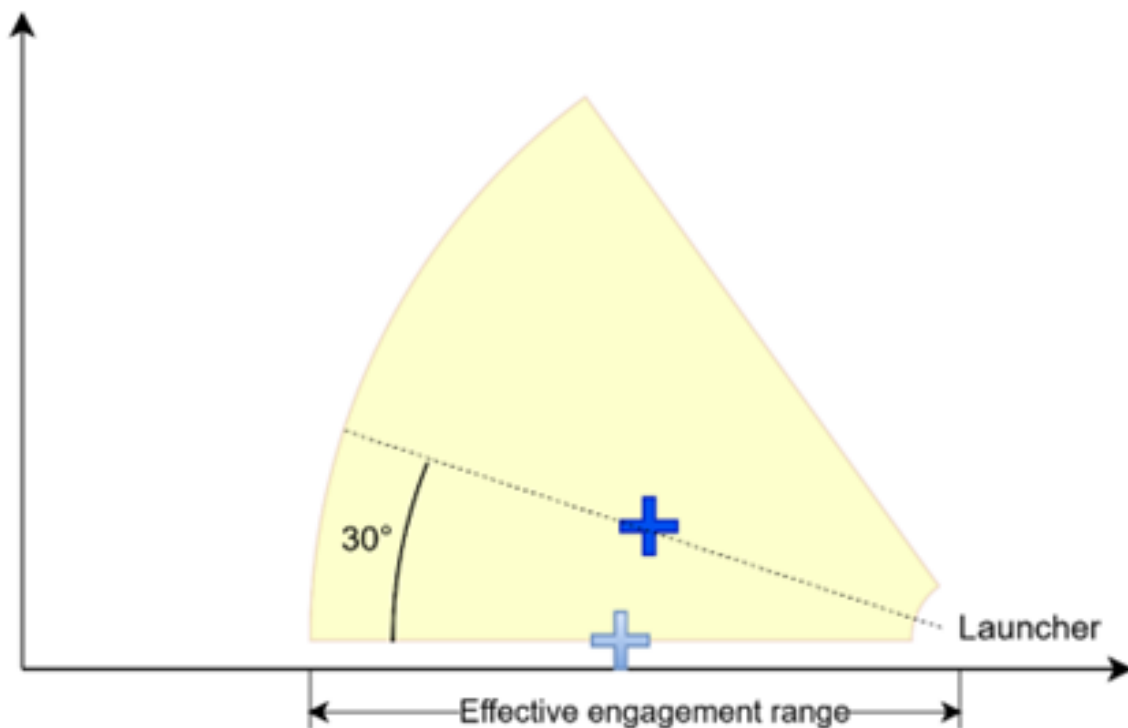


Figure B.1. Weapon envelope and threat position for engagement evaluation.

Since the engagement assumes detection, the only exception to this criterion occurs when this range is restricted by the radar horizon such that the target can only be detected closer than half of the effective engagement range. In this situation, the evaluation assumes engagement at maximum detectable range. Furthermore, our assessment assumes that the targets are in a level flight path.

## B.3 Probability of Fusing

As describe in [40], the process of estimation for the probability of fusing involves determining the propagator trajectory relative to target, the miss distance, and the detonation zones around the target. In turn, the detonation zones depend on the propagator trajectory and the fragment spray zone. The calculations in this section detail this process and were performed with support from MATLAB scripts.

### B.3.1 Fragmentary Spray Zones

For determining the payloads' fragment spray zones, all warheads were assumed to be cylindrical and possess a single end detonator. For payloads with a case length much larger than a diameter, Eq. 3.7 from [40] becomes valid for determining the fragment velocity ( $V_0$ ). For a Gurney constant ( $2E^{\frac{1}{2}}$ ) and mass ratio between the high explosive (C) and metallic case (M):

$$V_0 = \sqrt{2E} \left( \frac{\frac{C}{M}}{1 + 0.5 \frac{C}{M}} \right)^{\frac{1}{2}}. \quad (\text{B.1})$$

The mass ratio between the high explosive (C) and metallic case (M) were assumed to be 1. This would be the mid-range value for various different warheads since the C/M relation ranges from 0.5 to 1.5 [40]. Substituting this constant and the C/M ratio in the previous equation, fragment velocities were determined.

Table B.2. Calculated fragment velocities at detonation.

| Engagement Alternative                    | Fragment Velocity (ft/s) |
|---|--------------------------|
| Mk-45 – 5” HVP                            | 7,593.4                  |
| Griffin Missile System (GMS)              | 8,352.8                  |
| VAMPIRE – APKWS                           | 7,593.4                  |
| Chain Gun with 30x173mm Airburst Munition | 7,593.4                  |

Additionally, considering the detonation velocity and assuming the idealized static detonation of a circular cylindrical HE warhead from [40], the spray angle of each fragment can be expressed from Shapiro's equation (Eq. 3.8 of the referred book), which for the trailing

and leading fragment is given by:

$$\alpha_i = 90^\circ - \tan^{-1} \left( \frac{V_0 [1 + 0.25 (\frac{D}{l})^2]^{-1/2}}{2V_D} \right). \quad (\text{B.2})$$

In this equation,  $l$  is longitudinal distance from the detonator of the considered fragment. Thus, for the trailing fragment where distance from detonation is zero, this angle becomes:

$$\alpha_{trailing} = 90^\circ. \quad (\text{B.3})$$

In the same fashion, the leading and center spray angles were calculated, as listed in Table B.3.

Table B.3. Calculated fragment spray angles.

| Engagement Alternative                    | $\alpha_{trailing}$ | $\alpha_{center}$ | $\alpha_{leading}$ |
|---|---------------------|-------------------|--------------------|
| Mk-45 – 5” HVP                            | 90°                 | 82.26°            | 82.02°             |
| Griffin Missile System (GMS)              | 90°                 | 84.03°            | 82.72°             |
| VAMPIRE – APKWS                           | 90°                 | 82.16°            | 82.00°             |
| Chain Gun with 30x173mm Airburst Munition | 90°                 | 82.17°            | 82.00°             |

### B.3.2 Miss Distance

The probability of the fragmentation warhead fusing is closely related to the distance from the trajectory that the projectile will cover in relation to its target, while the expected number of fragments that will hit depend on where it fuses along the trajectory [40]. The distance from the projectile flight path relative to its target is the miss distance. Considering a vertical z-axis and a horizontal x-axis, the miss distance vector ( $s$ ) in 2D is composed of:

$$s_x = S_x + (v_p)_x t, \quad (\text{B.4})$$

$$s_z = S_z + (v_p)_z t, \quad (\text{B.5})$$

where  $S_x$  and  $S_z$  are the initial separation distances between the target and propagator. Therefore, the propagator's flight-path angle with respect to the target is calculated by:

$$\psi_p = \arctan\left(\frac{(v_p)_z}{(v_p)_x}\right). \quad (\text{B.6})$$

The minimum separation distance would occur at time:

$$\tau = \frac{-[S_x(v_p)_x + S_z(v_p)_z]}{v_p^2}. \quad (\text{B.7})$$

When the proximity warhead fuses, a second launch happens, this time involving the fragments. Therefore, similar equations can be derived by replacing the distance between the propagator and target with that between the fragment and target. With this in mind, detonation zones can be constructed based on where the leading and trailing fragments cross the nose and tail of the target. The size of the detonation zone legs are therefore dependent on the length of the target.

