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Trade-Space Analysis of a Small Unmanned Vehicle System for Radiological Search Missions

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THESIS

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Abstract

Nuclear and radiological terrorism is a persistent threat to United States national security. The research and development of new technological capabilities is vital to bolstering emergency response and prevention capabilities in support of national security initiatives. This research characterized the applicable trade-space for a system of unmanned vehicles deployed for search, detection, and identification of radiological source material. Exploration included the development of a CONOPS, a functional decomposition and physical allocation, design considerations, and an analysis of feasibility and utility. The concept system comprises of a ground control station, ground vehicle, hybrid-electric multirotor, and fixed-wing vehicle with an open architecture permitting the exchange of payload components. Payload options include a Geiger-Müller detector or scintillator for large area search and a scintillator or high purity germanium semiconductor for radioisotope identification. Endurance estimates revealed that a hybrid-electric multirotor is capable of carrying a 6.8-kilogram payload for 58 minutes. Similar estimates indicated that a battery-powered fixed-wing vehicle can provide a minimum of 41 minutes of endurance with a payload mass fraction of 15% (1.36-kilogram payload), whereas a gasoline-powered vehicle with the same payload mass fraction (1.95-kilogram payload) can operate for 12 hours. Electric multirotors are limited to a maximum endurance of 20 minutes, which is insufficient for radiological search missions. The system concept proves effective to the radiological search mission and can be expanded to other mission areas through its open architecture.

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TRADE-SPACE ANALYSIS OF A SMALL UNMANNED VEHICLE SYSTEM FOR RADIOLOGICAL SEARCH MISSIONS

I. Introduction

Overview

The purpose of this research is to characterize the applicable trade-space for a small unmanned vehicle system (SUVS) to conduct search, detection, and identification of radiological and nuclear materials. The system will comprise a combination of airborne and ground platforms with integrated radiation detectors to complete a radiological search mission with input from a human operator. Both the platforms and radiation detectors suitable for the platforms will be discussed to understand the limitations and feasibility of employment.

Background

Compared to chemical and biological weapons, which also fall under the weapons of mass destruction (WMD) umbrella, nuclear and radiological materials utilize more sophisticated and technical processes in order to produce quality material for use. Due to this complexity, terrorist organizations are unlikely to produce their own materials and must acquire them through illicit means. These materials are characteristically secured and monitored during production, transportation, storage, and use so that they are not compromised. However, there are also large quantities of material available on the black market due to deficient security and accountability from previous decades. Due to the numerous uses and locations of radiological and nuclear materials, the opportunity for

these materials to fall outside of responsible control and be utilized in nuclear terrorism is a very real threat to national and international security. In order to locate and secure these materials, federal, state, local, and international partners deploy personnel, technology, and other investigative methods to detect and interdict illicit radiological and nuclear materials before being weaponized. As stated by President Trump in the 2018 National Strategy for Countering Weapons of Mass Destruction Terrorism, "as the threat of WMD terrorism continues to evolve, however, our defenses against it must evolve as well" [1].

As part of the counter-WMD mission space, it is necessary for law enforcement and military organizations to be able to detect, locate, and confirm radioactive source material within moderate to large-sized geographic areas. Intelligence gathering may provide advanced knowledge of personnel, vehicles, infrastructure, location, and intent associated with radiological materials. However, the radiological search mission is still a difficult and potentially dangerous logistical problem that is traditionally accomplished by personnel with handheld detectors. Depending on the quantity and activity of the radiological isotope as well as the delivery method of an assembled WMD, hazards exist from both the radioactive material and the weapon's delivery system. Detectors capable of confirming radiological materials must be operated and sometimes placed within short distances of source material for long periods of time to produce accurate and usable data. Radiation exposure from highly radioactive material can cause health effects or even death if too much time is spent near the material. Furthermore, explosively driven WMDs present the potential for severe injury or death if detonated near responding

personnel. The capability to find, locate, and confirm the existence of these hazardous materials utilizing an unmanned system would be a valued asset that could mitigate these hazards to personnel.

Research and development of unmanned vehicles for radiological response began in the 1970s with the reactor meltdown at Three Mile Island, which was further expanded with the second global nuclear accident at Chernobyl in 1986 [2]. There are many sources of research that have looked at optimizing detector technologies, configurations, and software to effectively detect, locate, and map radiation strengths [3]–[8]. There are commercially available systems that utilize detector technologies to provide usable data to an operator about radiation concentrations as well as real-time video imagery [9]. These systems have only been commercially available for a matter of years, and with constantly improving hardware and software, this is an area that will continue to progress and provide a more accurate and practical product to the end user. However, there is little research looking at utilizing a system of UVs to accomplish radiological search operations. The development of this system poses unique challenges due to the differing unmanned platforms: vehicles capable of rapid search may not be capable of dwelling near a target, while vehicles capable of long dwell times generally have short mission duration and are incapable of quickly covering large geographic areas. Creating a flexible system with multiple platforms and multiple integrable detectors allows the use of one system in several configurations to accomplish a variety of detection, location, and confirmation scenarios.

Problem Statement

Several hazards endanger personnel when conducting radiological search operations. There are potential health effects from the radiation being emitted from the source material, as well as threats from enemy combatants and potential deterrent devices in contested areas. Radiation exposure should be kept as low as reasonably achievable, commonly known by the acronym ALARA [10]. The concept of the ALARA principle is to expose the minimum amount of people to the minimum amount of radiation for the minimum amount of time. The same principle can also be applied to the other inherent dangers of radiological WMD search that are posed by enemy combatants, which would be to limit time on target to minimize the risk to responding personnel. Therefore, the development of an unmanned vehicle system for radiological search could contribute to the radiological search mission by reducing hazardous exposures to personnel and minimizing the number of personnel required for search operations.

Research Objectives

As mentioned in the background, the threat of WMD terrorism is ever present and capabilities need to be continually developed and improved to counter their employment [1]. Establishing a system of UVs for the detection, location, and identification of radiological and nuclear materials can assist in this mission set and act as a force multiplier for law enforcement and military organizations. Several research objectives have been established to fully characterize the system of UVs that could be developed for radiological search operations:

1. Characterize the SUVS trade-space for radiological search missions

2. Develop the system framework along with the system limitations, capabilities, and design considerations
3. Assess the operational feasibility and utility from a functional and scenario perspective

For the purposes of this research, a trade-space analysis frames the solution space in which a viable and feasible result may reside [11]. When considering a radiological search SUVS and the research objectives identified above, several questions arise that will assist with addressing the objectives and the concept system design. What radiological sources are of the most interest? Which detectors are suitable for finding these sources and can be incorporated on an unmanned platform? What are the operating characteristics and limitations of these detectors? What would a shared system architecture consist of in terms of similar and differing components for radiological search and detector integration?

Methodology Overview

This research is a targeted mission area analysis scoped at the feasibility and suitability of a SUVS in support of radiological search and geolocation missions. The methods include a survey of the existing state of technology for both radiological detection and unmanned vehicle capabilities, the development of a concept of operations (CONOPS), a system decomposition, and an analysis of the feasibility and utility of the proposed system.

Research Limitations

The focus for this research is limited to sealed radiological and nuclear source material search, detection, location, and confirmation. A sealed source is any radioactive material that is encased in a manner that prevents leakage or escape of the material [10]. The encasement's primary purpose is to prevent the spread of contamination during regular use or transportation of the material. Radiological sources can be found in medicine, agriculture, industry, transportation, research, construction, geology, and mining. These sources are regularly lost or stolen, which can lead to weaponization in the form of a WMD. This research is not addressing WMD-related hazards or tactics, techniques, and procedures for operating in the vicinity of suspect WMDs. Additionally, this research is not focusing on nuclear and radiological incident consequence management operations that address the spread of contamination to people and the environment [12].

Previous Work

A previous Air Force Institute of Technology (AFIT) graduate student researched various radiation detector technologies to be flown on a small autonomous unmanned air vehicle and developed algorithms to rapidly detect, locate, and identify radiation sources. Another AFIT graduate student investigated the use of employing chemical sensors on unmanned aerial systems (UAS) in a tactical environment. The research focused on developing and employing tactics, techniques, and procedures for conducting chemical, biological, radiological, and nuclear (CBRN) reconnaissance and surveillance utilizing small UAS [13]. This research was used as a starting point for this thesis.

Preview of Thesis

This thesis is written in a traditional format. Chapter II discusses terminology, existing technologies, and previous research regarding radiation detectors and unmanned platforms. Chapter III addresses the methodology used to characterize the unmanned system and radiation detection trade-spaces. The findings and results from trade-space analysis are detailed in Chapter IV. The thesis is concluded with Chapter V, which reviews the research findings and presents potential avenues for additional research.

II. Literature Review

Chapter Overview

This chapter will cover the fundamental science of radiation detectors to better understand the different parameters that may affect design decisions for equipping an unmanned vehicle. Furthermore, current unmanned technologies will be discussed to provide background information on the current state of technology that is available through commercial sources or pre-existing government systems.

Types of Radiation

There are multiple forms of radiation that are typically categorized by charged particle emissions and uncharged radiation. Charged particle radiation includes alpha particles, beta particles, and fission fragments. Uncharged radiation includes neutrons, gamma rays, and x-rays. X-rays, alpha particles, and beta particles are typically measured for contamination monitoring or for surveying and assessing a consequence management scenario (e.g. post nuclear detonation). Gamma rays and neutrons travel orders of magnitude further than alpha or beta particles, making them better suited for initial detection and location of radiological material [14]. Within the confines of the radiological search mission space and this research, gamma rays are the primary radiation of concern.

Gamma rays are photons with energies typically in the kilo- and mega-electron volt (keV, MeV) range. These photons are typically emitted when an excited nuclei transitions to a lower energy level, with the gamma energy determined by the differential

of the excited and ground states of the nucleus. Many radioisotope decay events, such as alpha particle emission or nuclear fission, produce subsequent gamma photons in order to maintain nuclear stability [14].

Radiological Sources of Concern

There are over one thousand isotopes that have been found or created on earth, with the large majority being radioactive. Of the hundreds of radioactive isotopes, the International Atomic Energy Agency (IAEA) developed a list of isotopes that have hazardous direct human health effects when exposed to a sufficient quantity of said isotopes over a period of time. Using this list, the US Nuclear Regulatory Commission (NRC), working with the Department of Energy (DOE) and other agencies, established a list of 16 radionuclides of concern that, if gathered in significant quantities based on radioactivity (measured in Terabecquerels or Curies), carry the greatest risk of being incorporated into a radiological dispersal device (RDD) by terrorists (Table 1). The 16 threat isotopes can be found in most developed countries and are commonly used in research, medical, and industrial applications [15].

Table 1. Category 1 and category 2 radioactive material thresholds [16]

Radioactive Material	Category 1 (Terabecquerel)	Category 1 (Curie)	Category 2 (Terabecquerel)	Category 2 (Curie)
Americium-241	60	1,620	0.6	16.2
Americium-241/Be	60	1,620	0.6	16.2
Californium-252	20	540	0.2	5.4
Cobalt-60	30	810	0.3	8.1
Curium-244	50	1,350	0.5	13.5
Cesium-137	100	2,700	1	27
Gadolinium-153	1,000	27,000	10	270
Iridium-192	80	2,160	0.8	21.6
Plutonium-238	60	1,620	0.6	16.2
Plutonium-239/Be	60	1,620	0.6	16.2
Promethium-147	40,000	1,080,000	400	10,800
Radium-226	40	1,080	0.4	10.8
Selenium-75	200	5,400	2	54
Strontium-90	1,000	27,000	10	270
Thulium-170	20,000	540,000	200	5,400
Ytterbium-169	300	8,100	3	81

Categories of Radiological and Nuclear WMDs

In the realm of WMDs, there are a few types that encompass the radiological and nuclear category, which are radiological dispersal devices (RDD), radiological exposure devices (RED), and improvised nuclear devices (IND). INDs are different from RDDs and REDs in that they use fissile materials, such as Uranium-235 or Plutonium-239, in order to create a nuclear yield through a nuclear fission chain reaction. They can either be an illicit nuclear weapon that is bought, stolen, or obtained from a nuclear state, or is fabricated by a terrorist group using illegally obtained fissile nuclear material. The

nuclear explosion from an IND releases intense amounts of energy through shockwaves, heat, prompt radiation emission, and radioactive fission fragments (also known as radioactive fallout). INDs are not the focus of this research, as they present unique challenges for detecting, but it is important to understand the differences between INDs, REDs, and RDDs. REDs utilize highly radioactive materials to irradiate some arbitrary area without physically disbursing the radioisotopes [17]. An example of a RED is a gamma ray source, such as Cobalt-60, that is taped to the underside of a public bus seat. This would expose all passengers within a certain area with potentially harmful doses of gamma radiation while remaining inconspicuous. RDDs also utilize highly radioactive materials, but actively disburse them using delivery systems such as explosives, pressurized containers, fans, sprayers, crop dusters, or building ventilation systems. Compared to REDs, RDDs can potentially contaminate very large areas with extremely small pieces of radioactive material [17]. The resultant cleanup and decontamination are a serious and challenging problem for emergency first responders, which stresses the importance of detecting and locating illicit source material before a WMD can be constructed and employed.

