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AN ANALYSIS OF SIZE, WEIGHT AND POWER (SWAP) FOR EMP SHIELDING OF THE RAAD SYSTEM

by

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December 2021

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An air assault execution revealed the challenges of performing a complex forcible entry operation in a contested, anti-access/aerial denial (A2/AD) environment. Even with future aircraft, the air assault operation was vulnerable to enemy air defense capabilities. Landing zone restrictions reduce the number of areas the multinational forces could conduct air assault operations, providing a marked advantage to near-peer adversaries in planning likely counterattack operations and increasing the risk to forces. Through a combination of integrated air defense systems (IADS), indirect fires, direct fires, and reserve formations specifically tasked with contesting air assault operations, threat forces are expected to contest the air assault force during insertion. As the report stated, the wargame demonstrated the need for new Army air assault capabilities.

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ABSTRACT

In 2019, the U.S. Army's Future Study Program designed and led the Unified Quest Multinational Seminar Wargame. This wargame examined U.S. forces, partners, and allies' interoperability requirements to defeat a near-peer threat in a future operational environment. As part of the seminar wargame, Army forces executed a critical air assault operation in adversary-controlled terrain to support a river crossing. This task covers multiple aspects of operational planning and coordination for an assault operation as outlined in AFC Pamphlet 71 20-1.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	Anti-Access / Aerial Denial
AFC	Army Futures Command
AME	Army Modernization Enterprise
AoA	Analysis of Alternatives
ARL	Army Research Laboratory
ATMS	Arc Thermal Metal Spraying
DARPA	Defense Advanced Research Projects Agency
dB	Decibel
DF	Direction Finding
DNA	Defense Nuclear Agency
DNA	Defense Nuclear Agency
DOD	Department of Defense
DoF	Degrees of Freedom
EMP	Electromagnetic Pulse
FLRAA	Future Long Range Assault Aircraft
IADS	Integrated Air Defense System
ISR	intelligence, surveillance, and reconnaissance
LIDAR	Light Detection and Ranging
LZ	Landing Zone
METT-TC	Mission, Enemy, Terrain, Troops–Time, Civilian Considerations
NCC	National Coordinating Center for Communications
PE	Protective Enclosure
RAAD	Robotic Air Assault Drone
SE	Systems Engineering
SWaP	Size, Weight, and Power
TREE	Transient Radiation Effects on Electronics

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EXECUTIVE SUMMARY

As part of a wargame conducted in 2019, the U.S. Army's Future Study Program analyzed the requirements to defeat a near-peer threat in a future operational environment. This wargame analyzed the execution of a critical air assault operation in hostile-controlled territory to support a river crossing. The result of the wargame revealed the challenges of performing a complex forcible entry operation in a contested, anti-access/aerial denial (A2/AD) environment. Even with future aircraft, the air assault operation was vulnerable to enemy air defense capabilities. Landing zone restrictions reduce the number of areas the multinational forces could conduct air assault operations, providing a marked advantage to near-peer adversaries in planning likely counterattack operations and increasing the risk to forces.

To address the concerns highlighted by the wargame, the Army tasked Team Ignite, at the Army Research Laboratory (ARL), to study how best to conduct an air assault operation using land-based robots that deploy forward of the human element. This capstone report serves to provide vital information to enable Team Ignite in development of the Robotic Air Assault Drone (RAAD) system. Through discussions with our stakeholders, the capstone team focused our research to studying the effects on size, weight, and power (SWaP) of the RAAD system by protecting against electromagnetic pulse (EMP) weapons.

The following problem statement was created to assist Team Ignite in accomplishing their mission: The high susceptibility of the RAAD system to EMP requires hardening, but the potential tradeoffs to SWaP may have significant impacts on the desired capability of the system. The primary research objective for this project was to execute a SWaP tradeoff analysis for EMP hardening on the RAAD system to reduce its EMP vulnerability while minimizing the effects on operational capability.

This study outlines the steps that the research team conducted to answer our problem statement and meet our research objectives. The team began by conducting a literature review of the most applicable literature to generate the SWaP trade space analysis and provides: the background for different types of EMP, traditional materials utilized for

EMP protection, alternative lightweight solutions that shield against an EMP, an overview of the Atlas Robot by Boston Dynamics that is used as the baseline system for the study, a summary of SWaP, and an introduction to an operational scenario that the RAAD system will likely be employed in.

Next, the team discussed the methodology used to answer the research objective. The capstone team methodology was developed based on an IDEF0 functional flow as a tailored systems engineering process.

The research problem focused on protecting the RAAD against EMP while minimizing the impacts on operational capabilities. Given the initial case study and design concept provided by Team Ignite of ARL, the methodology followed a successive process beginning with developing the operational context for which the RAAD will operate. From the information gathered while defining the operational context, the team performed a functional analysis to determine what the RAAD system must be able to do at its most basic level. The output of this analysis was a trace function to component list which was used to execute Analysis of Alternatives (AoA) and SWaP analysis. The result of our AoA was used to further understand how SWaP impacted the functions previously discussed. The research focused on methods of EMP shielding for the RAAD system and the tradeoff analysis with regards to SWaP considerations.

The outcomes of the methodology outlined previously were used to defined screening criteria of EMP shielding materials available, value factors to select the most appropriate materials for analysis, and discussion of categorical winners because of a SWaP analysis grounded in functional requirements for the RAAD/ATLAS robotics platform. Subsequently, the team examined the introduction of weight to the RAAD/ATLAS platform as the primary factor for the determination of operational effectiveness of the system as it relates to power requirements with size examined as a factor of inertial change because of subsequent weight increases.

Six material solutions were further analyzed to produce a SWaP tradeoff analysis of alternatives for EMP hardening of critical vulnerable components identified by the function-to-component trace matrix. EMP shielding and the solutions identified in this work should be integrated early in the design of the RAAD system to maximize shielding efficiency while minimizing undesired effects to the system.

Finally, the team discusses limitations to this research effort and provides focus for future studies. To minimize the effects of EMP hardening, EMP protection should be considered a system requirement and integrated early in the system design process to maximize efficiencies and minimize the SWaP tradeoff.

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I. INTRODUCTION

Air assaults, along with amphibious and airborne assaults, remain the most hazardous means for forcible entry into contested or enemy territory. Decisive engagement and destruction of enemy forces utilizing air assault operations has long been an effective and consistent means for seizing and holding key terrain in the most challenging of theater and tactical level operations (Department of the Army 2013b). Air assaults dramatically extend the commander's ability to influence operations through projection of power through conventional forces, but this forward projection often leaves these conventional forces vulnerable to counterattack, especially if surprise is not achieved as an element of the operation. Commanders should be empowered to execute firepower, mobility, and integration of helicopter assets to engage and destroy enemy personnel and structures with little to no physical threat to service members. This is the intent of the Robotics Air Assault Drone (RAAD), whose employment throughout theater-level operations allows commanders to surge manpower to where it is needed to effectuate decisive engagements within the theater.

The current military approach to the use of drones on the battlefield is predominantly as advanced aerial assets to conduct surveillance and aerial strike capabilities to avoid the insertion of ground forces in contested areas such as in the Middle East (Urcosta 2020). This inability to physically hold terrain with physical assets and forces on the ground leads to losses because of the short-term gains associated with bombing campaigns. There are, however, no known ground-based drones developed or deployed to engage enemy forces at the point of battle and physically able to occupy territory. The RAAD system addresses this capability gap and will involve the use of highly sophisticated composite materials and electronics to ensure maneuverability and survivability in most combat environments. The use of sophisticated equipment requires protection from electromagnetic interference and pulses that near-peer adversaries currently have the ability to deploy and will almost certainly employ in the future fight.

A. BACKGROUND

In 2019, the U.S. Army's Future Study Program designed and led the Unified Quest Multinational Seminar Wargame. This wargame examined U.S. forces, partners, and allies' interoperability requirements to defeat a near-peer threat in a future operational environment. As part of the seminar wargame, Army forces executed a critical air assault operation in adversary-controlled terrain to support a river crossing. This task covers multiple aspects of operational planning and coordination for an assault operation as outlined in *Army Futures Command Concept for Maneuver in Multi-Domain Operations 2028*, AFC Pamphlet 7120-1.

An air assault execution revealed the challenges of performing a complex forcible entry operation in a contested, anti-access / aerial denial (A2/AD) environment. Even with future aircraft, the air assault operation was vulnerable to enemy air defense capabilities. Landing zone restrictions reduce the number of areas the multinational forces could conduct air assault operations, providing a marked advantage to near-peer adversaries in planning likely counterattack operations and increasing the risk to forces. Through a combination of integrated air defense systems (IADS), indirect fires, direct fires, and reserve formations specifically tasked with contesting air assault operations, enemy forces are expected to contest the air assault force during insertion. As stated in the RAAD Discovery report, the wargame demonstrated the need for new Army air assault capabilities (Glaz et al. 2020).

The Army tasked Team Ignite, at the Army Research Laboratory (ARL), to study how best to conduct an air assault operation using land-based robots that deploy forward of the human element. Team Ignite had not considered the potential destructive effects of electromagnetic pulse (EMP) on the RAAD system and key considerations for its protection needed to be addressed to minimize impact to the RAAD systems operation. The RAAD system would be limited in size and weight to ensure maximum durability balanced with maximizing operational time as dictated by its assumed limited payload. Key considerations for the addition of EMP shielding to the RAAD system could present significant impacts regarding the size, weight, and power (SWaP) considerations. A tradeoff analysis needs to be conducted to highlight the impacts of EMP/EMI resistant material with respect to the Swap considerations.

B. PROBLEM STATEMENT

The high susceptibility of the Robotic Air Assault Drone (RAAD) system to Electromagnetic Pulse (EMP) requires hardening, but the potential tradeoffs for size, weight, and power (SWaP) may have significant impacts on the desired capability of the system.

C. RESEARCH OBJECTIVES

The primary research objective for the capstone project is to execute a size, weight, and power tradeoff analysis for EMP hardening on the RAAD system to reduce its EMP vulnerability while minimizing the effects on operational capability.

There are several secondary research objectives: recommend solutions for balancing size, weight, and power with operational performance for the RAAD system; analyze methods of EMP hardening to present quantifiable results pertaining to size, weight, and power; and to establish a baseline to explore the ability of the RAAD system to successfully conduct a wide gap crossing given the SWaP analysis conducted.

D. CAPSTONE OVERVIEW

This paper outlines the effort conducted by students, faculty, and officers of the Naval Postgraduate School to conceptualize, develop, and model applicable means for providing EMP protection for the RAAD and any future terrestrial drone applications out to 2035. We sought to describe the most applicable methods of protection for the Atlas robotics system, the effective levels of EMP protection, as well as the SWaP considerations to ensure effective deployment via most aerial deployment methods. Models generated will illustrate the effectiveness of EMP protection across multiple configurations to ensure a comprehensive and broad demonstration of EMP protection capabilities for terrestrial-based drone applications.

Chapter II introduces and summarizes the most applicable literature that capstone team researched to generate the SWaP trade space analysis and provides: the background for different types of EMP, traditional materials utilized for EMP protection, alternative lightweight solutions that shield against an EMP, an overview of the Atlas Robot by Boston Dynamics which is used as the baseline system for the study, a summary of SWaP, and an introduction to an operational scenario that the RAAD system will likely be employed in.