### **B.3.3 Effect of Uncertainty on Miss Distance**

In general, minimal miss distance isn't obtained by launching the propagator at the target elevation, as would likely cause the propagator to pass considerably below the target. Rather, an optimal angle away from the target elevation would need to be calculated in order to achieve minimal miss distance. To illustrate this with the Chain Gun, the resulting miss distance for various launching angles is given in Figure B.2.

It can be seen in the preceding figure that an optimal launch angle results in a nearly direct hit. However, as with any targeting system, there is uncertainty from sensor calibration, processing error, or even from lack of stability due to the sea state. According to EOS, the maritime version of their c-UAS system has a gimbal stabilization of less than 1 mrad ( 0.057°) [92]. Without further detail on other systems, this analysis assumes an overall targeting uncertainty of 1 mrad for all. With this definition, each system was tested at each error edge,  $-0.057^\circ$  and  $+0.057^\circ$  from the best launch angle, resulting in an early bird and late bird launch. The USV threat is an exception, in which only  $+0.057^\circ$  from the best launch

angle was considered. With this angular error, using the same example, an uncertainty box of  $\pm 0.06^\circ$  would result in a greater miss distance, as demonstrated in Figure B.3.

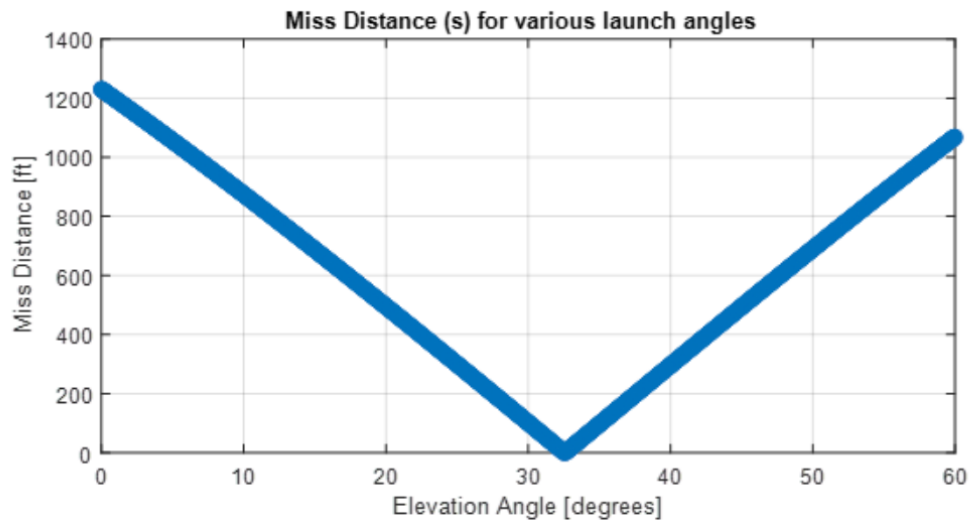


Figure B.2. Miss distance of various launch angles of the chain gun with  $30 \times 173$  mm versus UAS.

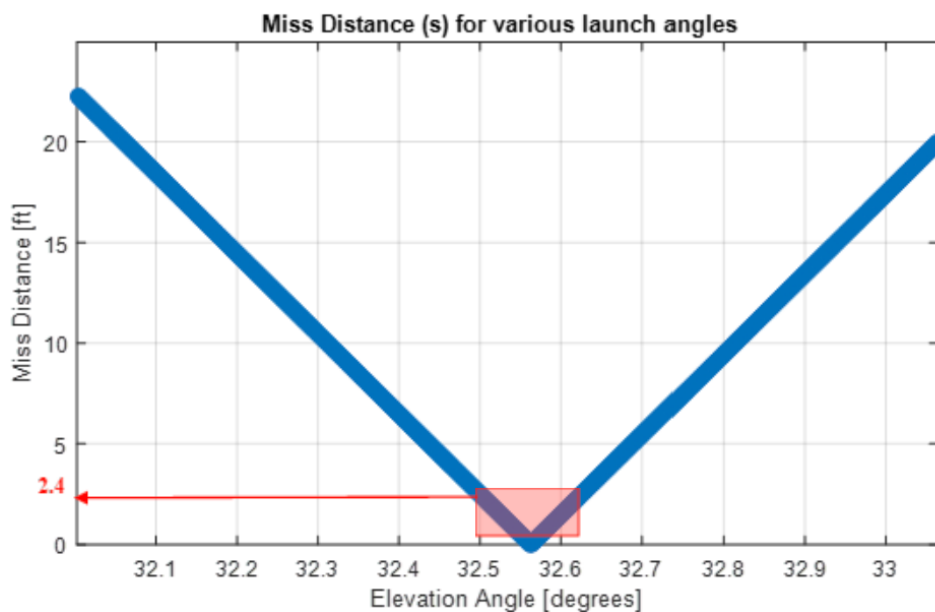


Figure B.3. Uncertainty of launch angle effect on miss distance.

### B.3.4 Velocity Compensation

The calculations for the detonation zones and miss distance, as described in [40], are underpinned by the assumption that propagator and target do not change velocity along their trajectories. However, besides the fact that any propagator will have at least some velocity changes due to drag, guided munitions and missiles will themselves have corrections of angle along their flight leading to potentially more intense velocity changes. Therefore, a standard compensation factor to the final calculation of the miss distance was given to each projectile. The guided munitions, the 5” HVP and the APKWS, had their final values reduced by half, and the missile, the Griffin C-ER, had its final value reduced by one third.

### B.3.5 Summary of Geometric Parameters Associated with Detonation

For each aiming situation (over or under), target elevation angles with corresponding miss distance ( $\delta$ ) and fragmentary angle with respect to the target ( $\psi_{leading}$  and  $\psi_{trailing}$ ) were calculated. These values for each alternative versus the Shahed-136 UAS are summarized in Table B.4, followed by the same values versus the Arash-2 UAS in Table B.5, and against the Sea Baby USV in Table B.6. As previously described, for the USV only the overshooting condition is calculated.