Gamma Interactions

In order to locate and identify gamma photons from the radioisotopes discussed previously, we need to understand how they will interact with materials in the environment as well as our detectors. There are two primary mechanisms by which this occurs; photoelectric absorption (PE) and Compton scattering (CS). In PE absorption, a gamma photon is absorbed by an atomic electron that is then ejected from one of the

atom's electron shells. This electron then deposits its energy in the material; if this interaction occurs in a radiation detector, it can produce a signal (voltage, current, etc.) that is proportional to the energy of the incident photon. Similarly, CS occurs when a gamma ray collides with an atomic electron; in this event, the gamma ray transfers a portion of its energy to the electron and scatters in a different direction from its incident trajectory. As with a PE electron, the recoiled electron will traverse the material where the interaction occurred and deposit its energy, possibly producing an output signal in our radiation detector [14].

Gamma Spectroscopy

Once the gamma photons interact with our detector and produce measurable signals, a histogram can be produced that correlates said signals to incident gamma energies. The measured gamma energies are grouped into energy bins, typically quantified in kiloelectron volts (keV). The height of an energy bin represents the number of counted interactions that correspond to the energy bin. Across the measured energy spectrum, the histogram of energy bins and corresponding counts represents a wave-shaped line called a pulse height spectrum. The clarity of a pulse height spectrum varies and is characterized by the detector resolution, which is a measure of the detector's ability to differentiate the signals produced by gamma interactions. The full width at half maximum (FWHM) is the width of the gamma ray peak at half of the highest point on the peak distribution. Detector resolution is the FWHM divided by the energy of this peak gamma ray and is conventionally expressed as a percentage. The lower the detector resolution percentage, the more defined a spectral line is, resulting in a higher likelihood

to identify radioisotopes. Detector resolution is affected by the detector technology, the algorithms associated with the detector software, and varies with the energy of the incident gamma ray [14]. An example pulse height spectrum delineated into energy bins and counted events is shown in Figure 1. It is important to understand how a detector's resolution impacts the accuracy of identifying the radioisotopes that are present.

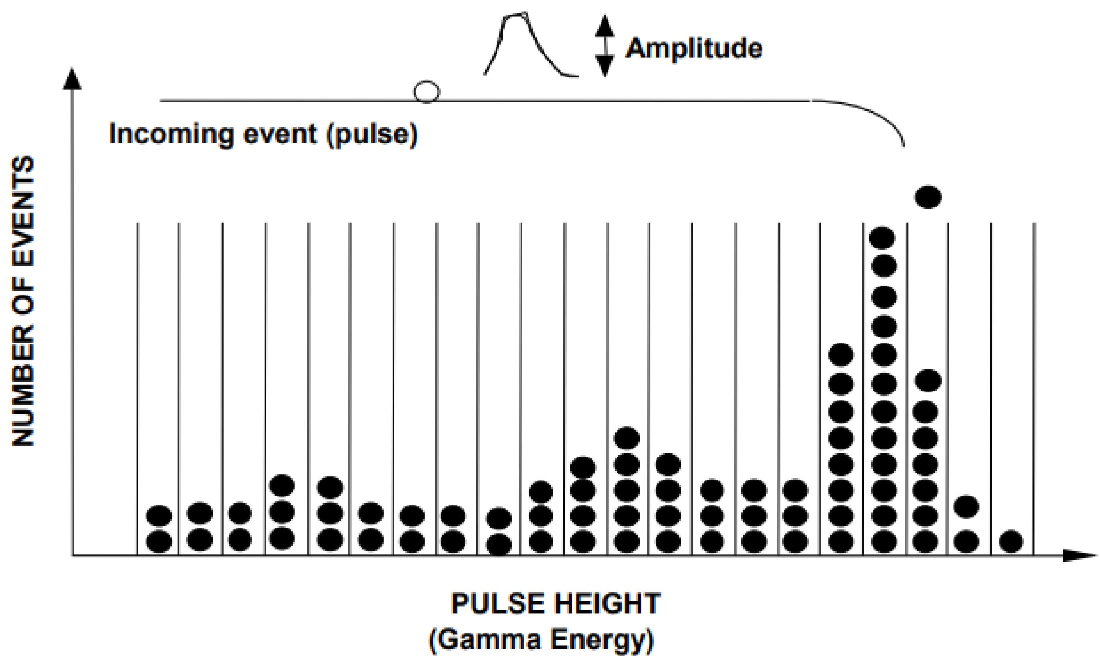

Figure 1. Voltage pulses collected into energy bins [18]

High-resolution (low percentage) detectors are more likely to differentiate between measured energy bins, allowing a more accurate assessment of which isotopes may be present. Low-resolution (high percentage) detectors may struggle to differentiate gamma photons that have similar energies, as they may be lumped together into a single energy bin. The precision of different detector technologies can be seen in Table 2. Energy

resolutions of different radionuclide identification devices (RID) gamma ray detector types and Figure 2.

Table 2. Energy resolutions of different radionuclide identification devices (RID) gamma ray detector types [19]

Detector Type	Resolution at 662 keV
Thallium-doped Sodium Iodide (NaI(Tl))	6 - 8%
Lanthanum Bromide ($LaBr_3$)	2 - 4%
Cadmium Zinc Telluride (CZT)	1 - 2%
High Purity Germanium (HPGe)	< 0.2%

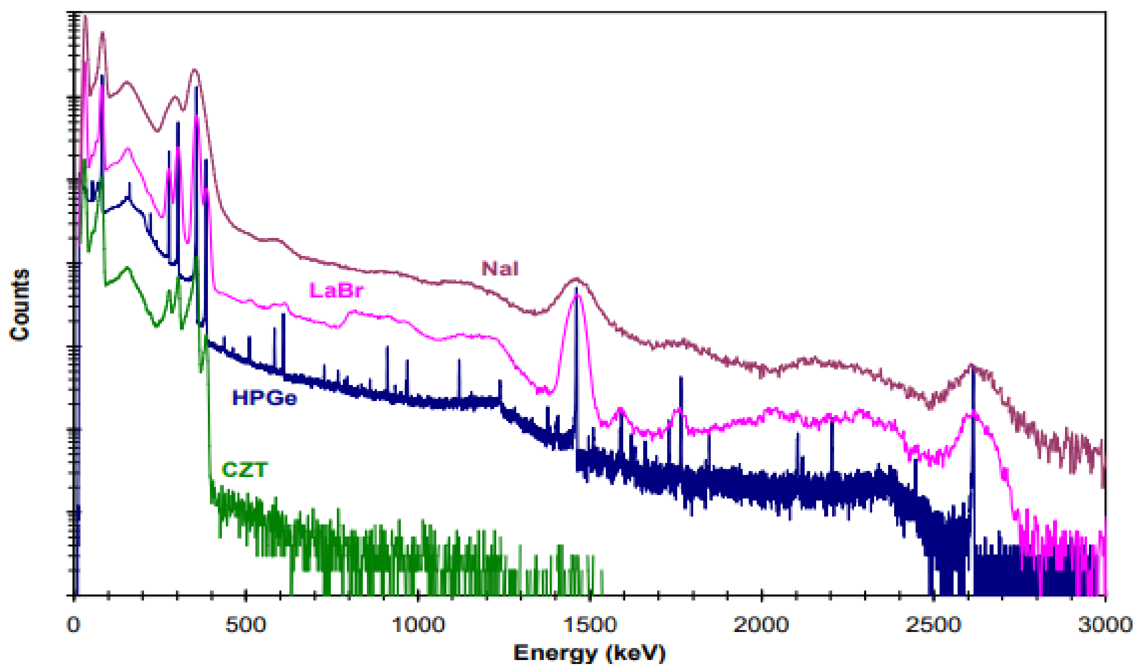

Figure 2. Barium-133 gamma ray spectra acquired with various RIDs [19]

Low-resolution detector materials, such as NaI, can lead to energy measurements blurring together into one energy peak, which does not accurately represent the energy spectrum and can lead to the misidentification of a radioisotope or a false negative. This blurring

of NaI spectra can be seen in Figure 2 in the 300 keV to 400 keV range when compared to the other detector technologies. Furthermore, to attain the resolution of 7% listed in Table 2, the NaI detector measurement has a FWHM of about 47 keV from a 662 keV incident gamma ray. On the other hand, high-resolution detectors (e.g. high purity germanium) can differentiate between gamma energies that are within a few keV of each other [19]. In order to achieve a resolution of 0.2% listed in Table 2, the HPGe detector measurement has a FWHM of about 1.5 keV at 662 keV.

Detection Efficiency

A competing characteristic to detector resolution is efficiency; there are two components that make up detection efficiency, geometric and intrinsic. The geometric efficiency is determined primarily by a detector's distance from the radiation source and, to a lesser degree, the size of the detector. If we make the reasonable assumption that our gamma source is emitting photons isotropically, and that the size of the detector is small compared to the distance between it and the source, the fraction of emitted photons that will reach the detector (ε_G) is inversely proportional to the square of the separation distance (r^2) (Equation 1) [14].

$$\boldsymbol{\varepsilon_G \propto \frac{1}{r^2}} \tag{1}$$

If there is little to no material for the gammas to interact with between the source and the detector, this relationship can inform operational parameters such as standoff distance and loiter time.

In contrast, intrinsic efficiency is a function of the detector itself, and is determined by the interaction material, its volume, and the energy of the incident photon. Dense materials, such as scintillators and semiconductors discussed later, have a higher concentration of electrons per volume for photons to interact with compared to gaseous material. All other parameters being equal, e.g. charge collection or conversion efficiency, a detector with a low-density material will need a larger volume than one with a higher density, affecting operational parameters such as vehicle size and carry capacity [14], [18].

Gamma Attenuation

Gamma attenuation is when a certain quantity of gamma rays passes through an intervening material. This is due to the previously mentioned PE and CS interactions that occur. Attenuation can have a large effect on the amount and strength of gamma energies incident on a detector volume. When intervening material is present, the quantity of incident gamma rays is decreased and Equation 1 no longer applies; such intervening material, such as building walls or radiation shielding, would require a detector to be closer for detection and identification.

Gas-Filled Detectors

Gas-filled detectors operate when incident radiation interacts with fill gas to create ionizations. Using an applied voltage across a cathode and anode, ions are collected to create an electrical signal in the form of a current or pulse [20]. Gas-filled detector volumes are typically sealed and pressurized in order to preserve the

performance of the fill gas [21]. The output signal of a gas-filled detector is dependent on the voltage applied, which is pictured in Figure 3. The higher the applied voltage, the higher the output signal. Gas-filled detectors for radiation surveying are typically operated in three regions: ionization, proportional, and Geiger-Müller (G-M). Due to the low voltage of the ionization region, there is no amplification of the number of ions created by incident radiation, resulting in a detector measurement that is directly proportional to the number of original ion pairs created. The proportional region has a higher-applied voltage and operates similarly to the ionization region, except that the original ion pairs are amplified, creating more ionizations in the detector volume. The measurement of the resulting pulse is proportional to the number of original ion pairs formed. The G-M region has the highest usable operating voltage. This significant voltage difference leads to an avalanche effect following gamma interactions, increasing the produced ions by up to one million-fold throughout the entire detector volume [22].

Gas is not dense and has a low probability for interaction with incident radiation. Therefore, a larger gas-filled volume increases the probability for interaction. Additionally, operating gas-filled detectors in the G-M region increases the potential for ion pairs to be attracted to the charged electrodes, making it ideal for large area searches. Operation in this region gives the most sensitive detection capability but requires the addition of a separate power supply in order to meet voltage requirements.