Chapter III discusses the methodology used by the Capstone team to define the operational concept, conduct functional analysis and decomposition, conduct function to component tracing, and to conduct a SWaP Analysis of Alternatives (AoA) to deliver analytical data for future research into this concept.

Chapter IV discusses EMP shielding materials available, value factors to select the most appropriate materials for analysis, and discussion of categorical winners because of a SWaP analysis grounded in functional requirements for the RAAD/ATLAS robotics platform.

Chapter V concludes with the analysis of several different commercial material solutions and the techniques used to provide critical component protection with minimal impacts to SWaP and negligible effects to the operational capability of the system.

II. LITERATURE REVIEW

A. WHAT IS AN ELECTROMAGNETIC PULSE?

Electromagnetic pulses were first identified in 1945 during the United States' first nuclear test. Dr. Enrico Fermi theorized that one of the byproducts of a nuclear explosion would be the production of gamma rays that would accelerate the electrons near the speed of sound, and that once these electrons impacted electrical devices it would cause them to malfunction (Baiocchi 2011). To further understand the devastating effects of an EMP, a high altitude EMP test was conducted over Johnston Island in the Pacific Ocean in 1962 as part of Operation Starfish Prime. A 1.4 megaton nuclear weapon was detonated 400 km over the island, generating a 14 kV/meter EMP blast that affected the entirety of Johnston Island. One hundred nanoseconds later, the island of Oahu on Hawaii experienced a 5.6 kV/m EMP that blew fuses in streetlights, interrupted inter-island telephone communications, and damaged vehicle ignition systems. The island of Oahu is roughly 900 miles away from Johnston Island.

1. How an EMP Is Produced

The National Coordinating Center for Communications (NCC) categorized EMP waves into three primary categories that generate devastating effects on electronic devices or components: natural, non-military manmade, and military manmade (National Coordinating Center for Communications [NCC] 2019). Electronic components are created to be able to conduct and transmit electric voltages and currents within a specific range; the effects of an EMP can significantly increase the amount of electricity within a component rated capacity, resulting in an electrical surge that can destroy the component and possibly render the entire system inoperable.

Naturally occurring EMPs happen in one of three distinct ways: solar flares, lightning strikes, and unipolar pulses created by earthquakes. The Carrington Event of 1859 was a worldwide EMP that was caused by natural means and occurred because of a geomagnetic storm that was caused by a massive solar flare and coronal mass ejection from the sun (Oreskovic 2011). Geomagnetic storms can produce enormous electrical interference and will impact electromagnetic spectrums across a large area, and possibly even on a worldwide scale.

Non-military manmade EMP generators focuses on energy generation near population centers. Examples of these types of energy generators are high-voltage power lines and converter stations that can malfunction and generate limited wide-spectrum pulses across varying ranges depending on their severity (Li 2021).

Military manmade EMP generators are weapons specifically designed to disrupt, disable, and potentially destroy electrical systems. Nuclear weapons such as the one used during Operations Starfish Prime, were detonated in the Earth's atmosphere and released radiation that was ultimately responsible for generating an EMP. The effects of radiation may only last a few seconds, but gamma rays created as a result of the radiation would severely damage all unshielded electronic devices within the EMPs blast radius (Podgorski 1984).

2. The Effect of an EMP on Electronic Devices

In a Defense Nuclear Agency (DNA) EMP Awareness report, Transient Radiation Effects on Electronics (TREE) cause electronic components to surge past their rated capacity which degrades and damages electrical devices due to exposure to gamma radiation (Mindel 1977). Lower level EMP events can generate small levels of electrical noise or interference in electronic components that may result in damage either immediately or slowly over time. Higher level EMP events can cause electronic components to spark and catch on fire, therefore, generating physical damage to the entirety of the system rather than just the incident area. Higher level EMP events can also increase the current and voltage rates that electronic components or wires connecting the component are rated for, therefore causing long term or irreplaceable damage. Each of these can completely immobilize electronic platforms ranging from small consumer cell phones to airplanes, or even entire population centers (Mishra and Sashi 2014). Figure 1 displays the effect that a lower level EMP can have on electronic circuits if they are exposed and have limited shielding.

Figure 1. The Effects of a Low Level EMP Against Unshielded Electronic Circuits. Source: Mishra and Sashi (2014).

3. Current Military Manmade Uses for Creating an EMP

During Operation Starfish Prime, the United States military and the Atomic Energy Commission wanted to better understand the effects of a weapon that could contain the electromagnetic spikes generated by a nuclear weapon. Their results realized the foundation for the E-bomb:

> An e-bomb is a kind of weapon that uses the electromagnetic spectrum, emitting short, but very high power, microwave burst pulses that spikes into the gigawatts power range lasting for only microseconds causing some specific levels of damage by emitting enough energy to overwhelm electronic devices and their components. (Yurtoglu 2009, 3)

These weapons are easily targetable and produce controlled EMP effects that can be delivered via a bomb or glide bomb platform, or a missile onto a strategic enemy position (Kopp 1996). There has been extensive study into the use of e-bombs and their prevalence on the battlefield and the e-bomb likely the greatest threat to the RAAD system.

B. EMP SHIELDING METHODS

1. How to Shield Against an EMP—Traditional Shielding Methods

To protect the internal actuators, sensors, and vulnerable electronic components housed within the RAAD System from an EMP, we must understand traditional shielding methods. Small consumer electronics and even commercial or military equipment electronics must be enclosed in some form of shielding that blocks out the electromagnetic pulse. The shielding used to surround electronic components must have some varying degree of shielding effectiveness against the effects of an EMP, meaning, shielding components can both absorb and reflect the effects of an EMP to preserve the functionality of the component.

A common method used to shield against an EMP is the Faraday cage which has applications ranging from small consumer electronics to military and commercial structures. Faraday cages can be used to shield against the effects of an EMP by enclosing susceptible components inside a case or fixture that blocks external static and non-static electrical fields (Pereira 2013). Several of the examples that are mentioned later in this chapter employ a Faraday cage, meaning that they use metal plates, rewire mesh or reinforced concrete to enclose electronic components to protect them against the effects of an EMP.

A traditional commercial or military structure built to withstand the effects of an EMP would include plywood walls to a thin sheet of galvanized steel on one or both sides of particleboard panels along with steel support structures welded with steel plates, which is an example of a larger constructed Faraday cage. The overall thickness for the outer walls of a facility of this composition would be thicker than 0.01 in (0.254 mm) and would provide shielding against an EMP (Kim, Min, and Park 2021). Figure 2 shows how a typical manmade EMP structure would appear.

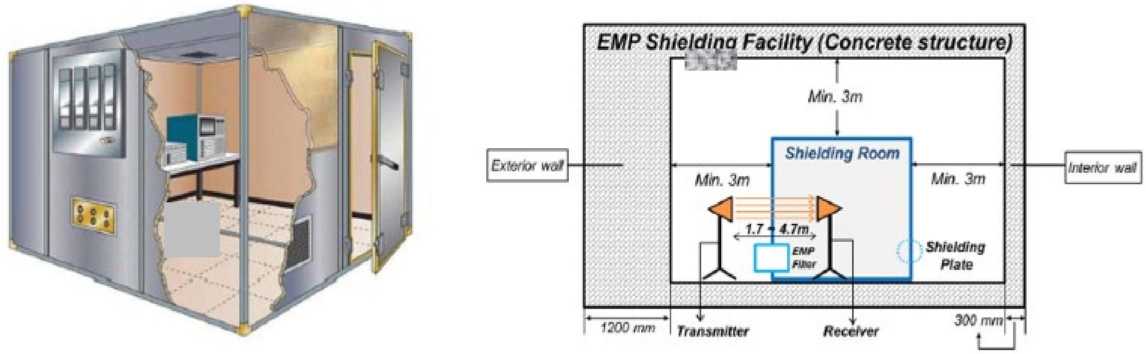


Figure 2. Conventional EMP Shielding Method for Military Command and Control Rooms. Adapted from Kim, Min, and Park (2021); Lee (2017).

The AN/UYK series of minicomputers used by the Army and Navy in the 1980s through the 1990s is an example of EMP protection on a smaller scale. The AN/UYK computers' outer casing was designed with a metal mesh plate that would absorb and reflect the EMP radiation and were tested extensively during this period so that researchers could better understand the effects that varying levels of EMP had on electronic components (Naval Surface Weapons Center 1977).

Both heavy and lightweight materials utilized to shield against an EMP have two things in common with each other: they can reflect and/or absorb the output of an EMP to a certain degree, normally represented by decibels (dB) which is the metric used to measure the energy attenuation within specified a frequency range that the shielding material can protect against. If the effects of the EMP exceeds the dB within the frequency range that the component is shielded against, then the possibility for the component to be damaged is greatly increased. Faisal Shahzad and his team provide the following quote describing the characteristics of an effective shielding material in a research article submitted to Science magazine in 2016:

> The primary function of EMI (electromagnetic interference) shielding is to reflect radiation using charge carriers that interact directly with the electromagnetic fields. As a result, shielding materials need to be electrically conductive. However, conductivity is not the only requirement. The second mechanism of EMI shielding requires absorption of electromagnetic radiation due to the material's electric and/or magnetic

> dipoles interacting with the radiation. High electrical conductivity is the primary factor determining reflectivity and absorption characteristics of the shield. (Shahzad et al. 2016, 1137)

2. Materials Used to Shield against an EMP

The two most common materials used to shield against an EMP are reinforced concrete and various forms of metal such as steel due to their commercial availability, ruggedness, and structural longevity. Metals are widely used in EMP facilities due to their excellent electrical shielding properties but are too heavy for most robotic applications. Composite materials with polymers have recently been introduced into commercial application to provide protection against an EMP threat. These materials are lightweight and more environmentally resistant than traditional structures. “Most fibers are made of natural or synthetic polymers with significantly high electrical resistance and are often used in applications such as electric heating, protection from electromagnetic waves, and signal transmission due to their ability to either reflect or absorb electromagnetic waves” (Kim, Min, and Park 2021, 5).

An additional material utilized to provide EMP shielding is electromagnetic shielding paint, which is obtained by dispersing metal fillers of nickel, copper, and silver on the surface of the resin components. Once created the paint is applied to the surface that you want to harden against the effects of an EMP to further reinforce the base material. This solution is not advisable as a primary means of shielding and should only be used to further increase protection to a certain degree. Electromagnetic paints have little durability, especially in hazardous environments as the paint generally peels off the structure it is applied to, therefore degrading EMP shielding effectiveness (Kim, Min, and Park 2021). Electromagnetic shielding paint is another example of utilizing a Faraday cage to shield against an EMP.

