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SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

ADVANCED AIRBORNE DEFENSIVE LASER FOR INCORPORATION ON STRIKE FIGHTER AIRCRAFT

by

Stephen Cannon, Timothy Kaniss, Nathan Lautzenheiser, Cesar Rios, Greyson Siegel, Jeremy Smith, and Eric Wright

September 2017

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For power supply, we recommend the use of the Next Generation Jammer's ram air turbine (called the HiRAT) for airborne power generation. Lithium-ion batteries are recommended for power storage. The recommended technology for the tracking system is the F-35's Distributed Aperture System. Finally, the recommended laser technology is the Ytterbium fiber laser.

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ADVANCED AIRBORNE DEFENSIVE LASER FOR INCORPORATION ON STRIKE FIGHTER AIRCRAFT

Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

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AND

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ABSTRACT

This report is a technical and operational analysis of an airborne "hard-kill" laser-based anti-missile system for use on strike fighters. The analysis begins with a set of requirements and a concept of operations showing the function of the Advanced Airborne Defensive Laser (AADL). These concepts are developed into a generalized functional, physical, and allocated architecture for the system. Research was then done into current and near-future technologies to create alternative configurations. The combat performance of these alternatives was simulated using physics- and discrete-event-based modeling. This simulated performance and other factors were scored to develop recommendations for technologies to be incorporated into the design.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

AADL	Advanced Airborne Defensive Laser
AFIT	Air Force Institute of Technology
ATGI	Advanced Technologies Group, Inc.
BMS	battery managing system
CDE	Air Force Institute of Technology Center for Directed Energy
CIWS	close-in weapons system
CONOPS	concept of operations
COTS	commercial off-the-shelf
CPU	computer processing unit
DAS	Distributed Aperture System
DIRCM	Directional Infrared Countermeasures
DOD	Department of Defense
FdYAG	frequency-doubled neodymium-doped yttrium aluminum garnet laser
FEL	free-electron laser
HEL	high energy laser
HELEEOS	High Energy Laser End-to-End Operational Simulation
HiRAT	High Powered Ram Air Turbine
IR	infrared
LAIRCM	Large Aircraft Infrared Countermeasures
LaWS	Laser Weapons System
Li-ion	lithium-ion
MANPADS	man-portable air defense system
MOE	measure of effectiveness
MOP	measure of performance
MWS	Missile Warning System
Nd:YAG	neodymium-doped yttrium aluminum garnet laser
NGJ	Next Generation Jammer
PITBUL	Physics-based Imaging and Tracking of Ballistics, UAVs, and LEO satellites

RAT	ram air turbine
RATG	ram air turbine/generator
SAM	surface-to-air missile
SE	systems engineering
SHaRE	Scaling for High Energy Laser and Relay Engagements
THEL	Tactical High Energy Laser
ThNDR	Threat Nullification Defensive Resource
TRL	technology readiness level

EXECUTIVE SUMMARY

Short-range missiles pose a significant threat to U.S. strike fighters. These missiles are usually small and highly mobile. These types of missiles can be carried on light vehicles and by individual people. Although these missiles do not have a long range, the unpredictability of their launch sites increases their lethality (Bartak 2005, 6–7). Also contributing to their lethality are the methods of homing on their targets. Most are passive methods, such as infrared. Unlike active radar homing, these missiles provide no warning to the aircraft that it is being tracked until the missile has been launched. The varieties of homing methods for these missiles can also provide problems for aircraft countermeasure systems. Each type of homing method requires a different type of countermeasure. All current airborne countermeasure systems rely on "soft-kill" methods of protection involving confusion or distraction of the homing system. These systems work differently for different homing methods and must be constantly upgraded to protect against ever more complex targeting systems (Ball 2003, 335–358).

This report is a technical and operational feasibility analysis for a "hard-kill" Advanced Airborne Defensive Laser (AADL) system to destroy or physically disable incoming missiles. This system uses a high-energy laser either to destroy an incoming missile or to cause enough physical damage to prevent the missile from intercepting its target. The AADL will be an external pod mounted on a strike fighter and will be almost entirely autonomous. The system will detect missile launch, track targets, and eliminate them. It will use built-in systems for power generation, target tracking, and laser transmission.

The concept of operations (CONOPS) of the system begins with detecting missile launch. The system detects the missile and automatically begins tracking it and plotting a firing solution. Simultaneously, the mission computer of the AADL uses the host aircraft's communication systems to alert the pilot and friendly forces to the threat. Once a firing solution has been determined and the laser transmitter moved into position, the incoming missile is fired upon and neutralized. This action is taken without input from the pilot as any delay from human reaction time can cause disaster. After the threat is neutralized, the pilot and friendly forces are once again notified. If there are further incoming missiles, the highest priority threat is targeted and engaged. A set of requirements describing the actions necessitated by the CONOPS in further detail was also developed. Due to the nature of the early stage of development for this system, these requirements are notional and subject to change based on future analysis.

Based on these requirements, a functional architecture was created. This architecture breaks those requirements down into a hierarchy of functions and allows, in combination with the physical architecture, creation of an allocated architecture. This physical architecture is a generalized relationship of components based on research into existing systems analogous to the subsystems of the AADL. Following this, an allocated architecture was developed, showing that every function is accomplished by a component. These functions can then be traced back to requirements.

Research was then conducted into currently existing technology that could be used to develop design alternatives for the AADL. These alternatives consisted of technology for the power supply, laser transmission, and targeting subsystems. These specific subsystems were analyzed because these were the main subsystems whose functions could not be accomplished by technology commonly used by the U.S. military. These technologies were analyzed for cost, effect on flight performance, technology risk, and functional performance. Because of the immature nature of many of these technologies, the cost could not always be established with a firm dollar amount. Where that information was not available, information on construction materials and methods was used to provide a comparative cost between alternatives. Effect on flight performance was established by comparing the weights and speed limits of the alternatives. Technology risk was based on the Technology Risk Level standards established by the Department of Defense. Finally, the functional performance was assessed through the use of computer simulations. These simulations use a program made by Imagine That Inc. named ExtendSim to model the positions and velocities of the aircraft and incoming missiles. This information was then passed to a physics-based high-energy laser modelling program called HELEEOS to determine the amount of time needed to neutralize the missile. The total time to neutralize all incoming missiles was compared between the alternatives to calculate the functional performance metric.

Based on this analysis, it was determined that the best configuration based on technologies currently available uses the ram air turbine of the Next Generation Jammer (named HiRAT) for airborne power generation and lithium-ion batteries for power storage. For laser transmission, the optimal technology is the Ytterbium fiber laser. Finally, the Distributed Aperture System, used by the F-35, was determined to be the best alternative for the tracking system.

References

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Bartak, John. 2005. “Mitigating the MANPADS Threat: International Agency, U.S., and Russian Efforts." Master’s thesis, Naval Postgraduate School. http://calhoun.nps.edu/bitstream/handle/10945 /2321/05Mar_Bartak.pdf?sequence=1&isAllowed=y.

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I. INTRODUCTION

Modern conflicts have changed the threat profile facing military aircraft. Most engagements in the last 20 years have been against non-state actors rather than against countries. Military aircraft now face threats from highly mobile, short-range surface-to-air missiles more often than from aircraft or long-range stationary air defense systems. These are generally man- or light vehicle-portable missiles and can be launched from almost anywhere. In addition, these missile threats generally use passive guidance systems, such as infrared (IR). Unlike radar, these passive systems give no indication to the pilot that their aircraft has been targeted. These types of systems are widely available to many of the non-state actors faced by the militaries of the world today. Although countermeasures such as chaff, flares, and jammers are employed on aircraft, increasingly sophisticated seekers continue to limit their effectiveness (Bartak 2005, 6–7). A countermeasure that could execute a hard-kill on any type of missile could offer comprehensive protection from current and future threats. This hard-kill countermeasure is the Advanced Airborne Defensive Laser (AADL), also known as the Cyclops pod.

A. PROBLEM STATEMENT

The F/A-18 multi-mission strike fighter suffers from a vulnerability if it comes under attack from short-range missiles. A defensive system capable of detecting and disabling incoming missiles would increase the aircraft's probability of surviving. The primary function of this system is to physically disable the incoming missile by weakening the structure or destroying the seeker head so that pursuit is no longer possible. In addition, because infrared-based tracking systems use light to home in on their targets, a laser strike on these types of seeker heads can “blind” them without destroying them and functionally disable these threats.

B. OBJECTIVES

The goal of this report is to provide a baseline for future development of the Cyclops pod. This is done through the development of a system architecture as well as a feasibility analysis. This shows the system's concept of operations, shows its technical feasibility, and provides a framework for future development of this system.

C. SYSTEMS ENGINEERING PROCESS

The systems engineering (SE) process used for this report will be the Three-Phase approach shown in Figure 1. This process was developed by John M. Green for modeling a ship as a weapon system. The first phase was to establish the report's requirements as well as to evaluate the current capabilities of existing equipment in both the commercial and defense industry. The second phase focused on research and model development to determine the possible configurations of the system. Finally, the third phase of the report used modeling and simulation, as well as other analytical tools to qualitatively and quantitatively evaluate the AADL for incorporation with the F/A-18. The various phases and sub-phases of this process are discussed below.

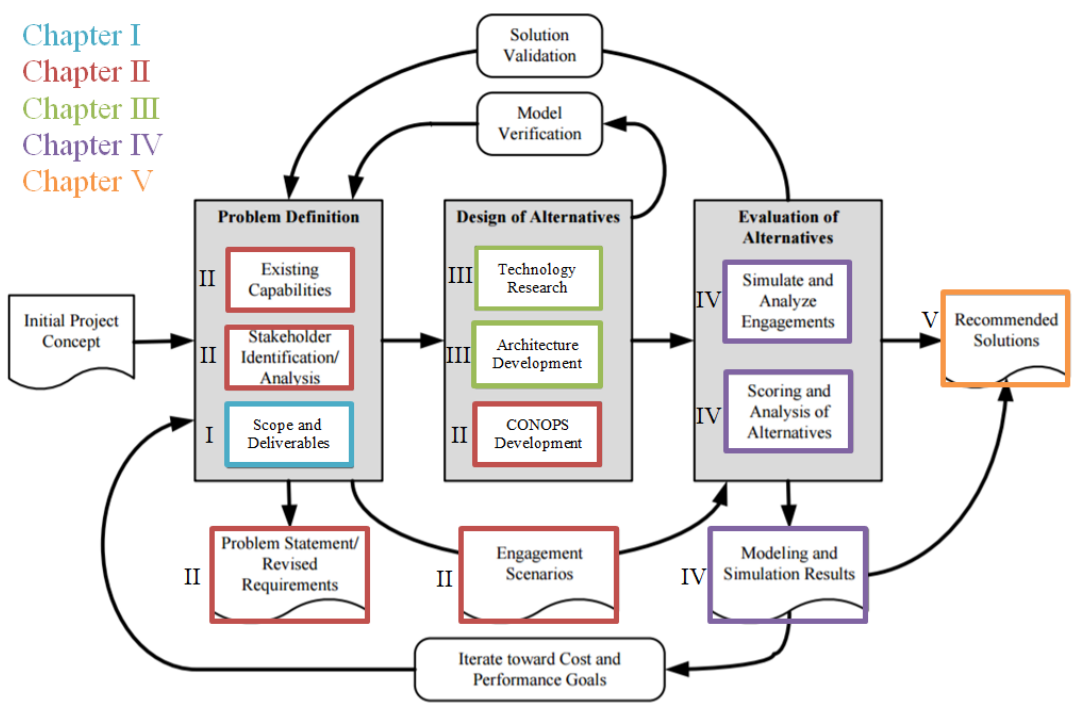

Figure 1. Three-Phase Systems Engineering Plan. Adapted from Bechtel (2011).

1. Problem Definition

The first phase of the SE process used in this report was the Problem Definition phase. This stage involved three main sub-phases: researching existing capabilities, identification of stakeholders, and defining the project constraints, limitations, and boundaries. Each of these sub-phases were executed simultaneously and are discussed below. The outputs of this phase of the SE process were a problem statement for the report, the report requirements, and scenarios used for the evaluation phase.

a. Existing Capabilities

The existing capabilities of the current technologies were researched and analyzed during this phase of the report. This sub-phase was used to identify if any similar reports have been completed or attempted to prevent duplicate research and effort. This sub-phase is covered in Chapter II.

b. Stakeholder Identification/Analysis

The stakeholders of the report were identified and analyzed to help develop the report throughout the entire SE process. It was important to identify stakeholders early in the SE process as their input ensures the created system will be appropriate for its intended utilization. Stakeholder analysis helps prioritize stakeholder input and ensures the proper constraints are placed on the report. Because stakeholder input was used throughout the SE process, early and accurate identification and analysis of the various stakeholders was critical in successful system creation. This sub-phase is covered in Chapter II.

c. Scope and Deliverables

This sub-phase of the report is devoted to laying out the end items of the report as well as documenting what will not be covered in this report. This sub-phase is related to the Objectives section, which describes the intent of the report. It is also related to the Limitations and Constraints section, which describes limitations associated with the CONOPS and analysis. This sub-phase is covered in Chapter I.

2. Design of Alternatives

The second phase of the SE process is the Design of Alternatives phase. This phase consists of three sub-phases: Research, Model Development, and Operations Development, which were conducted concurrently and described further below.

a. Technology Research

The purpose of the research from the Problem Definition phase was to understand current technology capabilities and limitations. Unlike the Existing Technologies sub-phase, this is an examination of technologies at a more detailed level. Where that portion focused more on entire systems, this sub-phase focuses more on the technology at a component level. This sub-phase was developed in support of several sections and so does not have a section specifically devoted to it. This sub-phase is covered in Chapter III.

b. Architecture Development

This sub-phase is devoted to the development of the physical and functional architecture. The intent of this section is to clearly and thoroughly lay out what the system will be doing and what components will allow it to do so which will then be used in developing the Evaluation of Alternatives. This sub-phase is covered in Chapter III.

c. Concept of Operations Development

The operations development of the report was an important process that defined how the final product will be used. These scenarios were important for the model development and system validation and critical during the analysis of alternatives. This sub-phase is covered in Chapter II.

3. Evaluation of Alternatives

The final phase of this SE process is to evaluate the possible solutions and provide recommendations. The sub-phases within this SE phase are to simulate and analyze engagements, as well as to score and compare the alternatives. The primary output of this phase was the final recommended solution.

a. Simulate and Analyze Engagement

The previously developed models were used to simulate and analyze engagements of the various solutions within the chosen scenarios. The results of these simulations were analyzed to understand the strengths, weaknesses, and tradeoffs of each solution. The results were evaluated against the original constraints, cost, and performance goals of the report, developed initially in the first SE phase. This sub-phase is covered in Chapter IV.

b. Scoring and Analysis of Alternatives

Each alternate solution was appropriately scored and evaluated to determine the optimal solution. An appropriate set of system metrics was selected and used throughout this phase to ensure the best solution is properly identified. Metrics and analysis methods were identified prior to this phase to eliminate possible evaluation bias. This sub-phase is covered in Chapter IV.

D. SCOPE AND DELIVERABLES

This report contains a system architecture and technical/operational feasibility analysis assessing design considerations for creating the most effective system to reduce F/A-18 susceptibility to short-range missiles. Areas considered are:

- concept of operations
- performance requirements for incoming missile neutralization
- AADL system architecture
- aircraft integration requirements
- potential aircraft modification requirements
- subcomponent technical requirements
- analysis of suitability of existing and near-future technologies
- future research recommendations
- additional design considerations
- solution recommendation

Because an integrated, hard-kill missile defense system on an aircraft is largely unprecedented, this report focuses primarily on the design principles for effectiveness, with only minor consideration given to logistics, support, test & evaluation, and life cycle maintenance.

E. REPORT ROADMAP

Chapter II defines and explains the system’s high-level and functional requirements. In addition, detailed CONOPS are laid out for several different scenarios involving an aircraft coming under fire.

Chapter III covers the development of the system architecture. This section outlines the interactions of the system, both internal and external. This chapter also ties the requirements outlined in Chapter II to the functional architecture laid out in this chapter.

Chapter IV builds on the technical analysis in the previous chapter and covers the analysis of alternatives. Chapter IV also includes a description of the scoring standards used, a list of the configurations to be tested, their scoring, and an assessment of technology risks.

Chapter V contains a summary of the report as well as the report’s findings and recommendations with regards to technical/operational feasibility.

II. PROBLEM DEFINITION

The requirements and CONOPS act as both the foundation and the framework for any project. They are driven by an analysis of the stakeholders in the project, their needs, and each other. The CONOPS needs to form a functional plan to meet stakeholder needs, and the requirements needed to ensure a system is delivered that is capable of executing that CONOPS. These will provide the foundation from which the architecture builds and a framework for the development of the simulation models used for scoring of alternatives.

The uniqueness of the concept behind this system means the CONOPS and requirements are unlike most systems. The CONOPS for this system is based largely on existing anti-missile systems such as Phalanx close-in weapons system (CIWS), Tactical High Energy Laser (THEL), and Iron Dome. These systems use 20 mm rounds, chemical lasers, or missiles to destroy incoming rockets and missiles. While all of these provide the same type of protection as the Cyclops, none of them include carriage on a strike fighter as part of their CONOPS. Existing hard-kill missile systems are large, heavy, and (in some cases) fairly delicate.

A. EXISTING CAPABILITIES

There is a limited amount of previous research on the utilization of a high energy laser on an aircraft as a countermeasure. Therefore, this section focuses on the three main hardware subsystems of the Advanced Airborne Defensive Laser (AADL). These are the laser transmission system, the tracking system, and the power supply system. The significant performance requirements and state-of-the-art technology required from these subsystems identified these as the best candidates for investigation in this report.

1. Laser Transmission System

The use of high energy lasers (HEL) for missile defense is not a new concept for the Department of Defense (DOD). As far back as 1984, plans were being developed with the Strategic Defense Initiative to mount powerful lasers on satellites to shoot down incoming ballistic missiles. Although these plans never came to fruition, later development in the 1990s would yield better results. In 1996, the U.S. military developed the THEL. This ground-based system and its mobile variant are used to destroy incoming surface to surface indirect fire weapons such as rockets, mortars, and artillery (Northrop Grumman 2017e). Although this system proved its ability to neutralize incoming threats, its size and logistical footprint made it a poor fit for the modern battlefield. In 2002, the Air Force made its first flight with the YAL-1, a Boeing 747 modified with a large chemical laser designed to neutralize airborne ballistic missiles. However, the relatively close ranges needed for large missiles and the high cost led to the cancellation of the program (Nogee 2014).

In 1999, Northrop Grumman developed the Directional Infrared Countermeasure System (DIRCM). This system provides a firing solution for a weak, onboard laser to confuse the incoming missile's seeker sensor and programming. The DIRCM system was not designed for fast-moving aircraft, and numerous challenges arise when trying to adapt a comparable system for use with a strike fighter. This system is also the basis for the Northrop Grumman Guardian system, which is designed to provide an anti-missile capability to commercial aircraft (Pike 2011b).