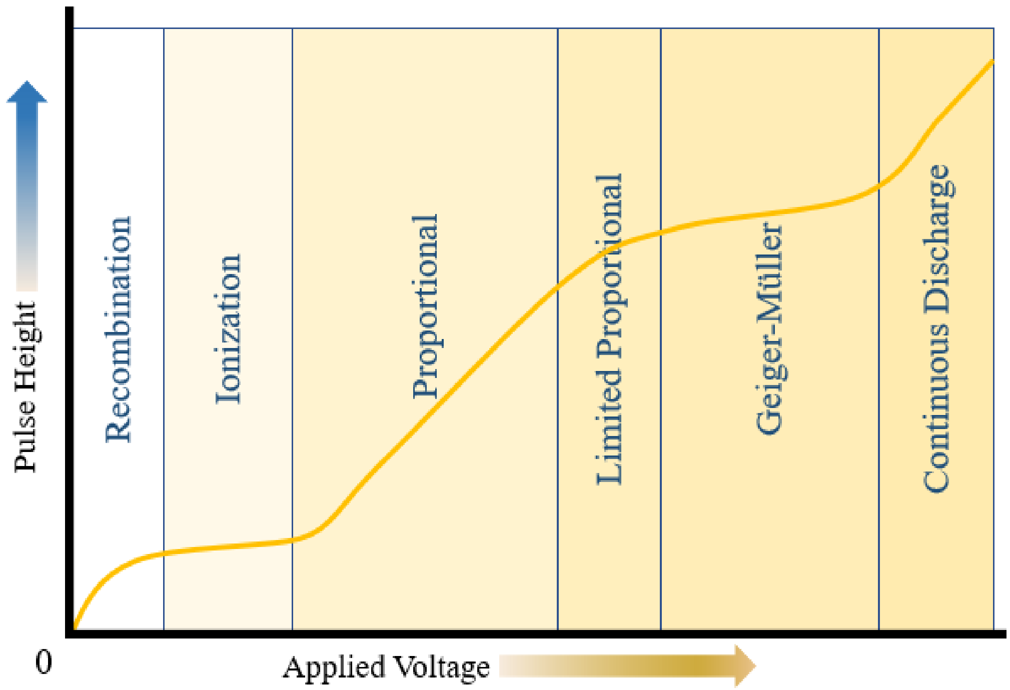

Figure 3. Gas-filled detector six region curve for gamma interactions [22]

The extra batteries, along with the necessity to increase detector volume, increases weight and space requirements and adds heat to the system. A negative aspect of gas-filled detectors is the inability to differentiate between different radiation energies. However, this is a capability that scintillators and semiconductors possess.

Scintillation Detectors

Scintillation is when radiation interacts with certain detector media and produces visual light. Scintillators can be organic or inorganic and can be a liquid, solid, or gas, but solid materials are the most common for detectors. They are typically encased in reflective materials to provide extra rigidity, waterproofing, and to prevent luminesced

light from escaping [20]. A photomultiplier tube or photodiode converts the light into an electrical pulse that can be interpreted by detector software [14].

Each scintillation material has different inherent properties that need to be considered for detector selection, such as hygroscopicity, decay time, and sensitivity to shock. Some materials degrade if exposed to water, even water vapor in ambient air, so airtight chambers are required for certain scintillators. Additionally, scintillators are typically dense crystals that require photomultiplier tubes to convert light into meaningful data. This adds weight and space requirements that need to be considered for UV application. However, scintillators require significantly lower applied potential compared to gas-filled detectors, so a separate power supply is not necessary for operation. Vibrations can also be of concern for some scintillating materials. Depending on the scintillator, vibrations can induce counts in the materials and can damage brittle crystals, which could produce false positives and unreliable data if using for search operations [3], [23].

Plastic scintillators are low-cost, robust, and can be made very large. However, the detectors lack resolution and are ineffective for identification of a radioisotope. NaI scintillators are very common and have been employed for decades. NaI crystals can be made large (in excess of 10 centimeters x 10 centimeters x 46 centimeters) but are considerably more expensive than plastic scintillators. The advantage of sodium iodide is that it can be applied to both initial search and identification of source material. Handheld versions may be undersized for UV purposes, but a larger crystal could give

better detection efficiency while maintaining spectroscopic abilities for isotope identification [4].

Semiconductor Detectors

Semiconductor detectors do not luminesce when interacting with gamma rays. The process is similar to gas-filled detectors, which measure resulting ionizations from radiation interactions over a voltage difference [14]. However, semiconductor detectors differ from scintillators and gas-filled detectors in that they directly measure excited electrons, which produces much better energy resolution [22]. HPGe detectors are commonly used for the detection and identification of radioisotopes due to their excellent resolution. The disadvantages of these systems are that they must be cryogenically cooled with liquid nitrogen or an electromechanical Stirling-cycle cooler, resulting in a very heavy instrument. Additionally, HPGe detectors are significantly more expensive than scintillators. An example system is the Ortec Micro-Detective. This is a 15-pound (6.8-kilogram) handheld detector that utilizes an electromechanically cooled HPGe crystal. It is capable of producing a resolution of less than one percent and can operate for 5 hours on a rechargeable Lithium-ion battery. However, the detector performance can be affected by vibration and heat [4].

Multirotor Unmanned Aerial Vehicles

Current commercially available multirotor systems use either electric power plants using lithium polymer batteries or hybrid-electric systems that utilize gas engines as generators to produce power for electrically driven motors. Electrically driven

systems have limited operational flight times due to the low energy density of battery technology. Electric multirotor systems with sensors other than small cameras are typically limited to 30-minute duration flights, which is not ideal for conducting radiological search operations. On the other hand, hybrid-electric systems have had success in more robust and longer duration applications due to the higher energy density that gasoline provides as an energy source [24]. Gasoline-powered generators allow hybrid-electric multirotor vehicles to fly much longer and farther than their all-electric counterparts. Commercially available hybrid-electric systems currently on the market list specifications that are vast improvements upon battery powered systems. Claims of 5-hour flight duration, payloads as heavy as 12 pounds (5.5 kilograms), and a range of 110 miles (177 kilometers) are a few examples from Skyfront's Perimeter-8 model [25]. The longer duration, range, and heavier payload capabilities make multirotor systems much more attractive and applicable to arenas such as emergency response and military operations [24]. However, gasoline engines present unique design and operating issues that do not affect battery-powered systems, such as mechanical noise, combustion noise, engine start-up, generator maintenance, exhaust, cooling, and vibrations. These additional side effects of a hybrid-electric power plant could affect the overall performance of the system and the feasibility of deploying and operating in constrained environments.

Fixed-wing Unmanned Aerial Vehicles

The purpose of a fixed-wing vehicle within this system would be to cover a large area during initial the search for radiological material. In order to increase the likelihood

for successful detection, the vehicle should operate at lower altitudes to have the highest probability of radiation interaction with the on-board radiological detection system. Additionally, time over target is also an issue due to detector hardware and software delays. A fast platform may not detect radiological material during overflight compared to a slower moving platform. Therefore, a balance between speed and endurance must be managed in order to adequately meet desired performance outcomes. Fixed-wing platforms have been around longer than multirotor systems and can vary greatly in size and in the type of power plant. Hand-thrown battery-powered platforms have been operated in many restrictive and rural environments but are limited by the payload weight and area that can be covered. Incorporating liquid fuel engines to drive single propellers has proven successful for platforms over 20 pounds (9.1 kilograms). An example of small UAS capabilities is the UAV Factory Penguin series. It is available as a battery-powered system or with an electronic fuel-injected engine, with claims such as endurance from 110 minutes to 20 hours, range of up to 60 miles (97 kilometers), and a payload upwards of 22 pounds (10 kilograms). Early models of the system have been flown since 2009 and are utilized in more than 43 countries [26].

Unmanned Ground Vehicles

Unmanned ground vehicles were some of the earliest operated unmanned mobile systems. They were utilized as early as 1981 during the Chernobyl nuclear reactor meltdown in the attempt to limit exposure to responding personnel [2]. Many variants and sizes are currently operated by federal and local governments across the United States and internationally. Ground vehicles have the advantage of being able to loiter in

an area for long periods of time and also carry the heaviest payloads compared to aerial vehicles. However, ground vehicles are limited in range and can be disabled by rough terrain and obstructions.

III. Methodology

Chapter Overview

The purpose of this chapter is to discuss the methods used for analyzing multiple focus areas of the radiological search mission. The resulting research will culminate in characterizing the trade-space for the unmanned vehicle system. Methods to be used include a concept of operations, a system decomposition, and a feasibility analysis of utilizing the system for radiological search operations and other mission areas. The flow of this research will resemble the highlighted portion of the systems engineering "V", which is depicted on the left side of Figure 4.

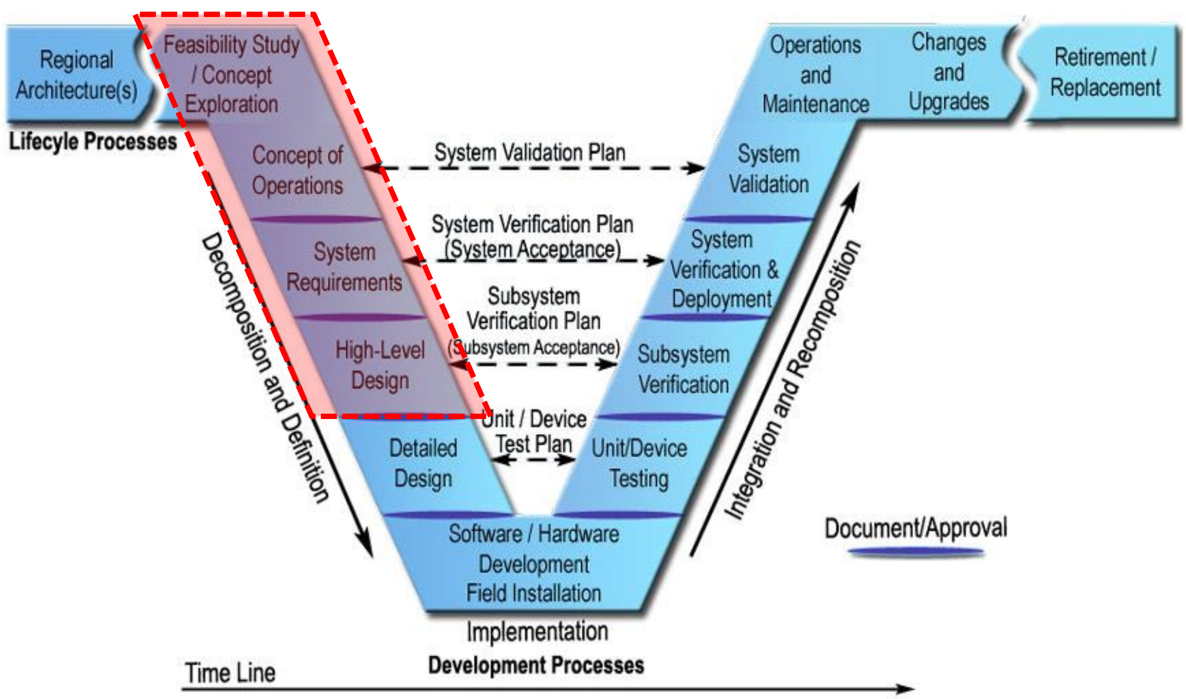

Figure 4. Systems engineering "V" for system development [27]

A CONOPS for the system will be established with corresponding measures of effectiveness (MOEs) at the mission level. The CONOPS is not linked to user requirements, but rather a hypothetical approach to unmanned vehicles for completing radiological search missions currently accomplished with human operators. Use cases will be derived from the CONOPS, as well as resulting tasks, attributes and measures of performance (MOPs). A system decomposition of the functional system architecture with functional tasks and a physical hierarchy will be derived in order to allocate system functions to componentry. The approaches to these methods will be further discussed below.

Concept of Operations

An assessment of radiological search operations will be conducted in order to determine the realistic operational umbrella that an unmanned system could be deployed in support of. Understanding the limitations of the mission space that the system is applicable to will also apply to the derivation of the system's architectural makeup as well as potential architecture modifications needed to make the system useful in other mission areas. Within the overarching mission of performing radiological search, it is important to understand what limitations there are by introducing unmanned platforms and what information needs to be collected and delivered by an unmanned system. A CONOPS will be established which will detail mission needs, limitations, capabilities, and scenarios appropriate to the system. Additionally, it will include the tasks, attributes, and measures of the conceptualized system [28].