Conductive and composite fibers are a suitable lightweight alternative to traditional EMP shielding methods due to having inherent electromagnetic shielding properties and are elastic and pliable enough to be placed around the joints of several robotic platforms to provide protection. The shielding effectiveness of composite materials depends on the intrinsic conductivity, aspect ratio, and content of the fillers used to alter the original compound (Lee 2017). Fillers such as copper, silver, or aluminum, like with several previous examples, create a Faraday cage around the electronic component to provide shielding. This category of fiber is created by mixing metal with raw materials such as silver and copper. At the end of the conductive fibers production process a hollow fiber structure is used to reduce the weight of the material while also increasing structural integrity. These types of materials also demonstrate EMP shielding performance in the frequency bands of 30 MHz and 10 GHz (Kim, Min, and Park 2021). Several examples of conductive fibers would be carbon fibers and fibers coated with metal mixtures such as aluminum, silver, or copper. "When fiber materials and structures contain electromagnetic properties, fiber materials can be used to shield electromagnet waves" (Kim, Min, and Park 2021, 5). They also conclude that fiber materials are known to have excellent electrical properties making them suitable to utilize as an EMP shielding component.

3. Features of Conductive Fibers Utilized in EMP Shielding

Kim, Min, and Park's study of carbon and fiber-based materials that provided shielding against an EMP focused on lightweight and commercially available solutions to create an EMP protected command tent for the South Korean Military. Kim studied and tested 21 different types of materials and categorized them into the following categories: films, fiber textile materials, wallpapers, and shielding tapes. Kim tested these materials utilizing the ASTM-4935-10 test, which is the standard for EMP shielding performance (ASTM International 2009). These materials were also tested against the traditional MIL-STD-188-125 standard (United States Department of Defense 2004) that mandates that EMP protection performance for facilities must be up to 80dB in the 10kHZ–1GHz frequency bands which is also the standard that the team used to conduct the Analysis of Alternatives within the SWaP trade space for the RAAD system (Kim, Min, and Park 2021).

Kim, Min, and Park summarized their findings by presenting the model number, manufacturer, and classification for the material in each category that displayed the highest shielding effectiveness. For films, the EMC pro SF2209 model displayed the highest shielding performance of 35.0 dB in the 30MHz frequency band. The Holand Shielding branded Systems BV 4711 fabric displayed the highest shielding effectiveness in the fiber textile materials category protecting against 87.1 dB in the 50 MHz frequency band. For wallpapers, Less EMF Inc's Stick E Shield established a shielding effectiveness of 71.3 dB in the 30 MHz frequency band. Finally, the copper-based metal foil tape from E-Song EMC in Seoul, Korea displayed 99.2 dB in the 1.5 GHz frequency band. These materials will support the SWaP trade-space analysis by providing a breakdown of each component that requires shielding for the Atlas robot and weight increase that it will provide to the overall system.

Materials studied by Kim, Min, and Park are valuable to the research that is being conducted on the RAAD system to increase its EMP shielding effectiveness. The System of Interest will have many maneuverable joints, a large chest cavity that will house electronics, sensors, and actuators, two hands, and two feet. The totality of the maneuverable components of the RAAD system will need to be protected against EMP; therefore, the lightweight and flexible materials provided by Kim's study may be a tradeoff solution to consider as they could further reduce the overall weight of the RAAD system. Table 1 is adapted from the test results of all 21 different materials that Kim, Min, and Park tested during their team's research.

Table 1. Shielding Effectiveness Test Results of Conductive Fibers. Adapted from Kim, Min, and Park (2021).

Product Number		**Frequency (MHz)**					
		30 MHz	**50 MHz**	**100 MHz**	**400 MHz**	**1000 MHz**	**1500 MHz**
SGF-D130	**Decibels (dB)**	68.1	68.1	66.0	71.2	75.1	76.8
SGF-D150		58.3	59.1	59.5	61.1	62.6	63.2
SGF-WD270		66.1	65.0	66.1	68.9	74.5	74.6
W-290-PCN		64.3	64.5	65.4	68.4	70.3	71.5
CFT-235-FR-NH		66.6	66.2	64.1	65.2	67.8	67.9
CFT-290-FR-NH		65.7	65.1	63.0	63.8	66.2	67.2
Systems BV 4711 Series		71.9	87.1	72.8	71.8	76.0	75.4
Stick E Shield		78.0	75.3	72.6	73.7	74.0	72.0
COBALTEX		68.6	77.0	71.6	73.7	77.9	80.0
Nickel/Copper Ripstop Fabric		77.2	70.2	73.6	75.1	78.3	77.6
Pure Copper Polyester Taffeta		70.8	74.2	74.3	77.7	79.4	78.5
Silver Mesh Fabric		32.9	32	31.8	32.0	34.6	37.1
YCF-60-100		71.3	66.5	67.3	64.2	60.9	58.9
SF2209		35.0	34.3	34.4	34.5	34.3	34.8
WT 70 MNT		22.6	22.2	22.2	22.6	23.1	23.8
SGWF26		23.9	23.4	23.5	23.8	24.2	24.8
Scotch Tint		32.5	32.8	33.2	33.4	33.5	34.0
Scotch Tint Super		23.2	21.7	21.0	21.0	21.4	22.0
Metal foil tape, copper		86.9	72.3	80.8	83.1	82.3	73.8
Metal foil tape, aluminum		90.5	79.9	85.6	84.3	86.1	99.2
BV3212 series		79.5	74.5	90.1	92.3	84.5	88.0

The Arc Thermal Metal Spraying Method (ATMS) was researched in 2017 as means to replace metal plating to shield a structural facility against the effects of an EMP. ATMS is an anti-corrosion and pliable spray that forms a metal coating onto a structure by using metal wire mesh such as zinc and aluminum through adherence. Lee (2017) discussed two primary reasons as to why he believed the ATMS method would display suitable progress as an EMP shielding method: since ATMS uses metallic materials it would provide shielding against an EMP; when ATMS coating endures prolonged exposure to corrosive environments it creates an oxidation layer and becomes more compact. Figure 3 displays the shielding effectiveness test results conducted for ATMS. Testing found that ATMS with coating with zinc and aluminum exceeded the required minimum shielding effectiveness against an EMP. Additionally, at higher frequencies, such as 300–400 Hz, ATMS coating outperformed the effectiveness of metal and copper plating.

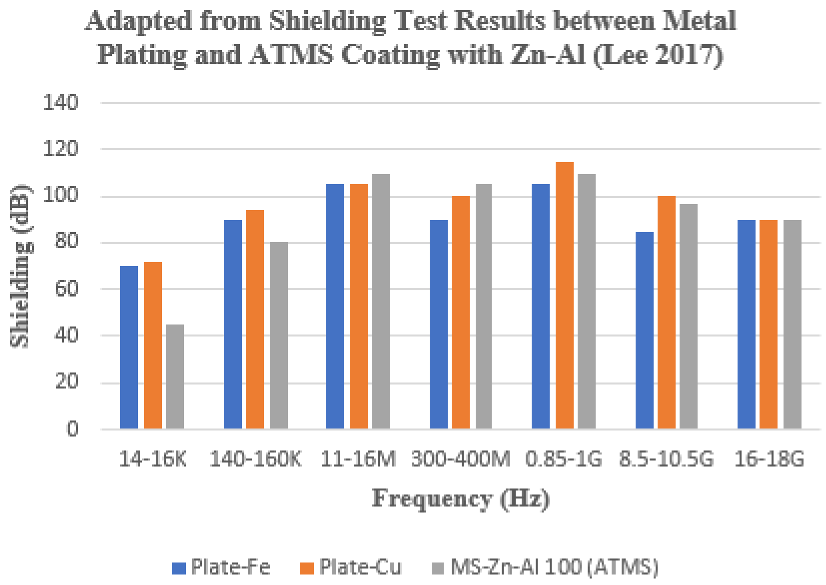


Figure 3. Shielding Effectiveness Test Results Between Metal Plating and ATMS Coating with Zn-Al. Adapted from Lee (2017).

Lee's study is theoretical in nature. Its applicability onto a humanoid-based robotic platforms has not been verified. Once the ATMS method is applied to a surface it is unknown if it can be removed; however, it has been tested in non-robotic applications and has provided sufficient EMP protection due to its metallic base structure.

C. THE ATLAS ROBOT—CURRENT ANALOGOUS BASELINE FOR THE RAAD SYSTEM

1. General Specifications for the Atlas Robot

The Atlas robot was developed by Boston Dynamics for DARPA and made its debut in 2013. In its original form, the Atlas weighed 330 lbs. (150 kg), had a height of 74 in. (188 cm), and carried a host of electronic components embedded to ensure its functionality. The electronics onboard the Atlas robot consisted of a LIDAR head sensor with stereo cameras that support it with 28 degrees of freedom (DoF), and the system was powered by 28 hydraulic actuators that ensured that joints of the neck (1 actuator), arms (6 actuators each), torso (3 actuators), and legs (6 actuators each) could move freely and function correctly. The Atlas also utilized an on-board computer with 10Gbps optic fiber ethernet and was powered by a 480-V three-phase battery that utilized an on-board hydraulic pump with thermal management. The power consumption for the original 480-V three-phase battery was only good enough to allow the Atlas system to operate for around two-hours during the DARPA Robotics Challenge competition, and will therefore, require further optimization and refinement for the RAAD system in an operational scenario (Kuindersma et al. 2015).

2. Electronics Size, Weight, and Location of the Atlas Robot that are Susceptible to an EMP

To protect the RAAD systems electronic components from the effects of an EMP, the team generated a validated list of key components that will require shielding based on their electronic circuitry which are vital to the operation of the Atlas platform. Every item listed in Table 2 will need to be shielded to ensure that the RAAD system remains operational after an EMP or EMI event. Recommended shielding is split up into two categories: primary components are level one and secondary components (if applicable) are considered level two. Weight and dimensions are added for each device but the conclusiveness of the actual weights and dimensions for communications components vary significantly from vendor to vendor and specified application; therefore, this portion is simply a redesign estimate based on the available literature. Additionally, the vast preponderance of the identified components can be centralized apart from most actuators which help provide the Atlas platform sufficient degrees of freedom. These actuators may need to be located distally from the primary electronics housing architecture to facilitate Atlas operation and may require separate shielding to ensure their operation (Kuindersma et al. 2015).