Table B.4. Geometric parameters for alternatives against the Shahed-136 UAS.

| Engagement Alternative                      | Elev. Angle | $\delta$ (ft) | $\psi_{leading}$ | $\psi_{trailing}$ |
|---|-------------|---------------|------------------|-------------------|
| Mk-45 – 5” HVP                              | 148.509°    | 61.15         | 270.12°          | 263.63°           |
|   | 148.629°    | 60.83         | 27.61°           | 34.01°            |
| Griffin Missile System (GMS)                | 128.221°    | 8.24          | 237.38°          | 229.93°           |
|   | 128.415°    | 8.21          | 21.82°           | 28.32°            |
| VAMPIRE – APKWS                             | 139.680°    | 4.56          | 250.73°          | 242.94°           |
|   | 139.830°    | 4.52          | 30.31°           | 37.57°            |
| Chain Gun with 30mm×173mm Airburst Munition | 147.375°    | 2.48          | 268.68°          | 262.07°           |
|   | 147.499°    | 2.46          | 27.22°           | 33.66°            |

Table B.5. Geometric parameters for alternatives against the Arash-2 UAS.

| Engagement Alternative                      | Elev. Angle | $\delta$ (ft) | $\psi_{leading}$ | $\psi_{trailing}$ |
|---|-------------|---------------|------------------|-------------------|
| Mk-45 – 5” HVP                              | 146.842°    | 61.19         | b 269.74°        | 263.31°           |
|   | 146.968°    | 60.98         | 25.44°           | 31.68°            |
| Griffin Missile System (GMS)                | 83.206°     | 8.18          | 206.65°          | 197.95°           |
|   | 82.828°     | 8.22          | 0.26°            | 6.15°             |
| VAMPIRE – APKWS                             | 127.286°    | 4.55          | 241.69°          | 233.59°           |
|   | 127.484°    | 4.60          | 17.47°           | 24.23°            |
| Chain Gun with 30mm×173mm Airburst Munition | 35.615°     | 2.46          | 267.88°          | 261.36°           |
|   | 35.481°     | 2.46          | 23.48°           | 29.66°            |

Table B.6. Geometric parameters for alternatives against the Sea Baby USV.

| Engagement Alternative                      | Elev. Angle | $\delta$ (ft) | $\psi_{leading}$ | $\psi_{trailing}$ |
|---|-------------|---------------|------------------|-------------------|
| Mk-45 – 5” HVP                              | 179.941°    | 61.08         | 300.91°          | 294.43°           |
| Griffin Missile System (GMS)                | 179.922°    | 8.21          | 287.03°          | 280.05°           |
| VAMPIRE – APKWS                             | 179.933°    | 4.54          | 289.29°          | 281.72°           |
| Chain Gun with 30mm×173mm Airburst Munition | 179.940°    | 2.47          | 300.15°          | 293.56°           |

## B.4 Detonation Zones

Four generalized detonation zones are described in [40], with two of these assumed to be lethal zones. These are the green and yellow zones in Figure B.4.

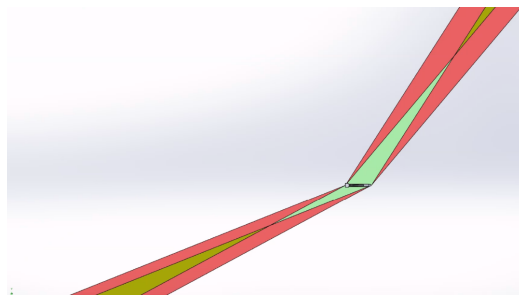


Figure B.4. Detonation zones around the target.

Our analysis assumes a uniform distribution for the probability of fusing along the propagator's path length within a detonation zone. In other words, once inside the first detonation zone, there is an equally likely chance at all points along the flight path that the warhead will detect the target and detonate. Once the warhead exits the final detonation zone this probability returns to zero. Therefore, the probability of fusing along the flight path of length  $p$  from entry point  $a$  to exit point  $b$  within a zone of length  $\Delta p$  is given by:

$$P_F = \frac{\Delta p}{b - a} = \frac{\Delta p}{p} . \quad (\text{B.8})$$

Considering the most lethal zones as the desired path region for detonation, the entrance and departure points, as well as the path length under this region are illustrated in Figure B.5.

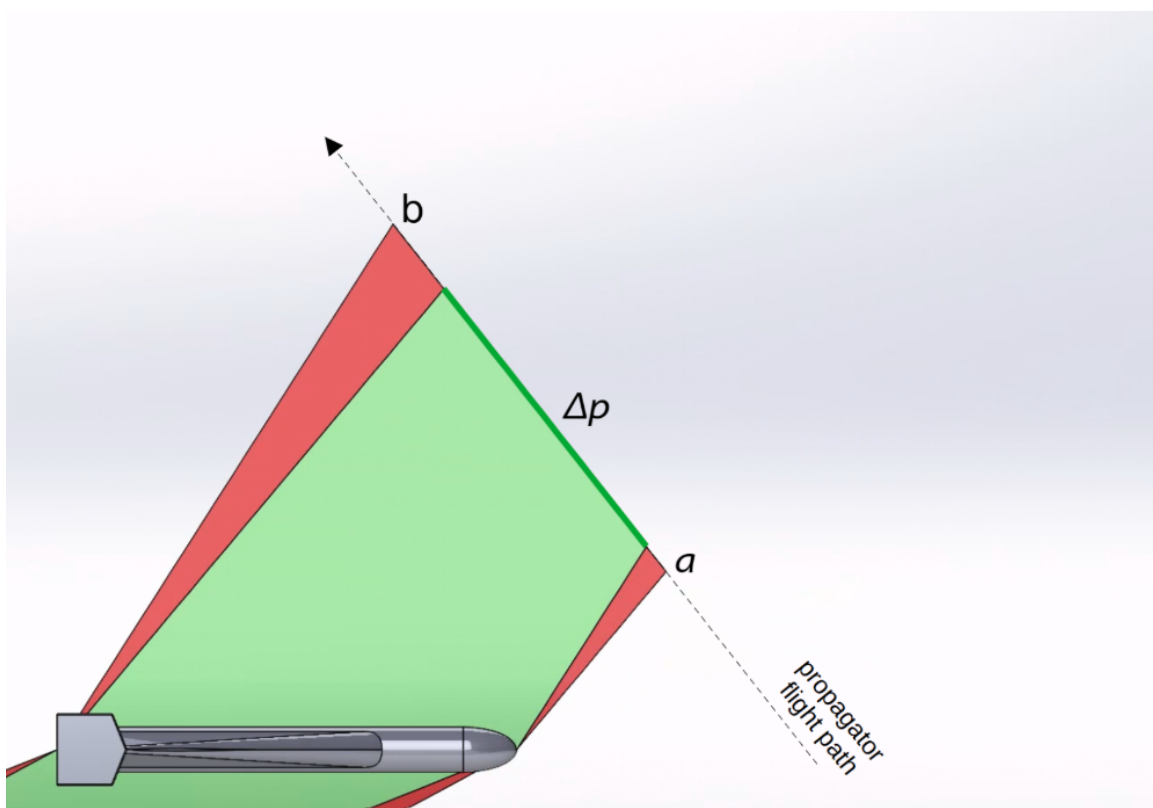


Figure B.5. Propagator path length under detonation zones along respective entrance and departure points.