The CONOPS will also include a mission timeframe, operational needs, system limitations, enabling capabilities for system operation, and valid scenarios for system employment. The system CONOPS will frame the mission set that it can be deployed in support of. An example CONOPS from the 2019 AFIT UAS three-course design and testing series will be used as a baseline for this research. In addition, some imposed design requirements of the system will be presumed and discussed in terms of their functionality to the mission and why they are important for operational use.

Mission needs will provide information about expected capabilities the system should have to perform the radiological search mission. These can be made for both friendly and adversarial conditions and will be logical, realistic, and necessary for continuing the conceptualization process. Unrealistic assumptions will be avoided, with the focus being placed on gaps in knowledge that are important for successful planning and characterization of the system. Operational limitations can be physical in nature or be due to self-imposed policy that restricts operational functionality. Policy can be leadership driven, multinational, or economic based. Operational constraints can be imposed in the form of rules of engagement, which can vary between commands, organizations, and political boundaries. Policy concerns will not be discussed in this research, with the focus being placed on physical operational limitations of the various subsystems of the unmanned system. Environmental and scenario-specific constraints will be addressed as part of the physical limitations.

Lastly, scenario examples will be provided in order to understand the range of missions that the conceptualized system can cover. These scenarios define friendly and

adversarial conditions, enabling capabilities for system functionality, and the expected value toward mission completion. The scenarios used in this research are not all-encompassing of the system's abilities but provide context to the potential utility of the system.

System Decomposition

Using the CONOPS, a decomposition of the system will be derived. The decomposition will consist of a use case model for the system, a functional decomposition, and an allocation of system functions to physical componentry. The CONOPS will drive the contents of the functional decomposition. The CONOPS will have traceability to the functional decomposition and the physical architecture of each system module. At the basic level, physical componentry of the various systems will be linked to performing all tasks associated with completing the radiological search mission.

The functional decomposition and allocation will be completed using Cameo System Modeler 19.0, which is a model-based systems engineering software tool that uses Systems Modeling Language (SysML) to develop systems engineering solutions [29]. As a starting point for the functional decomposition and allocation, a reference architecture will be used and expanded upon. The reference architecture (RA) was developed by several AFIT professors associated with the small unmanned aerial system courses [30]. The RA is organized by four top-level packages, which comprise a component library, a basic multirotor system, a basic ground control station (GCS), and an example system concept integrating the GCS and fixed-wing UV. Components within each package are further broken down into value properties and ports that characterize

the component, such as memory capacity, operating system type, radio frequency, and cost. The properties are customizable for the user's desired specificity, but not comprehensive of everything that may need to be measured. Additional properties can be added to the concept system's componentry blocks as needed. Lastly, the RA provides an example of a decomposed CONOPS for a remote targeting system with a use case model and the associated activity diagrams. The user of the RA is responsible for developing a use case model and functional tasks that meet the requirements for the pertinent CONOPS with traceability to physical componentry, which is the end state of the system decomposition for this research.

Using the established use cases, tasks, attributes, measures, as well as MOEs, MOPs, and performance factors will be derived that exemplify mission execution of the use cases [31]. Mission-level tasks that feed into mission execution will be identified along with important attributes that are valuable and feasible to measure. These tasks, attributes, and measures are evaluating the mission space from an agnostic perspective, pertaining to both human and system execution. An MOE is a measure of how well an operational task or set of tasks is executed within its expected operational environment. MOEs will be established that pertain to the radiological search mission and the expected operating environmental conditions yet are mission-based and not system-specific [32]. MOPs are a refinement of MOEs and provide measurable performance factors that help evaluate an MOE's status. The attributes will coincide with MOPs and the attributes' measures will be analogous to listed performance parameters. The list will not be exhaustive of all potential MOEs, MOPs, and performance parameters, but will highlight

key factors that characterize the system's effectiveness at completing the radiological search mission.

Analysis of Feasibility and Utility

The last segment of this research is to evaluate the feasibility of incorporating the system into radiological search operations. The spectrum of mission operations will be considered, to include execution of the entire operation with an unmanned system, incorporating the system into a portion of operations, or not utilizing the system for radiological search missions. However, the focus of the feasibility discussion will be the scenarios identified in the CONOPS. As part of the feasibility analysis, estimates of vehicle endurance will be determined corresponding to vehicle size, battery and fuel capacity, and payload size. Furthermore, the system's utility to other mission areas will be assessed, along with the necessary system architecture modifications to expand its capabilities for current and emerging missions.

IV. Analysis and Results

Chapter Overview

From the methodology presented in Chapter III, the analysis of the radiological search system will be approached from an academic yet practical perspective. Characterizing the system, its capabilities, and the physical framework to meet those capabilities are beneficial for gaining an accurate sight picture of the conceptualized system. However, the academic approach will culminate with the feasibility analysis of the system by realistically considering the potential benefits and possible drawbacks that this system could present to gaining units and agencies for the radiological search mission and other mission areas. New technological capabilities are not always viable to replace or supplement current tactics, techniques, and procedures, which will be discussed at the end of this chapter.

Concept of Operations

This CONOPS defines a prototype system and the associated efforts to assess system architecture and demonstrate the feasibility and utility of a concept solution before a prototype demonstration phase. The CONOPS, and the proposed system framework solutions associated with it, address the system’s vehicles, sensors, user interface software, communication system, support functions, and operator actions for application to the radiological search mission.

Scope

This CONOPS is intended to be an enabling concept and is written at the tactical level. More specifically, the radiological search CONOPS describes the projected utilization by Department of Defense (DoD) CBRN personnel, explosive ordnance disposal (EOD) technicians, and special operations forces (SOF), as well as analogous federal, state, and local entities necessitating the capability to detect, locate and confirm the existence of hazardous radiological material. The radiological sources will be in one of two categories: an orphan source where the material is lost or stolen or when the material has already been weaponized into an RDD or RED.

Mission Timeframe

Mission timeframe refers to the expected time it will take to research, develop, acquire, test, and deploy the objective system to operational units. The intent for the system's research and development phase is to utilize commercial off the shelf (COTS) and government off the shelf (GOTS) technologies to reduce initial startup time typically seen for newly developed systems. Applying previously researched and tested equipment to system construction will expedite this portion of the process. It will also shorten the time required to develop training programs and support equipment required to field the system. The mission timeframe is expected to be between two and five years. Two years is a best-case estimate to allow for research, acquisition, testing of the separate components, and assembling them into an operative system of systems. This also includes the procurement of support equipment and the development and execution of training for system operation and maintenance. The system should be completed and fielded within

five years due to the rapid pace of innovation in the unmanned vehicle industry. A system under development for a longer period of time will be outpaced and become obsolete prior to becoming operationally fielded.

Mission Needs

The system will deploy to meet intelligence-based missions as required or to aid in the search and recovery of lost, stolen, or other forms of radiological source material. The system under consideration should be small in size but capable of searching an area of 3 square kilometers or larger, to include, but not be limited to, large urban buildings and sea-based vessels. The system is to be used by tactically deployable units from federal, state, and local organizations, so logistical requirements should be moderately small in size. The system should function with no more than four human operators and should be deployable utilizing no more than a transport vehicle and trailer for transportation. The objective system should be easily maintainable and should integrate as many COTS and GOTS components as possible. Garrison maintenance equipment capabilities and battery charging units are within the scope of the objective system. This does not include commonly found tools such as wrenches and screw drivers. While the unmanned vehicles are intended to be reusable, the cost of the systems should be sufficiently low to allow disposal in lieu of costly decontamination, hazardous recovery, and vehicle loss or theft. Due to the potential operation in contested areas, loss or theft of system vehicles should not provide substantial exploitable information or materiel to adversarial forces.

The baseline system shall contain a combination of air vehicles, a ground vehicle, and a ground control station for user interface. Using the system of vehicles equipped with various and interchangeable payloads, the system will be able to locate and confirm the existence of radiological source material, as well as generate a three-dimensional radiation dose rate contour map of the search area. Due to the continuous improvement of technology in unmanned vehicles and radiation detection equipment, the system shall employ a modular, open system architecture which facilitates the integration of new sensors and subsystems throughout its lifecycle. This includes but is not limited to defense programs of record (PORs), COTS and GOTS technologies, and sensors associated with other CBRN constituents. However, the system should make extensive use of COTS and GOTS componentry and existing vehicles in order to minimize development time and system cost. The objective system's air vehicles shall adhere to DoD UAS Group 1, Group 2, or small Group 3 weight, altitude, and speed requirements for low altitude maneuverability and tactical deployability (Table 3).

Lastly, the system will allow for semi-autonomous operation with real-time, human-in-the-loop control. Each operational task will require a certain level of human input, which necessitates a varying degree of control given to the GCS or on-board processor. The level of autonomy will be driven by the risk of each task and the impact it has on mission completion. The overall level of autonomy is relatively low, with most tasks requiring operator input or pre-planned tasks for the system to execute. Consequentially, the shared responsibility between a human operator and the system GCS

Table 3. Unmanned aircraft systems categorization chart [33]

UA Category	Maximum Gross Takeoff Weight (lb)[kg]	Normal Operating Altitude (ft)[m]	Speed (KIAS)	Representative UAS
Group 1	(0-20) [0-9]	(< 1,200 AGL) [< 366 AGL]	(100)	WASP III, TACMAV RQ-14A/B, Buster, Nighthawk, RQ-11B, FPASS, RQ16A, Pointer, Aqua/Terra Puma
Group 2	(21-55) [10-25]	(< 3500 AGL) [< 1,067 AGL]	(< 250)	ScanEagle, Silver Fox, Aerosonde
Group 3	(< 1,320) [< 599]	(< 18,000 MSL) [< 5,486 MSL]	(< 250)	RQ-7B Shadow, RQ-15 Neptune, XPV-1 Tern, XPV-2 Mako
Group 4	(> 1,320) [> 599]		Any Airspeed	MQ-5B Hunter, MQ-8B Fire Scout, MQ-1C Gray Eagle, MQ-1A/B/C Predator
Group 5	(> 1,320) [> 599]	(> 18,000 MSL) [> 5,486 MSL]	Any Airspeed	MQ-9 Reaper, RQ-4 Global Hawk, RQ-4N Triton

Legend

AGL	above ground level	m	meter
ft	feet	MSL	mean sea level
KIAS	knots indicated airspeed	UA	unmanned aircraft
kg	kilogram	UAS	unmanned aircraft system
lb	pound		

will range from #1 to #4 across the Taxonomy of the Distribution of Responsibility between Human and Computer (Figure 5).

1. Human does all planning, scheduling, optimizing, etc. and turns task over to computer merely for deterministic execution.
2. Computer provides options but the human chooses between them, plans the operations, and then turns task over to computer for execution.
3. Computer helps to determine options, and suggests one for use, which human may or may not accept before turning task over to computer for execution.
4. Computer selects option and plans action, which human may or may not approve, computer can reuse options suggested by human.
5. Computer selects action and carries it out if human approves.
6. Computer selects options, plans, and actions and displays them in time for human to intervene and then carries them out in default if there is no human input.
7. Computer does entire task and informs human of what it has done.
8. Computer does entire task and informs human only if requested.
9. Computer does entire task and informs human if it believes the latter needs to know.
10. Computer performs entire task autonomously, ignoring the human supervisor who must completely trust the computer in all aspects of decision making.

Figure 5. Taxonomy of the distribution of responsibility between human and computer [34]

Enabling Capabilities

Some capabilities fall outside of the radiological search SUVS scope but are necessary to enable the system's effective use. While the system may make use of on-board navigation sensors for terrain avoidance, it is anticipated that the system will utilize the global navigation satellite system (GNSS) for maneuvering to waypoints, tracking its position, and mapping radiation strength of the search area. Low cost alternative navigation (non-GNSS) technologies are emerging but may not be available for deployment in the two to five-year window envisioned for this system. The system should be transportable by a light to medium-duty truck with a trailer or a small

waterborne vessel for deploying the system to the operational area of concern. The transport vehicle should be capable of powering the GCS and associated GCS-operated equipment, as well as charging vehicle batteries when forward deployed. However, external power may be required when forward deployed for multiple missions or long durations.

Scenarios

The listed scenarios are broad and cover the entirety of mission phases that need to be accomplished by the system. The scenarios not only pertain to the conceptualized system, but also entail inherent interactions and inputs from the human operators of the system. The envisioned phases of system operation include ground control setup and teardown, vehicle deployment, mission execution, and system recovery.