Table 2. Validated Components Listing for the RAAD System Based on the Atlas Robot as an Analogous Baseline

Level 1 Components (Primary)	
Component	**Dimensions and Weight**
Battery: biomorphic battery x 1 (primary power source)	D: 7.62cm x 5cm x 12.7cm W: 2.5kg
CPU: Qualcomm QRB5165 x 1 or Edge CPU (primary processor)	D: 59.7mm x 32.mm W: 1.5g
Data storage (solid state): PM971-NVMe SSD x 1	D: 20x16x1.5mm W: <1g
Motherboard: ELSKY Intel Skylake Core i7-6500U MSATA Motherboard	D: 20cm x 20 cm x 8 cm W: 0.5kg
Temporary storage (RAM/Flash): AT89c51 or similar microprocessor x 12 located at each major joint	D: 8mm x 8mm (est.) W: <1g (each)
Sensors: IRs(D6T-44L-06/06H) x 1 (primary visual sensor)	D: 18mm x 14mm x 4mm W: 1.2kg (est.)
Endeffectors (Actuators): Linear Variable Displacement Transducers x 28 (each corresponding to a sensor)	D: 9mm x 9mm (est.) W: <1g
Communications: Receiver x 1(TX/RX) (SparrowHawk Tactical Nano –UAS Drone)	D: 147.7mm x 68.7mm x 8.5 mm W: 260g
Level 2 Components (Secondary)	
Battery: Lithium-Ion x 2 (LIR18650 or similar)	D: 18.4mm x 65.2mm W: 46.5g (each)
Battery: Solar charging cell: (optional linked to primary and secondary batteries)	D: 342.9mm x 216.9mm x 34.04mm (est.) W: <1kg (est.)
Sensors: 3D sensor x 2 (B5L 3D TOF) primary and secondary	D: 108.6mm x 43.1mm W: 2.2kg (est./each)
Sensors: Gyroscopic x 2 (SCR2100-D08-05) primary and secondary	D: 8.5mm x 4.3mm W: <1kg (est./each)
Endeffectors (Actuators): Op-amps (LM741 or similar) x 8 (number will vary based on design)	D: 9.08mm x 9.08mm W: 1.5g (est./each)
Endeffectors (Actuators): Load Cells x 2 (LMGZ205. 581861.RF.H13.H14)	D: 100mm x 86mm x 25mm (est) W: 295g (each) (est)
Electric Hydraulic Pump: x1	D: 257.8mm x 88.3mm (est) W: 3.2kg (est)
10Gps Fiber Optic Cable: x1	D: 3m x 62.5/125 microns W: <1kg
Inertial Measurement Unit (IMU): x1 (KVH 1750)	D: 13.3mm x 33.5mm (est) W: <1kg (est)
Lidar Sensor: x1 (Hokuyo LIDAR UTM-30LX-EW)	D: 88mm x 75mm x 15mm (est) W: 1.5kg (est)

D. SUMMARY OF SWAP AND AN ANALYSIS OF ALTERNATIVES (AOA) FOR SHIELDING IN ROBOTICS

Size, Weight, and Power (SWaP) vulnerabilities present varying degrees of effects on the dimensions, weight distribution, and operation of robotic platforms. For example, by adding EMP shielding to the RAAD system using metals such as steel, the weight increase of the system will increase. This in turn causes the systems' power consumption to be greater, causing a more rapid battery drain, which would result in less operating time. Conversely, by utilizing lightweight composite materials to increase EMP shielding, all other things being equal, the system would draw less power due to the reduced weight of the shielding materials but may not be suitably protected to survive an EMP attack. A SWaP analysis will be conducted to determine the system design specifications that minimize vulnerabilities and maximizes operational performance to increase the RAAD systems probability of survivability in an operational environment.

1. Shielding for Size, Weight, and Power

Size will be an extremely important consideration during the research and development of the RAAD system due to there being a subjective trade-off when determining the relative size of a robotic system. Determination of physical size will be influenced by several factors such as technological advances in microelectronics, the desire to prevent detection the electronic direction finding (DF), and payload capacity. If the RAAD system is too small, then it may not provide the desired battlefield capability. Concerning the current size of the Atlas robot at 74 in, the end design of the RAAD system must be large enough to house all electronic components to include shielding materials, but small enough to be rapidly employed out of Future Lift Rotary-Wing Assault Aircraft (FLRAA). A balance of size, weight, and power must be met for all three factors to succeed during the development of the RAAD system.

The culmination of this research for the RAAD system should generate design alternatives for a humanoid robotic system that balances size, weight, and power specifications with EMP protection. This system will, however, be much heavier than a traditional soldier carrying their weapon, body armor, and ruck sack would be. It is assumed that electronics and robotics will continue to advance prior to the RAAD systems implementation on the battlefield; however, the overall weight of the RAAD system may increase due to additional EMP shielding protection given the existing material and capabilities.

E. STAKEHOLDER PROBLEMS, CONSTRAINTS, AND DESIRED END STATE

To provide some additional context and that helped the team scope the problem domain as to how the RAAD system would be employed, the team decided to utilize a wet-gap or wide-gap crossing event as our operational scenario. Researchers, scientists, and servicemembers from across the Army Modernization Enterprise (AME) conducted a focused excursion (FE) event in September 2020 to develop an early concept for the RAAD system. One capability hypothesis that was used to scope potential future research was the use of the RAAD system as a rapid forcible entry mechanism into contested or denied landing zones (LZ) (Glaz et al. 2020).

The RAAD system would be employed as an additional intelligence, surveillance, and reconnaissance (ISR) platform to help commanders conduct large-scale air assault operations. In a wide-gap crossing scenario, the RAAD system would be inserted by rotary wing aircraft on the far-side of a gap to collect information such as enemy composition and disposition, terrain, as well as civil developments during the development and action of battle. The RAAD system would potentially be able to drive the enemy away from the wide-gap crossing location by utilizing non-lethal intervention means as determined by METT-TC (mission, enemy, terrain, troops available, time, and civilian considerations). Bridging units on the near-side of the terrain would then be able to conduct bridge employment and crossing operations to allow a larger follow-on force (light and mechanized infantry) to maneuver across the terrain to the far-side to continue the larger operation. This is where the team proposed that the RAAD system would be most vulnerable if the enemy used some form of EMP bomb or missile against the RAAD system.

There was no mention on directed energy during AME's focused excursion event, which was primarily concerned with the theoretical operational concept for the RAAD system, and the team saw this as a critical vulnerability for future combat operations as technology continues to evolve. To provide valuable research, the team decided to model the RAAD system after an existing humanoid robotics platform, namely the Atlas Robot, and to conduct a SWaP trade-space analysis for varying levels of EMP shielding protection so that the future system can protect itself and mitigate threats from EMP platforms.

III. METHODOLOGY

The capstone team methodology was developed based on an IDEF0 functional flow as a tailored systems engineering process. The analyses in the next chapter were derived using the SE process seen in Figure 4. The research problem focused on protecting the RAAD against EMP while minimizing the impacts on operational capabilities. Given the initial case study and design concept provided by Team Ignite of ARL, the methodology followed a successive process beginning with developing the operational context for which the RAAD will operate. From the information gathered while defining the operational context, the team performed a functional analysis to determine what the RAAD system must be able to do at its most basic level. The output of this analysis was a trace function to component list which was used to execute Analysis of Alternatives (AoA) and SWaP analysis. The result of our AoA was used to further understand how SWaP impacted the functions previously discussed. The research focused on methods of EMP shielding for the RAAD system and the tradeoff analysis with regards to SWaP considerations.

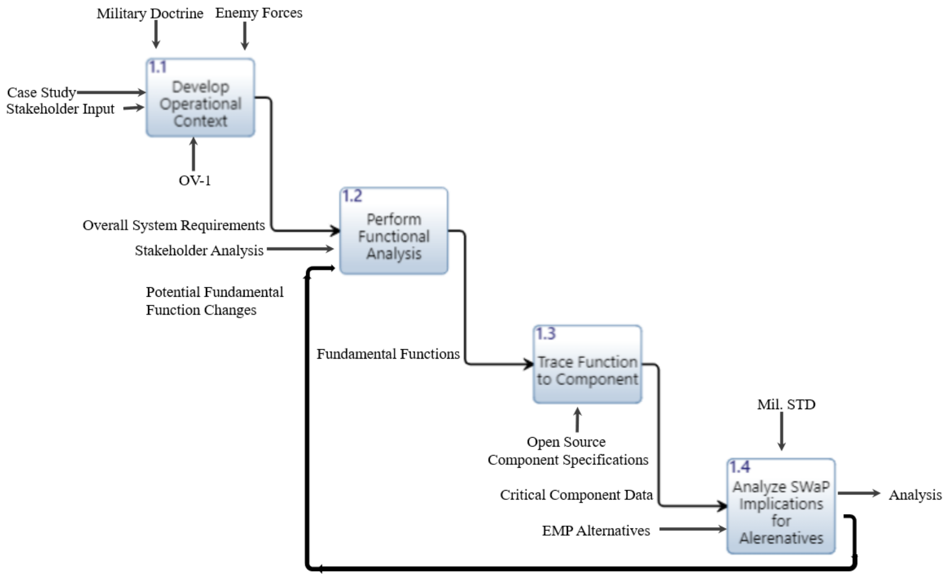


Figure 4. Tailored SE Process. Adapted from Blanchard and Fabrycky (2011).

The tailored methodology for the research uses an SE approach adapted from Blanchard and Fabrycky (2011). This process is divided into four phases: Develop the Operational Context, Perform Functional Analysis, Trace Function to Component, and Analyze SWaP implications for each shielding alternative that will inform design specifications. We discuss these phases in the following sections of this chapter.

A. OPERATIONAL CONTEXT

As previously discussed in chapter two, the team's approach to understanding the operational context was derived from the case study presented by ARL. The operational context represented the external environment which influenced the operation of the robot. We scoped the initial problem to focus on EMP protection and used that aspect as our initial input for the operational context. The team included the environmental parameters given in the case study and discussed in chapter one, as well as specific information described by the primary stakeholders.

The development of the operational context was governed by two important controls, military doctrine, and enemy force capability. The military doctrine provided the team with a set of rules which constrained the environment and execution of the function (ART 1.6.1.3 Conduct Gap Crossing Operations). The enemy force capabilities represented a set of conditions which the team considered while defining the environment. The team utilized an OV-1 to specify the physical environment and structure of the military operation. The output of these activities was the overall system requirements which the team used to initiate the functional analysis of the robotic system.

B. FUNCTIONAL ANALYSIS AND DECOMPOSITION

Given the mission objectives and our overall system requirements, the functional analysis identified the fundamental functions for the future RAAD system. The functional analysis began at the system level. Figure 5 depicts the decomposition of the top-level functions into the most elemental system functions. The top-level functions were identified as: Provide Power, Actuate Movement, Sense Environment, and Provide Communication. Understanding the decomposition of these functions was integral to performing our functional analysis.

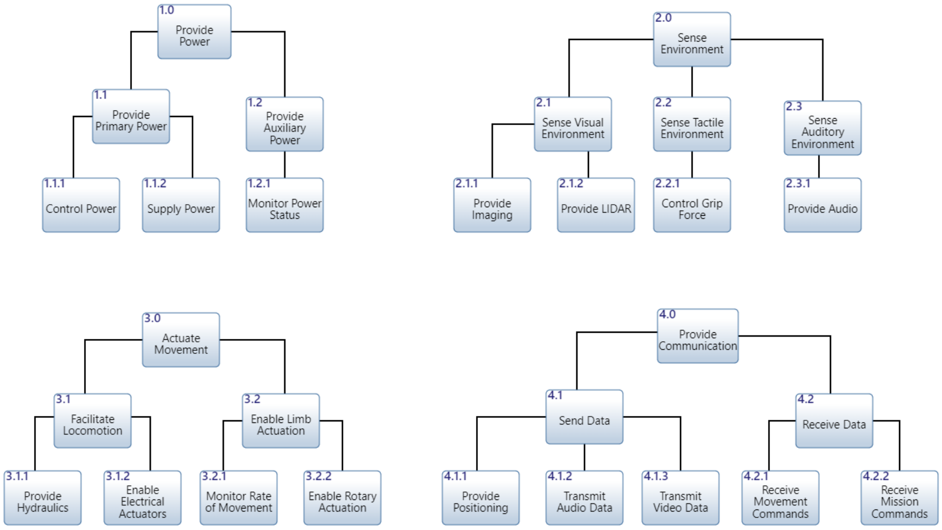


Figure 5. Tree Diagrams Representing Functional Decomposition

The inputs that were used to build the functional tree diagram included overall system requirements, stakeholder analysis, and the potential fundamental functional changes. The overall system requirements and stakeholder analysis were the primary considerations for the functional analysis. Results from SWaP analysis in phase four may potentially reshape the functional analysis and the set of fundamental functions of the system.