Using SolidWorks, the detonation zone and trajectory corresponding to each engagement system and threat combination were sketched from the previous calculations, and the path ratios were determined. Figure B.6 shows an example of the trajectory and measurement of path lengths for determining the probability of fusing. In this example, the probability of fusing for the propagator passing under the target would be given by 929.27 mm ( $\Delta_p$ ) divided by 1531.95 mm ( $p$ ), thus equaling 60.66%. The final probability was determined by the average value between the propagator passing under and the propagator passing over the target in the case of a UAS. Meanwhile, for the USV, only the value obtained by the propagator passing over the target was defined as the final probability.

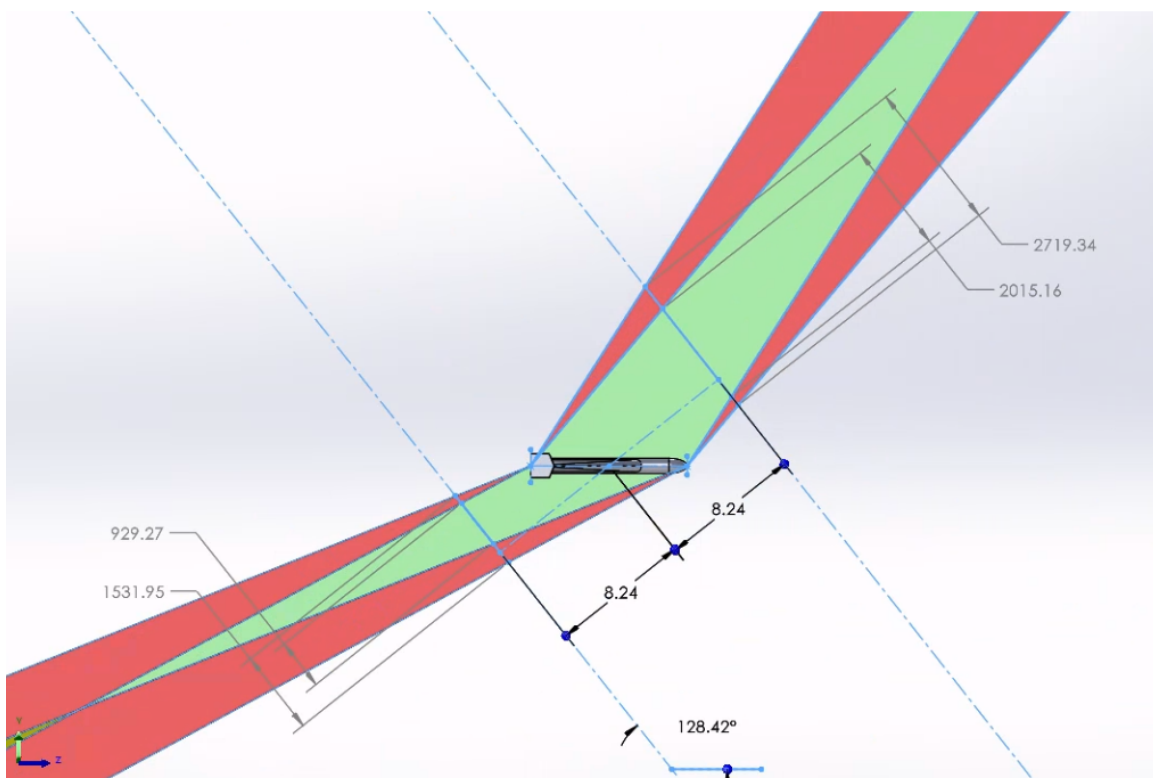


Figure B.6. Path lengths inside detonation zones for probability of fusing calculation.

Finally, omitting the need for any further assumptions or data regarding the targets' ability to sustain damage, it was assumed for the purpose of our simulation that detonation inside either of the two lethal zones would indicate a kill.

---

## List of References

---

- [1] A. Masquelier-Page, “Lessons from Red Sea and Ukraine’s Black Sea fight help prep Navy for possible conflict with China,” *The Associated Press*, Sep. 18, 2024. Available: <https://www.ap.org/news-highlights/spotlights/2024/lessons-from-red-sea-and-ukraines-black-sea-fight-help-prep-navy-for-possible-conflict-with-china/>
- [2] Al Jazeera Staff, “Yemen’s Houthis emerge from Gaza war emboldened, and with more enemies,” *Al Jazeera*, Feb. 13, 2025. Available: <https://www.aljazeera.com/news/2025/2/13/yemens-houthis-emerge-from-gaza-war-emboldened-and-with-more-enemies>
- [3] J. Saul and C. Cohn, “Red Sea insurance costs soar as Houthi shipping threats loom, sources say,” *Reuters*, Sep. 19, 2024. Available: <https://www.reuters.com/world/middle-east/red-sea-insurance-costs-soar-houthi-shipping-threats-loom-sources-say-2024-09-19/>
- [4] A. Abdurasulov, “Ukraine war: The sea drones keeping Russia’s warships at bay,” *BBC*, Mar. 11 2024. Available: <https://www.bbc.com/news/world-europe-68528761>
- [5] L. C. Williams, “Mideast missile duels have cost US Navy nearly \$1b, secretary says,” *Defense One*, Apr. 16, 2024. Available: <https://www.defenseone.com/threats/2024/04/mideast-missile-duels-have-cost-us-navy-nearly-1b-secretary-says/395791/>
- [6] W. Rumbaugh, “Cost and value in air and missile defense intercepts,” *Center for Strategic and International Studies*, Feb. 13 2024. Available: <https://www.csis.org/analysis/cost-and-value-air-and-missile-defense-intercepts>
- [7] BBC, “Who are the Houthis and why is the US targeting them?” *BBC*, Mar. 25 2025.
- [8] UAS Task Force Airspace Integration Integrated Product Team, “Department of Defense unmanned aircraft system airspace integration plan version 2.0,” Department of Defense, Washington, DC, USA, Rep. 1-7ABA52E, Mar. 2011. Available: [https://web.archive.org/web/20160121155841/http://www.acq.osd.mil/sts/docs/DoD\\_UAS\\_Airspace\\_Integ\\_Plan\\_v2\\_\(signed\).pdf](https://web.archive.org/web/20160121155841/http://www.acq.osd.mil/sts/docs/DoD_UAS_Airspace_Integ_Plan_v2_(signed).pdf)
- [9] R. Singh, “Advanced radar algorithms in combat Naval systems,” *Defense Radar Review*, vol. 10, no. 2, pp. 35–50, 2021.