Ground Control Setup & Teardown Phase

This phase encompasses all actions necessary to deploy the SUVS including unpacking, inventory, assembly, function checks, mission planning, disassembly, and reconstitution. Since the system is intended for use with forward deployable units, transportation of the system must be compatible with deployed vehicles or small waterborne vessels. The system must be capable of operating without externally supplied power. A system built-in-test will signal to the operator if the system is fully operational; if the system is not 100% operational, the built-in-test will identify all system faults. Mission planning for the system should be practicable prior to deployment, prior to beginning operations when on site, and modifiable during on-going operations once vehicles have been launched.

Vehicle Deployment Phase

This phase encompasses all actions necessary to achieve initial vehicle movement starting from a properly configured vehicle or vehicles and a ground control station. No more than two operators should be required to deploy a vehicle. Following built-in-tests, mission plans should be wirelessly uploaded to involved vehicles prior to launch. The vehicle deployment phase ends once movement toward the target area is achieved and the system begins waypoint navigation.

Mission Phase

This phase includes a variety of tasks as defined by the selected payloads and established mission plan. It is envisioned that the system will be capable of waypoint navigation to both pre-planned and ad-hoc waypoints, can loiter or hover depending on the vehicle type, can navigate terrain, and can operate attached sensors at designated waypoints per the mission requirements. Mission tasks that should be accomplished in order to meet the desired capabilities of the system include:

1. Loiter or hover about a waypoint or navigate to a sequence of waypoints while providing real-time radiological strength measurements to the ground control station. Video imagery from search should be recorded and displayed to the ground control station in real-time. Video options will be available for both daytime and low-light conditions, with enough quality for the ground control station operator to detect human figures based on the displayed imagery. The operator will designate a target search area with the ground control station software and the system will

search the designated target area based on vehicle telemetry, with a desired accuracy of 15 meters distance root mean squared (DRMS). The initial search should yield calculated location(s) of radiological source material based upon maximum radiation readings and telemetry data. The system should be capable of displaying a radiological strength contour map of the target area to the ground control station operator.

2. Navigate to a waypoint and hover, land, or dwell at the location while providing real-time video imagery to the ground control station. Video imagery should be recorded and displayed to the ground control station in real-time. The operator will designate the target location(s) calculated from the initial area search. Once at a designated target location, the system will confirm the detected radiological sources by collecting a gamma spectrum of the source material. Spectrum data will be provided to the ground control station and the system will predict the radioisotopes based off the measured gamma energies.

3. Traverse the exterior wall faces of an urban structure, covering both the horizontal and vertical extent of a building. The system should employ terrain avoidance while maintaining a safe distance from a structure in order to avoid damage to or loss of a vehicle. The desired location accuracy of 15 meters DRMS is driven by the need to avoid collateral damage in urban environments. While traversing the exterior wall faces of a building, the system will record radiation strength measurements at

locations adjacent to the walls. These radiation measurements will be used to develop a three-dimensional contour map to pinpoint probable locations for the source material.

4. Perform a commanded ditch or crash maneuver in the event of system faults or circumstances making recovery impossible or undesirable, such as unavoidable contact with hostile personnel or compromise of the system. Each system vehicle will encompass a self-destruct module to make the system unusable if seized by unfriendly forces.

5. Perform a return to launch (RTL) at any time during operation. An RTL will return the vehicle to a pre-programmed location where it will perform the recovery phase.

Recovery Phase

This phase involves recovering the vehicles upon completion of the mission or as deemed necessary. The UVs should be capable of navigating to a recovery location designated by the ground control station operator. Unassisted takeoff and landing of air vehicles are desirable if done safely and to ensure rapid recovery and reuse of the vehicle. Batteries must be replaceable in the field and additional fuel should be available for sequential search or continuing large area search or surveillance operations.

System Decomposition

Use Cases

A use case model for the system has been developed using Cameo Systems Modeler to visualize the main operational functions that the system needs to perform, as

well as the interactions the system has with actors, external systems, and the environment (Figure 6). The use cases are based on mission needs, enabling capabilities, and scenarios previously mentioned. The entire system is responsible for performing setup, planning the mission, deploying and ingress, performing search and confirmation activities, egressing and recovery, and self-destruction if necessary. Several use cases require interactions with the GNSS, the physical environment, and human operators,

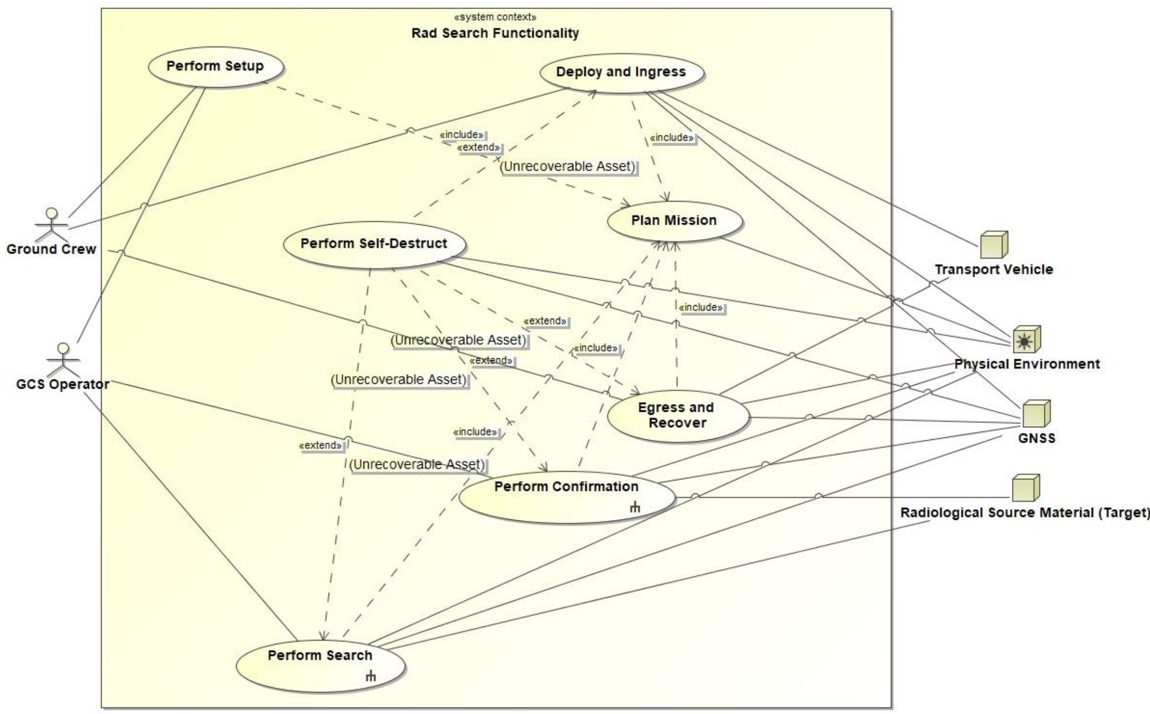

Figure 6. Use case model for the radiological search system

whereas the target radiological source material only relates to performing search and confirmation. The use cases holistically provide the necessary functions to execute the entire spectrum of the radiological search mission, as determined by the CONOPS. The details of the individual use cases can be found in Appendix B.

Tasks, Attributes, and Measures

Within the confines of the radiological search mission, there are basic tasks that must be accomplished as part of mission execution. The tasks, along with the associated attributes and measures, can be seen in Table 4. This list highlights important variables

Table 4. Mission-level key tasks, attributes, and measures

Task	Attribute	Measure
Search	Coverage	Duration [min]
		Total area searched [m²]
		Area coverage rate [m²/s]
Detect	Accurate	Probability of detection [%]
		False alarm rate [alarms/mission]
Navigate	Accurate	DRMS absolute location error [m]
		DRMS relative location error [m]
Communicate	Secure	Encrypted/not encrypted
	Range	Range [m]
Confirm	Spectral resolution	Resolution [% FWHM]
	Source position accuracy	DRMS location error [m]
Mission-wide	Workload	Minimum crew size required [# personnel]
	Availability	Mission turn time [min]
		Mission ready rate [% mission capable]

that apply to the mission. The tasks are essential for executing the individual use cases, and therefore meeting the intent established in the CONOPS. The attributes and measures capture what can be considered significant measurable data for task evaluation if system development were to occur. It should be noted that the list does not encompass all tasks that need to be performed nor all measures that should be considered for evaluation. Additionally, there are some attributes and measures that apply across all mission tasks, which are combined in a "mission-wide" task category. The major tasks

for mission completion are search, detection, navigation, communication, and confirmation. The established mission-level tasks feed MOEs for the radiological search mission and the expected operating environmental conditions [32]. From there, system-specific MOPs were developed including measurable performance factors for evaluating the MOEs. The MOPs are related to the task attributes and the attributes' measures correspond to performance parameters. The list of developed MOEs, MOPs, and performance parameters are in Table 5. As mentioned previously, the MOEs, MOPs, and performance parameters are not exhaustive and provide an academic assessment of critical data that should be measured to assess system performance against mission execution.

Table 5. MOEs with system-specific MOPs and performance parameters

MOE	MOP	Performance Parameters
Success rate of locating and identifying radiological source material in a 3 square kilometer search area	Location accuracy of radiological source(s)	Detector dead time [ms]
		Detector dose rate range [mSv]
		DRMS relative location error [m]
		DRMS absolute location error [m]
	Confirmation accuracy of radiological isotope(s)	Spectrum resolution [%]
		Minimum energy detected [keV]
		Maximum energy detected [keV]
	Endurance	Weight [kg]
		Power capacity [W]
	Area coverage rate	Camera FOV [°]
		Operating altitude [m]
		Vehicle cruise speed [m/s]
	Degree of autonomy	Autonomy scale [Figure 5]
	Video imagery resolution	Ground sample distance [m]
Ability to communicate data to a remote-control point across a 3-kilometer distance	Data processing speed	GCS processing speed [GHz]
		Data transmission rate [Mbps]
	Data encryption	Y/N
	Transmission range	Tx power [dB]
		Rx power [dB]

Functional Decomposition and Physical Allocation

Continuing with the system hierarchy, the functional decomposition and allocation of physical componentry can be produced. For the purposes of this research, the CONOPS identified system requirements are based on assumptions and personal knowledge of the radiological search mission space. This is unlike traditional processes where requirements are identified by operational users of a conceptualized system [28]. The requirements as presented herein are traceable to the use cases, tasks, attributes, measures, and now to the functional decomposition and physical architecture of the system. Individual tasks are essential for the completion of the different scenarios mentioned in the CONOPS as well as for the execution of each use case. A conglomeration of all derived tasks for a vehicle and the GCS can be seen in Table 6.

Table 6. Derived system tasks between vehicle and GCS

Vehicle Activities		GCS Activities	
Auto land	Load MP	Analyze spectrum data	Display video
Auto takeoff	Loiter	Calculate target coord	Receive MP status
Capture video	Navigate waypoints	Combine rad data/telemetry	Receive rad data
Collect rad data	Send rad data	Connect to vehicle	Receive spectrum data
Collect rad spectrum	Send spectrum data	Construct MP	Receive telemetry
Conduct BIT	Send telemetry	Create rad map	Send cmd
Follow search pattern	Send video	Display rad data	Store rad data
Initiate search	Trigger self-destruct	Display rad map	Store spectrum data
		Display rad spectrum	Store target coord
		Display radionuclide	Store telemetry
		Display target coord	Store video
		Display telemetry	Write MP

The functional decomposition has been split at the system level into vehicle activities and GCS activities, represented in the MBSE format in Figure 7. For this research, the vehicle activities generally apply to and cover all activities for the ground, fixed-wing,

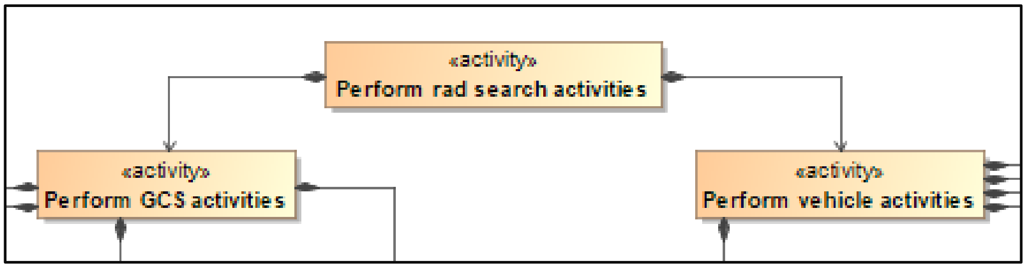

Figure 7. System functional decomposition

and multirotor UVs. The activities for the various vehicles are broken down into performing controlled movement, autopilot function, vehicle data communications, radiation measurement, and providing video (Figure 8).