An IDEF0 model was used as a control during functional analysis as a governing of procedure. A functional tree was then produced which allowed the team to split the higher-level functions and eventually derive the basic functions at the third level of decomposition. The research team determined this level of decomposition was sufficient for the scope of this project, while recognizing that further decomposition may still be required during the detailed design phase for the development of the RAAD system.

The output from the functional analysis and decomposition were the fundamental functions. These fundamental functions were used to produce a function-to-component trace matrix. The matrix allowed the team to map system components to required functions. The process involved identifying similar functions to determine what physical components would be required to perform each function.

C. FUNCTION-TO-COMPONENT TRACE MATRIX

The research team used the fundamental functions obtained from the functional analysis, as the input to develop a function to component trace matrix. The process for completing the matrix also involved identification of vulnerable components. The team primarily utilized open-source specifications for size, weight, and material of components identified as critical for hardening to complete our list. We considered this data a mechanism because it enabled the research process and provided a path for analysis.

The research team then used the traceability matrix to produce data detailing the critical components used to examine the SWaP analysis of alternatives. Knowing the size, weight, and material of the components helped the team analyze the material alternatives in the next phase of our process.

Table 3 is the component to function trace matrix which the team developed. This matrix shows the linkage between functions and the components which need to be shielded on the robot. Visually depicting the association between components and functions aided the research team in identifying the data needed to conduct the analysis on SWaP implications for each alternative.

Table 3. Function-to-Component Trace Matrix

	5 Batteries	5.1 Battery: Biomorphic Battery	5.1.1 Lithium-Ion Battery (Secondary)	5.1.2 Solar Charging Cell (Tertiary)	6.0 Motherboard	6.1 Central Processing Unit (CPU)	6.1.1 Data Storage (SSD)	6.1.2 Temporary Storage (RAM/Flash)	6.1.3 Fiber Optic Cabling	7.0 Hokuyo Array	7.1 LIDAR Sensor (Hokuyo)	7.1.1 Infrared Sensor	7.1.2 3D Sensors	7.1.3 Gyroscopic Sensors	7.1.4 Inertial Measurement Unit (IMU)	8.0 Actuators	8.1 Operational Amplifiers (Op-amps)	8.2 Load Cells	8.3 Linear Variable Displacement Transducers (LVDTs)	8.4 Electric Hydrolic Pump	9.0 Communications	9.1 Communications Transceivers (TX/RX)	9.2 Speaker (Output)	9.2 Microphones (Input)
1 Provide Power																								
1.1 Provide Primary Power		x																						
1.1.1 Control Power						x									x		x	x	x	x				
1.1.2 Supply Power		x	x	x																				
1.2 Provide Auxiliary Power			x	x		x																		
1.2.1 Monitor Power Status						x					x							x				x	x	x
2.0 Sense Environment																								
2.1 Sense Visual Environment		x	x	x		x	x	x	x		x	x	x											
2.1.1 Provide Imaging		x	x	x		x	x	x	x		x	x	x									x		
2.1.2 Provide LIDAR		x	x	x		x	x	x	x		x		x									x		
2.2 Sense Tacticle Enivironment						x					x	x	x	x	x			x	x					
2.2.1 Control Grip Force		x	x	x		x											x	x						
2.3 Sense Auditory Environment		x	x	x		x																		x
2.3.1 Provide Audio		x	x	x																			x	
3.0 Actuate Movement																								
3.1 Facilitate Locomotion		x	x	x		x	x	x	x		x	x	x	x	x		x	x	x	x				
3.1.1 Provide Hydraulics		x	x	x		x								x	x		x	x		x				
3.1.2 Enable Electrical Actuators		x	x	x		x		x	x										x					
3.2 Enable Limb Actuation		x	x	x		x		x	x				x	x	x		x	x	x	x				
3.2.1 Monitor Rate of Movement		x	x	x		x	x				x			x	x				x	x				
3.2.2 Enable Rotary Actuation		x	x	x		x		x							x		x		x	x				
4.0 Provide Communication																								
4.1 Send Data		x	x	x		x			x		x	x	x	x	x					x		x		x
4.1.1 Provie Positioning						x	x	x					x	x										
4.1.2 Transmit Audio Data		x	x	x		x	x	x	x													x		
4.1.3 Transmit Video Data		x	x	x		x	x	x	x													x		
4.2 Receive Data		x	x	x		x	x	x	x													x	x	x
4.2.1 Receive Movement Commands		x	x	x		x		x	x								x	x	x	x				
4.2.2 Receive Mission Commands		x	x	x		x	x		x													x		

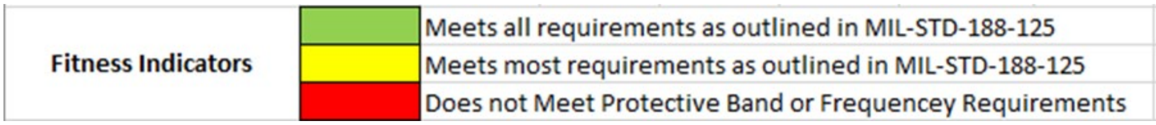
D. SWAP AND ANALYSIS OF ALTERNATIVES

The critical component data and a short list of EMP shielding material alternatives were the input for analyzing SWaP implications in phase four. This information was used to understand the impacts on SWaP by modeling the required thickness of different materials to shield against EMP energy. The team used the military standard for EMP protection as a set of rules to measure the alternative against. (MIL-STD-188/125) While examining the material alternatives, the research team discovered each product required different thicknesses to produce adequate shielding against the effects of EMP. The information derived from our function to component trace was used as an input to conduct the SWaP tradeoff analysis. The research team analyzed the approximate dimensions of components requiring shielding and applied the computed size to determine the overall added mass to the total system. The output from this function was the analysis of the material alternatives and potential fundamental function changes which were used as inputs for the functional analysis.

The commercial options for EMP shielding available today are extensive. As a result of this situation, we narrowed our analysis to a short list of carbon and fiber-based material as well as light weight protective films and foams. In consideration of SWaP analysis, the team discussed lightweight solutions for external and internal component structural design and component shielding. Preliminary discussion about carbon fiber reinforced polymers yielded promising avenues of potential research. We used this data to conduct tradeoff analysis for SWaP considerations to help inform the system design.

IV. ANALYSIS

The outcomes of the methodology outlined in the previous chapter were predicated on defined screening criterion for the plethora of EMP shielding materials available, value factors to select appropriate materials for analysis, and discussion of categorical winners as a result of a SWaP analysis grounded in functional requirements for the RAAD/ATLAS robotics platform. Subsequently, this chapter examines the introduction of weight to the RAAD/ATLAS platform as the primary factor for the determination of operational effectiveness of the system. Accordingly, the team examined power requirements with regard to size examined. The designated operational concept of a wet gap crossing as defined in (regulation) resulted in a determination of a minimum operational time of two hours for the RAAD system with potentiating factors such as the viscosity of any present water, wind conditions, and extraneous gravitational effects omitted. The results of the screening, less functional considerations, are presented as a factor of fitness in a color-coded fashion with the lightest materials (by density) providing the best protective properties highlighted in green, materials that meet at least half the requirements of protective properties highlighted in yellow, while materials that did not meet weight or protective requirements highlighted in red. Protection requirements for all materials are based on the standards outlined in MIL-STD-188-125 regarding military EMP protection for hardened facilities and their associated structures. Figure 6 highlights the fitness indicators used by the team when comparing the shielding effectiveness of the analyzed materials against MIL-STD 188–125.



Fitness Indicators	🟩	Meets all requirements as outlined in MIL-STD-188-125
	🟨	Meets most requirements as outlined in MIL-STD-188-125
	🟥	Does not Meet Protective Band or Frequencey Requirements

Figure 6. Initial Listing of Categorized Materials

A. FUNCTIONAL SCREENING CRITERIA

Screening and fitness factors were determined based on inputs directly received from relevant stakeholders and the operational capabilities based on our analogous operating platform, the ATLAS robotic system. The two primary determining factors chosen as a result of the discussion were the preservation of operational capability of the RAAD/ATLAS system and the provision of full scale EMP protection for critical components. The criticality of components was determined by identifying all relevant components necessary to facilitate the normal operation of the ATLAS system as defined by the functional requirements of Power, Sensing, Communications, and Movement. The mobility requirement for the RAAD system resulted in the elimination of all static EMP protection methods and the elimination of obviously heavy reinforcing requirements such as reinforced concrete. A focus on materials of light weight composition with sufficient EMP protective factors yielded a list of approximately seventeen materials. The remaining seventeen materials were broken down by category from which the highest performing materials were chosen. The categories are presented as follows: Film, Fabric, Fibers, Wallpaper, Metal Foil, and Paints. These categories were chosen due to their ability to potentially implement the best balance of mobility and protection as outlined by our primary determining factors. Table 4 depicts the total list of seventeen most feasible materials and the reasons for their elimination (if applicable) for consideration of the ATLAS/RAAD protection criteria. The elimination criteria were determined based infeasibility of their application on the platform due to RAAD’s intended operational environments and method of operation.

Table 4. Materials Listing and Reason for Elimination for Analysis if Applicable

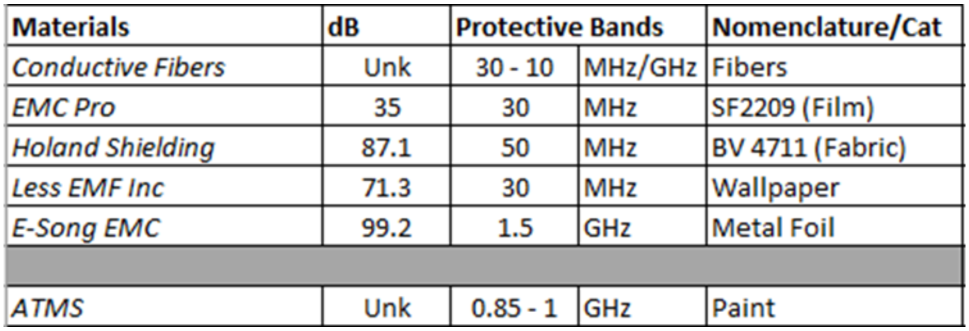
Materials	Category	Reason for Elimination
Conductive Fibers	Fibers	N/A
EMC Pro	Film	N/A
Holand Shielding	Fabric	N/A
Less EMF Inc	Wallpaper	N/A
E-Song EMC	Metal Foil	N/A
ATMS	Paint	N/A
Scotch Tint Super	Film/Tape	Inferior Protection in Comparison to EMC Pro
Nickel/Copper RIPSTOP	Fabric	Inferior Protection in Comparison to Holand Shielding
Steel Reinforced Concrete	Concrete/Metal	High Weight/Poor Pliability/Reduced Mobility
Six-sided EM Shield	(3-6mm steel) Metal	High Weight/Reduced Mobility
COBALTEX	Fabric	Inferior Protection in Comparison to Holand Shielding
Beryllium Copper	Metal Reinforcement	Inferior Protection in Comparison to E-Song EMC
Stainless Steel	Metal	Signal Amplitude Reduction/High Weight
Pre-tinplated Steel	Metal	Inferior Protection in Comparison to E-Song EMC
Copper alloy 770	Metal	Risk for ineffective area protection/High Weight
Silicone Adhesive	Film/Adhesive	Inferior Protection in Comparison to EMC Pro
Conductive Concrete	Shotcrete/Concrete	High Weight/Reduced Mobility

After appropriate categorization, the weights of materials were defined and due to rarity of the materials, they required an analogous comparison to existing materials of similar composition. Of note is that the preponderance of critical systems identified were centrally located and that an enclosed architecture protective enclosure (PE) was decided as the most efficient means of protecting the critical components of the RAAD system given the now better-defined protective materials. The dimensions of the protective enclosure were determined by identifying the largest components and adding three additional centimeters to facilitate operating space within the ATLAS system. Relevant weights for applicable materials were gathered based off calculated specific gravity and/or density of the material. The ATLAS total system weight was obtained, and analysis based on weight as a function of power to weight ratios served as the initial determining factor for material choice and fitness for applicability in an operational RAAD/ATLAS system. All measurements were standardized using the metric system and protective materials were calculated to show total coverage of the full PE.