- [10] A. Shepherd, “Houthi launch USV with explosives in Red Sea, U.S. military says,” *Inside Defense*, Jan. 4, 2024. Available: <https://insidedefense.com/daily-news/houthi-launch-usv-explosives-red-sea-us-military-says>
- [11] Maritime Administration, “2025-001: Southern Red Sea, Bab el Mandeb Strait, and Gulf of Aden—Houthi attacks on commercial vessels,” Department of Transportation, Feb. 14, 2025. Accessed Apr. 15, 2025. Available: <https://www.maritime.dot.gov/msci/2025-001-southern-red-sea-bab-el-mandeb-strait-and-gulf-aden-houthi-attacks-commercial-vessels>
- [12] Defense Express, “Media reveal Magura V5, the Ukrainian Naval drone: Features and specifications,” Jul. 30, 2023. Available: [https://en.defence-ua.com/weapon\\_and\\_tech/media\\_reveal\\_magura\\_v5\\_the\\_ukrainian\\_naval\\_drone\\_features\\_and\\_specifications-7471.html](https://en.defence-ua.com/weapon_and_tech/media_reveal_magura_v5_the_ukrainian_naval_drone_features_and_specifications-7471.html)
- [13] Defense Express, “Updated Sea Baby 2024 Naval Drone: One ton of explosives with a range of over 1000 km,” Mar. 6, 2024. Available: [https://en.defence-ua.com/weapon\\_and\\_tech/updated\\_sea\\_baby\\_2024\\_naval\\_drone\\_one\\_ton\\_of\\_explosives\\_with\\_a\\_range\\_of\\_over\\_1000\\_km-9748.html](https://en.defence-ua.com/weapon_and_tech/updated_sea_baby_2024_naval_drone_one_ton_of_explosives_with_a_range_of_over_1000_km-9748.html)
- [14] Newscast Pratyaksha, “Red Sea tension may risk disrupting global supply chain for a year – top shipping company warns,” *Newscast Pratyaksha*, Feb. 14 2024.
- [15] Business Executives for National Security, “Industry impact of Houthi Attacks in the Red Sea.” Accessed Apr. 21, 2025. Available: <https://bens.org/wp-content/uploads/2024/04/Houthi-Impact-on-Global-Trade.pdf>
- [16] O. Merk and A. Teodoro, “The Red Sea crisis: Impacts on global shipping and the case for international co-operation,” International Transport Forum. Accessed Apr. 21, 2025. Available: <https://www.itf-oecd.org/sites/default/files/repositories/red-sea-crisis-impacts-global-shipping.pdf>
- [17] Scientific Reports, “Figure 2,” *Nature*. Accessed: Apr. 21, 2025. Available: <https://www.nature.com/articles/s41598-021-96572-5/figures/2>
- [18] Sprinter Observer (SprinterObserve), “Map of military bases in persian gulf, red sea, middle east,” X, Apr. 21 2023. 11:53 AM. Available: <https://x.com/Watson995/status/1649540822075883522>
- [19] S. Park, H. T. Kim, S. Lee, H. Joo, and H. Kim, “Survey on anti-drone systems: Components, designs, and challenges,” *IEEE Access*, vol. 9, pp. 42 635–42 659, 2021. Available: <https://doi.org/10.1109/ACCESS.2021.3065926>
- [20] G. Markarian and A. Staniforth, *Countermeasures for Aerial Drones*. Norwood, MA, USA: Artech House, 2020.

- [21] A. Haider, "Aerodynamic optimisation and stability analysis of solar-powered unmanned aerial vehicle," *NED University Journal of Research in Applied Sciences*, vol. XX, no. 4, Dec. 2023. Available: <https://ssrn.com/abstract=5178177>
- [22] J. Kong, "UAS jamming and cyber threats to maritime operations," *Naval Electronics Journal*, vol. 18, no. 2, pp. 23–35, 2021.
- [23] A. Tiurin *et al.*, "Framework for counter-UAS operations: Readiness, detection, influence, and evaluation," *Defensive Systems Review*, vol. 8, no. 3, pp. 90–104, 2022.
- [24] J. Kang, B. Xu, and D. Li, "Sensor and mitigator integration in maritime counter-UAS systems," *Sensors and Defense*, vol. 6, no. 2, pp. 112–127, 2021.
- [25] C. Albon, "DIU seeks counter-UAS systems to defend ships from Red Sea drone threats," *C4ISRNET*, Mar. 19, 2024. Available: <https://www.c4isrnet.com/unmanned/2024/06/17/defense-innovation-unit-seeks-systems-to-counter-red-sea-drone-attacks/>
- [26] R. Ceder, "Navy successfully uses HELIOS laser to take out a drone," *Navy Times*, Apr. 9, 2024. Available: <https://www.navytimes.com/news/your-navy/2024/04/09/navy-successfully-uses-helios-laser-to-take-out-a-drone/>
- [27] I. S. Bisht, "DroneSentry-X tested by U.S. Navy to jam drones in maritime environment," *The Defense Post*, Apr. 1, 2024. Available: <https://www.thedefensepost.com/2024/04/01/dronesentry-x-tested-navy/>
- [28] T. Odom, "Radar system fundamentals for maritime defense," in *IEEE Radar Conference Proceedings*, 2019, pp. 320–325.
- [29] W. Lu and H. Zhang, "Comparison of S-band and X-band radar performance," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 56, no. 5, pp. 3922–3933, Oct. 2020.
- [30] S. Subramaniam, "Signal processing algorithms for low-RCS detection," *IEEE Signal Processing Letters*, vol. 25, no. 12, pp. 1802–1806, Dec. 2018.
- [31] R. Jones, "Swarm attacks and maritime defense preparedness," *Journal of Unmanned Defense Systems*, vol. 7, no. 1, pp. 13–26, 2021.
- [32] D. Andrews, "Surface search radar advancements for Naval vessels," *Marine Electronics International*, vol. 19, no. 3, pp. 40–47, 2022.
- [33] T. Hall and C. DuPont, "Phased array radar for maritime UAV threat detection," *Radar Systems Journal*, vol. 14, no. 2, pp. 72–85, 2021.