2. Target Tracking System

Bomb and missile technology has greatly improved from inception to today. With the increase in these technologies' sophistication, there has also been an increase in missile tracking systems and, subsequently, missile defense tracking systems. Since the beginning of missile threats, there have been missile defense programs in almost all shapes and sizes on land, water, and air. This report focuses on air defense, particularly in the form of an externally mounted HEL system that will be carried by a strike fighter and defend against surface-to-air missile systems by destroying incoming missiles before they can threaten the aircraft. Current laser missile defense systems, such as DIRCM and Large Aircraft Infrared Counter Measures (LAIRCM), are mounted on slower moving and larger aircraft. These work by jamming IR sensors on the head of the missile. These systems have their own missile tracking and warning capabilities that integrate with the laser system. The jammer is either an open-loop system, which confuses missiles with IR energy or a closed-loop system, which will send a specific jam code to cause the missile to break lock. The most common of these systems is Northrop Grumman's AN/AAQ-24(V) NEMESIS (Pike 2011a). This type of system leaves the pilot out of the kill chain and notifies him of what took place. This automation is critical when fractions of a second could be the difference between life and death. Unfortunately, there have been problems trying to integrate these same missile warning systems in tactical fast movers; too many false alarms arise. The tracking system can falsely identify IR energy as a target, and this effect is multiplied when integrating with tactical aircraft. Subsequently, tactical aircraft have continued to rely on maneuvers and older missile defense systems such as flares because these are the only reliable means of neutralizing missile threats. The missile tracking for F/A-18s is even more difficult as radar systems will warn pilots of incoming threats, but tracking is left up to the pilots and co-pilots.

3. Power Supply System

HELs are currently being investigated as a significant strategic capability with potential end application use on naval air platforms. However, HEL systems require high electrical power inputs, increasing the need for research in this area. High electrical requirements make external power generation a must on certain air vehicles such as the F/A-18. The use of ram air turbines (RATs) and lithium-ion batteries within a pod is a viable option that has been developed by the Navy with Next Generation Jammer (Warwick 2013).

The RAT designed for the Next Generation Jammer could be used for other applications. The high-power RAT developed by Advance Technologies Group Inc. (ATGI) has the potential to generate up to 700 kW. There has also been research on creating RATs that vary in size depending on power need. However, using a RAT is air vehicle speed dependent, and the use of a secondary power source may be required as well (Warwick 2013).

A second source of high power can be provided by lithium-ion (Li-ion) batteries. The Navy is currently developing more advanced Li-ion batteries through NAVAIR

Science and Technology Program projects with the goal of implementation of Li-ion batteries on aircraft. The F-35 currently has a high voltage lithium battery for backup power. Lithium batteries have high energy density increasing the output power with reduced size (McHale 2014).

B. STAKEHOLDER ANALYSIS

Table 1 lists the stakeholders whose interests align with the goals of the AADL project. The requirements and CONOPS are largely built off of inputs from representatives of the F/A-18 combat survivability and naval aviation platform integration communities. Although this project is intended to be usable on multiple aircraft, certain requirements are based on the F/A-18. This aircraft was chosen as the best driver for certain requirements because it is responsible for executing missions like all strike fighters but also must be capable of withstanding takeoff and landing on a carrier.

Table 1. Stakeholders

Stakeholder	Description
PMA-265	**The AADL system will reduce a vulnerability faced by the F/A-18, and its requirements are partially based on specifics from this aircraft.**
U.S. Naval Aviation	**Although focused more on the F/A-18, this project has applications for the F-35 and other future aircraft as well.**
Department of Defense	**As with the F-35, this project could also be extended to Air Force or even Army aviation aircraft.**

C. HIGH-LEVEL REQUIREMENTS

The system-level requirements are composed of four different categories:

First, the functional attributes of the store to aircraft system must be sufficient to allow for proper communication and electrical interfaces between the two systems. This requirement will define the type of information communicated to the aircraft from the pod as well as ensure that the correct military standards are followed.

Second, there are requirements for the laser subsystem performance. These requirements will ensure that performance of the laser is sufficient to defeat incoming missiles before they can damage the host aircraft.

Third, the power subsystem requirements for the Cyclops must be sufficient for the operational usage of the system without impacting the power requirements of the aircraft. These power requirements must be completed meeting the necessary standards to ensure safety and compatibility.

Finally, the tracking and detection subsystem on the Cyclops must be capable of tracking and targeting the appropriate amount of missiles reliably. It must also be capable of differentiating between friendlies and hostiles as well as appropriately prioritizing the targets to ensure maximum energy efficiency.

The above paragraphs give insight into the derivation of the system-level Cyclops system level requirements provided in Table 2 and discussed in the next section.

Table 2. High-Level Requirements

Number	High-Level Requirements
0	**System shall protect the aircraft from incoming missile threats**
1	**System shall communicate with friendly forces**
2	**System shall defeat incoming missile before damaging the aircraft**
3	**System shall be capable of powering all systems simultaneously**
4	**System shall track and target incoming missiles**

D. FUNCTIONAL REQUIREMENTS

The above system-level requirements of the Cyclops provide the core structure from which functional requirements can be developed in order to support various CONOPS. The following functional requirements have been derived from these system-level requirements and traceability is shown in numbering.

The power subsystem of the Cyclops must be able to provide all power needs to the other subsystems. Power requirements are based on laser and tracking and detection needs. The laser system has high power requirements for a few seconds (to produce pulsing power) to destroy a missile threat. Because the threat cannot always be known in advance, the power subsystem should be able to have enough power stored to eliminate the threat in the appropriate amount of time.

While the electric subsystem is tasked with providing power to destroy the threat, the Cyclops tracking subsystem must be able to detect, track, and target threats while not interfering with the aircrew normal mission operations. In order for this to be possible, the system will need to defend against the myriad of man-portable air defense systems (MANPADS) and other anti-aircraft missile systems. Table 3 shows the ranges in characteristics of the MANPAD threats faced by military aircraft today (Military Factory 2015; Bartak 2005, 3).

Table 3. MANPADS Threat Characteristics

Missile Series	Top Speed	Maximum Range
9K34 Strela-3	**415 m/s (1367 ft/s)**	**4.1 km (2.5 mi)**
9K38 Igla	**570 m/s (1870 ft/s)**	**5.2 km (3.2 mi)**
FIM-92 Stinger	**800 m/s (2625 ft/s)**	**4.8 km (3 mi)**

Because multiple threats can be fired at once, the tracking and detection subsystem must to be able to queue up multiple threats and prioritize which is the greatest. This range of threats drives the functional requirements of the tracking system.

Finally, the laser subsystem must be considered. While the implementation details are left to a contractor, research suggests a threshold of 10 kJ delivered to the incoming missile is needed to ensure destruction. This value will, therefore, be used for proof of concept calculations, modeling, and power estimates (Nielsen 2009).

Time for neutralization of an incoming threat is designed to defeat threats comparable to those listed in Table 3. The maximum time required for the Cyclops pod to destroy a missile is three seconds. This requirement is based off of the capabilities of the currently used DIRCM system (Northrop Grumman 2017d). This requirement also drives the engagement range requirement. It is possible that multiple missiles will be fired at an aircraft during the course of an engagement. To account for the need to destroy at least three missiles in flight before they intercept the aircraft, the engagement range requirement is 4.5 miles. This requirement is derived from the distance that the highest speed missile in Table 3 can cover in three seconds (the neutralization time requirement). This distance is approximately 1.5 miles. To account for the possibility of multiple missiles in flight, an engagement of three incoming threats is assumed for this requirement. In order to defeat three missiles in flight, Cyclops will need to be able to engage them at 4.5 miles.

Short-range missiles are most likely to engage an aircraft from below. However, the exact angle is arbitrary and based upon the speeds of the missile and aircraft, as well as their starting positions relative to each other. To account for this unknown, the laser must be capable of engaging a missile within at least a 90° arc below the aircraft. This is based off of the capabilities of the DIRCM system (Willers 2012). In additional, coverage arcs above and on each side of the aircraft would provide increased protection. The laser must also have safeguards to prevent the beam from causing damage to the aircraft.

Requirements for the Cyclops system were built in concert with the functional hierarchy shown in Figure 2. A more detailed set of requirements are listed in Appendix A. All requirements are based on unclassified data. All requirements are notional and subject to change based on future analysis.

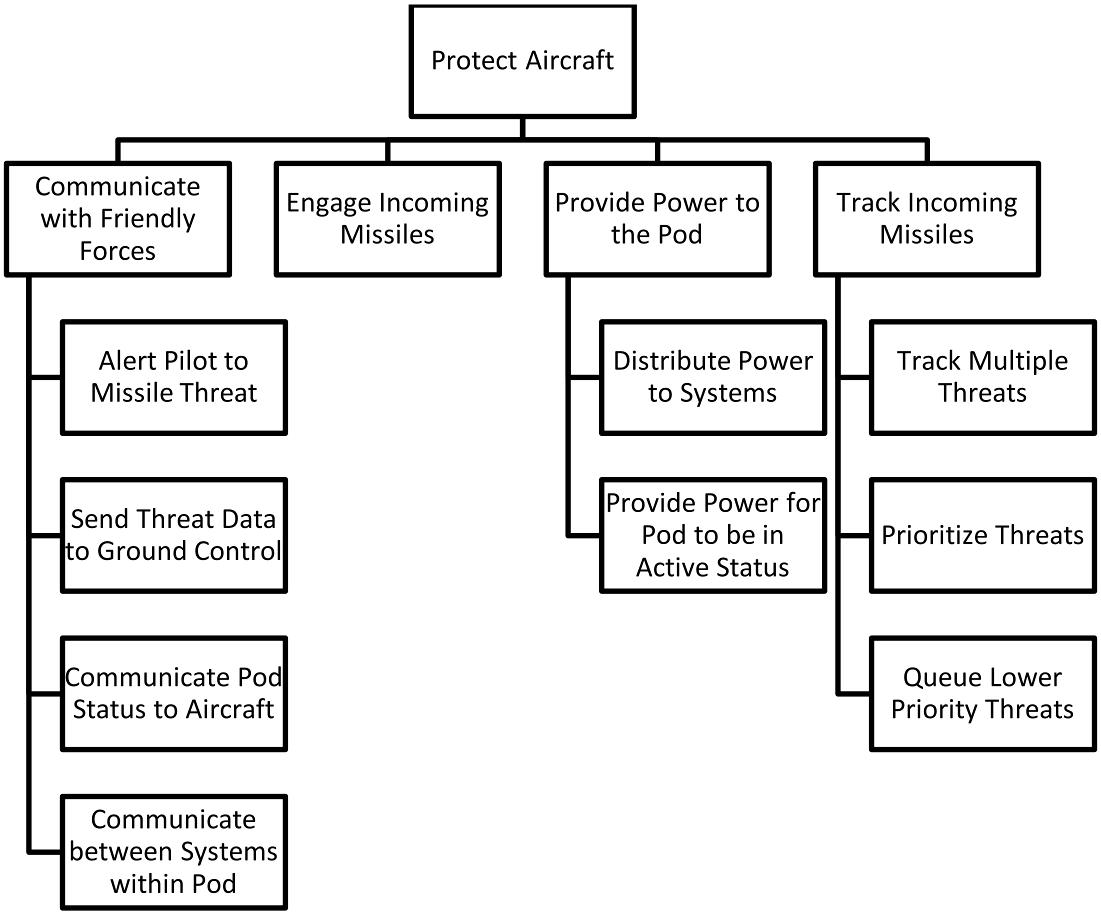

Figure 2. Functional Hierarchy Chart

E. LIMITATIONS AND CONSTRAINTS

All analyses in this report assume a clear day with no precipitation. Support requirements are also assumed to be essentially equal across alternatives. When modeling system performance against threats, information regarding designs and capabilities specific to individual models of missiles is not used. Instead, generalized values are used for parameters such as missile range, speed, and construction.

It is assumed that this system will be usable on different types of aircraft. However, certain requirements are based on the F/A-18. This is due to its high acceleration on takeoff and landing as well as its short takeoff requirements putting significant constraints on system weight and durability. It is further assumed that certain subsystems (such as the computer responsible for communicating with the aircraft) are not required to perform beyond the capabilities of currently existing technology employed by the military. As such, this report does not focus on them.

The main constraint faced with this report is performance information. Much of the technology in the three main subsystems is immature, so the best data available is from controlled tests or design specifications. Due to the lack of data, performance under battle conditions is simulated. Analysis of the logistical requirements for this system will be minimal. Unfortunately, trying to make estimates of support requirements by analogy would be impossible because no system like this has ever been fielded. When analyzing alternatives, support requirements are assumed to be equal.

Another constraint faced is sensitivity of the information associated with combat aircraft survivability. Including classified information in this report would significantly complicate its writing and limit the audience authorized to read it. Because it is difficult to specifically assess and compare aircraft survivability against different threats without delving into classified information, system effects on survivability will not be quantified. Instead, the scoring of alternatives focuses on performance in combat simulations.

F. CONCEPT OF OPERATIONS DEVELOPMENT

Today's aircraft require a countermeasure system that can accurately identify, prioritize, and direct strikes on incoming missiles while simultaneously communicating with host aircraft the position, status, direction and velocity of these threats. For example, during Desert Storm, six USAF A-10s are believed to have been brought down by infrared (IR) surface-to-air missiles (SAMs). These threats are still in existence today, such as MANPADs (Ball 2003).

1. Scenario 1 – Single Missile Fired at Host Aircraft

This single threat scenario is likely to be one of the most common the Cyclops pod encounters. In this circumstance, the aircraft has flown into enemy airspace and comes under fire from a single short-range IR homing SAM. The Cyclops shall be capable of protecting the aircraft from both hit-to-kill warheads and high explosive warheads with proximity fuses. The pod, mounted on the aircraft, detects missile launch.

The Cyclops will then begin tracking the flight path of the missile and developing a firing solution to efficiently neutralize the threat. Simultaneously, the pod alerts the pilot to the situation both audibly and visually. It also alerts friendly forces in the area, such as aircraft and Naval vessels to the threat. At this point, the pilot maintains a course with limited maneuverability to allow the pod the highest probability of intercepting the missile. The Cyclops then uses its beacon illuminating laser to reflect energy from the missile that provides data about the rapidly changing nature of the atmosphere along the sightline of the target. The battle management system uses this data to track and aim the laser at the threat. Once the laser is in position to fire, it will automatically do so without requiring input from the pilot. Depending on the properties of the incoming missile, the laser will either alter the missile's aerodynamics enough to prevent it reaching its target or outright destroy the missile. Once the laser has begun firing on the target, it will be neutralized before damaging the aircraft. The system will alert the pilot when the threat has been neutralized. In the event that the missile cannot be neutralized with a high probability, the Cyclops will alert the pilot to begin evasive maneuvers while it continues to attempt neutralization of the threat. This engagement scenario is shown in Figure 3.

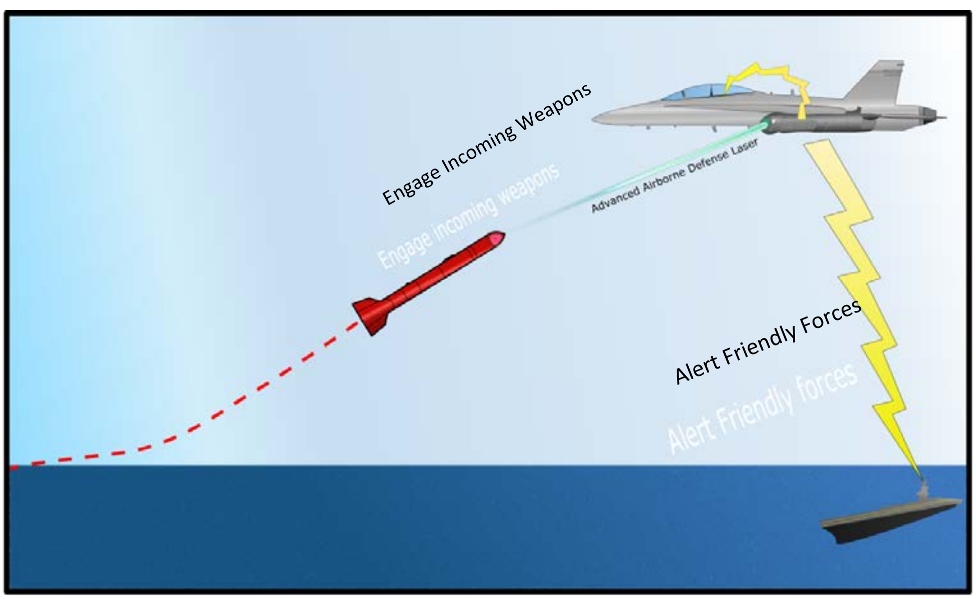

Figure 3. Single Missile Fired at Host Aircraft

2. Scenario 2 – Multiple Missiles Fired at Host Aircraft

The Cyclops will decrease the susceptibility of the strike aircraft in the event of an attack from the operationally realistic threat of multiple short-range IR homing SAMs. Cyclops will detect the launch of multiple threats. The tracking system will then analyze the flight path of the incoming missiles to determine which missiles are on track to impact the aircraft. Those that are not a threat are disregarded. The system can track multiple incoming missiles at one time. If more missiles are detected to be homing on the aircraft than the system can defeat with high probability, the pod will alert the pilot that it will not be able to neutralize the threat and advise the pilot to take evasive action. If eight or fewer missiles are determined to be threats, the pilot will maintain, to the extent possible, a steady, stable course to increase the laser's probability of kill by reducing jitter in the beam. Incoming missiles are then prioritized based on their proximity to the aircraft, with the closest target considered the highest threat. After that threat is neutralized, the next closest missile is targeted. The pilot is alerted to these actions but has no input in this process. This procedure is carried out until no further threats are airborne or, significantly, a threat is determined to have a low likelihood of neutralization before impact. The pod will then advise the pilot to take evasive maneuvers while it works to neutralize the threat. As with the previous scenario, once the laser has begun firing, the target will be neutralized within three seconds. This engagement scenario is shown in Figure 4.