B. MILITARY STANDARD SCREENING CRITERIA

The categorical winners as a result of the screening and fitness factors are outlined below. Table 5 shows the commercial name of the material, level of sound protection, and frequency band protection of each option. The material category and nomenclature (if any) are outlined to the far right of Table 5.

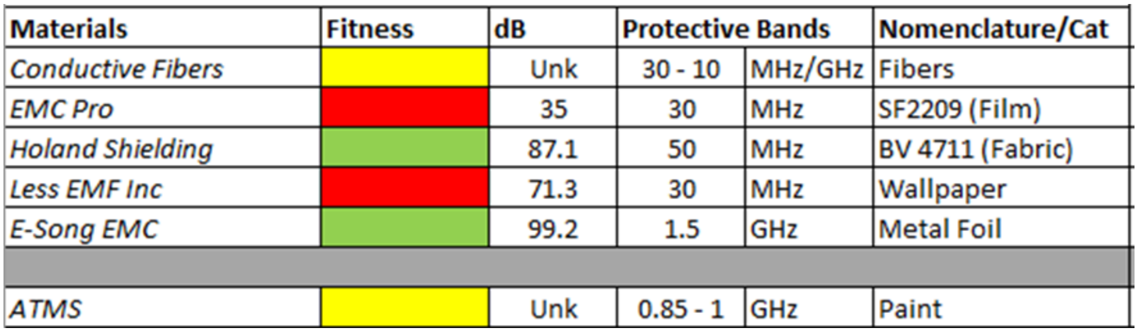
Table 5. Initial Listing of Categorized Materials



Materials	dB	Protective Bands		Nomenclature/Cat
Conductive Fibers	Unk	30 - 10	MHz/GHz	Fibers
EMC Pro	35	30	MHz	SF2209 (Film)
Holand Shielding	87.1	50	MHz	BV 4711 (Fabric)
Less EMF Inc	71.3	30	MHz	Wallpaper
E-Song EMC	99.2	1.5	GHz	Metal Foil
ATMS	Unk	0.85 - 1	GHz	Paint

An initial fitness assessment was conducted through the base comparison of the protective effectiveness of the materials. Table 6 provides a snapshot of the system’s fitness based on levels of protection with *E-Song EMC Metal Foil* and *Holand Shielding Fabric* providing protective measures that met or exceeded the minimum requirements outlined in MIL-STD-188-125. Of note, is that *ATMS* and generalized *Conductive Fibers* were given a yellow rating due to their unknown sound protection measures while *EMC Pro’s Film* and *Less EMC Inc’s Wallpaper* failed to meet the sound protection requirements outlined by the regulation.

Table 6. Initial Listing of Categorized Materials with Fitness Indicators

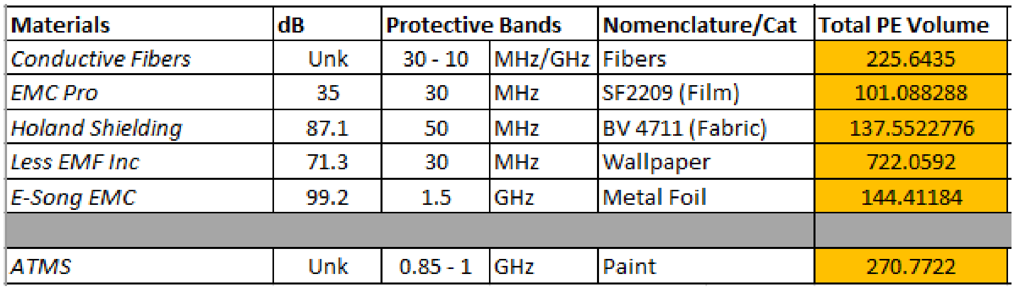


Materials	**Fitness**	**dB**	**Protective Bands**		**Nomenclature/Cat**
Conductive Fibers	🟨	Unk	30 - 10	MHz/GHz	Fibers
EMC Pro	🟥	35	30	MHz	SF2209 (Film)
Holand Shielding	🟩	87.1	50	MHz	BV 4711 (Fabric)
Less EMF Inc	🟥	71.3	30	MHz	Wallpaper
E-Song EMC	🟩	99.2	1.5	GHz	Metal Foil
ATMS	🟨	Unk	0.85 - 1	GHz	Paint

Individual material thickness was then determined based on analogous material estimation. Conductive fibers were based on an analogous comparison to nylon fibers with an average thickness of 0.25 mm^2 or 0.025 cm^2 (Shippee 2018). EMC film was compared to a Melinex type film which provided an average thickness of about 0.112 mm^2 (Dupont Teijin 2020). The Holand Shielding Fabric comparison was made to very lightweight fabric comparison used in the design of garments with a mean thickness of 0.0152 cm^2 (Proper Cloth 2021). Less EMC's wallpaper was compared to traditional household wallpaper (paper) having a mean thickness of 0.08 cm^2 (InterMESH 2021) while E-Song EMC foil was compared to typical aluminum foil with an average thickness of 0.016 cm^2 (P&W LLC 2021). Arc Thermal Metal Spray was analogously compared to a base coat thickness of an industrial enamel with a mean thickness of 0.03 cm^2 (Ravichandran 2021).

Once material thicknesses and corresponding densities were obtained, a volumetric calculation based on the corresponding density of the materials was conducted utilizing the standard volume formula for a rectangular prism. The study found that the proposed total volume of the PE with a height of 28.78 cm, a length of 91.3 cm, and a width of 15.7 cm yielded a structure with a volume 41,253.54 cm^3. Additionally, the surface area for a given PE was calculated for each individual material utilizing a standard volumetric formula accounting for the materials thickness to then calculate the total specific gravity of the material to determine the mass (weight) of each of materials utilizing an equation to determine total mass or mass = density x volume. The total corresponding volumes for each material are outlined in Table 7.

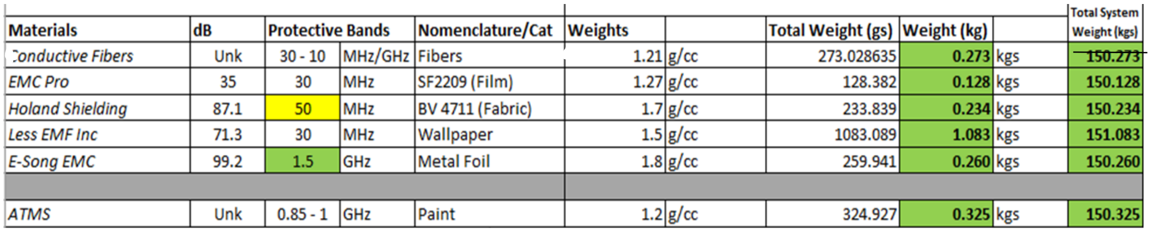
Table 7. Corresponding Surface Volume of the PE with Each Material Taken into Consideration Highlighted in Yellow



Materials	dB	Protective Bands		Nomenclature/Cat	Total PE Volume
Conductive Fibers	Unk	30 - 10	MHz/GHz	Fibers	225.6435
EMC Pro	35	30	MHz	SF2209 (Film)	101.088288
Holand Shielding	87.1	50	MHz	BV 4711 (Fabric)	137.5522776
Less EMF Inc	71.3	30	MHz	Wallpaper	722.0592
E-Song EMC	99.2	1.5	GHz	Metal Foil	144.41184
ATMS	Unk	0.85 - 1	GHz	Paint	270.7722

Given the new volumetric information for each material, total weights for the materials encompassing the coverage of the total PE were then determined and total additional weight calculated based on the amount of the material required to fully enclose the PE. Table 8 displays the total weights, in kilograms, for each material to encompass the PE. Total system weight was then calculated by adding the new shield weight with each individual material to the existing system weight of 150 kg.

Table 8. Protective Materials and Total System Weight in Consideration of the Full Enclosure of the PE



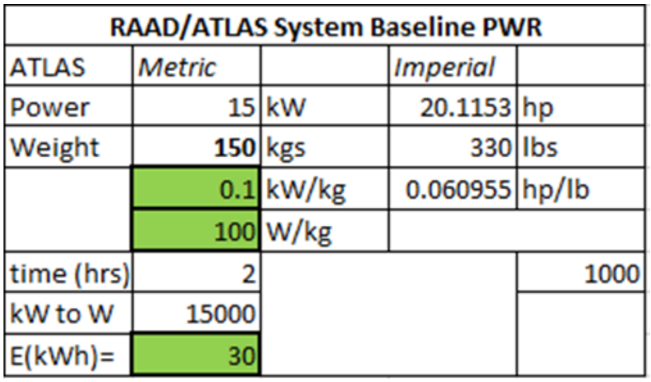
Materials	dB	Protective Bands		Nomenclature/Cat	Weights		Total Weight (gs)	Weight (kg)		Total System Weight (kgs)
Conductive Fibers	Unk	30 - 10	MHz/GHz	Fibers	1.21	g/cc	273.028635	0.273	kgs	~~150.273~~
EMC Pro	35	30	MHz	SF2209 (Film)	1.27	g/cc	128.382	0.128	kgs	150.128
Holand Shielding	87.1	50	MHz	BV 4711 (Fabric)	1.7	g/cc	233.839	0.234	kgs	150.234
Less EMF Inc	71.3	30	MHz	Wallpaper	1.5	g/cc	1083.089	1.083	kgs	151.083
E-Song EMC	99.2	1.5	GHz	Metal Foil	1.8	g/cc	259.941	0.260	kgs	150.260
ATMS	Unk	0.85 - 1	GHz	Paint	1.2	g/cc	324.927	0.325	kgs	150.325

Power to weight was then calculated utilizing the standard PWR formula:

$$E_{(\mathrm{kWh})} = P_{(\mathrm{W})} \times t_{(\mathrm{hr})} / 1000$$

Assuming a total operation time of 2 hours with a 15-kW standard power source and total system weight of 150 kgs, the ATLAS/RAAD system achieved a system E(kWh) power to weight of 30 kWh at 0.1 kW/kg or 100 W/kg. Table 9 provides an overview of this calculation.