- [34] M. Keller, “AN/SPY-6: Next generation maritime radar,” *Naval Technology Review*, vol. 22, no. 4, pp. 104–110, Jul 2019.
- [35] S. Brown, “Ship-to-ship data sharing and maritime threat detection,” *Naval Communication Quarterly*, vol. 9, no. 1, pp. 19–30, 2022.
- [36] J. Kim, “AIS exploitation and risks in maritime conflict zones,” *Maritime Cybersecurity Journal*, vol. 11, no. 2, pp. 57–68, 2021.
- [37] E. White and L. Chen, “Harsh environment considerations for Naval electronics,” *IEEE Transactions on Oceanic Engineering*, vol. 45, no. 1, pp. 11–20, Jan. 2020.
- [38] D. Roberts, “Electronic countermeasures and adaptive radar solutions,” *Journal of Military Technology*, vol. 33, no. 3, pp. 89–96, 2022.
- [39] S. Kamthan, H. Singh, and T. Meitzler, “Hierarchical fuzzy logic and application to survivability,” Department of the Army, Washington, DC, USA, Rep. AD1124435, 2021. Available: <https://apps.dtic.mil/sti/trecms/pdf/AD1124435.pdf>
- [40] R. E. Ball, *The Fundamentals of Aircraft Combat Survivability Analysis and Design*, 2nd ed. Reston, VA, USA: American Institute of Aeronautics and Astronautics, 2003.
- [41] Defense Acquisition University, “Total ownership cost.” Accessed Apr. 22, 2025. Available: <https://www.dau.edu/glossary/total-ownership-cost>
- [42] Defense Intelligence Agency, “Iran: Enabling Houthi attacks across the Middle East,” U.S. Department of Defense, Rep., 2024. Accessed: 2025-04-21. Available: [https://www.dia.mil/Portals/110/Documents/News/Military\\_Power\\_Publications/Iran\\_Houthi\\_Final2.pdf](https://www.dia.mil/Portals/110/Documents/News/Military_Power_Publications/Iran_Houthi_Final2.pdf)
- [43] M. Voskuijl, T. Dekkers, and R. Savelsberg, “Flight performance analysis of the Samad attack drones operated by Houthi armed forces,” *Science & Global Security*, vol. 28, no. 3, pp. 113–134, Aug. 2020. Available: <https://doi.org/10.1080/08929882.2020.1846279>
- [44] Jewish Institute for National Security of America, “Iran’s wide variety of unmanned aerial vehicle (UAV) capabilities.” Accessed Apr. 21, 2025. Available: <https://jinsa.org/wp-content/uploads/2024/02/Iran-Drones-9-14-22.pdf>
- [45] U.S. Army Training and Doctrine Command, “Sammad-3 Yemeni reconnaissance and loitering munition drone.” Accessed Apr. 21, 2025. Available: [https://odin.tradoc.army.mil/WEG/Asset/Sammad-3\\_Yemeni\\_Reconnaissance\\_and\\_Loitering\\_Munition\\_Drone](https://odin.tradoc.army.mil/WEG/Asset/Sammad-3_Yemeni_Reconnaissance_and_Loitering_Munition_Drone)

- [46] Defense Express, “Iranian Arash-2 kamikaze drones: Capabilities and specifications,” Oct. 16, 2022. Available: [https://en.defence-ua.com/analysis/iranian\\_arash\\_2\\_kamikaze\\_drones\\_capabilities\\_and\\_specifications-4555.html](https://en.defence-ua.com/analysis/iranian_arash_2_kamikaze_drones_capabilities_and_specifications-4555.html)
- [47] Iran Press, “Yemen army releases ‘Toofan1’ USV in action for first time,” *Islamic Republic News Agency*, Jun. 21, 2024. Available: <https://iranpress.com/yemen-army-release--toofan1--usv-in-action-for-first-time>
- [48] T. Newdick, “Small, agile Houthi drone boat shown obliterating ship during test,” *TWZ*, Jun. 21, 2024. Available: <https://www.twz.com/news-features/small-and-agile-houthi-drone-boat-shown-obliterating-ship-during-test>
- [49] H. Altman, “First look at Houthi kamikaze drone boat that struck cargo ship in Red Sea,” *TWZ*, Jun. 17, 2024. Available: <https://www.twz.com/news-features/first-look-at-houthi-kamikaze-drone-boat-that-struck-cargo-ship-in-red-sea>
- [50] H. I. Sutton, “Houthi’s Blowfish: Guide to explosive USV threat in Red Sea.” Accessed Apr. 21, 2025. Available: <https://www.hisutton.com/Yemen-Houthi-USV-Guide.html>
- [51] UNITED24, “Sea Baby naval drone.” Accessed May 15, 2025. Available: <https://u24.gov.ua/seababy>
- [52] H. I. Sutton, “Overview of maritime drones (USVs) of the Russo-Ukrainian war, 2022–24,” *Covert Shores*, Dec. 20, 2024. Available: <http://www.hisutton.com/Russia-Ukraine-USVs-2024.html>
- [53] U.S. Naval Forces Central Command, “CTF153 and USS Stout ‘ready together’ for Red Sea maritime security,” Feb. 2025. Available: <https://www.cusnc.navy.mil/Media/News/Display/Article/4074786/ctf153-and-uss-stout-ready-together-for-red-sea-maritime-security/>
- [54] R. O’Rourke, “Navy DDG-51 and DDG-1000 destroyer programs: Background and issues for Congress,” CRS Report No. RL32109, Washington, DC, USA, 2025. Available: <https://crsreports.congress.gov/product/pdf/RL/RL32109/274>
- [55] R. O’Rourke, “Navy lasers, railgun, and hypervelocity projectile: Background and issues for Congress,” CRS Report No. R44175, Washington, DC, USA, 2017. Available: <https://apps.dtic.mil/sti/pdfs/AD1030345.pdf>
- [56] Missile Defense Advocacy Alliance, “AN/SPY-1 radar.” Access Apr. 21, 2025. Available: <https://missiledefenseadvocacy.org/defense-systems/anspy-1-radar/>
- [57] Janes, “AN/SPY-1 series,” Nov. 9, 2023. Available: <https://customer.janes.com/display/JC4IM0028-JC4IM>