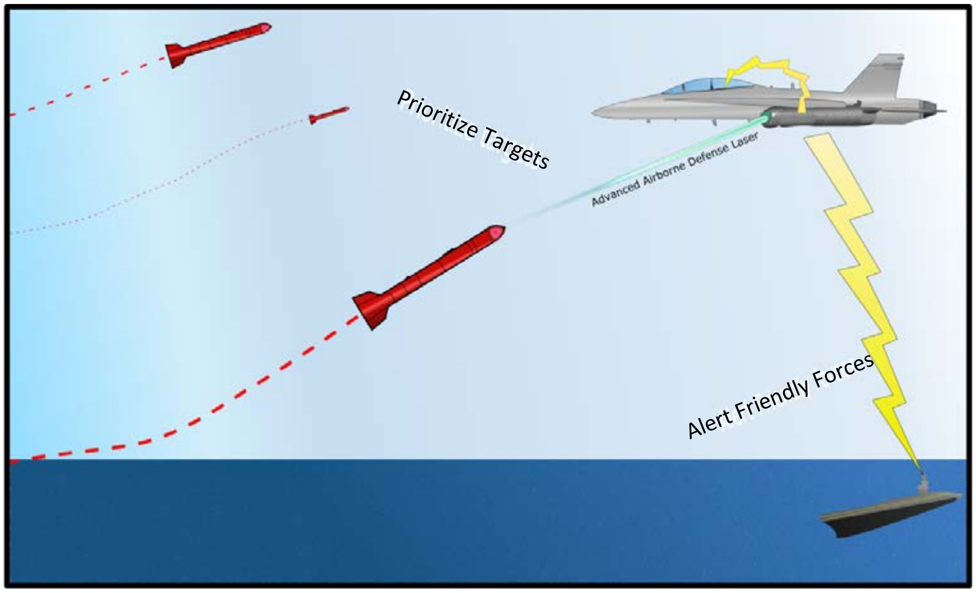

Figure 4. Multiple Missiles Fired at Host Aircraft

3. Scenario 3 – Single Missile Fired at Allied Aircraft

The Cyclops will also be capable of providing area defense against short-range missile threats. When flying on a mission with other aircraft, the Cyclops will fire on any incoming missiles without trying to determine whether or not it has maintained target lock on a friendly aircraft. When missile launch is detected by the pod, it will proceed to simultaneously track the missile and alert all friendly forces in the area. If a friendly aircraft without a Cyclops pod is targeted, it will begin evasive maneuvers to try to break missile lock. The Cyclops will then develop an optimal firing solution and fire on the missile. As with the previous scenarios, this process requires no input from the pilot and threat neutralization take no longer than three seconds. The pod will not coordinate with other Cyclops pods on wingmen or threat missile defense assets. It will provide information on incoming threat and alert friendly forces to the situation, but it is not intended to be used for broadcasting detailed information. This engagement scenario is shown in Figure 5.

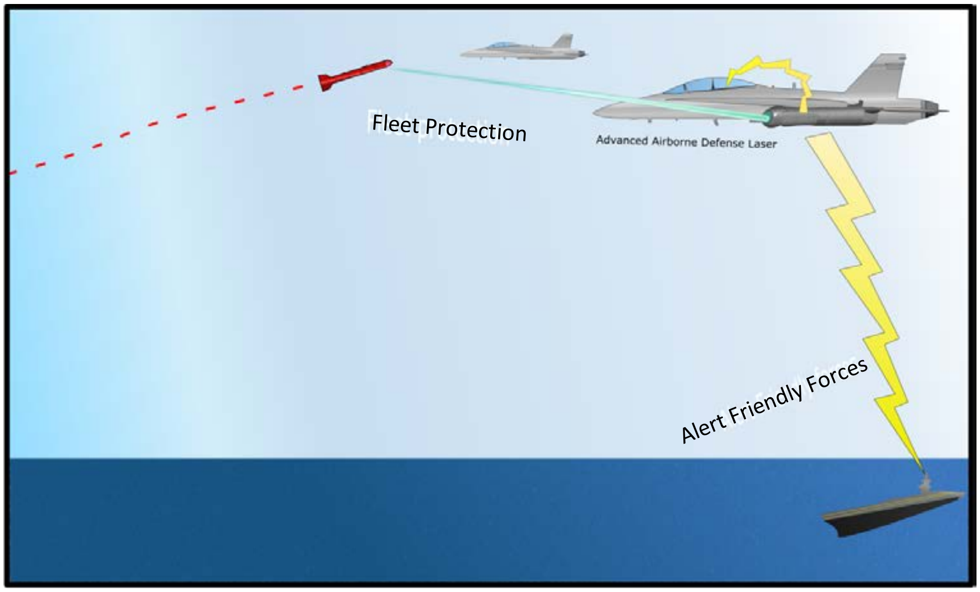

Figure 5. Single Missile Fired at Allied Aircraft

4. Scenario 4 – Multiple Missiles, Allied Target(s)

The most complex scenario for the Cyclops pod will occur when one aircraft loaded with the pod performs a mission with multiple aircraft and more than one of these aircraft come under attack from short-range missiles. The pod detects the launch of several missiles and alerts friendly forces in the area. It then proceeds to track the missiles in flight to determine which are homing in on the host aircraft. If more than eight are incoming on that aircraft, it will advise the pilot to take evasive maneuvers. If eight or fewer missiles are targeting the host aircraft, it will maintain limited maneuverability flight while other friendly aircraft in the area begin evasive maneuvers. Threat prioritization will then begin targeting the nearest missiles first. In most cases, this will result in missiles targeting the host aircraft taking priority over those targeted at others. The Cyclops pod will continue eliminating, reprioritizing, and firing on targets until no further airborne threats exist. As with the previous scenarios, this process will not require any input from the pilot, and the laser will take no longer than three seconds to neutralize each missile. This engagement scenario is shown in Figure 6.

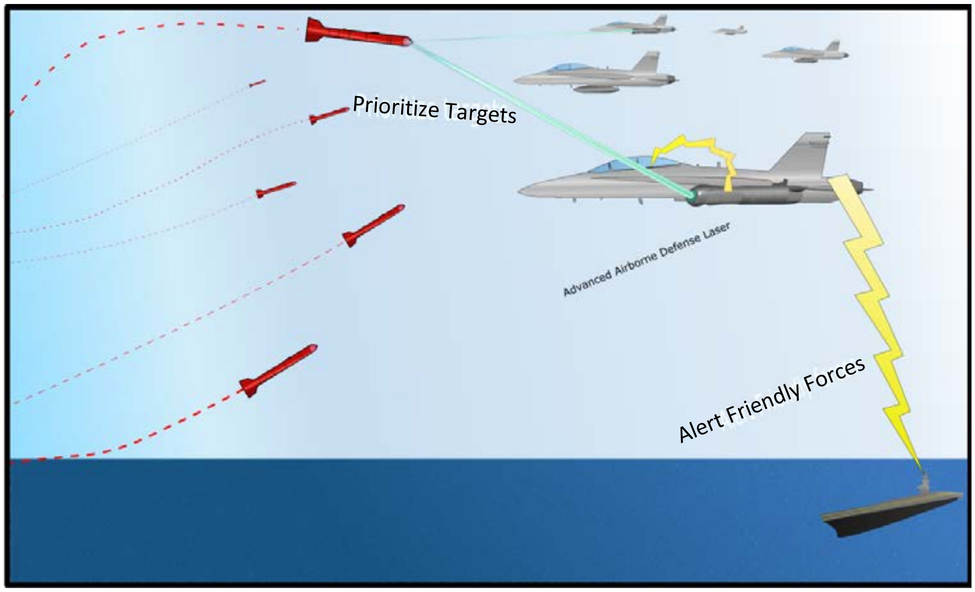

Figure 6. Multiple Missiles, Allied Target(s)

This area of denial role against short-range missiles will pair particularly well with the EA-18G Growler. A comprehensive anti-missile defense net can be created by combining the longer range jamming and anti-radar capabilities of the Growler with the short-range missile protection provided by the Cyclops pod. Using these two systems in concert as an escort for a strike package can provide the level of protection necessary for executing deep strikes into fortified enemy territory. This engagement scenario is shown in Figure 7.

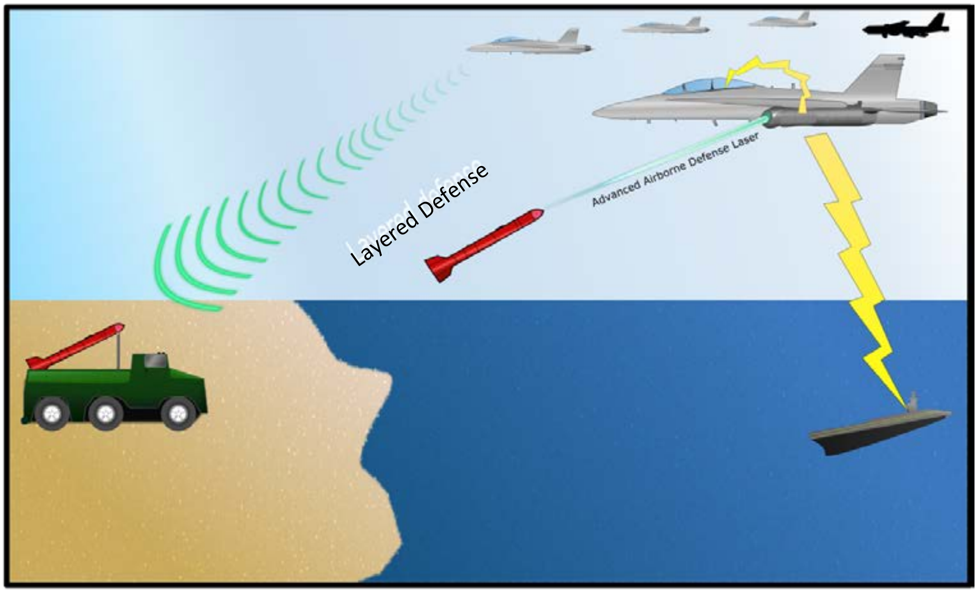

Figure 7. Multi-Layer Missile Defense

G. CHAPTER SUMMARY

This chapter provided both a background for and an overview of how the AADL will solve the vulnerability laid out in the problem statement. It focused on how the system will interact with the environment. These include interactions with incoming threats, the host aircraft, and friendly forces.

The following chapter will build off of this overview to translate the requirements and CONOPS into a detailed system architecture. The chapter will lay out the functions carried out in the CONOPS in detail. It will also describe the physical components of the pod as well as their interactions and the functions they support.

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III. ARCHITECTURE DEVELOPMENT

While the functional requirements and architecture can be established at a detailed level, it is significantly more difficult to reach a similar level of detail for the physical architecture. The unprecedented nature of this project and its requirements mean that there are very few existing systems on which to base the architectures. Because of this, several aspects of the physical characteristics will be kept to a higher, less detailed level. In addition, physical architectures for only the laser transmission, tracking, and power supply subsystems have been created. Although there are other subsystems such as the onboard computer or cooling system, the requirements of these components are already satisfied by technology currently in use and thus, are not closely examined in this report.

Initially, the functional architecture was developed based on the functional requirements discussed in Chapter II. From this functional architecture, research was conducted into prospective technologies that could be used in the design of the Cyclops pod. The physical architecture was developed from this research. Due to the relatively unprecedented nature of this system, the physical architecture is built by examining the requirements and determining what physical systems will be necessary to satisfy them. This process is in contrast to other projects, where existing systems can create an architecture "baseline" from which the physical and allocated architectures can be built. The physical architecture characteristics laid out in this chapter are based on research into cutting-edge and near-future technology specific to the individual subsystems.

A. FUNCTIONAL ARCHITECTURE

There are four main functions that the pod must perform, which were first identified through the high-level requirements discussed in Chapter II. These four functions are:

1. Communicate with Friendly Forces
2. Provide Power to the Pod
3. Track Incoming Threats
4. Engage Incoming Missiles

All of these functions performed together will meet the primary requirement to protect the aircraft from incoming threats. Figure 8 shows the "IDEF0" Functional Architecture for the Cyclops pod, which demonstrates the flow of inputs and outputs through the system. Each of these functions is further decomposed into functions. These functions and their decomposition are discussed in detail below.

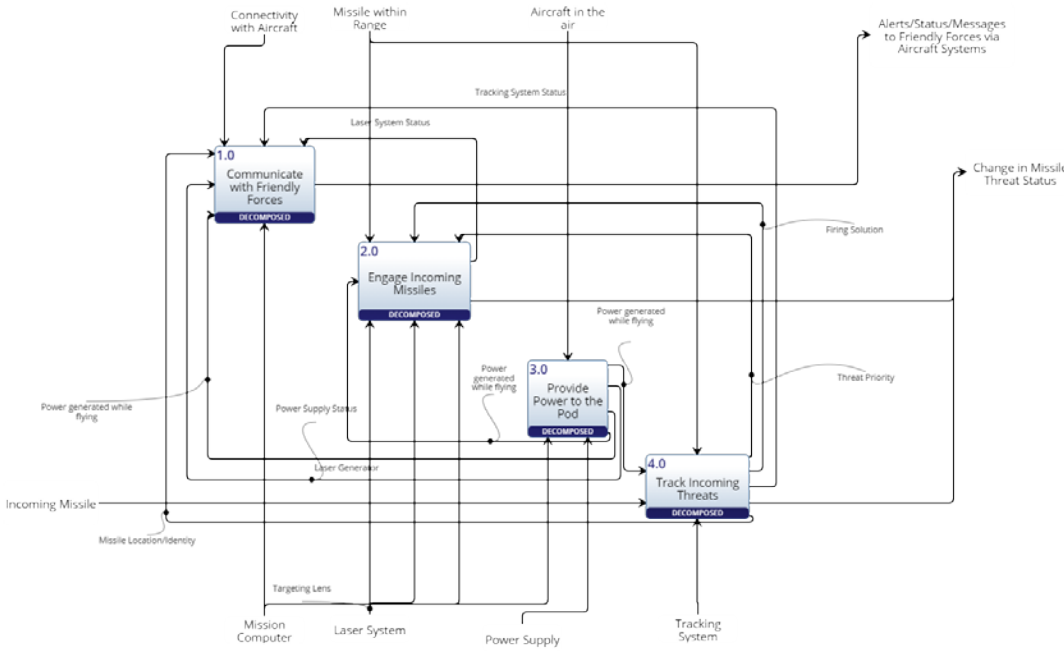

Figure 8. Cyclops IDEF0

1.0 Communicate with Friendly Forces

This function describes the communication between the Cyclops pod and the host aircraft, as well as the information that will be communicated to other friendly forces that are not carrying the pod. The inputs to this system are the power status, the power generated, and missile location/identity. These inputs provide the necessary power and information required by the host aircraft and, as appropriate, other friendly forces. The outputs from this function are the alerts and messages that are sent to the host aircraft and the friendly forces. All of this is achieved using the onboard mission computer within the pod system. It is controlled by the system statuses passed to it by the subsystems and the connectivity to the aircraft.

A decomposition of this function depicted graphically in the figures below, shows its functional architecture. These functions can be further decomposed until they fulfill the lowest level functional requirements. These decomposed functions will use controls, mechanisms, and inputs similar to Communicate with Friendly Forces.

Figure 9 shows the first decomposition of Communicate with Friendly Forces. This functional architecture consists of two functions, which identify all communication that will be performed between the carrying aircraft and, thus, friendly aircraft, and the pod.

1.1 Communicate to the Aircraft Information Concerning Incoming Threats

First, the pod must be capable of communicating information about the incoming threats which clearly relates to the primary mission to protect the host aircraft as the threats must be identified and tracked prior to engagement. Furthermore, when this information has been relayed to the host aircraft, the aircraft's communication system will be responsible for sending information to other friendly forces. This information will not flow directly from the pod to friendly forces.

1.2 Communicate Status of Cyclops Systems

Second, the pod must be able to communicate the status of its various systems. This function will ensure that the status of the pod is properly communicated so the pilot(s) may act accordingly if there are any potential performance issues with the pod.

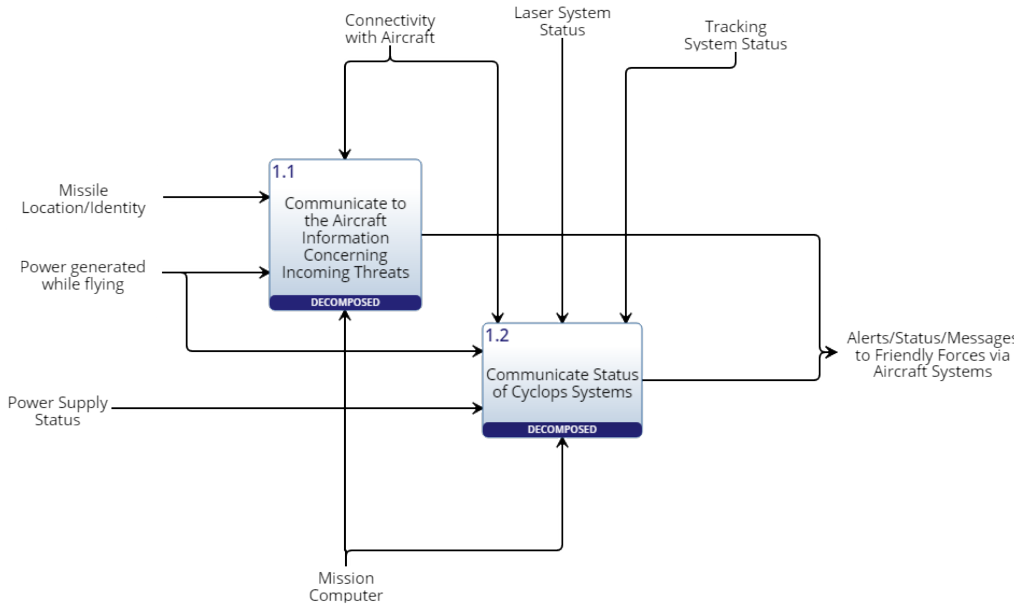

Figure 9. Communicate with Friendly Forces Decomposition

Communicate to the Aircraft Information Concerning Incoming Threats can be further decomposed. The first level of decomposition possesses one function. The second level of decomposition is shown in Figure 10.

1.1.1 Alert Pilot to Missile Threats

This function specifically involves alerting the host aircraft pilot to the incoming missile threats. A decomposition of this function reveals the numerous actions that this function entails. The flow between these functions can be seen in Figure 10. Each function will take an input of the power from the power system and the missile threat information. Each function will then output the appropriate message/alert about the threat.

1.1.1.1 Send Threat Data to Ground Control

First, the pod must be capable of sending the threat data to ground control via the host aircraft. This is a critical function for superior operational performance of the pod. This type of information will allow ground control to make real-time operational decisions.

1.1.1.2 Alert Pilot when Missile Threats are Defeated

Second, it is important for the host pilot to know when the missile threats have been defeated. If the threat is not defeated, the pilot will need to take evasive action. Alerting the pilot that a threat is defeated will allow the pilot's attention and energy to focus on the mission and not on the existence of a potential threat.

1.1.1.3 Pass Defeated Missile Data to Aircraft Mission Computer

Third, the pod must be able to pass the defeated missile data to the aircraft mission computer. The aircraft may use the information of the incoming threats to determine system actions, such as communication to other friendly aircraft. It is important that the system transmit the status of the defeated missile.

1.1.1.4 Validate True Threats to Reduce False Alarms

To ensure only the relevant information is passed to a pilot, the system must be capable of identifying true threats. For example, the system may correctly identify a missile launch, but choose not to communicate this threat as the trajectory of the incoming missile is not a threat.

1.1.1.5 Alert Pilot to Low Likelihood of Defeating Incoming Missiles

If the system detects that a missile threat is unlikely to be defeated before damaging the host aircraft, the system will alert the pilot to begin taking additional steps to avoid missile impact. This could be due to the system's inability to effectively engage a target or due to an excessive amount of threats incoming on the target.