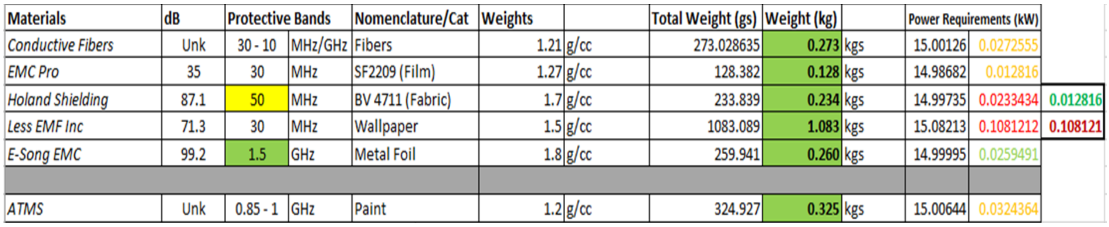
Table 9. Establishment of RAAD/ATLAS Baseline Power to Weight Ratio



RAAD/ATLAS System Baseline PWR				
ATLAS	*Metric*		*Imperial*	
Power	15	kW	20.1153	hp
Weight	**150**	kgs	330	lbs
	0.1	kW/kg	0.060955	hp/lb
	100	W/kg		
time (hrs)	2			1000
kW to W	15000			
E(kWh)=	30			

Given the RAAD/ATLAS power-to-weight ratio and requirements, additional power requirements were calculated based on the total system weight given each material multiplied by kW/kg requirement outlined above yielding the following results shown in Table 10:

Table 10. Display of Categorical Competitors by Power Requirements with the Winner Highlighted in Green and all other Color Coated by Effectiveness of Weight and Protective Properties



Materials	dB	Protective Bands		Nomenclature/Cat	Weights		Total Weight (gs)	Weight (kg)		Power Requirements (kW)		
Conductive Fibers	Unk	30 - 10	MHz/GHz	Fibers	1.21	g/cc	273.028635	**0.273**	kgs	15.00126	0.0272555	
EMC Pro	35	30	MHz	SF2209 (Film)	1.27	g/cc	128.382	**0.128**	kgs	14.98682	0.012816	
Holand Shielding	87.1	50	MHz	BV 4711 (Fabric)	1.7	g/cc	233.839	**0.234**	kgs	14.99735	0.0233434	**0.012816**
Less EMF Inc	71.3	30	MHz	Wallpaper	1.5	g/cc	1083.089	**1.083**	kgs	15.08213	0.1081212	**0.108121**
E-Song EMC	99.2	1.5	GHz	Metal Foil	1.8	g/cc	259.941	**0.260**	kgs	14.99995	0.0259491	
ATMS	Unk	0.85 - 1	GHz	Paint	1.2	g/cc	324.927	**0.325**	kgs	15.00644	0.0324364	

The categorical winner is the E-Song EMC Metal Foil material due to its superior protective requirements. Additionally, E-Song EMC Metal Foil is one of the lightest weight materials. The heaviest and lightest materials were calculated as the Less EMF Inc Wallpaper and EMC Pro Film, respectively. Although lightweight, the EMC Pro Film failed to meet sound protection requirements. The Conductive Fibers and ATMS were ranked lower due to their unknown sound protective qualities and Holand Shielding was eliminated due to its weight, although it offered the second-best protection after E-Song Metal Foil. Of note is that each of the individual weights for each material were significantly less than the predicted additional payload capability of 11kg for the Atlas robotic platform. Due to the negligible effect of weight on ATLAS/RAAD base operations, it is recommended that material decisions follow solely based on superior protective qualities for each material as it is outlined in MIL-STD-188-125.

C. SWAP ANALYSIS RESULTS

1. Size

When examining the RAAD/ATLAS system size, the study team used the system's overall height and length as a function of measurement against the speed of the system in addition to the systems base degrees of freedom to gauge the effects of the addition of the protective materials to the baseline structure. The PE's height and width present no conflicts with the existing ATLAS dimensions, but PE length presents a potential conflict due to the increase in size from 56 cm to 91.3 cm to accommodate the full length of the enclosure. Further analysis is needed to determine impact to system articulation and mobility if the additional length of 35.3 cm is distributed equidistant from the center of mass of the system both proximally and distally. It is recommended that PE dimensions present equally with 17.65 cm forward and aft of the system center. Theoretically, the ATLAS system should maintain full mobility with all 28 degrees of freedom listed in Figure 7 with minimal impact to the actuators located centrally which represent a total of 9 degrees of freedom for the total system.

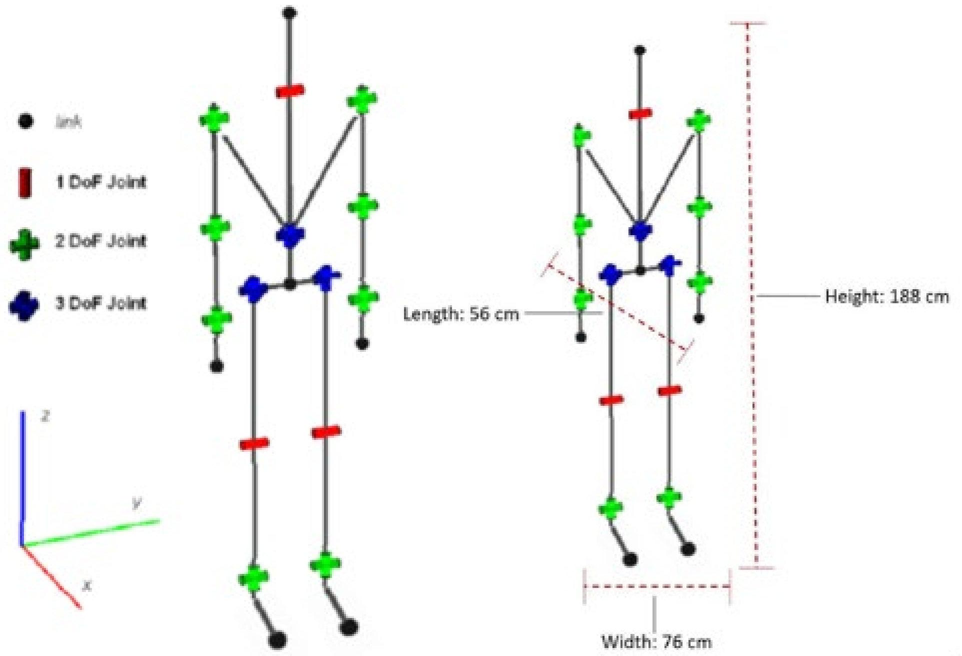


Figure 7. Display of ATLAS Robot Degrees of Freedom and Publicized Dimensions. Adapted from Maarten, Maarten, and Visser (2013).

2. Weight

Figure 8 depicts the total system weight in kilograms with the addition of the protective materials to the baseline ATLAS system. It is reasonable to expect that the addition of protective materials to the PE would have minimal to no effect on the operation of the ATLAS/RAAD system. It was calculated that a maximum additional weight of 1.083 kilograms and a min of 128 grams would result from the heaviest and lightest materials respectively. Less EMF Inc presented the heaviest material by weight while EMC Pro produced the lightest material overall. The categorical winner, E-Song EMC, presented an additional 260 grams of protective material to the ATLAS system PE with other materials falling in the median range for consideration. All additional weights fall well within the estimated payload capacity of the ATLAS system of 11 total kilograms. Centralizing the location of the weight would have a negligible impact on the total system center of gravity during normal operation and/or calculations for robot inertia vis payload.

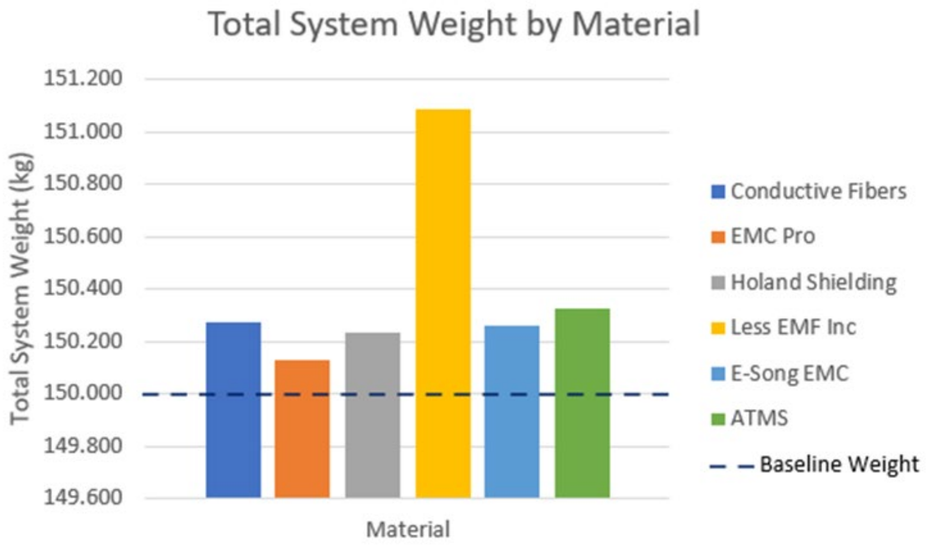


Figure 8. Total System Weight by Material

3. Power

Examining the previous chart depicting total system weight by material there appears a direct correlation between the weight of the system and the total power draw given standard operation. The heaviest material, Less EMF Inc's wallpaper subsequently draws the most power while EMC Pro Film draws the least power. The categorical winner, E-Song EMC metal foil drew an additional 0.0256 kW of power reducing total kWh negligibly from 30 kWh to 29.94801 kWh assuming a 2-hour operational time. The ATLAS system's top speed of 1.5 m/s is not affected as the addition of extra weight may serve to slow acceleration but will not reduce the systems top speed if wind resistance and aerodynamic drag are not considered. Given that the ATLAS/RAAD system will be traveling at relatively low speeds, the addition of weight has a negligible effect on total system movement. Central location of the additional weight via the PE also reduced the likelihood that system operational characteristics involving actuation, movement, and any inertial changes will negatively affect ATLAS/RAAD operation given the relative lack of change to its theoretical center of gravity. Figure 9 shows the additional system power consumption for each of the six analyzed materials.