- [58] J. Keller, “Raytheon to provide hardware for AN/SPY-6(V) radar aboard late-model Burke-class destroyer surface warships,” *Military+Aerospace Electronics*, Apr. 28, 2023. Available: <https://www.militaryaerospace.com/sensors/article/14292910/surface-warship-radar-gallium-nitride-gan>
- [59] Janes, “Electronic warfare system overview,” 2023. Accessed Apr. 21, 2025. Available: <https://customer.janes.com/display/JREW0357-JC4IM>
- [60] U.S. Central Command, “CENTCOM press releases.” Accessed May 22, 2025. Available: <https://www.centcom.mil/MEDIA/PRESS-RELEASES/>
- [61] Army Recognition, “Industry advances long range, precision munitions (by: BAE Systems),” *Army Recognition*, Apr. 6, 2015. Available: <https://armyrecognition.com/news/navy-news/2015/industry-advances-long-range-precision-munitions-by-bae-systems>
- [62] Janes, “5 inch 54-calibre naval gun ammunition,” Sep. 6, 2023. Available: [https://customer.janes.com/display/JAH\\_0350-JAH\\_](https://customer.janes.com/display/JAH_0350-JAH_)
- [63] Janes, “BAE systems to develop high-velocity projectile for USN’s railgun,” Nov. 25, 2023. Available: <https://customer.janes.com/display/idr16169-idr-2013>
- [64] S. N. Information, “Surface vessel weapon system – OtoMelara - OtoBreda 127/54C gun – 127mm (5") / 54-caliber compact dual-purpose automatic naval gun system,” Mar. 9, 2025. Available: <https://www.seaforces.org/wpnsys/SURFACE/Oto-Melara-127mm-54caliber-gun.htm>
- [65] BAE Systems, “HVP: Hypervelocity projectile,” BAE Systems, Feb. 23, 2025. Available: <https://www.baesystems.com/product/hyper-velocity-projectile-hvp>
- [66] Seaforces Naval Information, “Surface vessel weapon system – OtoMelara - OtoBreda 127/54c gun – 127mm (5") / 54-caliber compact dual-purpose automatic naval gun system,” n.d. Accessed: 2025-03-09. Available: <https://www.seaforces.org/wpnsys/SURFACE/Oto-Melara-127mm-54caliber-gun.htm>
- [67] Janes, “BAE systems to develop high-velocity projectile for USN’s railgun,” Nov. 25, 2023. Available: <https://customer.janes.com/display/idr16169-idr-2013>
- [68] L3Harris Technologies, “Shadow fox autonomous surface vehicle.” Accessed Apr. 15, 2025. Available: <https://www.l3harris.com/all-capabilities/shadow-fox-autonomous-surface-vehicle>
- [69] T. Harrison, Mar. 2025. email.

- [70] R. Kirill, “AGM-176 Griffin missile will be used on ships,” Topwar. Accessed Apr. 20, 2025. Available: <https://en.topwar.ru/34087-raketa-agm-176-griffin-budet-ispolzovatsya-na-korablyah.html>
- [71] Janes, “AGM-176 Griffin,” Nov. 23, 2023. Available: <https://customer.janes.com/display/JALWA063-JALW>
- [72] Janes, “AGM-176 Griffin/Griffin C (Sea Griffin),” Apr. 23, 2025. Available: [https://customer.janes.com/display/JNWSA049-JNW\\_](https://customer.janes.com/display/JNWSA049-JNW_)
- [73] Naval Sea Systems Command, “MK 60 Griffin Missile System (GMS),” Department of the Navy. Accessed Apr. 21, 2025. Available: <https://www.navy.mil/Resources/Fact-Files/Display-FactFiles/Article/2167883/mk-60-griffin-missile-system-gms/>
- [74] Missilery, “FGM-148 Javelin anti-tank missile system.” Accessed Apr. 21, 2025. Available: <https://en.missilery.info/missile/javelin>
- [75] Airforce Technology, “Griffin missile system.” Accessed Apr. 4, 2025. Available: <https://www.airforce-technology.com/projects/griffin-missile-system/?cf-view>
- [76] Global Security, “AGM-176 ‘Griffin’.” Accessed Apr. 4, 2025. Available: <https://www.globalsecurity.org/military/systems/munitions/agm-176.htm>
- [77] D. of Defense, “Explosive, plastic-bonded, cast, PBXN-110, MIL-DTL-82901 rev. a,” Department of Defense, Washington, DC, USA, Rep., 2002. Accessed Apr. 21, 2025. Available: <https://quicksearch.dla.mil/Transient/028630840BCE4908B74292771E2A91F3.pdf>
- [78] L3Harris, “VAMPIRE – product brochure,” Apr. 20, 2025. Available: [https://www.l3harris.com/sites/default/files/2023-05/L3Harris\\_Vampire\\_SellSheet\\_2023.pdf](https://www.l3harris.com/sites/default/files/2023-05/L3Harris_Vampire_SellSheet_2023.pdf)
- [79] BAE Systems, “APKWS laser-guidance kit – product brochure,” Apr. 20, 2025. Available: <https://www.baesystems.com/en-media/uploadFile/20230315034523/1434555339189.pdf>
- [80] Janes, “BAE systems demos APKWS ii in cuas role,” Oct. 12, 2021. Available: [https://customer.janes.com/display/BSP\\_7300-JMR](https://customer.janes.com/display/BSP_7300-JMR)
- [81] Arnold Defense, “LAND-LGR4 laser guided weapon system – product brochure,” Apr. 20, 2025. Available: <https://arnolddefense.com/wp-content/uploads/2022/02/LAND-LGR-2.pdf>

- [82] L3Harris, “WESCAM MX™-10 RSTA – product brochure,” Apr. 20, 2025. Available: <https://www.l3harris.com/sites/default/files/2022-12/ims-eo-WESCAM-MX-10-RSTA-0402AB-Sell.pdf>
- [83] Janes, “Arnold Defense discloses LGR-4 Fletcher development road map,” Sep. 27, 2021. Available: [https://customer.janes.com/display/BSP\\_6136-JMR](https://customer.janes.com/display/BSP_6136-JMR)
- [84] Janes, “APKWS set for penetrator warhead integration,” Apr. 20, 2016. Available: <https://customer.janes.com/display/jmr74323-jmr-2016>
- [85] Aircav, “Hydra 70 2.75 inch rockets.” Accessed Apr. 20, 2025. Available: <https://www.aircav.com/hydra70.html>
- [86] Janes, “Hydra-70 rocket system,” Jan. 31, 2025. Available: <https://customer.janes.com/display/JALW3854-JALW>
- [87] M. E. Pollack, R. T. Schimmel, and S. J. Lowell, “Composition B4, a non-exuding explosive filler for artillery shell,” Picatinny Arsenal, Dover, NJ, USA, Rep. AD0407079, 1963. Accessed: 2025-04-21. Available: <https://apps.dtic.mil/sti/pdfs/AD0407079.pdf>
- [88] Janes, “30×173 ammunition,” Mar. 10, 2025. Available: [https://customer.janes.com/display/JAH\\_A929-JAH\\_](https://customer.janes.com/display/JAH_A929-JAH_)
- [89] Electro Optic Systems, “EOS TITANIS counter drone defense system – US product brochure,” Apr. 20, 2025. Available: <https://www.eosdsusa.com/download/1028/>
- [90] Electro Optic Systems, “EOS TITANIS counter drone defense system – August 2023 product brochure,” EOS, Feb. 23, 2025. Available: [https://eos-us.com/wp-content/uploads/2023/11/EOS\\_PDS\\_CUAS\\_August-2023\\_DIGITAL.pdf](https://eos-us.com/wp-content/uploads/2023/11/EOS_PDS_CUAS_August-2023_DIGITAL.pdf)
- [91] Electro Optic Systems, “R800: Turret-level heavy-hitting lethality,” Feb. 23, 2025. Available: <https://eos-us.com/wp-content/uploads/2023/11/EOS-Defence-R800-flyer.pdf>
- [92] Electro Optic Systems, “R400 marine: Maritime firepower and protection – product brochure,” Feb. 23, 2025. Available: <https://eos-us.com/wp-content/uploads/2023/11/R400-maritime-BrochureAUS-2022-web.pdf>
- [93] J. Ng, “Taking out ‘the toys,’” May 9, 2022. Available: <https://www.asianmilitaryreview.com/2022/05/taking-out-the-toys/>
- [94] Northrop Grumman, “Mk44s STRETCH 30mm / 40mm Bushmaster® chain gun® - product brochure,” Feb. 23, 2025. Available: <https://cdn.northropgrumman.com/-/media/wp-content/uploads/Mk44S-30-40mm-Bushmaster-Chain-Gun.pdf?v=1.0.0>