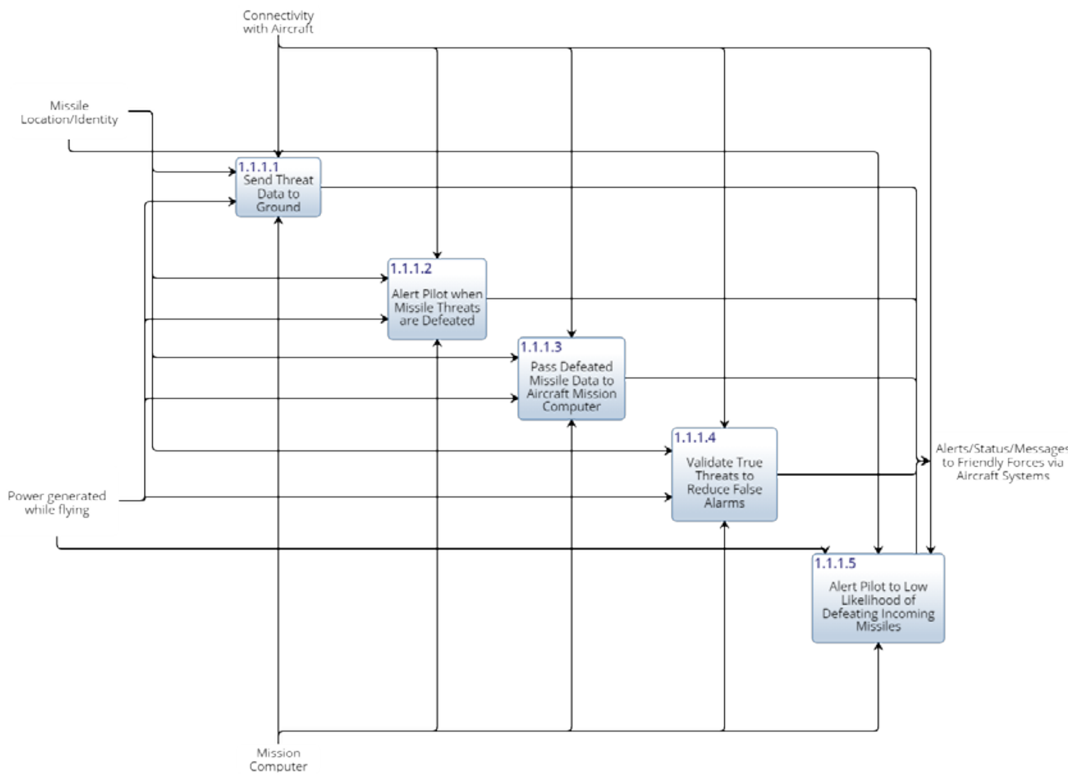

Figure 10. Alert Pilot to Missile Threats Decomposition

Communicate Status of Cyclops Systems can also be decomposed into two lower level functions fulfilling the requirements identified in Chapter II. The flow of attributes can be seen in Figure 11.

1.2.1 Communicate with All Systems within the Pod

The Cyclops pod contains several systems working together to perform the high-level functions. The status of these systems must be communicated within the pod so the overall status can be appropriately assessed and then communicated to the host aircraft. This status is passed from this function to Communicate Pod Status to Aircraft.

1.2.2 Communicate Pod Status to Aircraft

The Cyclops pod contains several systems working together to perform the high-level functions. It is important that Cyclops be able to communicate to the host aircraft the status of the various pod systems so the pilot can make the proper decision on how to proceed with the mission. This function will receive the status from Communicate with

All Systems within the Pod and output the appropriate alert or message to the host aircraft.

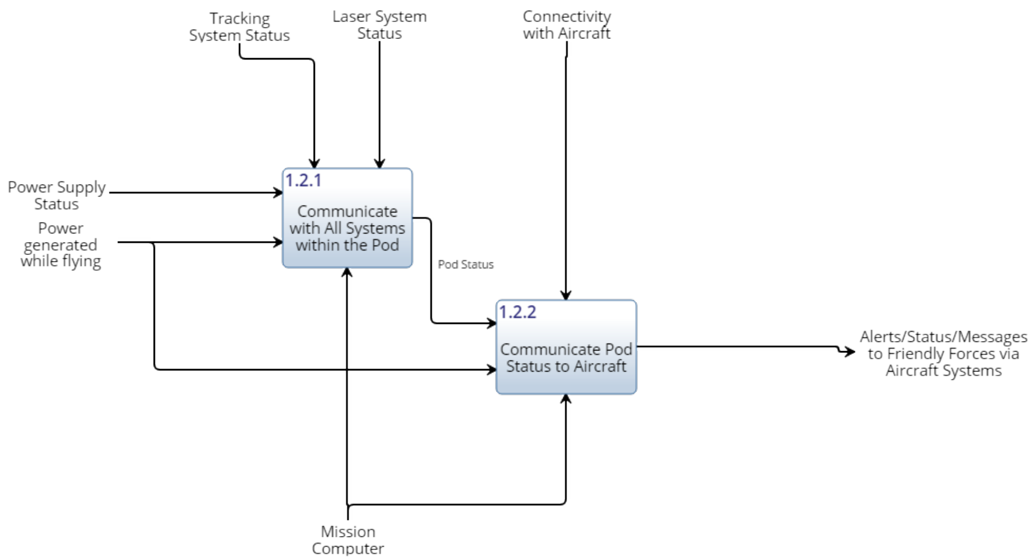

Figure 11. Communicate Status of Cyclops Systems Decomposition

2.0 Engage Incoming Missiles

This function describes the actions of the pod's laser system. It takes power from the power system and the threat priority as inputs and outputs the status of the threat missile to be used by external systems. This function is controlled by the missile being within range, the firing solution, and the threat priority

Figure 12 shows the first decomposition of the parent function. This functional architecture consists of three functions, which identify all the functions performed by the laser system.

2.1 Align Laser Transmitter with Firing Solution

This function refers to the laser aligning itself to the firing solution plotted out by the tracking system. The tracking system uses the missile location and velocity data to determine the optimum line of fire for incapacitating the target. This function takes that firing solution as input and moves the laser transmitter such that the system can project a beam along this solution.

2.2 Engage missiles around the platform

The laser needs to engage the missiles around the platform and incapacitate them before they damage the aircraft. This will include the ability to engage the missiles within the arc necessary to protect the aircraft.

2.3 Monitor Laser System Status

Finally, the system needs to be able to diagnose any malfunctions with the laser system. These malfunctions could range from power system failure to a calibration error. These status reports are then passed to the mission computer and relayed to the host aircraft.

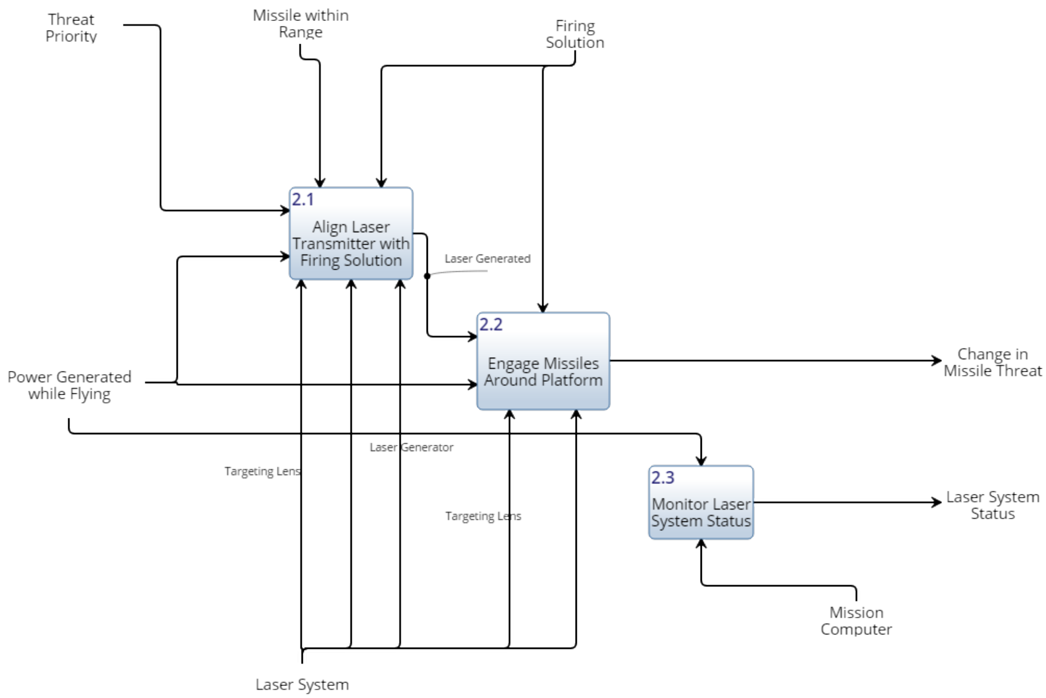

Figure 12. Engage Incoming Missiles Decomposition

3.0 Provide Power to the Pod

This function describes the actions of the pod's power system. There are no inputs to this function. However, the output (generated power) is an input for all other functions of the pod, highlighting its importance to the overall system. The system will also output the supply status, which is used by Communicate with Friendly Forces. This function is controlled by the aircraft being in the air, as the power supply is dependent upon the aircraft being in the air and in motion. Finally, this function will use the onboard computer and existing power supply.

A decomposition of this function depicted graphically in the figures below, shows its functional architecture. These functions can be further decomposed until they fulfill the lowest level functional requirements. These decomposed functions will use controls, mechanisms, and inputs similar to Provide Power to the Pod.

Figure 13 shows the first decomposition of the parent function. This functional architecture consists of three functions, which identify all the functions performed by the power system.

3.1 Provide Electrical Power to Pod while Flying

This function identifies the primary purpose of the power system, which is that power must be supplied to the various systems within the pod throughout the flight. This is the only function of this system that will be further decomposed. This function outputs power to be used throughout the Cyclops pod.

3.2 Monitor Power Supply Status

Finally, the power supply status must be monitored so the system can verify that the pod possesses enough available power to perform the desired tasks. The output from this function, the power system status, is an input into Communicate with Friendly Forces.

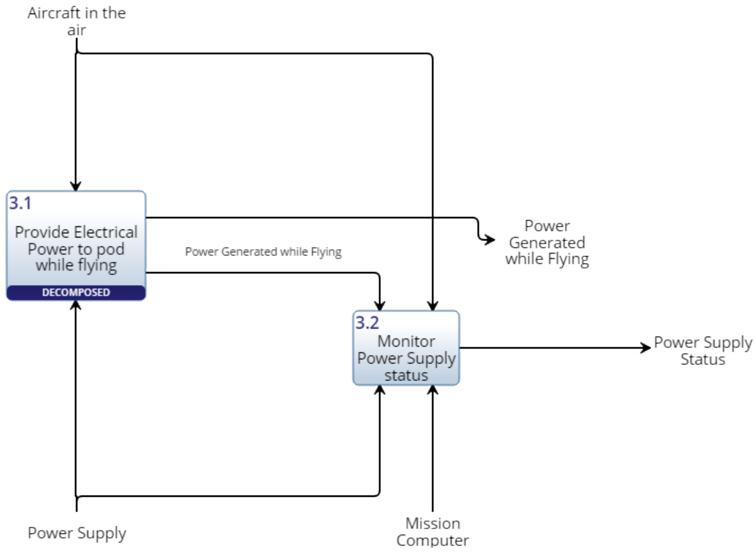

Figure 13. Provide Power to the Pod Decomposition

The decomposition of Provide Electrical Power to Pod while Flying is shown in Figure 14. This decomposition consists of four functions, fulfilling the requirements identified in Chapter II.

3.1.1 Generate Electrical Power

First, the power system needs to generate enough electrical power to supply all systems within the pod. This function provides raw electrical power to Convert Electrical Power.

3.1.2 Convert Electrical Power

The pod power system must convert the generated electrical power into the appropriate type of power required for each system within the pod. This function will use the power passed by Generate Electrical Power and convert it to usable power to be passed to the other functions within this decomposition.

3.1.3 Store Electrical Power

Third, since not all power will be used immediately after generation, the pod must possess a method to store a sufficient amount of power to meet the needs of other system functions. This usable power from Convert Electrical Power will be converted to the stored power passed to Distribute Electrical Power.

3.1.4 Distribute Electrical Power

Finally, the system must be able to appropriately distribute the electrical power throughout the pod as required by each subsystem. This function receives the usable and stored electrical power and then distributes it to the rest of the pod.

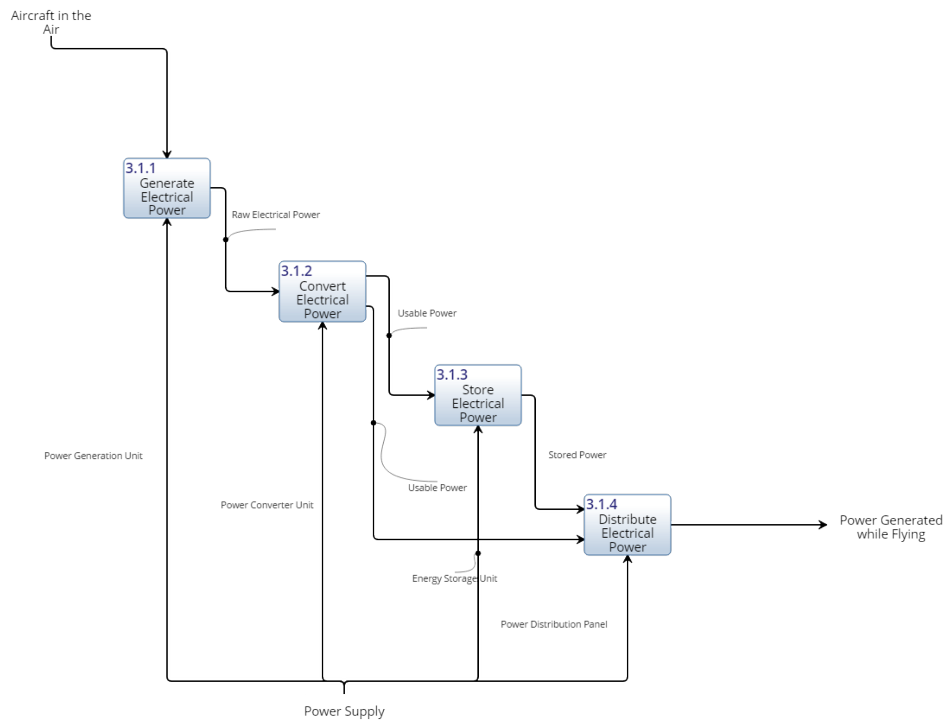

Figure 14. Provide Electrical Power to Pod While Flying Decomposition

4.0 Track Incoming Threats

This function describes the actions required to track incoming missiles. Before the Cyclops pod can execute the system's main function of defeating an incoming missile, it must be able to track and identify the threat. This function receives power from the power system as well as incoming missile information from the environment outside of the pod. Both the firing solution and threat priority are passed to Engage Incoming Missiles as outputs. Another output of the system is the change in missile threat status. The final output is the tracking system status to be used by Communicate with Friendly Forces. The system is controlled by the missile being within range.

A decomposition of this function depicted graphically in the figures below, shows its functional architecture. These functions can be further decomposed until they fulfill the lowest level functional requirements. These decomposed functions will use controls, mechanisms, and inputs similar to Track Incoming Threats.

Figure 15 shows the first decomposition of the parent function. This functional architecture consists of four functions, which identify all the functions performed by the tracking system.

4.1 Detect and Track Incoming Missiles

The system must be capable of tracking incoming threats. This function will identify incoming missiles and then pass the threat count to Prioritize Threat Missiles. This function will be limited to the missiles within range and the maneuvering limits of the pod, as calculated by the pod's onboard sensor that determines the ability of the pod to engage a threat accurately.

4.2 Prioritize Threat Missiles

When there are multiple threats, it is important that the system be able to prioritize the threats based on threat level. This function will use the threat count passed from Detect and Track Incoming Missiles and will output the missile location and identity, to be used by Engage Incoming Missiles and Communicate with Friendly Forces.

4.3 Monitor Tracking System Status

Finally, the system needs to be able to diagnose any malfunctions with the tracking system. These malfunctions could range from power system failure to a calibration error. These status reports are then passed to the mission computer and relayed to the host aircraft.

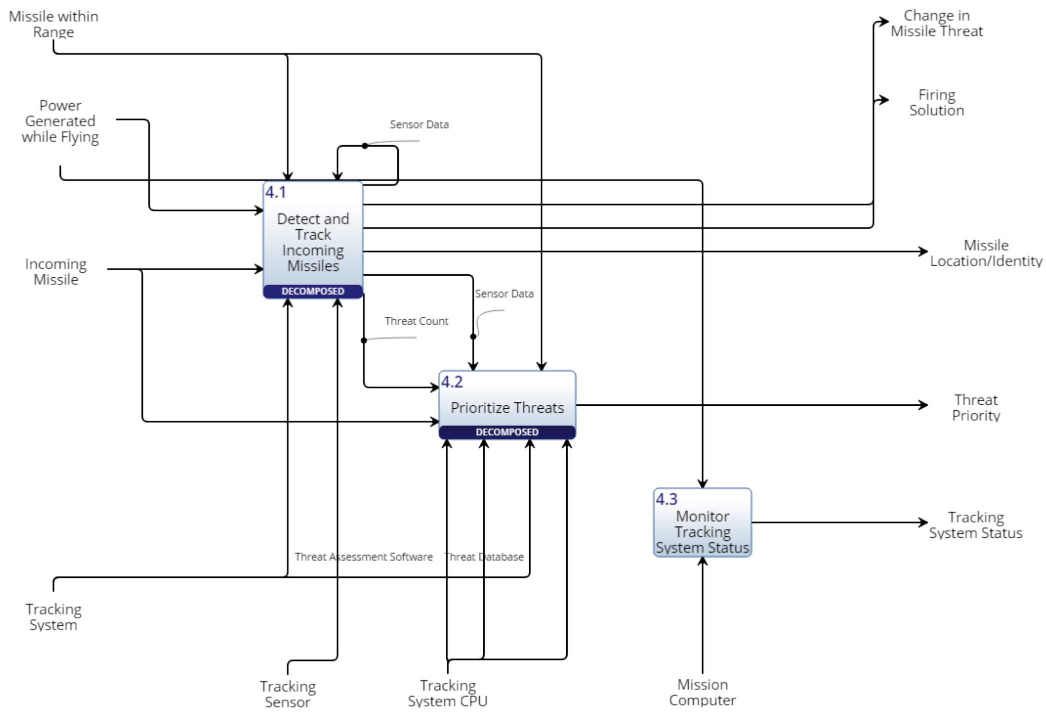

Figure 15. Track Incoming Threats Decomposition

The decomposition of Detect and Track Incoming Missiles is shown in Figure 16. This decomposition consists of four functions, fulfilling the requirements identified in Chapter II.

4.1.1 Detect Missile Threats

The tracking system must be able to detect incoming threats. These individual threats are inputs for this function, resulting in a threat count as an output to be used by Prioritize Threats.

4.1.2 Track Missile Threats

The system must be able to track detected threats in flight. It must track airborne threats and generate the firing solution to be used by Engage Incoming Missiles. It also generates the threat count to be used in prioritizing threats.