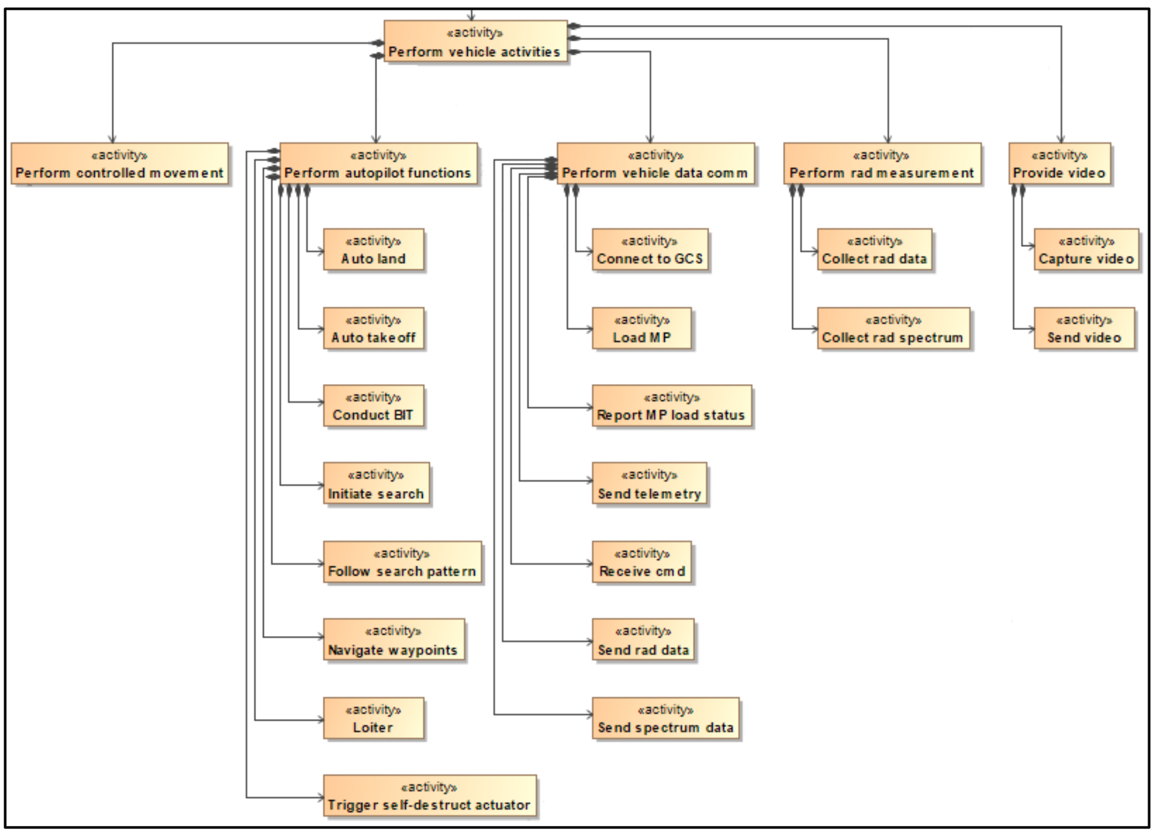

Figure 8. Generic vehicle functional decomposition

For the ground control station, the functional decomposition is categorized by processing, providing data communication with system vehicles, providing interface and output for the GCS operator, and receiving video from vehicles. The GCS sends commands to system vehicles, receives and displays video, and receives, processes, and displays critical flight and radiation measurement data (Figure 9).

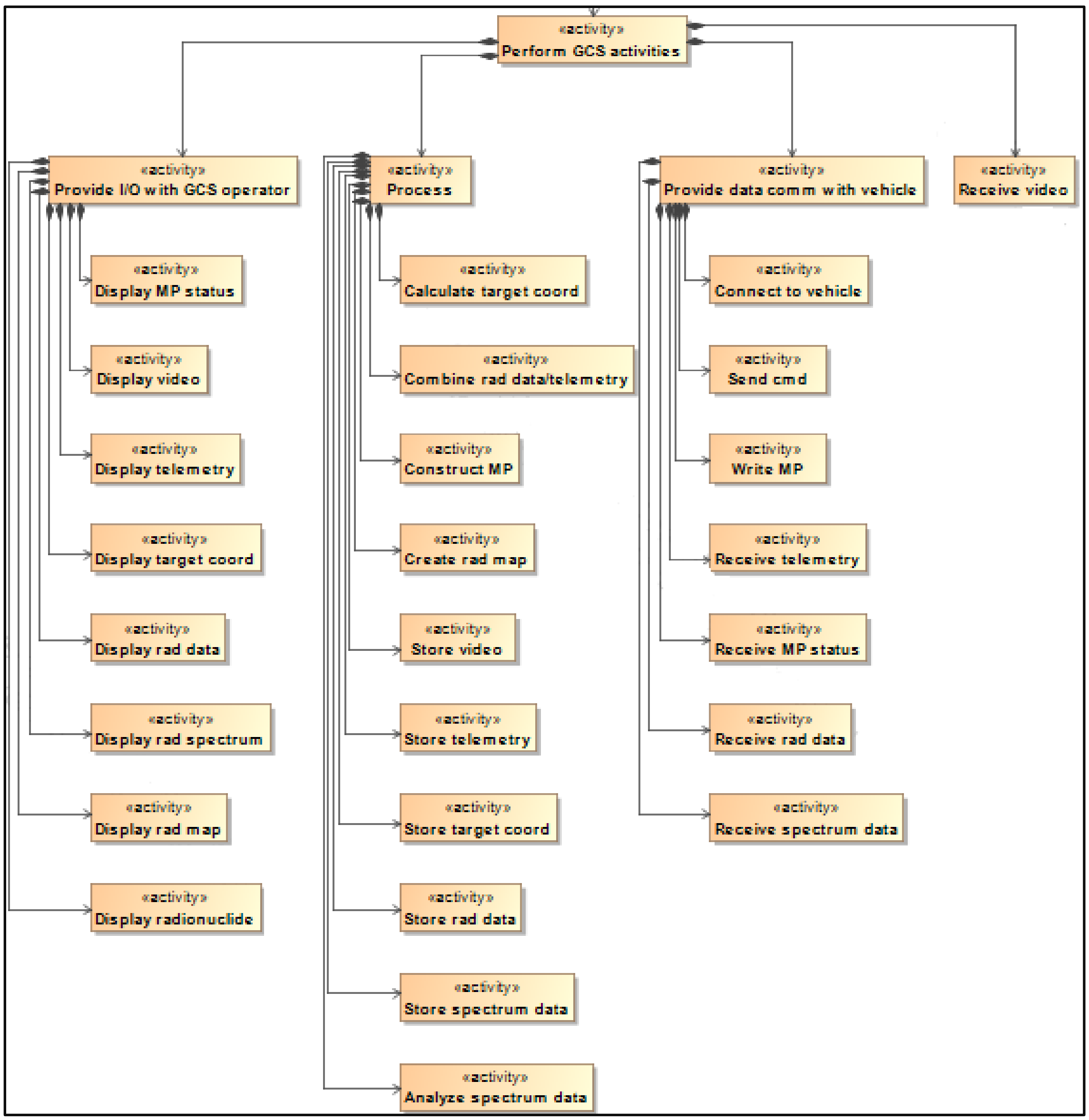

Figure 9. GCS functional decomposition

The physical architecture consists of singular components, organized into system modules, that fulfill the execution of tasks listed in the vehicle and GCS functional decompositions (Figure 10-13). The vehicle modules are navigation, payload, power, self-destruct, and the vehicle itself. The subsystem breakdowns are not exhaustive lists

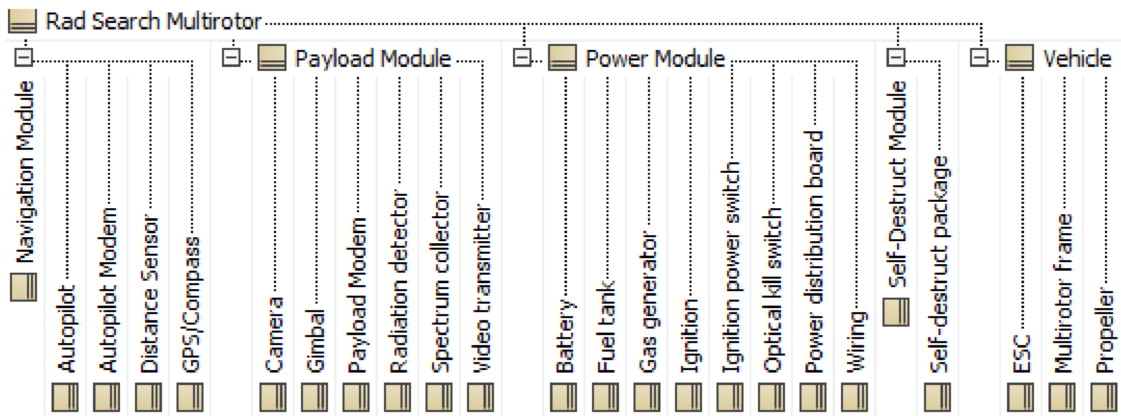

Figure 10. Multirotor physical architecture

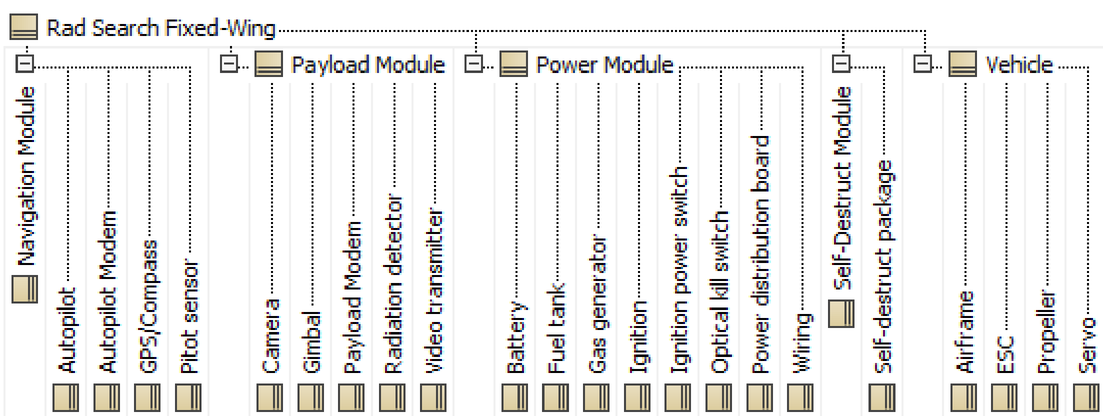

Figure 11. Fixed-wing physical architecture

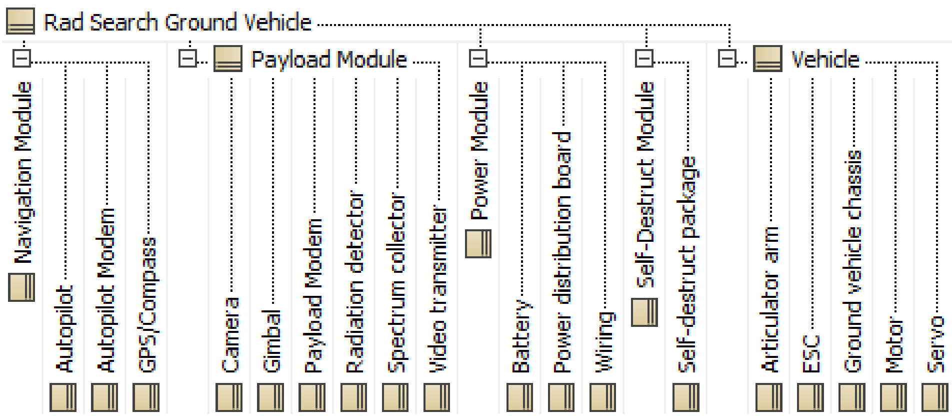

Figure 12. Ground vehicle physical architecture

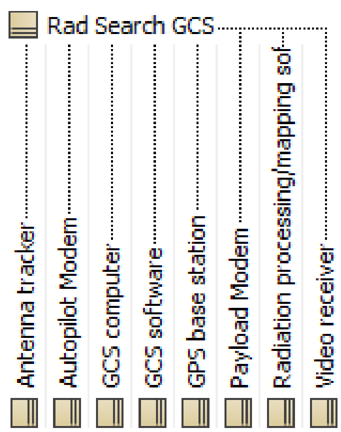

Figure 13. Ground control station physical architecture

of all physical hardware but include major components that should be considered for future design and sizing. It should be noted that the power modules for the multirotor and fixed-wing vehicles contain both batteries and gasoline-based engines, which will be discussed later in Chapter IV. Additionally, there is no power system listed for the ground control station, as this will be powered by the transport vehicle used to deploy the system and human operators.