- [95] Northrop Grumman, “30mm x 173 mm suite of ammunition product brochure,” Feb. 23, 2025. Available: <https://cdn.northropgrumman.com/-/media/Project/Northrop-Grumman/ngc/what-we-do/advanced-weapons/bushmaster/30x173mm-Full-Ammo-Suite-Product-Brochure.pdf>
- [96] Northrop Grumman, “30mm x 173 mm suite of ammunition product brochure,” Northrop Grumman, Feb. 23, 2025. Available: <https://cdn.northropgrumman.com/-/media/Project/Northrop-Grumman/ngc/what-we-do/advanced-weapons/bushmaster/30x173mm-Full-Ammo-Suite-Product-Brochure.pdf>
- [97] Electro Optic Systems, “R800: Turret-level heavy-hitting lethality,” EOS, Feb. 23, 2025. Available: <https://eos-us.com/wp-content/uploads/2023/11/EOS-Defence-R800-flyer.pdf>
- [98] Northrop Grumman, “Mk44s stretch 30mm / 40mm Bushmaster® Chain Gun® - product brochure,” Northrop Grumman, Feb. 23, 2025. Available: <https://cdn.northropgrumman.com/-/media/wp-content/uploads/Mk44S-30-40mm-Bushmaster-Chain-Gun.pdf>
- [99] RWM Schweiz AG, “ABM/KETF 30mmx173 ammunition/pmc308 product brochure,” Mar. 9, 2025. Available: <https://www.rheinmetall.com/Rheinmetall%20Group/brochure-download/Weapon-Ammunition/D127e0823-ABM-KETF-30x173-PMC308-RWMS.pdf>
- [100] J. Akhavan, *The Chemistry of Explosives*, 2nd ed. Cambridge, UK: Royal Society of Chemistry, 2004.
- [101] Janes, “30×173 ammunition,” Janes, Mar. 10, 2025. Available: [https://customer.janes.com/display/JAH\\_A929-JAH\\_](https://customer.janes.com/display/JAH_A929-JAH_)
- [102] Electro Optic Systems, “EOS TITANIS counter drone defense system – US product brochure,” EOS, Feb. 23, 2025. Available: <https://www.eosdsusa.com/download/1028/>
- [103] A. R. Washburn, “Notes on firing theory,” Naval Postgraduate School. Accessed May 22, 2025. Available: <https://faculty.nps.edu/awashburn/Files/Notes/FiringTheory.pdf>
- [104] J. Hemler, “American USV builders anticipate mass demand from U.S. Navy,” *Defense and Security Monitor*, Feb. 27, 2025. Available: <https://dsm.forecastinternational.com/2025/02/27/american-usv-builders-anticipate-mass-demand-from-u-s-navy/>

- [105] R. Smith. “3 companies building america’s unmanned Navy vessels.” Nov. 19, 2023. Available: <https://www.fool.com/investing/2023/11/19/3-companies-building-americas-unmanned-navy-vessel/>
- [106] J. Spector, “The Navy must lead the small and medium USV era,” *Proceedings*, vol. 151, no. 4, Apr. 2025. Available: <https://www.usni.org/magazines/proceedings/2025/april/navy-must-lead-small-and-medium-usv-era>
- [107] P. Sedivy and O. Nemeč, “Drone RCS statistical behaviour,” in *STO-MP-MSG-SET-183*. Pardubice, Czech Republic: NATO Science and Technology Organization, 2021. Available: <https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-MSG-SET-183/MP-MSG-SET-183-04.pdf>
- [108] Wikipedia, “Hesa Shahed 136,” *Wikipedia*, 2025. Accessed Mar. 2, 2025. Available: <https://commons.wikimedia.org/wiki/File:Shahed-136-350-250draw.svg>
- [109] R. C. Harney, *Sensor Signals and Functions*. Monterey, CA: Naval Postgraduate School, 2013, vol. 1.
- [110] C. Payne, *Principles of Naval Weapon Systems*, 2nd ed. Annapolis, MD, USA: Naval Institute Press, 2010.
- [111] F. E. Nathanson, *Radar Design Principles*, 2nd ed. Raleigh, NC, USA: SciTech Publishing, 1999.
- [112] Radar Tutorial, “RAWL-02 Naval radar.” Accessed May 22, 2025. Available: <https://www.radartutorial.eu/19.kartei/07.naval/karte038.en.html>
- [113] Radar Tutorial, “AN/SPX-6(V) naval radar.” Accessed May 22, 2025. Available: <https://www.radartutorial.eu/19.kartei/07.naval/karte066.en.html>
- [114] International Telecommunication Union, “Recommendation ITU-R P.838-3: Specific attenuation model for rain for use in prediction methods,” ITU Radiocommunication Sector, Rep. P.838-3, Mar. 2005. Available: [https://www.itu.int/dms\\_pubrec/itu-r/rec/p/R-REC-P.838-3-200503-I!!PDF-E.pdf](https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.838-3-200503-I!!PDF-E.pdf)
- [115] MathWorks, “Receiver operating characteristic (ROC) curves part i: Theoretical performance analysis.” Accessed May 22, 2025. Available: <https://www.mathworks.com/help/radar/ug/receiver-operating-characteristic-roc-curves-part-1-theoretical-performance-analysis.html>

---

---

## Initial Distribution List

---

1. Defense Technical Information Center  
Fort Belvoir, Virginia
2. Dudley Knox Library  
Naval Postgraduate School  
Monterey, California



## DUDLEY KNOX LIBRARY

NAVAL POSTGRADUATE SCHOOL

[WWW.NPS.EDU](http://WWW.NPS.EDU)

---

WHERE SCIENCE MEETS THE ART OF WARFARE