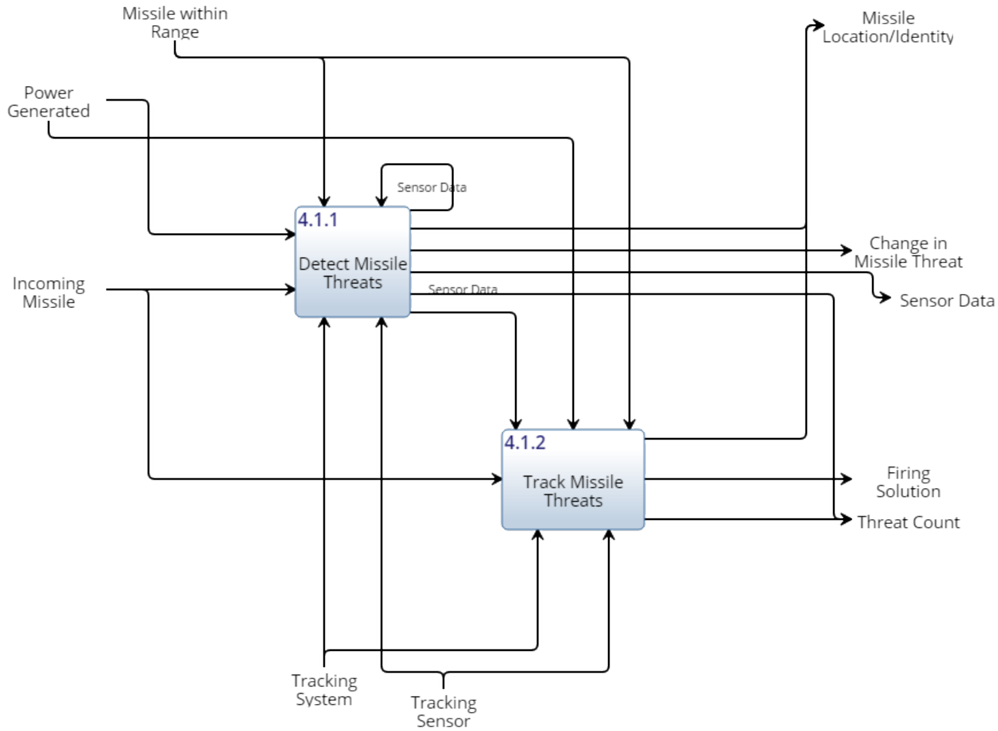

Figure 16. Detect and Track Incoming Missiles Decomposition

The decomposition of Prioritize Threats can be seen in Figure 17. This decomposition consists of two functions, fulfilling the requirements identified in Chapter II. These functions will require a dedicating computer processing unit (CPU) to perform the appropriate calculations.

4.2.1 Identify Highest Threat Missiles

First, the tracking system must be able to identify the highest priority missiles after an incoming missile has been identified. It will then output the threat priority to be used by Engage Incoming Missiles and missile location/identity to be used by Engage Incoming Missiles and Communicate with Friendly Forces.

4.2.2 Queue Additional Lower Priority Missiles

Finally, the ability to identify the highest threat will also require that the other lower threats are appropriately queued.

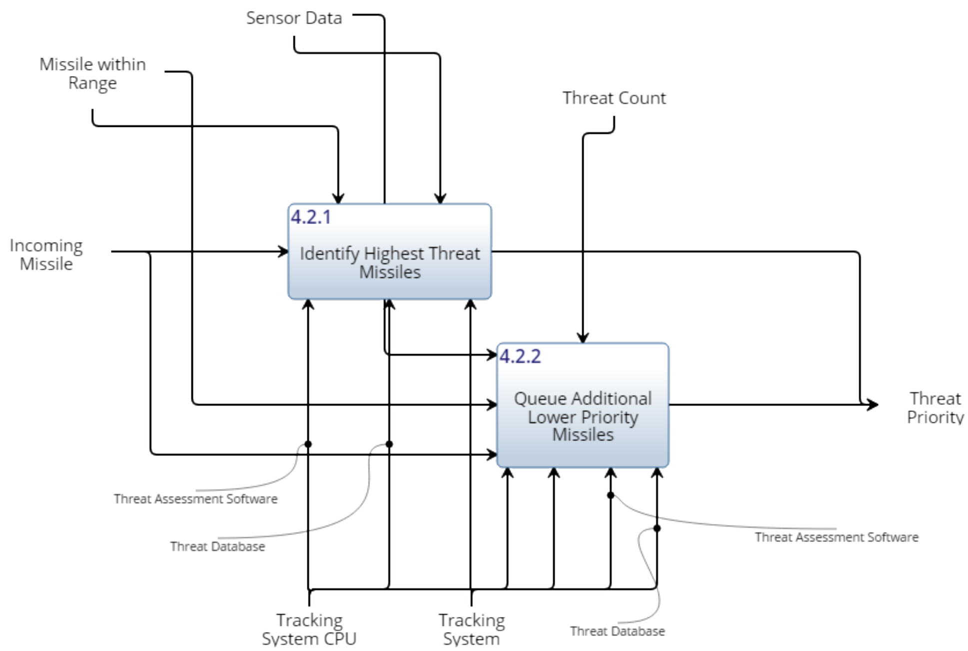

Figure 17. Prioritize Threats Decomposition

B. PHYSICAL ARCHITECTURE

The physical architecture of the system is broken down into three main subsystems, each approximately corresponding to a high-level function. These systems are the Laser, Power Supply, and Tracking subsystems. These correspond to Engage Incoming Missile, Provide Power to the Pod, and Track Incoming Threats respectively. The subsystem responsible for Communication with Friendly Forces is the Mission Computer located in the pod. This system is responsible for diagnosing malfunctions in the pod as well as passing messages and information to the host aircraft systems for transmission to friendly forces. This subsystem is not closely examined in this report, as mature technologies similar to this are currently in use by the military.

1. Laser Subsystem

The laser subsystem is responsible for defeating incoming missiles. It accepts inputs from the tracking system for the prioritization and targeting of incoming missiles, and then receives power from the generator to generate a laser and respond to the threat. The strength and range of the laser is limited by the maximum available power from the generator and the maximum safe output power of the laser. Figure 18 shows the breakdown of the laser subsystems.

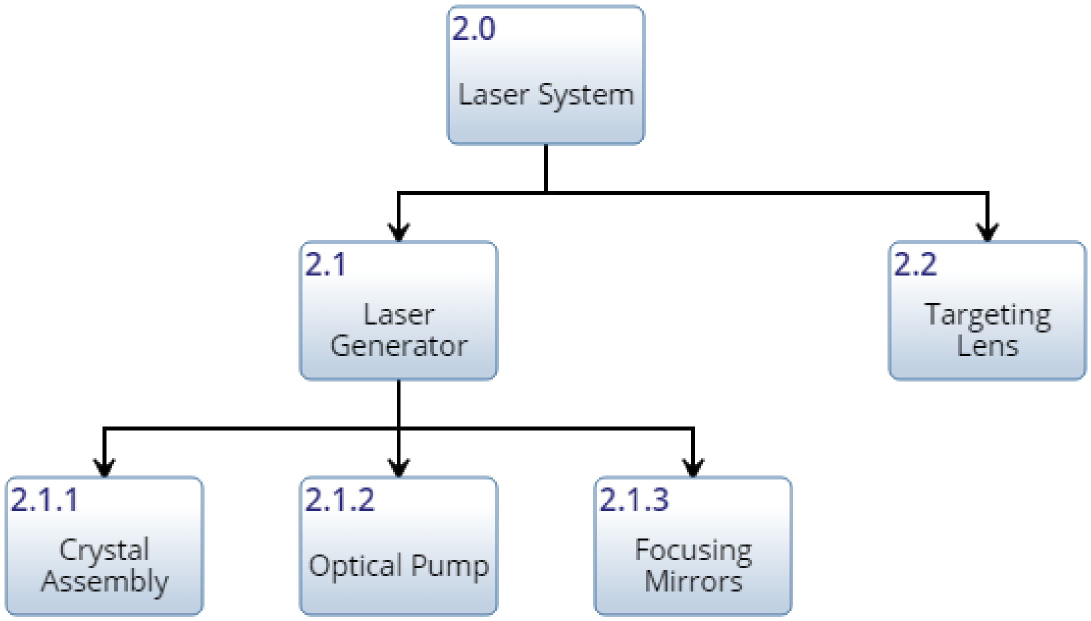

Figure 18. Laser Subsystem Physical Hierarchy

The physical architecture of the laser-generating subsystem could have variations based on the laser's source. For instance, a chemical oxygen iodine laser requires sources of oxygen and iodine gas to generate the laser beam while a free-electron laser uses a series of electromagnets and a solid state laser would employ an optical pump and crystal assembly to accomplish the same purpose. The most likely implementation given current technologies would be a solid state laser, but any design that meets the mission requirements would be acceptable. Ultimately, any proposed laser system will feature a laser generator, focusing mirrors, and a targeting lens. It could also have an active cooling element. The generator element is responsible for generating the laser beam. The focusing mirrors direct the laser into the targeting lens. The lens then aims the beam at the target.

The most likely implementation, based upon the currently available technologies, is a solid state laser. A chemical or free-electron laser would be too large and heavy for installation on the aircraft at this time. Because of this, the architecture shown above is representative of a solid state laser with optical diode pump.

2. Power Supply Subsystem

Figure 19 shows the Power Supply system decomposed in its four top-level subsystems. Each unit has also been decomposed into components to fulfill the functions shown in the functional architecture.

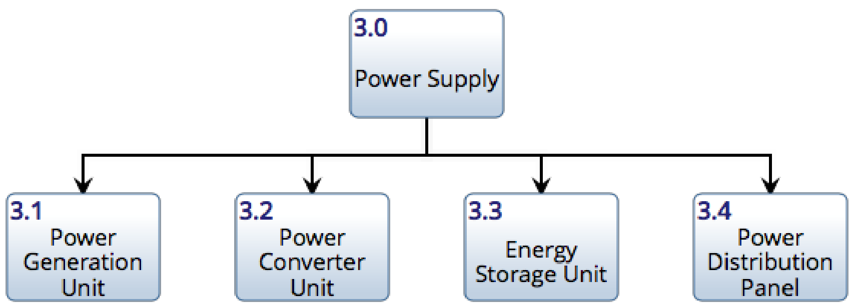

Figure 19. Power Supply Physical Architecture Decomposition

The Power Supply subsystems are then decomposed into components; Figure 20 shows the power generation unit breakdown components. Throughout our research, we have found that the use of a ram air turbine (RAT) and an electrical generator is the most optimal way to generate power within the pod while the aircraft is flying. The RAT uses air to spin the turbine that is connected to the generator shaft producing electrical power.

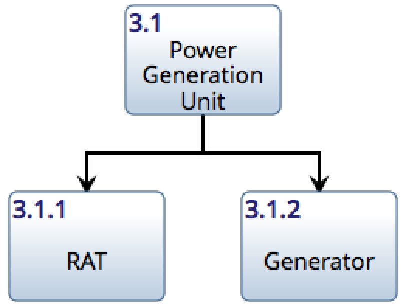

Figure 20. Power Generation Unit Physical Architecture Decomposition

Figure 21 shows the Power Converter Unit breakdown components. Since the laser uses high amounts of power, it was found that two types of conversion were necessary: high voltage conversion for the laser high energy requirements and low voltage conversion to power all electronics within the pod. The high voltage power generated by the Power Generation Unit is rectified and regulated to meet an optimal high voltage to be used by the laser; the high DC voltage is also connected to a DC to DC converter that will lower the voltage to be used by the pod electronics.

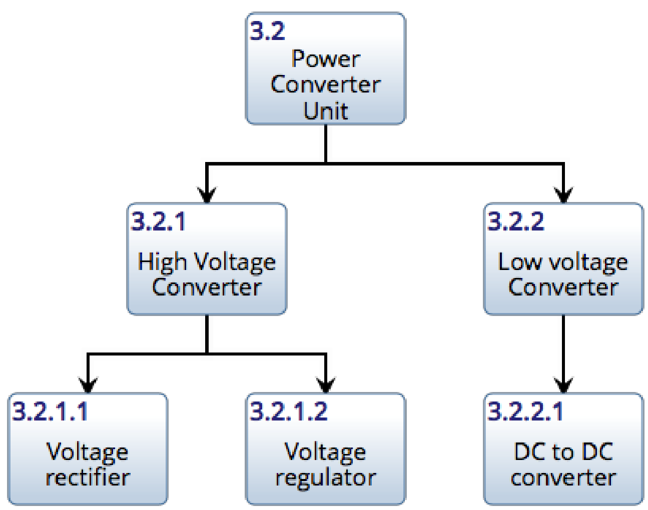

Figure 21. Power Converter Unit Physical Architecture Decomposition

Figure 22 shows the component breakdown for the Energy Storage Unit. The advantages of using storage devices are significant to this project. These systems can provide power at any moment, and high energy devices can provide the required amount of power to eliminate the threat. We found in our research that the use of high energy and power density batteries are ideal to meet the pod's high power requirements. The components in the breakdown consist of a battery and a battery charger for high voltage for the elimination of threats and lower voltage as backup power in case of generator failure.

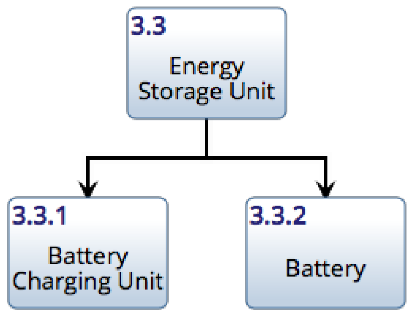

Figure 22. Energy Storage Unit Physical Architecture Decomposition

Figure 23 shows the component breakdown for the Power Distribution Panel. The use of voltage buses can make the distribution of power through the system very efficient. The buses used would include a high voltage bus for the laser and low voltage bus for the pod's electronic components.

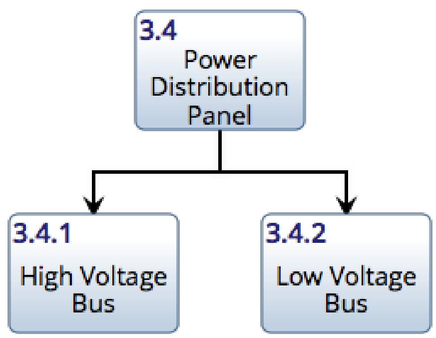

Figure 23. Power Distribution Panel Physical Architecture Decomposition

3. Tracking Subsystem

The Physical Architecture of the Tracking System is broken down into the Sensor and CPU. The Sensor then breaks down to a UV Sensor, and the CPU breaks down into

Threat Assessment Software and the Threat Database. The SV-1 diagram of the Tracking and Detection System can be seen in Figure 24.

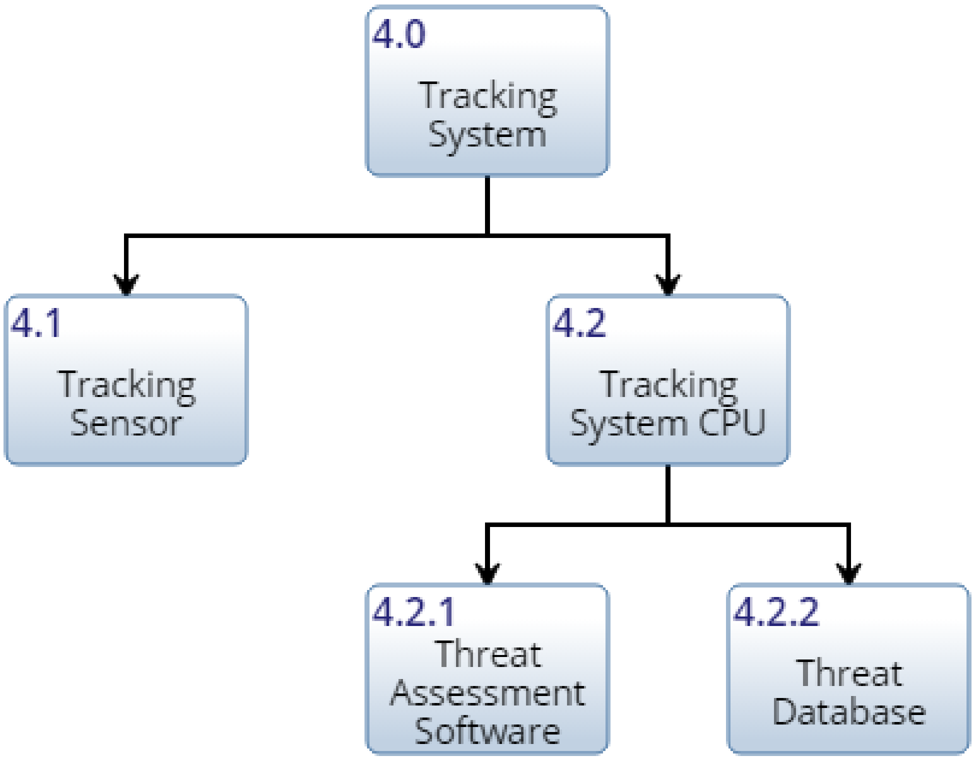

Figure 24. Tracking System Physical Architecture Decomposition

The CPU uses a database of known threats to determine the specific identification of the missile. The sensors initiate the tracking through detection of missile threats and send the data to the CPU for classification.

C. ALLOCATED ARCHITECTURE

Table 4 is a matrix displaying the connection between each of the requirements and the component that performs it. Some components have been omitted from the matrix as their level of decomposition would make their allocation redundant. An example of this is the laser generator component which can be decomposed into the crystal assembly, optical pump, and focusing mirrors. However, none of these components support functions separate from the laser generator. Thus, allocating these components would have been unnecessary. These assets were included in the physical architecture for the sake of clarity and thoroughness in this report.