From the different physical architectures, the subsystem components can be allocated against all system tasks from the functional decomposition. Allocating each individual task against each component within the system continues the traceability from the CONOPS, to the use cases, to the tasks, and lastly to the physical hierarchy of the system. An allocation of each activity to a subsystem component satisfies this traceability (Table 7). Each activity that is necessary for mission completion is being satisfied by at least one component or one subsystem module. The individual vehicle and GCS physical allocation matrices can be found at Appendix A. By categorizing the subsystems, the physical components, and the executable tasks, a simplified analysis for potential hardware redundancy is possible.

Table 7. System physical allocation matrix

Legend Allocated - ↗	Rad Search Fixed-Wing	Rad Search Ground Vehicle	Rad Search Multirotor	Rad Search GCS
Analyze spectrum data				↗
Auto land	↗	↗	↗	
Auto takeoff	↗	↗	↗	
Calculate target coord				↗
Capture video	↗	↗	↗	
Collect rad data	↗	↗	↗	
Collect rad spectrum		↗	↗	
Combine rad data/telemetry				↗
Conduct BIT	↗	↗	↗	
Connect to GCS	↗	↗	↗	
Connect to vehicle				↗
Construct MP				↗
Create rad map				↗
Display MP status				↗
Display rad data				↗
Display rad map				↗
Display rad spectrum				↗
Display radionuclide				↗
Display target coord				↗
Display telemetry				↗
Display video				↗
Follow search pattern	↗	↗	↗	
Initiate search				↗
Load MP	↗	↗	↗	
Loiter	↗	↗	↗	
Navigate waypoints	↗	↗	↗	
Perform autopilot functions	↗	↗	↗	
Perform controlled movement	↗	↗	↗	

Legend Allocated - ↗	Rad Search Fixed-Wing	Rad Search Ground Vehicle	Rad Search Multirotor	Rad Search GCS
Perform GCS activities				↗
Perform rad measurement	↗	↗	↗	
Perform rad search activities	↗	↗	↗	
Perform vehicle activities	↗	↗	↗	
Perform vehicle data comm	↗	↗	↗	
Process				↗
Provide data comm w/ vehicle				↗
Provide I/O w/ GCS operator				↗
Provide video	↗	↗	↗	
Receive cmd	↗	↗	↗	
Receive MP status				↗
Receive rad data				↗
Receive spectrum data				↗
Receive telemetry				↗
Receive video				↗
Report MP load status	↗	↗	↗	
Send cmd				↗
Send rad data	↗	↗	↗	
Send spectrum data		↗	↗	
Send telemetry	↗	↗	↗	
Send video	↗	↗	↗	
Store rad data				↗
Store spectrum data				↗
Store target coord				↗
Store telemetry				↗
Store video				↗
Trigger self-destruct actuator	↗	↗	↗	
Write MP				↗

Design Considerations

There are several avenues for system design based on the established CONOPS and system decomposition. These include similar and dissimilar componentry as well as factors that could attribute to certain design decisions such as payload type, processing capabilities, and the operating environment. In order to evaluate the system componentry, the three vehicle systems and the ground control station were assessed. A comparison of subsystem components and their equivalent to other systems is shown in Table 8, identifying hardware that can use similar components, hardware that is similar but likely use different components, and hardware that is dissimilar.

Similar Componentry

After a rudimentary comparison, it is evident that there are multiple overlapping components in the payload, navigation, and power modules, as well as the self-destruct package. Due to the assumed simplicity of the system concept and maximizing existing COTS and GOTS hardware, equivalent components should be selected in order to duplicate the capability of each component within the overarching system. This creates redundancy throughout the system, enabling the cannibalization of one vehicle system in order to make another system fully operational. For instance, similar modem components should be incorporated for transmitting telemetry data, payload data, and video stream. Redundant hardware facilitates the interchange of system components with little to no re-programming if operational constraints arise. This can be crucial to operators if they are limited on spare parts or if geographically separated from the main operating location by providing the ability to troubleshoot a subsystem when hardware becomes inoperable.

Table 8. Comparison analysis of subsystem componentry

	Component	Fixed-Wing	Multirotor	Ground	GCS
NAVIGATION	Autopilot	Green	Green	Green	
	Autopilot Modem	Green	Green	Green	Green
	GPS/Compass	Green	Green	Green	
	Pitot Sensor	Red			
	Distance Sensor		Red		
PAYLOAD	Camera	Green	Green	Green	
	Gimbal	Green	Green	Green	
	Payload Modem	Green	Green	Green	Green
	Radiation Detector	Green	Green	Green	
	Video Transmitter	Green	Green	Green	
	Spectrum Collector		Green	Green	
POWER	Battery	Green	Green	Green	Green
	Fuel Tank	Green	Green		
	Gas Generator	Yellow	Yellow		
	Ignition	Yellow	Yellow		
	Ignition Power Switch	Yellow	Yellow		
	Optical Kill Switch	Green	Green		
	Power Distribution Board	Green	Green	Green	
	Wiring	Green	Green	Green	
SD	Self-Destruct Package	Green	Green	Green	
VEHICLE	Electronic Speed Controller	Green	Green	Green	
	Air Frame	Red			
	Propeller	Yellow	Yellow		
	Servo	Yellow		Yellow	
	Articulator Arm			Red	
	Ground Vehicle Chassis			Red	
	Motor	Red	Red	Red	
	Multirotor Frame		Red		
GCS	Antenna Tracker				Red
	GCS Computer				Red
	GCS Software				Red
	GPS Base Station				Red
	Radiation Processing/Mapping Software				Red
	Video Receiver				Red

Green	Similar component, could be same
Yellow	Similar component, likely different
Red	Different component

The decision to swap components from one system to another is driven by mission and scenario need. For example, intelligence identifies a single building as the target location for a radiological source. This would not require the use of a fixed-wing UV since a large area search is not needed. The components of the fixed-wing UV can be cannibalized in order to ensure mission execution with the other two system vehicles. On the contrary, a large area search requires a fixed-wing UV for initial detection of the radiological material. However, the fixed-wing UV can be disassembled after initial detection is complete, the search area has been narrowed, and when follow-on search and identification can be managed by the multirotor or ground vehicle. Hardware redundancy provides the flexibility to prioritize and execute mission needs when necessary.

Hardware Variations

There are also multiple componentry differences amongst the vehicle systems and the ground control station. Modules with major variations from other systems include power production, the ground control station, and the vehicle itself. As is anticipated, the vehicle chassis will be dissimilar for the various UVs. This includes the vehicle propulsion system, which consists of the motors (electric and gasoline-fueled), servos, propellers, and wheel tracks. The last distinctive vehicle component is an articulator arm on the ground vehicle, which can be used for object manipulation and as an extra mounting point for vehicle payloads.

In order to meet the system's intent of searching large areas as well as carrying payloads in excess of 15 pounds (6.8 kilograms), the power plants for the different vehicles cannot be restricted to battery-powered systems. Other options to be considered

include small combustion engines and hybrid-electric motors. The fixed-wing vehicle is required to accomplish an initial search to localize where radiological material is located, with the potential to continue operations as a surveillance asset. Due to the potential for long-duration flights, this capability is best supported using a combustion engine in lieu of batteries to drive the propeller. A gasoline engine will enable flight times of several hours and increases the required size of the vehicle, which is beneficial for payload capacity. Battery-powered fixed-wing vehicles can achieve flight durations over 1 hour but will not be able to carry equivalent payload weights with comparable endurance times to gasoline-powered systems. Comparatively, a battery-powered multirotor system would not have the endurance to cover all potential source locations within a 3 square kilometer area for collection of a gamma spectrum. A hybrid-electric system would provide greater endurance and offers an increased payload capacity compared to battery-powered multirotor vehicles. Battery-powered systems of the desired sizing are typically limited to 30-minute flight times, which is insufficient for carrying detector payloads to the farthest sites of a large search area. Additionally, batteries can take 30 minutes to an hour for recharging if spare batteries are unavailable, which can hamper the ability to execute consecutive sorties. Endurance estimates supporting the above discussion can be found later in Chapter IV. Opting for fuel-based power systems is ideal for providing longer endurance due to a higher energy density compared to battery technology, which can be visualized in Figure 14. Utilizing liquid fuels for the fixed-wing and multirotor UVs will increase flight durations, area coverage, and maximum allowable payload, optimizing performance of these systems and providing optionality for other uses such

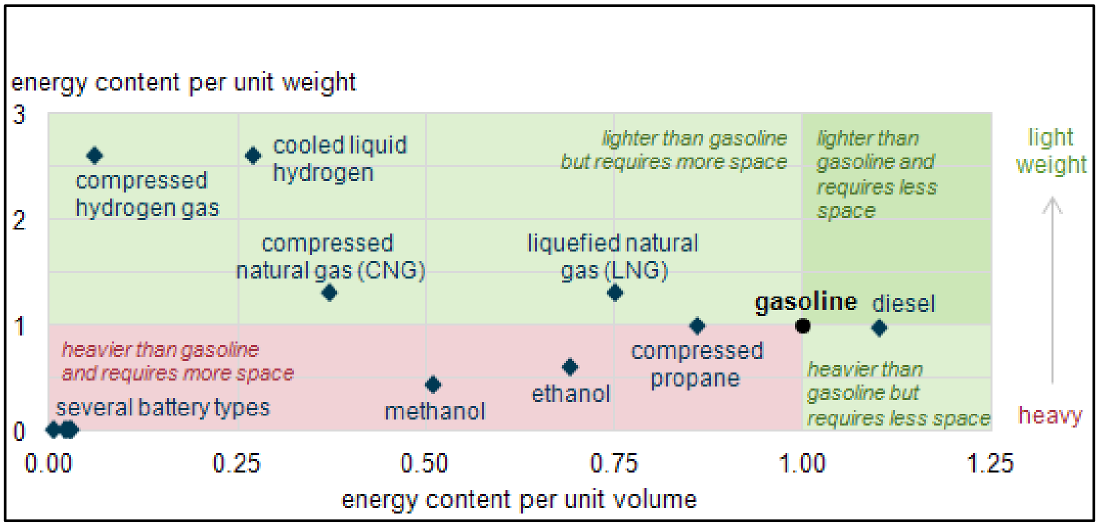

Figure 14. Energy density comparison of several transportation fuels (indexed to gasoline = 1) [35]

as surveillance missions.

In addition to the detector payloads, additional payloads should be included on vehicles to assist with navigation and surveillance. Light detection and ranging (LiDAR) or other distance measuring sensors should be incorporated on the multirotor to provide accurate navigation when flying around buildings and other potential obstacles. This will provide more accurate radiation measurements and enhanced safety by decreasing the likelihood that a collision occurs. Additionally, the fixed-wing UV could benefit from a higher quality video camera compared to cameras installed on the other vehicles. The fixed-wing's optionality to provide aerial surveillance would benefit from high-quality video and would better support ground operators.

Physical Limitations and Imposed Design

System components are constrained to the mission needs listed in the CONOPS and limited to the operational requirements of the mission area. Two important

limitations to highlight are the restrictions on system mass and the extended endurance required to cover a 3 square kilometer search area. The two limitations drive the sizing of each subsystem vehicle, their power plants, and the quantity of vehicles utilized in the system. A minimum of three unmanned vehicles (fixed-wing, multirotor, and ground), a ground control station, and the accompanying storage, power, communications, and maintenance equipment must be containable in a truck and trailer for system deployment. Additionally, due to the nature of radiation emissions discussed in Chapter II, detector payloads are more likely to detect gamma radiations when closer to the radiological source material. This negates the viability of using large unmanned vehicles that operate at higher altitudes such as the RQ-1 Predator and MQ-9 Reaper that are categorized as DoD UAS Group 4 and Group 5 systems (Table 3).

On-board processing has been removed from the conceptualized design in the physical architecture. This capability requires additional vehicle power and produces unwanted heat, which would reduce mission endurance and could present overheating issues in warmer operating environments. Additionally, an on-board processor introduces the risk of leaking sensitive information regarding system software and vulnerabilities to adversarial forces if captured or ditched in a contested area. This will be discussed in more detail later in Chapter IV.