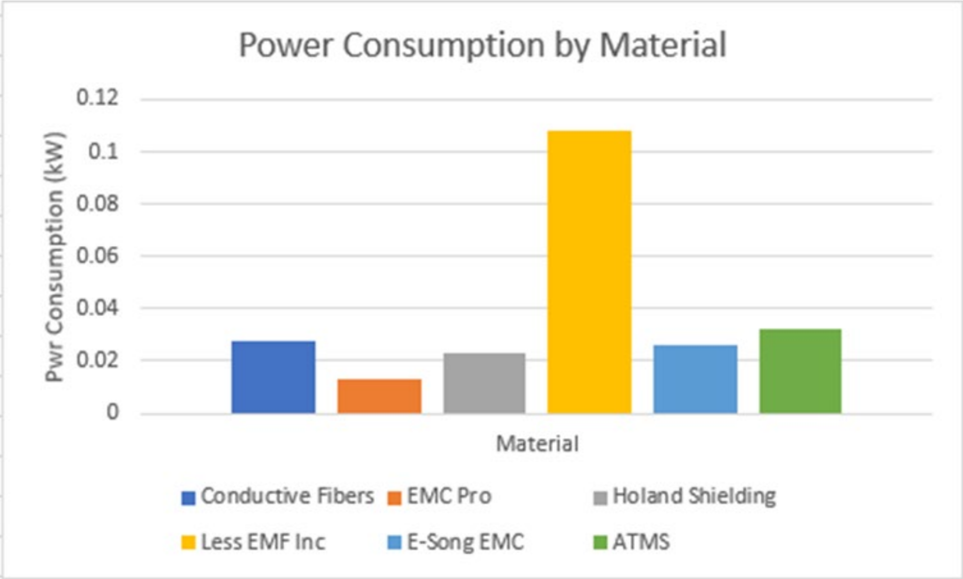
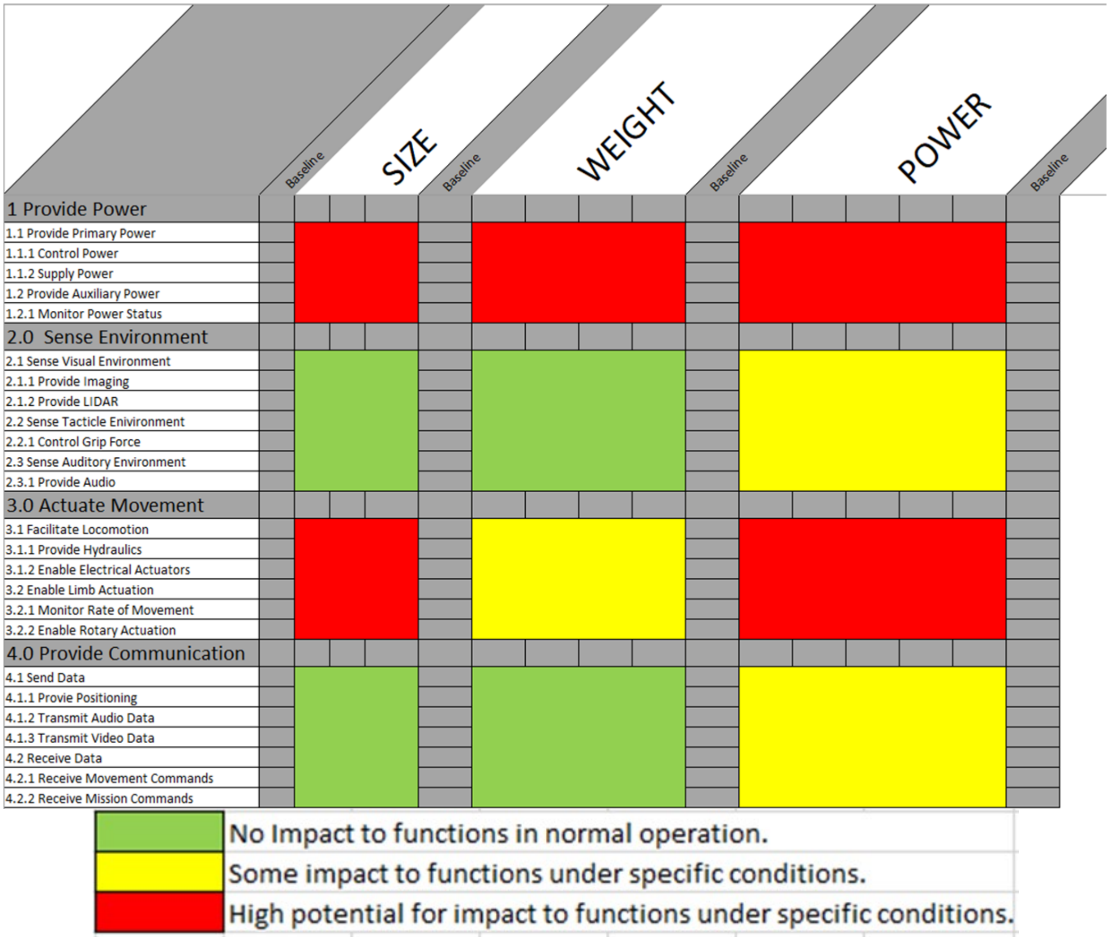


Figure 9. Additional System Power Consumption by Material

D. FUNCTIONAL IMPACT ANALYSIS

Table 11 is the snapshot of the analysis of impact of the SWaP considerations on the baseline functions of the RAAD system. As is indicated by the matrix, the provision of power is most impacted by SWaP considerations due to the potential effects of power control and the provision of auxiliary power for the addition of weight which affect inertial and momentum considerations for the system. Given the relatively light weight of the addition of the EMP protective materials, effects on power for SWaP remain negligible. The impact to the "Sense Environment" function of the ATLAS/RAAD system presents a moderate impact to system operation if through additional weight of the system primary power, auxiliary power, and power control are affected. Due to the onboard equipment suite, including LIDAR and other environmental sensing technologies, the Sense Environment function is the second largest drain of power to the ATLAS system behind Actuate Movement.

Table 11. Functional Impact of Size, Weight, and Power of the ATLAS/ RAAD System



	Baseline	SIZE	Baseline	WEIGHT	Baseline	POWER	Baseline
1 Provide Power							
1.1 Provide Primary Power		🟥		🟥		🟥	
1.1.1 Control Power		🟥		🟥		🟥	
1.1.2 Supply Power		🟥		🟥		🟥	
1.2 Provide Auxiliary Power		🟥		🟥		🟥	
1.2.1 Monitor Power Status		🟥		🟥		🟥	
2.0 Sense Environment							
2.1 Sense Visual Environment		🟩		🟩		🟨	
2.1.1 Provide Imaging		🟩		🟩		🟨	
2.1.2 Provide LIDAR		🟩		🟩		🟨	
2.2 Sense Tacticle Enivironment		🟩		🟩		🟨	
2.2.1 Control Grip Force		🟩		🟩		🟨	
2.3 Sense Auditory Environment		🟩		🟩		🟨	
2.3.1 Provide Audio		🟩		🟩		🟨	
3.0 Actuate Movement							
3.1 Facilitate Locomotion		🟥		🟨		🟥	
3.1.1 Provide Hydraulics		🟥		🟨		🟥	
3.1.2 Enable Electrical Actuators		🟥		🟨		🟥	
3.2 Enable Limb Actuation		🟥		🟨		🟥	
3.2.1 Monitor Rate of Movement		🟥		🟨		🟥	
3.2.2 Enable Rotary Actuation		🟥		🟨		🟥	
4.0 Provide Communication							
4.1 Send Data		🟩		🟩		🟨	
4.1.1 Provie Positioning		🟩		🟩		🟨	
4.1.2 Transmit Audio Data		🟩		🟩		🟨	
4.1.3 Transmit Video Data		🟩		🟩		🟨	
4.2 Receive Data		🟩		🟩		🟨	
4.2.1 Receive Movement Commands		🟩		🟩		🟨	
4.2.2 Receive Mission Commands		🟩		🟩		🟨	

🟩	No Impact to functions in normal operation.
🟨	Some impact to functions under specific conditions.
🟥	High potential for impact to functions under specific conditions.

The actuation of movement within the ATLAS/RAAD system is directly affected by the size of the ATLAS system with weight influencing power consumption under normal operating conditions. Due to the centralized weight distribution of the PE in the ATLAS/RAAD system, impacts to locomotion, actuation, movements, and hydraulics are minimized. The centralized weight of the PE helps the ATLAS/RAAD platform maintain its baseline center of gravity and therefore has minimal impact on the inertia produced by locomotion within the confines of normal operation for the system. Over time, the ATLAS/ RAAD system will suffer in operational effectiveness from reduced actuation and movement functionality as the system loses power. The provision of communications is not affected by the size or weight of the total ATLAS/RAAD system but is directly affected through power considerations. Communications will be negatively affected if through additional power consumption through weight or other means reduces the active amount of power available to provide power for transmission of data and the sending and receipt of commands.

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V. CONCLUSION

This study served to answer the primary research objective of executing a SWaP tradeoff analysis between EMP hardening on the RAAD system and minimizing the effects on operational capability. To address this objective, the research team developed an operational context and performed a functional analysis and functional decomposition. A function-to-component matrix was then created to identify critical components of the system that must be shielded to mitigate catastrophic vulnerabilities. An analysis of alternatives was then conducted to examine the effects of using various materials to harden RAAD critical components. The results were analyzed to show the SWaP tradeoffs that are introduced when shielding the system from EMP and the potential impacts to operational capability of the system.

Many material solutions were analyzed in terms of SWaP of the system. Of all the materials that were evaluated, E-Song EMC Metal Foil offered superior protection with minimal impacts to SWaP. This material is therefore recommended for shielding of the RAAD system. EMP shielding and the solutions identified in this work should be integrated early in the design of the RAAD system to maximize shielding efficiency while minimizing undesired effects to the system.

Creative solutions can be incorporated into the design to increase the cost-benefit tradeoff of shielding. Such techniques include collocating components that require shielding so that they can be shielded as one single component to further maximize efficient use of shielding material. Design engineers may also consider combining shielding materials to attain increased levels of protection for the most critical components. For instance, the design team may elect to provide an additional level of EMP protection by wrapping certain components in protective foil and then covering it with protective paint. This technique may increase the likelihood of survival against EMP attack of greater magnitude or at closer distance than analyzed in this study. The calculations used in this study should be valuable in making critical design decisions based on accurately predicting SWaP impacts when considering the addition of such enhanced shielding techniques of certain components. The methodology used for SWaP analysis proved to be a reasonable approach for studying shielding material and may be valuable tool for the RAAD design engineers.

A. LIMITATIONS AND FUTURE RESEARCH

The scope of this research was limited to unclassified information. Other material solutions or technologies may exist that were not considered by the research team because they are not available for commercial use at this time. A comprehensive search without the confines of unclassified information should be conducted to ensure that all possible materials are considered in an analysis of alternatives.

Another limitation to this research is that our analysis is based on the Atlas Robot, and not based on the actual RAAD system that is still in development. The RAAD critical component list may vary from that of the Atlas Robot based on functional system requirements. This study should serve as a baseline of information to be considered as well as some potential solutions, however, it will not fully encompass the shielding requirements and SWaP effects to the actual RAAD system components. Future research should be conducted as a RAAD prototype is developed and component requirements are finalized.

New technologies and innovative materials are being developed at a rapid pace in the modern world. New material solutions may emerge after this study that provide increased protection with decreased effects to SWaP and operational capability of the RAAD system. An additional analysis of alternatives should be conducted before prototyping to ensure that all new material solutions are considered. This study provides the mathematical framework to adapt emerging material solutions to RAAD system components as they are developed.

Another possibility for future research would be to consider integrating EMP resistant materials into the manufacturing of critical components. Structural components manufactured with infused EMP resistant materials would provide necessary protection without the requirement for wrapping additional materials or painting components.

B. FINAL THOUGHTS

EMP shielding is an important design consideration to ensure the survivability and effectiveness of the Robotic Air Assault Drone system. This study analyzed and identified several different commercial material solutions and techniques that can be used to provide critical component protection with minimal impacts to SWaP and negligible effects to the operational capability of the system. EMP protection should be considered a system requirement and integrated early in the system design process to maximize efficiencies and minimize the SWaP tradeoff.

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