Table 4. Allocated Architecture Matrix

	CYCLOPS to Related Entities	Functions																													
		0.0 Protect F/A-18 with Cyclops	1.0 Communicate with Friendly Forces	1.1 Communicate to the Aircraft Information Concerning Incoming Threats	1.1.1 Alert Pilot to Missile Threat	1.1.1.1 Send Threat Data to Ground Control via Aircraft System	1.1.1.2 Alert Pilot when Missile Threats are Defeated	1.1.1.3 Pass Defeated Missile Data to Aircraft Mission Computer	1.1.1.4 Validate True Threats to Reduce False Alarms	1.1.1.5 Alert Pilot to Low Likelihood of Defeating Incoming Missiles	1.2 Communicate Status of Cyclops Systems	1.2.1 Communicate with All Systems within the Pod	1.2.2 Communicate Pod Status to Aircraft	2.0 Engage Incoming Missiles	2.1 Align Laser Transmitter with Firing Solution	2.2 Engage Missiles Around Platform	2.3 Monitor Laser System Status	3.0 Provide Power to the Pod	3.1 Provide Electrical Power to pod while flying	3.1.1 Generate Electrical Power	3.1.2 Convert Electrical Power	3.1.3 Store Electrical Power	3.1.4 Distribute Electrical Power	3.2 Monitor Power Supply status	4.0 Track Incoming Threats	4.1 Detect and Track Incoming Missiles	4.1.1 Detect Missile Threats	4.1.2 Track Missile Threats	4.2 Prioritize Threats	4.2.1 Identify Highest Threat Missiles	4.2.2 Queue Additional Lower Priority Missiles	4.3 Monitor Tracking System Status
Components	1.0 Mission Computer System	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X						X	X							X
	2.0 Laser System	X												X	X	X																
	2.1 Laser Generator	X												X	X																	
	2.2 Targeting Lens	X												X	X	X																
	3.0 Power Supply	X																X	X					X								
	3.1 Power Generation Unit																			X												
	3.2 Power Converter Unit																				X											
	3.3 Energy Storage Unit																					X										
	3.4 Power Distribution Panel																						X									
	4.1 Tracking Sensor																								X	X	X	X				
	4.2 Tracking System CPU																								X				X	X	X	
	4.2.1 Threat Assessment Software																												X	X	X	
	4.2.2 Threat Database																												X	X	X	

Every function is supported by a component of the physical architecture. All of the "administrative" functions of the pod, such as malfunction diagnosis and communication, are handled by the Mission Computer System. These are all functions currently performed by pods in use by the U.S. armed forces, and so the supporting technology is not closely examined in this report.

D. CHAPTER SUMMARY

While Chapter II gives a broad overview of the pod's behavior and interactions, Chapter III goes further in-depth. It breaks down the functional architecture that will allow the system to meet the CONOPS. Furthermore, it breaks down the physical systems that support those functions.

Chapter IV will build off of the physical architecture laid out in Chapter III to develop a series of alternatives to analyze. These alternatives will be put through a series of simulations based on the functional architecture to determine combat performance. Finally, these alternatives will be scored based on their performance. These performance metrics will be based on the requirements established in Chapter II.

IV. ANALYSIS OF ALTERNATIVES

The requirements established in Chapter II created a foundation on which to base the Cyclops pod's functions. This functional architecture was then used as a framework to build a physical architecture. In this chapter, that physical architecture is then used as a baseline from which to research and develop a design of alternatives.

The alternative technologies considered were based on the three main subsystems analyzed in this report: the power supply system, the laser transmission system, and the tracking system. Once the technologies considered as alternatives were identified, they were evaluated using several metrics. These metrics include cost, the effect on flight performance, and functional performance.

A. ALTERNATIVE DESCRIPTIONS

This section is dedicated to the description of characteristics of the alternatives as well as the criteria used to identify them as viable technologies. An analysis of the risks associated with each of the alternatives is also included in this section.

1. Laser Subsystem

The F/A-18 platform has extreme size and weight constraints that limit feasible options for laser design. The most common laser types are gas, chemical, and solid state. Free-electron lasers are also somewhat common and warrant consideration. Gas lasers have short life expectancies, making them poor candidates for use in military equipment (Paschotta 2008). Chemical lasers provide the basis for the Tactical High-Energy Laser and have a proven track record for defeating incoming threats (Schwartz 2002). Unfortunately, chemical lasers are far too large and heavy for installation on an F/A-18. Solid state lasers provide a smaller, lighter alternative to chemical lasers. Some solid state mediums, such as titanium sapphire, are too inefficient for consideration (Payne 1989), but the higher efficiency solid state options can be configured to reach efficiencies of 20% or more routinely. Among these is the neodymium-doped yttrium aluminum garnet (Nd:YAG) laser medium and the ytterbium and erbium fiber lasers. These three laser mediums are further analyzed within this section. Finally, the free-electron laser (FEL) provides an alternative to a chemical laser, but weight continues to remain a concern. Shipboard FEL designs are over 100,000 lbs. and have lower wall plug efficiency than solid state lasers (Mansfield 2005). Therefore, FEL lasers are considered poor alternatives at this time.

Solid state lasers continue to have promising candidates for laser mediums. The Nd:YAG laser has an expected wall plug efficiency of 18% and a wavelength of 1064 nm (Mansfield 2005), or 30% wall plug efficiency and 532 nm wavelength using frequency doubling techniques (Wall 1990). The latter is known as the frequency doubled Nd:YAG (FdYAG) laser. While the current limited market for high power weaponized lasers makes weight estimates difficult, modeling by Boeing provides a scaling factor for the output power to weight of a solid state laser at 172 W/kg when wall plug efficiency is at 20% (Vetrovec 2002). This results in an expected weight of 1025 lbs. for an 80KW Nd:YAG laser.

Fiber lasers have already been proven effective for shipboard configurations of lasers, specifically the Laser Weapon System (LaWS). The LaWS system combines six individual fiber lasers into a single high energy beam. The ytterbium fiber laser medium provides a heavier, but more energy efficient, alternative to the Nd:YAG laser. The ytterbium laser has a wavelength of 1055nm, nearly identical to the Nd:YAG. However, fiber lasers have an efficiency of 30% (Hecht 2012). An expected weight can be calculated by considering the weight of a 1KW laser and extrapolating for an 80KW variant (Sprangle 2008). An estimated 20 lbs. per KW predicts a final weight of 1600 lbs. for a fiber laser.

The erbium fiber laser medium has comparable weight and efficiency to the ytterbium laser, but the wavelength, 1550 nm, is nearly 50% larger. All four of these alternative configurations, including the standard and frequency, doubled Nd:YAG, will be compared via modeling to determine the most appropriate material.

Risk consideration of the various laser systems is constrained by the limited number of real world HEL lasers currently developed by the DOD. The greatest risk is damage to the HEL due to the heat generated while firing. The repeated heating and cooling of the system can cause metal fatigue, warping of the targeting and focusing lenses, and reduction in beam quality (Vetrovec 2002). These issues could result in degraded system performance and ultimately system failure. The expected reduction in performance over time, as well as the possibility of a mitigating cooling system, is outside of the scope of this project and left for future investigation. A design risk also exists due to the cutting edge nature of the proposed system. If the power to weight scaling factor for the Nd:YAG laser is inaccurate, the system may be too heavy to be installed on the F/A-18. This is of less concern for the fiber lasers, due to their scalable nature.

2. Tracking Subsystem

While numerous missile tracking and detection systems exist in today's military, not many of them can integrate with the F/A-18 platform due to the excessive numbers of false alarms brought on by the operational speeds of the aircraft. The goal of this part of the analysis of alternatives is to determine which current missile detection system could best support strike fighters' missions. One assumption that has to be taken into account for each assessment is that the system will integrate and function with the Cyclops pod. The research of tracking and detection systems on jets has the potential to be a whole new capstone project and is not the goal of this paper. Therefore, assumptions about current systems had to be made due to time and unclassified information limitations. Three main systems emerged as potential options.

The AN/AAQ-37 Distributed Aperture System (DAS) system is currently being employed on the F-35. This tracking and detection system readily integrates with the Threat Nullification Defensive Resource (ThNDR) system. This system provides missile detection, tracking, and targeting/cueing capabilities to the F-35 missile defense systems and the pilot. The DAS allows for a 360-degree sphere for detection and tracking capabilities. The DAS uses a single-color IR sensor that can process images faster than existing missile warning systems, which has allowed the DAS to function on fast moving jets without creating false alarms. While this system has not seen much operational use, it is currently being used on the F-35, and it has had extensive laboratory testing and has proven to track multiple missiles simultaneously (Northrop Grumman 2017b). This system was designed specifically for the F-35 and has proven a valuable system on the aircraft thus far. Transferring the technology that has been fully integrated with a fast moving jet such as the F-35 to the F/A-18 is a very plausible option.

The risk associated with attempting to integrate the DAS with the Cyclops system is that DAS was specifically built for the F-35 platform and to integrate with that aircraft's ThNDr system. This will cause some work for integrating the DAS with the Cyclops as it will have a different laser and power system configuration.

The AN/AAQ-24(V) DIRCM system is a more familiar name as it is installed on over 750 aircraft, including large, small, rotary wing, and tilt-rotor aircraft (Northrop Grumman 2017a). The DIRCM system simultaneously detects, tracks, and defeats threats in cluttered environments. Because the system is installed on over 750 aircraft and has been around for over 50 years, it has been battlefield tested. Therefore, technology failure risks are low. While the DIRCM system in its current form has proven to be a rather robust system, there have been difficulties trying to integrate it with fast-movers, such as the F/A-18. One of the initial issues was too many false alarm notifications while moving at high speed. In addition, the size of the DIRCM system was too large and the laser not powerful enough to defend the aircraft (*Aviation Week* 2013). While the DIRCM system has issues when integrating with fast movers, it has proven itself on many aircraft platforms.

The biggest risk with using the AN/AAQ-24(V) DIRCM is the two-color IR sensor the DIRCM uses. The two-color IR sensor has shown low operational functionality when integrating with fast moving jets due to the system not being able to process the images quick enough. One-Color IR sensor processing time is lower than two-color due to a reduction in noise and false alarms to be filtered out. Another risk involved with moving forward with the DIRCM is integrating the tracking and detection capabilities of the system without using the current laser that is being used with it. The Cyclops will use a powerful laser to destroy the missile, thereby disabling it architecturally. This would mean the laser of the DIRCM system would have to be replaced and continue to work. There is also the functional risk of using the DIRCM as currently, the operational use of it is to disable the seeker head by jamming the IR sensor of the missile. The tracking and detection system would have to employ a new operational concept now and direct the laser to anywhere on the missile that the laser could structural damage the threat.

The final system under consideration is the AN/AAR-54(V) Missile Warning System (MWS). This system is a fourth-generation missile warning system that is available for use on virtually every platform, including fast movers. The system provides clutter rejection, long and short-range missile detection, cueing to the countermeasure system, classifies the source, and can track multiple sources (Northrop Grumman 2017c). Similar to the DAS system, the MWS does not have much operational experience. However, initial tests have shown very promising results. The system also readily integrates with DIRCM system. Because the MWS was designed with the intention of being placed on fast movers, it is an ideal candidate for the Cyclops Tracking and Detection subsystem.

Similar to the risk associated with the DAS with the MWS is also relatively new and has not been flown for an extensive amount of time when compared to DIRCM systems which poses a technology risk as well. The system has gone through extensive testing, but the lack of operational use is concerning. Another risk with the MWS is the UV sensors have not shown much success with fast jets thus far, especially when compared to the single-color IR employed by the DAS.

3. Power Supply Subsystem

Alternatives for the power supply system have been broken into two sections. The first covers airborne power generation. The second covers storage of power within the pod. This stored power will mainly be used to operate the pod while the onboard power generation system is not in use.

a. Ram Air Turbine/Generator (RATG) Alternatives

Ram air turbine/generator consists of a turbine connected to an electrical generator to be used as a power source. Cyclops will generate its own power since the power generated by the aircraft is limited, and Cyclops power requirements are high.

commercial off-the-shelf (COTS) Ram Air Turbines are available and are currently being used on commercial airplanes. However, these RATs are used for emergency power when the aircraft loses its primary power sources. These COTS RATs are not capable of high enough power output to meet Cyclops electrical power requirements. A large RAT on a commercial aircraft could produce from five to 70 kW; smaller, low airspeed models may generate as little as 400 watts. The primary purpose of the COTS RAT is to keep the battery charged. Performance is a risk associated with COTS RAT. Electrical power required for the laser is too high for COTS RAT to provide it power directly. Therefore power must come from battery alone and once the battery has been depleted the system will no longer be effective (Zolidis 2002).

ATGI designed a Hi-Powered Ram Air Turbine (HiRAT) that was awarded Phase III SBIR contract to be implemented in the Next Generation Jammer (NGJ). "The HiRAT has been successfully integrated into applications ranging from 300 watts to over 300 kW" (Warwick 2013) and demonstrated that it can produce 90KW at the low speed, low altitude designed for NGJ (220 Knots and 25000 feet) (ATGI 2017). The HiRAT can be designed to get high power at the operational speed and altitude to meet Cyclops electrical power requirements. Schedule and cost is a risk associated to HiRAT. Since the HiRAT has to be designed to meet our requirements; it must still go through development and testing to make sure it works as expected, thus increasing the possibilities of schedule delays and cost increase.

COTS RAT has lower cost since HiRAT must be designed to meet our requirements, but the power output provided by HiRAT will allow the system to be powered most of the time by the RATG only using battery power when necessary. Thus the system will be active throughout the mission.

b. Battery

Batteries will provide backup power for the laser or when the power generating unit is not able to produce enough power to the laser to destroy a threat; this could happen when operational speed and altitude changes due to incoming threats affecting the performance of the RATG.

The battery selected must be able to provide power to a high energy laser:

> Energy Density (Wh/kg) is a measure of how much energy a battery can hold. The higher the energy density, the longer the battery can provide power. Power Density (W/kg) indicates how much power a battery can deliver on demand. Manganese and phosphate-based lithium-ion, as well as nickel-based chemistries, are among the best performers. (Battery University 2017)

Figure 25 compares the energy density of some of the currently used Lithium ion technologies with lead acid, nickel-cadmium, and nickel-metal-hydride.

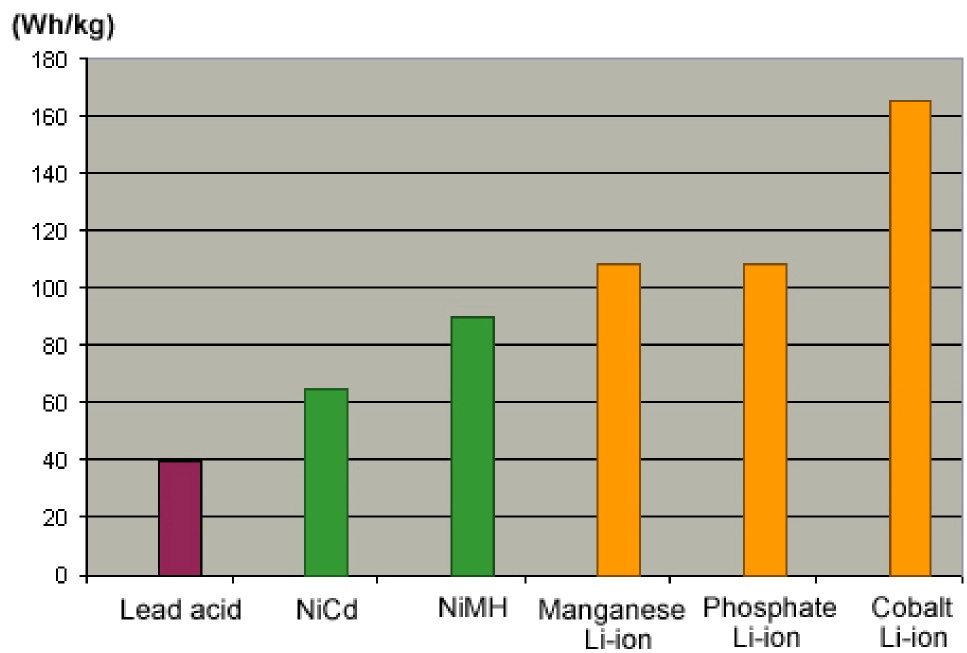

Figure 25. Battery Energy Density Chart. Source: Battery University (2017).

Lithium ion technology continues to grow, so a battery could be designed to have an energy density of approximately ten kWh to provide 300 kW power to the laser for up to two minutes. Since lithium-ion batteries have higher energy, their weight will be less than any other battery technology. However, lithium-ion must have battery managing system (BMS), which is an electronic device that manages how each cell is charged and discharged to protect the cells and avoid thermal runaway since lithium-ion based batteries are flammable. The schedule is the biggest risk associated with lithium-ion batteries; development and testing have to be completed incurring the risk of schedule delays.

Lead acid batteries have low power density; therefore they will be heavy and big for the required Cyclops power. Cost is lower since they will not require electronics (BMS) and will not require much development. Weight and Size constraints are the biggest concerns with lead acid risking meeting such requirements (Battery University 2017).

B. SCORING STANDARDS

There are four main categories used for scoring and comparing each system. Each category has a relative weight, expressed as a percentage, which was derived from discussions with the project stakeholders. The four categories and their relative scoring weights are:

1. Aircraft Performance (10%)
2. Cost (30%)
3. Risk 10%)
4. Functional Performance (50%)

Each alternative was scored for each category, listed above. This original score is considered to be the "raw score." This raw score was then divided by the maximum possible value to be given a "scaled score." Thus, the scaled score was between zero and one. For cases where a lower scaled score was optimal, the listed scaled score was found by subtracting the original scaled score from one. For each alternative, the scaled scores were multiplied the weighted percentage for each category and then summed to provide a final score between zero and one.

For example, in the first line of Table 5, the Functional Performance of the "Alt. #1" was given a raw score of four, out of a possible 10, as indicated in the "Maximum" column which translated to a scaled score of 0.40. For Aircraft Performance, “Alt. #1” received a raw score of four, out of a possible five. However, since a lower value for this category was more desirable, for this particular example, the scaled score was 0.20, which is found by subtracting the raw score (4) divided by the maximum (5) from one. A total score of 0.75 for Alt. #1 was calculated by multiplying each scaled score by the relative value in the “Weight” column. This scoring process is used for each system. A description of each scoring category is provided in the following paragraphs.

Table 5. Example Scoring Table

		Functional Component				
	Weight	Maximum	**Alt. #1 (Raw)**	**Alt. #1 (Scaled)**	Alt. #2 (Raw)	Alt#2 (Scaled)
Functional Performance	0.5	10	**4**	**0.40**	8	0.80
Comparative Cost	0.3	3	**6**	**2.00**	2	0.67
Aircraft Performance	0.1	5	**4**	**0.20**	3	0.40
Technology Risk	0.1	9	**8**	**0.89**	9	1.00
Total	1.00			**0.91**		0.74

1. Functional Performance (50%)

Each system must first be evaluated based on the ability to perform the desired function. Since this is the actual purpose of each system, this score contributes the most (50%) to the overall alternative score.

The alternative scoring is established using research and analysis of known systems. The system with the best score of each comparison is given a 10, and the other system(s) are scored relative to that. The scoring is based linearly, so a score of a five is considered half as good as a score of a 10. The modeling and simulation output is used to score each laser, and the rating system uses laser dwell time, discussed in more depth below.

2. Aircraft Performance (10%)

Aircraft performance refers to the effect that the given system will have on the overall performance of the aircraft. There are several categories assessed for the systems that can influence the aircraft performance. The scoring of these categories was determined using a combination of predictive research and analysis of existing systems. Finally, not all of the categories are relevant for comparing each specific subsystem, and only the relevant ones will be used during the scoring. Thus, the scoring method for aircraft performance varies by subsystem.

The limitations posed to overall aircraft performance are weighted as 10% of the overall score for each system, indicating that it is important, but not the most important attribute.

a. Weight

Weight plays a major role in aircraft performance. Most notably, the weight will impact fuel efficiency and aircraft maneuverability. There are two main components that will determine the weight of the system - the battery, and the laser. The other components can be merged into “everything else.” This “everything else” is estimated to be 700 lb. based on analogous systems currently in use. The maximum allowable weight for the entire system was established to be 4100 lb. This is based on the heaviest single load commonly carried on an F/A-18 (a full FPU-12 480 gallon external fuel tank).

b. Size/Shape

The size/shape of a system will influence the aircraft performance as well. A physically large system will impact the ability of the aircraft to fly as desired.

c. Limits to Flight

If the tracking system or laser requires the aircraft to maneuver in a specific manner to properly function, this will also impact the aircraft performance.

3. Comparative Cost (30%)

Cost is always a factor during the acquisition process. Creating accurate cost predictions is difficult, and even more so when the program uses emerging technology. The department of defense has a fiscal responsibility to the tax payer, and cost must be considered as a large portion of the overall system rating. So, cost is evaluated as 30% of the overall system score.

It can be assumed that for all of the system alternatives, the following can be considered the same for this research.

- material cost (except the power supply batteries)
- operations and sustainment cost
- production and deployment cost

These are reasonable assumptions for each system given the similarity between materials and expected system maintenance over the life cycle.

The main differentiator between the systems will be in the integration and testing. Thus, the cost will connect closely with the TRL/Risk. Integration and testing of mature technologies will be notably cheaper than using emerging technologies. The TRL specifically captures the risk of the technology, while the cost comparison takes into consideration the integration with the Cyclops system.

Given the relative similarities between the existing options, it is not predicted that the costs of the systems will differ by any more than 10x, or "one order of magnitude," between the most and least costly alternative. So, a scoring system will be used to compare costs where each system is scored with the following ratings:

3 – The cheapest alternative

2 – 5 x the cheapest alternative (1/2 an order of magnitude)

1 – 10 x the cheapest alternative (1 order of magnitude)

So, if one system is not reasonably expected to differ by more than one-half magnitude of another system, then the costs will be assumed to be the same.

4. Technology Risk (10%)

There is an inherent risk in using any technology that is not currently operational. The consequence of building a system around an immature technology may be realized in increased cost (evaluated through the "cost" score), increased schedule, degraded performance, or a combination of all three. The technology readiness level (TRL) is used to compare each system. The score is a raw score from zero through nine with zero referring to a technology that is in the early research stage, while nine refers to technology that is already being used operationally for the intended purpose. These ratings follow the guidelines in the Defense Acquisition Guidebook. Since the Cyclops Pod is a next generation system using emerging technology, it is expected that some technologies are still immature. Thus, the technology risk is weighted only as 10% of the overall score.

C. MODELING AND SIMULATION DEVELOPMENT

The modeling and simulation research was conducted through two programs, High Energy Laser End to End Operational Simulation with SHaRE (HELEEOS) and ExtendSim. These programs allowed a simulation of activating the various alternatives of Cyclops through three different environments. Two additional programs, LEEDR and PITBUL, were also in review but saved for a later study. All three of these programs are sensitive programs that required user agreements from the modelers and the advisors and were not to be shared freely. In the end, these programs enabled a better understanding and evaluation of the lasers systems under review.

HELEEOS is an Air Force Institute of Technology (AFIT) product that was shared with us by Dr. Kevin Keefer and the AFIT Center for Directed Energy (CDE). HELEEOS assumes that the tracking and power systems of the Cyclops perform as designed. The program models the laser's given power output parameters, host aircraft aerial position, environmental and geographic parameters, and target missile physical and aerial position characteristics and determines the dwell time required for the laser to defeat the target missile. The measure of effectiveness (MOE) in the simulations is the ability of the AADL to protect the aircraft from multiple threats. The measures of performance (MOPs) are the total dwell time to defeat the incoming missiles and the number of missiles defeated before intercepting the aircraft.

HELEEOS is a discrete mathematical model that measures the dwell time of the simulated directed-energy that is delivered on a target over a broad range of environmental factors and scenarios. The dwell time is the period of engagement that is required for the Cyclops laser to neutralize a threat. A shorter dwell time enables an increase in the number of missiles that the Cyclops is capable of defeating within an 8,000m range if all targets are fired at the same time from the same distance. HELEEOS uses a time-advanced model that was set at ⅔ second for each step along with two key components that aided in this prediction, the stochastic component is the Laser Environmental Effects Definition and Reference (LEEDR) module, and the deterministic component is Scaling for High Energy Laser and Relay Engagements (SHaRE).

The LEEDR component creates an environmental picture that includes sand/dust storms, fumes, vapor, haze, and moisture droplets. These factors are known to affect the quality of a laser beam between the transmitter and the target. The SHaRE software enables the assessment of a HEL's effect on target due to appropriate scaling laws, high energy beam characteristics, and irradiance distributions. Inputs for HELEEOS include the target's lethality, size, velocity, and position. The strike fighter inputs include position, velocity, laser's power and wavelength. However, the platform's optics were not considered for this study. The scenario may include a plethora of information. This includes the global position, atmospheric conditions, clouds/rain, ground level, and timeline of the various discrete events. There was also the option of enabling an observer. Jointly these components determine a HEL's dwell time on target as well as various irradiance measures and other parameters.

This simulation compares four different solid-state lasers: The Nd:YAG laser, the frequency doubled Nd:YAG, the Erbium fiber laser, and the Ytterbium fiber laser. Each laser provides the necessary level of energy while providing different levels of power efficiency that leads to differing dwell times. The simulation is conducted over four different scenarios: a single aircraft against multiple threats, a single threat targeting an allied aircraft, multiple threats targeting a formation of allied aircraft, and a multi-layered air defense system targeting a formation of allied aircraft. Each laser operates within the bounds of each scenario in three different environments. Pyongyang experiences long and cold winters with temperatures at or below freezing. It is located near the eastern shore of the Yellow Sea in the valley of the Taedong River. Mosul in the summer experiences hot, dry and windy weather that often results in dust storms (also called Haboobs). It is a major city, located along the western bank of the Tigris River in northern Iraq. Manila in the summer experiences very tropical weather. It is one the oldest cities in the Philippines, located along the eastern shore of the Manila Bay at the mouth of the Pasig River. Each environment involves a unique degree of turbulence, particulate pollution, and moisture levels. These factors degrade the lasers ability to focus its beam on the target that leads to extended dwell times. The results of the simulation indicate the ability of the Cyclops to reduce the susceptibility of the strike fighter to short-range missile threats within 8,000 m of the aircraft. ExtendSim simulates the process of detection, prioritization, acquisition, targeting, strike, assessment, and recovery for multiple MANPADS using the data derived from the HELEEOS runs. The purpose of this simulation is to provide metrics with which to evaluate the various alternatives for optimal performance on a strike fighter aircraft.

This simulation is intended to be a benchmark. The scenarios are designed to be the same for every alternative. The only part of the simulation involving probability distributions is the calculation of the dwell time required to kill a missile. The simulation begins in ExtendSim. An aircraft is simulated in flight with three missiles simulated as launching from ground level 10,000 m away. All three missiles have the same velocity. The ExtendSim model assumes that the pod will always take the same amount of time (two seconds) to reset and re-aim before engaging the next target. It also assumes that the missile tracking systems will not fail before being engaged by the Cyclops pod. The system immediately begins engaging the first of the missiles. The location and movement data are passed from ExtendSim into the HELEEOS. These parameters are then used with the technical characteristics of the laser alternative to determine the dwell time to destroy the missile in question. This dwell time data is then passed back to the ExtendSim model to determine the new location and movement information for the missiles and aircraft.

The second missile is then engaged, the new location and movement data passed to HELEEOS, and the process repeated. The simulation continues with this process until all missiles are destroyed, or the aircraft is intercepted. The performance of these systems is based on whether they were able to shoot down all three missiles and how much total dwell time was required to defeat all missiles. Figure 26 shows this process. The source model used for the ExtendSim portion of the simulation is shown in Appendix B.

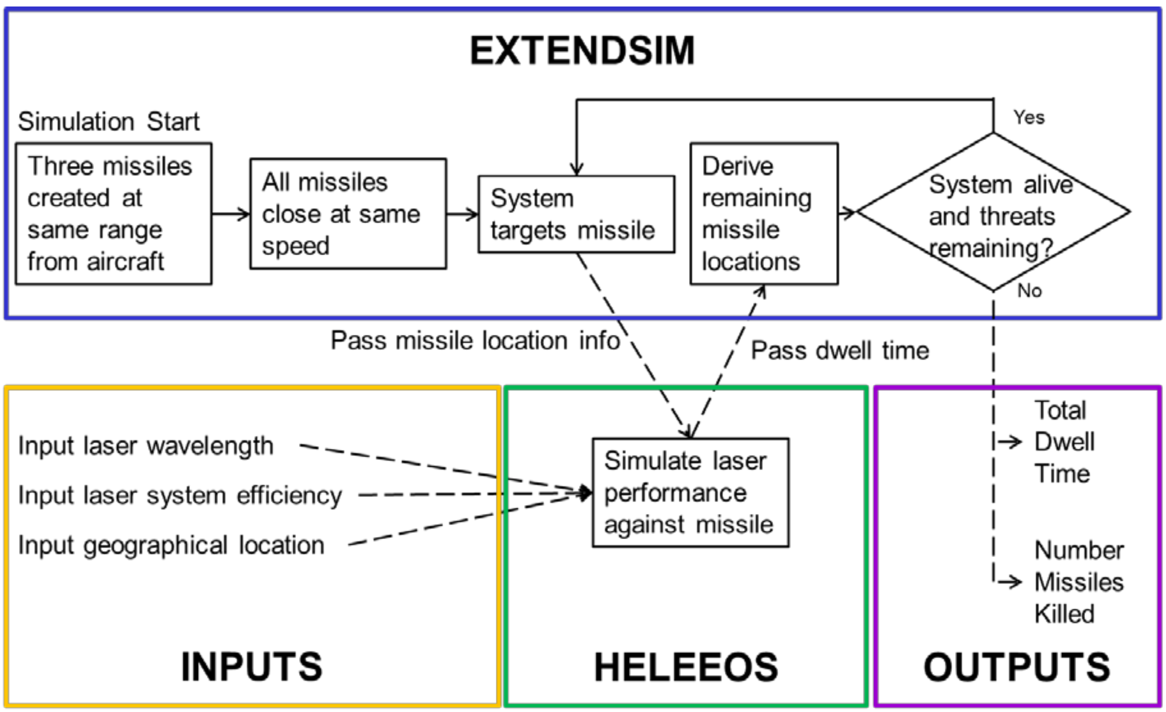

Figure 26. Functional Performance Simulation Flowchart

The results of the HELEEOS simulation give the dwell time of the Cyclops over various horizontal and vertical distances. The laser was supplied with 300kW of electric power and used a 0.33 m exit aperture diameter. The strike fighter flew at 10,000 m. This value was based on performance data from ATGI (ATGI 2017). The Cyclops required two seconds between engagements to perform process actions, used a Gaussian shaped far-field beam with a normal effect distribution. This value was based on the performance of the Guardian countermeasures system, which is an adaptation of DIRCM technology (Northrop Grumman 2017d). The missile was simulated with a round geometry, 0.05m diameter, and effect threshold of 10kJ/cm^2 (Carter 1984, 17).

Table 6 shows the results of the simulations. It shows the average total laser dwell time to neutralize three missiles for each of the laser alternatives across each of the environments.

Table 6. Average Laser Alternative Dwell Times (Sec)

	YAG	FdYAG	Ytterbium	Erbium
Pyongyang	0.567	0.271	0.385	0.464
Mosul	1.306	1.204	0.873	0.958
Manila	1.786	0.496	0.861	1.346
Average	1.220	0.657	0.707	0.923

One aspect of these results that stands out is the apparent inconsistency of the effect of environment on laser alternative. The Nd:YAG laser performs better in Mosul than it does in Manila, yet the FdYAG performs better in Manila than Mosul. The key to these differences lies in the wavelength of the light being projected. Different types of particulates in the air absorb different amounts of energy from the light that passes through them. The portion of energy absorbed when the light passes through these particulates is dependent in large part on the wavelength. In a sense, the particulates in the air are more opaque to certain wavelengths than to others. Figure 27 shows the absorption spectra for water (Prahl 1998). Lower absorption indicates less energy removed by passing through the particulate.

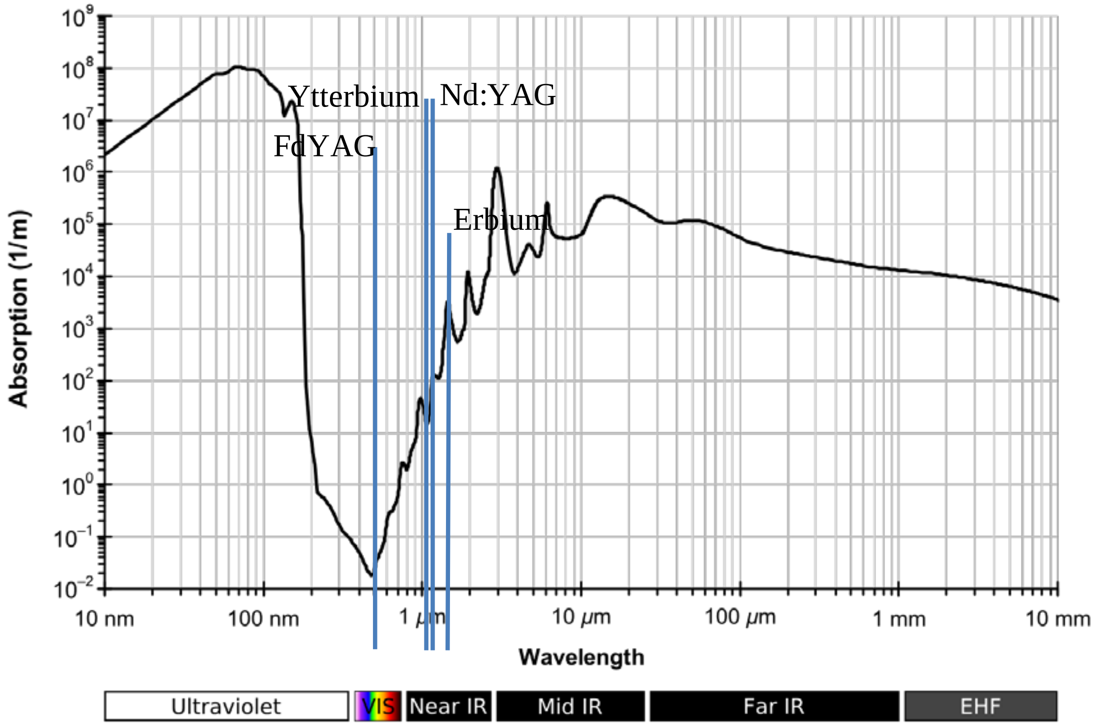

Figure 27. Water Absorption Spectrum. Adapted from Prahl (1998).

The reason the FdYAG alternative performs so well in Manila is that, with a wavelength of 532 nm, the absorption is extremely low. For this type of laser, the water in the air is almost transparent. Although the Ytterbium and Nd:YAG lasers have very similar wavelengths (1055 and 1064 nm, respectively), the increased efficiency of the Ytterbium allows for reduced dwell times. The Erbium, with the highest wavelength (1550 nm), also has the highest absorption.

The main environmental factor affecting laser performance in Mosul is the dust in the air. The absorption spectrum for dust is significantly different from water. The absorption coefficients vary based on the composition of the particulates in the air. However, there does seem to be an overall pattern to dust absorption spectra. At the lowest wavelengths, the absorption is high. It trends downward as the wavelength increases. At around 1,000 nm, the absorption begins increasing again before continuing to drop around 1,500 nm. With a wavelength of 532 nm, this explains the increase in dwell times in Mosul for the FdYAG. Similarly, this increase in absorption at or greater than 532 nm is shown in the increase in dwell times (Bergstrom 2007).

D. SCORING AND ANALYSIS OF ALTERNATIVES

This section details the results of the alternative scoring using the analytical methods laid out in Sections B and C. Using these methods, the best alternatives from Section A are identified. These conclusions will then be used in Chapter V to establish recommendations.

1. Laser Subsystem

The laser system alternatives were evaluated and scored on the four different categories. The results of the scoring can be seen in Table 7. The Ytterbium laser received the highest score of 0.73 (out of a possible 1.0). The relatively poor simulation results of the Nd:YAG (standard) and the Erbium, significantly hurt their overall score (0.64 and 0.68, respectively). While the Nd:YAG (double frequency) performed well in the simulation, the poor cost and large technology risk ultimately contributed to the lower score of 0.64.

Table 7. Laser Subsystem Alternative Scoring

		Laser								
	Weight	Maximum	Nd:YAG (Std) (Raw)	Nd:YAG (Std) (Scaled)	Nd:YAG (2x Freq) (Raw)	Nd:YAG (2x Freq) (Scaled)	Ytterbium (Raw)	**Ytterbium (Scaled)**	Erbium (Raw)	Erbium (Scaled)
Functional Performance	0.5	2	1.220	0.61	0.657	0.33	0.707	**0.353**	1.112	0.56
Comparative Cost	0.3	3	2	0.67	2	0.67	3	**1**	3	1.00
Aircraft Performance	0.1	2900	1025.00	0.35	1025.00	0.35	1600.00	**0.55**	1600.00	0.55
Technology Risk	0.1	9	4	0.44	4	0.44	6	**1**	6	0.67
Total	1.00			0.50		0.64		**0.73**		0.63

a. Performance

Section C discusses the M&S methods used to evaluate the laser type alternatives. The results from this simulation were averaged for each laser at each location, producing an average total dwell time, seen Table 8. This average score (raw score) was then divided by the maximum allowable score of 2 seconds, to produce the scaled core in Table 7, above. Since a higher average time indicates a poorer laser performance, this value was subtracted from 1 during to calculate the total score for each alternative.

Table 8. Average Laser Dwell Times

	Average Dwell Time (sec)
Nd:YAG	1.21982
NdYAG (2x Freq)	0.65690
Ytterbium	0.70662
Erbium	0.92266

b. Comparative Cost

The fiber lasers have been used for ship based operations. Meanwhile, the other laser types have not been used for any operations at the required power output of the Cyclops pod. It is reasonable to believe that the integration costs of the Nd:YAG lasers will be notably larger than that of the fiber lasers. Thus, the fiber lasers receive a scaled score of three, while the other lasers receive a score of two.

c. Aircraft Performance

This was determined solely as a function of weight. The weight was calculated using the expected size of the laser, given the necessary power output. The weight was calculated in pounds and then divided by the overall allowable weight of the pod, 2,900 pounds. Since a higher weight negatively affects the aircraft performance, this value was subtracted from 1 during to calculate the scaled score for each alternative.

d. Technology risk

The fiber lasers have been used on ship based operations for the United States Navy. There is a substantial difference between the ship based operations when compared to the air operations of the F/A-18. Namely, the limited size and weight restrictions when carried on an aircraft versus a large ship. Thus, the fiber lasers receive a TRL score of six, for the raw score. Meanwhile, the Nd:YAG lasers have not been used in an operation the size of the Cyclops pod. While the theoretical usage has been proven, there have not been any real tests as a laser of this size. Thus, the Nd:YAG lasers receive a TRL of 4.

2. Tracking Subsystem

The final scoring of the tracking system alternatives, discussed in Section A, can be found in Table 9. The DAS system received the highest comparative score, 0.99, out of 1.0. The other systems received a 0.88 (MWS) and 0.85 (DIRCM). Overall, the high technology readiness, low expected cost, and superior performance of the DAS set it apart from the other systems.

Table 9. Tracking Subsystem Alternative Scoring

		Tracking & Detection							
	Weight	Maximum	**DAS (Raw)**	**DAS (Scaled)**	DIRCM (Raw)	DIRCM (Scaled)	MWS (Raw)	MWS (Scaled)
Functional Performance	0.5	10	**10**	**1.00**	10	1.00	10	1.00
Comparative Cost	0.3	3	**3**	**1.00**	2	0.67	2	0.67
Aircraft Performance	0.1	10	**10**	**1.00**	5	0.50	5	0.50
Technology Risk	0.1	9	**8**	**0.89**	9	1.00	7	0.78
Total	1.00			**0.99**		0.85		0.83

a. Performance

All tracking system alternatives will perform well in the expected environments. Each system is a proven tracking system capable of tracking the desired targets. As such, each system received the maximum raw score of 10.

b. Comparative Cost

The DAS was designed for use on the F-35 Joint Strike Fighter to the similar flight profile of the Cyclops mission. So, the system is already designed meeting the complicated requirement of integration with a high-performance aircraft environment. The other systems use technologies that are not suited for the intended operational envelope of the Cyclops pod, so it is reasonable to assume that their integration efforts will cost notably more.

The DAS receives a raw score of three, while the other two systems receive a score of two.

c. Aircraft Performance

The functionality of the DIRCM & MWS systems degrade significantly with fast-moving and high-maneuvering aircraft, as discussed in Section A. DAS, meanwhile, is designed to work with high-speed aircraft, so it receives a score of 10. The DIRCM and MWS both receive a raw score of five. This score of 5 highlights the effect of the mission impact of the F/A-18 by limiting the flight to the subsonic regime with limited maneuverability.

d. Technology Risk

The DIRCM is a proven system, in existence and operation for several decades. Thus, the tracking system receives a TRL score of nine, for the raw score.

The MWS has not been used solely in a mission environment, though operational testing has proven the system's performance within the limited operational environment. The MWS receives a TRL score of seven.

The DAS has demonstrated its functionality throughout F-35 testing through IOC. However, the newness of the system limits the TRL rating of an eight.

3. Power Supply Subsystem

The power system alternatives were scored for both the Battery and the RAT, with the specific alternatives discussed in Section A. The results of the analysis are seen in Tables 10 and 11. For the RAT, the ATGI system received a higher rating (0.77) than the generic COTS (0.70), largely due to its superior performance. Also, the Li-ion battery (0.84) received a higher rating compared to the lead-acid batteries (0.75) because of its higher predicted performance.

Table 10. Power Supply Subsystem Alternative Scoring (RAT)

		RAT				
	Weight	Maximum	COTS (Raw)	COTS (Scaled)	**ATGI (Raw)**	**ATGI (Scaled)**
Functional Performance	0.5	10	4	0.40	**10**	**1.00**
Comparative Cost	0.3	3	3	1.00	**1**	**0.33**
Aircraft Performance	0.1	10	10	1.00	**10**	**1.00**
Technology Risk	0.1	9.000	9	1.00	**6**	**0.67**
Total	1.00			0.70		**0.77**

Table 11. Power Supply Subsystem Alternative Scoring (Battery)

		Battery				
	Weight	Maximum	Lead-Acid (Raw)	Lead-Acid (Scaled)	**Li-Ion (Raw)**	**Li-ion (Scaled)**
Functional Performance	0.5	10	6	0.60	**10**	**1.00**
Comparative Cost	0.3	3	3	1.00	**2**	**0.67**
Aircraft Performance	0.1	2900	550.00	0.81	**200.00**	**0.93**
Technology Risk	0.1	9	6	0.67	**4**	**0.44**
Total	1.00			0.75		**0.84**

a. Performance

RAT

As discussed in Section A, the COTS will perform significantly worse than the ATGI RAT, forcing the system to use battery power as the primary power for the laser. Since the main purpose of the RAT is to supply power, the COTS receives a notably lower raw score (4/10) than the ATGI (10/10).

Batteries

The expected performance of the Li-ion will exceed that of the lead-acid batteries. While both may be able to provide the necessary power, the Li-ion batteries will provide the power in a more efficient and reliable method. The cells of the lead-acid batteries will fail more often, leading to a significant decrease in the performance expectation. So, the Li-ion battery receives a raw score of 10, while the lead-acid battery receives an eight.

b. Comparative Cost

RAT

The main benefit of the COTS product is that it will be cheap since a system can be selected that is already proven and integrated with an aircraft. The ATGI, meanwhile, is a new technology with unknown integration costs. The COTS receives a raw score of 3, while the ATGI receives a one, representing the 10x difference between the two systems.

Batteries

The upfront integration costs of the lead-acid will be much cheaper than the Li-ion batteries. The Li-ion batteries, with the expected power output, are a newer technology that has not been developed for use on a system the size of the Cyclops pod. This will lead to a greater integration effort and cost to ensure that the proper power output can be provided within the Cyclops pod. This difference leads to a raw score of three for the lead-acid battery and a two for the Li-ion battery.

c. Aircraft Performance

RAT

There is no appreciable difference in the effect on aircraft performance between each RAT, so they are rated the same

Batteries

Aircraft performance was determined solely as a function of weight. The Wh/kg of each battery type was estimated as 110 Wh/kg for lead-acid batteries and 40 Wh/kg for Li-ion batteries. This weight was calculated in pounds and then divided by the overall allowable weight of 2900 pounds, discussed in Section B. Since a higher weight negatively affects the aircraft performance, this value was subtracted from one to produce the scaled score during to calculate the total score for each alternative.

d. Technology Risk

RAT

Similar to the aircraft performance, the COTS product receives a raw score of 9 due to its use in current mission environments. Meanwhile, prototype HiRATs have been used in relevant environments, earning a TRL score of six.

Battery

The Li-ion batteries are still early in the developmental process for this type of system. While laboratory and analysis tests have provided positive results, the system has not matured beyond a TRL of four, for the raw score. While Lead-acid batteries are a more understood system, they also have not been used to this kind of scale as the Cyclops Pod in an operational environment. So, the lead-acid batteries receive a TRL score of six.

E. CHAPTER SUMMARY

In many ways, this chapter served as the culmination of the work of the previous sections. The first three chapters were devoted to creating the conceptual framework for the Cyclops pod. This conceptual design process is especially important for a relatively unprecedented project such as this. The requirements and architecture drove the selection of technology alternatives. Similarly, the CONOPS and requirements drove the scoring metrics and design of the simulation.

This chapter proved that existing and near-future technology can meet the requirements of this project. It also clearly showed the important benefits and drawbacks of the technology alternatives. Chapter V will conclude this report. It uses the scores calculated in this chapter to choose the best alternatives.

V. RECOMMENDATIONS

This chapter is the final chapter of the report. It is a collection of recommendations both for topics covered in this paper and for further development of the project. Using the research and analysis from Chapters I–IV, the optimal alternatives are identified. Recommendations for future work on the project have also been created using this information and the experience of creating this report. These recommendations are intended not only to alleviate some of the most significant constraints on this report but also to continue to develop this project down avenues of research unavailable for this report.

A. ALTERNATIVE RECOMMENDATIONS

This section uses the scoring results of Chapter IV as well as additional research into the technologies to determine the technologies best suited for use in the Cyclops pod. These recommendations are based on analysis of the alternatives separate for each system. Due to the immature nature of the technology and the unprecedented design of the Cyclops system, predicting integration problems between subsystems was considered outside the scope for this report.

1. Laser Subsystem

Ultimately, two lasers remained worthy of consideration after simulation. The frequency doubled Nd:YAG (average dwell time 0.66 seconds) laser is the best overall performer, and the Ytterbium laser is second (average dwell time 0.71 seconds) but with a more mature design. As both lasers meet the dwell time performance requirement, the advantage is given to the Ytterbium laser. The more mature technology allows for a lower anticipated cost and risk and shorter development cycle. The expected result is a more cost-effective acquisition process and a more rapid fielding schedule for the fleet.

2. Tracking Subsystem

Among all these technologies there are a few things that distinguish one from the rest. First, while the DIRCM system is extremely well tested, it has integration issues with fast jets due to the two-color IR sensor and was not designed to integrate with them as it does not currently have a light enough design and powerful enough laser to be operational effective for the F/A-18. The MWS system was designed to work with fast movers and integrate with whatever subsystems they employ. However, when compared to the other two suggested technologies, it is the least tested. This is especially alarming as it employs a UV sensor system, which has had difficulty integrating with fast jets in the past. The DAS system was designed to work with fast movers and was specifically designed for the F-35; therefore, it is already operational. Finally, the single-color IR sensor processing speed has proven itself on fast jets and therefore stands as the best choice for the tracking and detection system for the Cyclops.

3. Power Supply Subsystem

The Cyclops pod must generate its own power due to lack of available power from the aircraft; therefore, the Power supply has high power requirements for the effectiveness of the laser. It is also important that the system maintains active during missions; for that reason, we are going to concentrate the power supply recommendations to the Ram Air Turbine (RAT) and the battery. The purpose of the RAT is to provide enough power to the pod during flight and provide high power to the laser during operational conditions (speed and altitude). The purpose of the high power battery is to provide power to the laser when flying conditions do not allow the RAT to generate enough power.

To meet power requirement, we recommend the use of HiRAT. This type of generation unit has been used in the development of the Next Generation Jammer, and its innovative design allows producing high power at the expected operational speeds and altitudes. We believe that this technology can be used to develop an effective Power Generation Unit capable of supplying power to the pod and laser during incoming threats.

As discussed throughout this paper, backup power is necessary to keep the Cyclops system active; therefore, we recommend the use of high powered batteries. Lithium Ion batteries are currently the leading technology in high power and energy density. We also have to consider the weight and size constraints, so the use of this technology is highly recommended.

4. Optimal Configuration Physical Characteristics

Table 12 shows a weight estimate of this recommended system. Due to the lack of information on some aspects of the pod, weights of analogous components were used. Specifically, the skin and structure of the pod were approximated by the weight of an FPU-12 external fuel tank. The mission computer was approximated by a similar subsystem on the ATFLIR pod known as the Pod Electronics Housing. Finally, the weight of the DAS was approximated by the Pointer/Tracker Assembly of the DIRCM system. Due to the HiRAT's early stage in development, it is difficult to estimate its weight. Instead, the HiRAT is assumed to make up the same proportion of weight for the AADL as it does for the ALQ-99 jamming pod. The weight of the entire ALQ-99 is 1000 lb. (Walker 1990). The weight of the RAT powering it is 160 lb. (NSN Central 2017). Based on this, the HiRAT is expected to make up 16% of the total weight of the AADL. All told, the recommended system weighed in at 3500 lb. This was less than the 4100 lb. weight of the full FPU-12 external fuel tank.

Table 12. Recommended System Weight

Component	**Weight (lb)**
Skin/Frame	850
Mission Computer	70
DAS	220
Ytterbium Laser	1600
Li-Ion Batteries	200
HiRAT	560
Total Weight	**3500**

Figure 28 shows a notional 3D model of the AADL. Included in the diagram are outlines indicating areas for certain subcomponents. The dimensions for these components are based on analogous, existing components where available. The large diameter of the pod is driven by the Ytterbium laser. That dimension of the pod is based on an industrial laser which has similar performance characteristics (IPG Photonics

2015). The volume of the batteries is based on the need to deliver 300 kW of power. At 5.8 kW/l, approximately 3,100 cubic inches are required (A123 Systems 2017). DAS is not taken into account in this figure since it sensors are distributed around the aircraft. The model is notional and shows the general shape and placement of the various components.

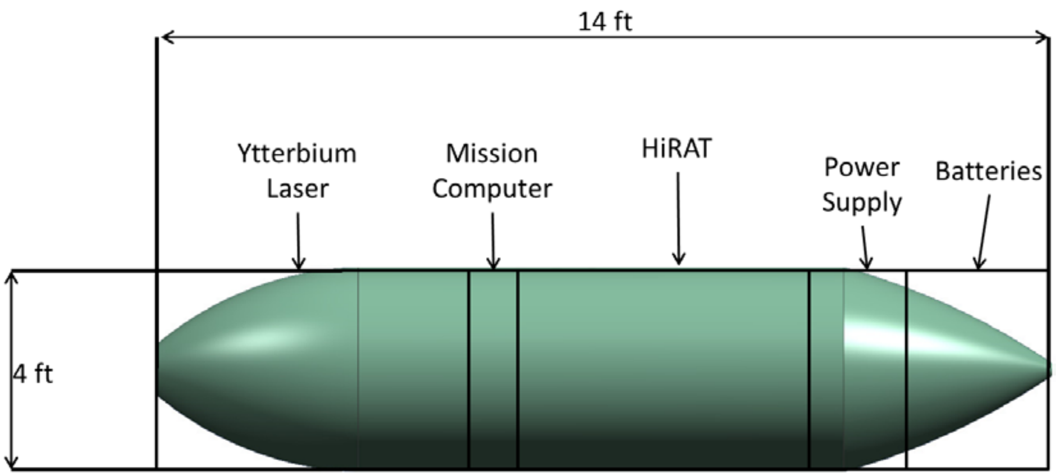

Figure 28. AADL 3D Model Subcomponent Breakdown

B. FUTURE DEVELOPMENT

The largest constraint on this report has been the lack of available information on the technology critical to the report. This lack of information was due to either the immature nature of the technology or the classification of the information.

Due to the shortage in applicable performance research on much of the technology in the report, the next step of the project development is to begin creating that research. Limitations on budget, facilities, and timeline of this report prevented any sort of testing to supplement the information from the literature review. Almost all laser performance data was based on laser performance tests done in laboratory conditions for civilian uses. Testing under more realistic could verify the laboratory results as well as identify potential concerns that would not show up in an academic setting. In addition, integration issues between subsystems were not considered for this report due to the lack of available information on hardware and software interaction on the relevant systems.

When the physical performance testing takes place, early interface testing should begin as well. While this will not replace the more in-depth testing later in development, it will provide an early idea on further concerns to be overcome before project completion.

The next phase of the project development should also be classified. Much of the performance specifications for the tracking subsystem and existing countermeasures systems are classified. The decision was made to maintain this report as unclassified was made to keep sharing and communication between team members as easy as possible. Unfortunately, this decision forced the scoring of the alternatives to be relatively high level, especially the tracking subsystem. By making the next phase classified, a much more detailed analysis will be possible.

Lastly, while the benchmark-style simulations used for scoring are adequate for the purposes of this report, a more realistic combat scenario simulation should be developed and tested. This simulation should simulate performance in a 3D environment and model an aircraft's flight path on a combat mission with randomized encounters with incoming missiles at different ranges.

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APPENDIX A. REQUIREMENTS

Table 13. Detailed Requirements

Number	Requirements
0.0	**Protect F/A-18 from incoming missiles**
1	**Communicate with friendly forces**
1.1	**Communicate to the aircraft information concerning incoming threats**
1.1.1	Alert pilot to missile threat
1.1.1.1	Send threat data to ground control
1.1.1.2	Alert pilot when missile threat(s) are defeated
1.1.1.3	Pass defeated missile data to aircraft mission computer
1.1.1.4	Validate true threats to reduce false alarms
1.1.1.5	Alert pilot to incoming threat with low likelihood of interception
1.2	**Communicate status of Cyclops systems**
1.2.1	Be able to communicate with all systems within the pod
1.2.2	Communicate status to aircraft
2	**Defeat incoming missile before damaging the aircraft**
2.1	**Defeat incoming missile at 4.5 mile range**
2.2	**Capable of defeating incoming missiles within three seconds**
2.3	**Capable of engaging missiles within 90° arc around aircraft**
2.3.1	Capable of engaging missiles within a 90° arc below the aircraft
3	**Be capable of powering all systems simultaneously**
3.1	**Be capable of completely powering the pod**
3.1.1	Provide electrical power to all Cyclops systems
3.1.1.1	Convert and regulate supplied power to be used by all systems
3.1.1.2	Be able to store generated power to be used by all systems
3.1.2	Distribute electrical power to all Cyclops systems
3.2	**Capable of spending prolonged periods in an active status**

4	**Track and target incoming missiles**
4.1	**Track threats posed by multiple incoming missiles**
4.1.1	Detect missile threats
4.1.2	Capable of tracking multiple incoming missile threats simultaneously
4.1.3	Track missiles within effective range
4.1.4	Track missiles regardless of seeker type
4.2	**Tracking system shall prioritize threat missiles**
4.2.1	Tracking system shall identify highest threat missiles
4.2.2	Capable of queueing additional lower priority threats
4.3	**Detect and track missiles during aircraft maneuvers**
4.4	**Track missile over a 90° arc**
4.4.1	Track missiles in a 180° radius

APPENDIX B. EXTENDSIM SIMULATION MODEL

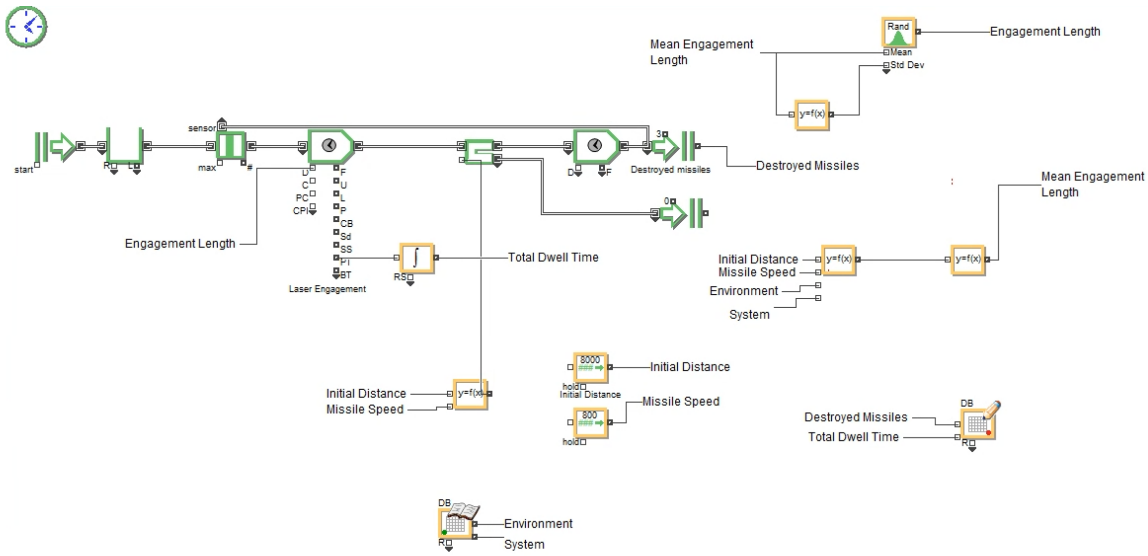

Figure 29. ExtendSim Performance Simulation Model

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