Power

As discussed previously, power production can be an issue for the fixed-wing and multirotor platforms. This is dependent on payload selection for the system and the required flight endurance for the individual vehicles. A liquid-fuel engine for the fixed-

wing would increase the size of the vehicle but would greatly improve the endurance and the payload capacity. Similarly, a hybrid-electric motor for the multirotor would have a comparable effect. However, using combustion engines would increase the complexity of the system regarding mechanical components and potential maintenance. Furthermore, a deployable system may be constrained by available types of fuel. DoD Directive 4180.01 promotes the use of multiple energy sources for weapon systems and equipment, where appropriate, and becoming operational with one battlefield fuel [36]. Typical small combustion engines used on fixed-wing and multirotor vehicles consume 91 octane fuel or higher [25]. Expeditionary vehicles, aerospace generation equipment, and power generation assets are typically fueled with diesel or jet propellant-8 (JP-8). Expanding the capabilities of the system to utilize heavy fuels, if combustion engines are chosen for power generation, would provide more options for system deployment and would reduce vulnerabilities if 91 octane fuel is unavailable. Small two-stroke gasoline engines (10 cm^3 to 100 cm^3) have been proven to run on heavy fuels with minimal degradation to peak performance power. However, this required engine modifications such as replacing carburetors with throttle body fuel injection systems and changing stock engine control units to adjustable ignition timing maps [37].

In addition to meeting endurance and payload capacity, adequate power needs to be generated or supplied on-board in order to power video cameras, navigation systems, and payloads. The largest payload consumer of power would be gas-filled detectors and semiconductor detectors, which operate at higher voltages. With this being the case, it is advisable to power these detectors with separate power supplies. Utilizing separate

power supplies for all detector payloads would enable optionality for handheld use and would reduce the complexity and drain on the vehicle's power system. It is possible to power these systems, but this also increases the size of the combustion engine and the vehicle frame to support the engine. A good example is the Airborg H8 10K Hybrid UAS. It claims a flight endurance of 1 hour carrying a 22-pound (10-kilogram) payload, with a power output of 100 watts and built-in 5 voltage direct current (VDC) and 12 VDC wiring. The longest dimension of the vehicle is 6.4 feet (1.95 meters) and the total weight with a 22-pound payload is 110 pounds (50 kilograms) [38]. This would be sufficient voltage for the Ortec Micro-Detective, which requires 10 to 17 VDC for operation [19].

Environmental

The operating environment of this system is important to understand since operations will primarily be outside. Many common components used for unmanned vehicles are designed for use in -20° to 50° Celsius temperatures, but some components, such as the Ortec Micro-Detective, may have a smaller temperature window for operation [19], [25], [26], [39]. Other components that may be affected are batteries and circuit boards. Extreme cold weather can reduce the overall power output of a battery, whereas extreme heat can lead to physical damage. On-board processing equipment such as autopilot systems and detector payloads can also be affected by hot weather, causing damage to circuity and decreased performance. Desired operating temperatures for the system could affect component selection and design for each vehicle.

In addition to temperature constraints, other weather constraints could affect the operational utility of the system. Visual capabilities could be limited by fog, precipitation, smog, and sunlight. Unless night vision video cameras or other imaging solutions are utilized, night operations would be dangerous or not viable. Additionally, precipitation may affect system functions, either from individual component waterproofing or physical limitations of vehicle propulsion. Lastly, flying vehicles must maintain stable flight while airborne. Strong steady and gusting winds would limit the use of flying vehicles, with the wind limits being better defined during system design.

The last environmental concern is from obstacles and human interference. The operating area may contain trees and buildings that could impede flying operations, or uneven terrain such as ditches and rocks for a ground vehicle. Design considerations should be made to mitigate these risks, such as the addition of specific payloads to see and avoid terrain or the ability to traverse uneven ground with the addition of extendable wheels or tracks. Additionally, the human element can interrupt vehicle operations. Threats can be in the form of thrown rocks, nets, vehicle theft, small arms fire, or man-portable air defense systems. There are few design decisions that can currently mitigate these threats, but technology is continuously progressing and the capability to avoid human threats may present itself in the future.

Detector Payload

In order to optimize the performance of the radiological search system, detectors for initial detection and spectrum collection should be evaluated separately. It is valid to employ multiple detector technologies due to the diversity of radiological search

scenarios. Detector selection can vary due to several reasons: 1) detector selection can be driven by the type of area to be searched; 2) detector selection can be dictated by the size of area to be searched; 3) detector selection is limited by the vehicle it will be deployed on; and 4) detector selection can be determined by the desired mission outcome.

Gas-filled detectors are well suited for area surveying during initial searches. More specifically, the higher applied voltage in G-M detectors results in a sensitive detector, which is ideal for large area searches that may require detection from long distances [14]. Additionally, typical COTS G-M detectors have higher radiation dose rate thresholds. The high threshold enables G-M detectors to avoid detector saturation when in strong radiation fields, and therefore continue to function and provide radiation strength readings [19]. This results in a more defined geolocation of source material after the initial search. However, G-M detectors do not measure the energy of incident gamma rays, which can be important for determining health and safety concerns for responding personnel.

Scintillators can also be used for area searches but tend to have lower radiation dose rate thresholds [19]. This translates to detector saturation in strong radiation fields where G-M detectors could still be operating, resulting in a less accurate geolocation than G-M technologies. However, both scintillators and semiconductors are well suited for gamma spectrum collection because they can distinguish between different energies of incident gamma rays, allowing for the identification of radioisotopes. Scintillators are cheap and lightweight but produce low resolution spectrums. On the contrary, semiconductors are expensive and heavy due to the required cooling systems that

maintain low operating temperatures but provide very high-resolution spectrums [21]. Equipping the system with multiple technologies gives the capability for high-resolution spectrums, but the optionality to use the less expensive and lighter scintillator in unfavorable conditions.

The vehicle type can determine payload selection. For instance, a spectrum collection payload is not ideal for deploying on a fixed-wing vehicle. Spectrum collection should be completed at a constant distance from a radioisotope and in a stable position. A fixed-wing vehicle is unable to maintain a constant distance during flight but is well-suited for searching large areas when the location of source material is unknown. The optimal payload for a fixed-wing vehicle is a G-M detector due to its sensitivity, but scintillators are also a practical option. Terrain and environmental conditions can force a fixed-wing UV to fly over one hundred meters AGL, making higher-sensitivity detectors more desirable for initial detection. For isotope identification, the current government "gold standard" for gamma spectroscopy is a liquid or electromechanically cooled high purity germanium crystal [40]. This setup provides a superior resolution spectrum compared to existing scintillator technology but may not be feasible on a multirotor or ground vehicle due to weight limitations and the operating environment.

The physical and immediate surroundings of each vehicle should also be assessed. The two main considerations for detector mounting are material interactions and susceptibility to impact. Interactions with other vehicle materials can include vibration-induced gamma counts, gamma counts produced from other on-board electronic equipment, and self-imposed shielding. Unintentional shielding can happen when an

intervening material from a vehicle is between the detector media and the radiological source. The intervening material can weaken or alter the gamma energies incident on the detector, ultimately decreasing the potential for initial detection and degrading the accuracy of spectrum collection [19]. Similarly, shielding material may need to be utilized between the detector and other electronic hardware in order to reduce false gamma readings that occur from other types of electromagnetic radiation. The other physical consideration is the potential for detector impact. Collision with obstacles, human interactions, and harsh landings can affect detector performance and can dictate payload attachment and hardening design. Depending on the detector and the vehicle, attachment options can be limited due to size and weight. Vehicle center of gravity constraints and chassis strength will drive mounting options to ensure that vehicles safely fly and maneuver as designed. Detector hardening may also be limited due to vehicle payload capacity but should be evaluated during system design.

One last consideration for payload selection is the additional capability for the detectors to be used in a handheld configuration by the system's human operators. Situations may present themselves where the initial search, the spectrum collection, or both methods are not appropriate for unmanned vehicles. Terrain, environmental conditions, and other on-scene factors can differ from provided intelligence. Once an operational team arrives at the search location, it may be logical to modify the mission plan to conduct a portion of or the entire mission using personnel search teams. Depending on their equipping, they may need the capability to conduct searches with the same equipment deployed on the UV system. Commonly used GOTS and COTS

handheld detectors can vary in price from $1,000 to $100,000, which is contingent on the type of technology purchased [39]. It may be more cost effective to include handheld-operable equipment in the system. This would limit the overall detector acquisition cost to the end user, avoiding the need for redundant technologies that are dedicated to either a UV system or a human operator. If handheld detectors are employed, it is essential that the detector's human interface can be bypassed in order to send data and receive commands. A commonly used COTS semiconductor detector designed for handheld use is the Ortec Micro-Detective. As previously mentioned, it utilizes an HPGe crystal to provide a spectral resolution of less than one percent. The purchase price for this equipment is upwards of $100,000 but provides the highest-quality gamma spectrum compared to other spectrum-collection technologies. With a weight of 15 pounds (6.8 kilograms), this equipment is only suitable for the ground UV and for short-duration trips with a large multirotor [19]. However, including this piece of equipment also enables the human operator to collect a high-resolution spectrum if the mission dictates. Additionally, there are many COTS handheld detectors that come equipped with G-M and scintillation technology [19]. This could increase the efficiency of a mission by completing the initial search and radioisotope identification with one vehicle trip, thus avoiding payload exchange when a high-resolution spectrum is not required. This is only practical on the ground and multirotor UVs due to the constant distance required for spectrum collection. The flexibility of equipping the UV system with handheld technology increases the probability of mission success regardless of evolving or

unforeseen circumstances. Table 1Table 9summarizes considerations for UV detector selection in order to meet operational needs.

Table 9. Vehicle and detector compatibility selection

	Ground	Multirotor	Fixed-wing
Limitations	Terrain/obstacles Slow 2-D coverage	Endurance Payload weight	No dwell
Advantages	Dwell time/stability Manipulator arm Heavy payload	3-D coverage Accessibility Hover/land for stability	Large area coverage Long endurance Aerial surveillance
Suitable Technologies	Gas-filled Scintillator Semiconductor	Gas-filled Scintillator Semiconductor	Gas-filled Scintillator
Detector Selection Criteria	Mission requirement Desired performance Environmental conditions Permissibility		

Communication Modems & On-board Processing

As mentioned in the similar componentry assessment, comparable communication modem pairs could be used to provide redundancy and flexibility throughout the system if hardware becomes inoperable. Additionally, on-board processors have been removed from the Cameo physical decomposition to reduce power-draw, weight, heat, and to avoid sensitive data exploitation if a vehicle is lost or stolen. If vehicle on-board processors are included during system design and testing, multiple modems may not be necessary for each vehicle. However, in order to capture, combine, and encrypt multiple payload data and video feeds, a custom communication modem and processor may be required that is not available commercially or through existing government PORs.

The development of a custom communication modem and processor will depend on the established requirements, payload selection, and discoveries during the design and testing phases. The system needs the ability to communicate amongst a GCS and multiple UVs while encrypting and combining data streams, and also providing the flexibility for future payloads to be added to the system. There may not be a component that will satisfy system demands and be available commercially. Sourced payload manufacturers may not have compatible output data and could pose problems when sending or processing different data packet types and lengths. These reasons could force a requirement for on-board processing to assist with data management before communicating from a vehicle to the GCS. The on-board processor could be integrated with a communication platform that is equipped on each UV and the GCS. This could solve issues posed by data compatibility, encryption, data combination, and time synchronization. A solution for these issues would most likely necessitate a custom-designed component in order to function properly, as well as provide the flexibility to for additional payloads and other mission areas.

Processing Software

In addition to a custom-designed communication and processing package, custom software will likely need to be developed. This includes software on the GCS platform as well as software for the on-board processors. Vehicle software should be capable of combining data from various payloads and the autopilot before relaying the information to the GCS. Simultaneously, the software must decipher commands received from the GCS before relaying the commands to the appropriate vehicle components. On the

ground, GCS software provides input and output functionality to the GCS operator. The software should be able to merge pertinent data received from a vehicle autopilot, detector payload, and video camera into one visual interface. It should have the capability to display real-time radiological data, display a three-dimensional radiological strength contour map of the search area, and provide source location estimates from the combined radiation data and telemetry data (Figure 15). Additionally, the software

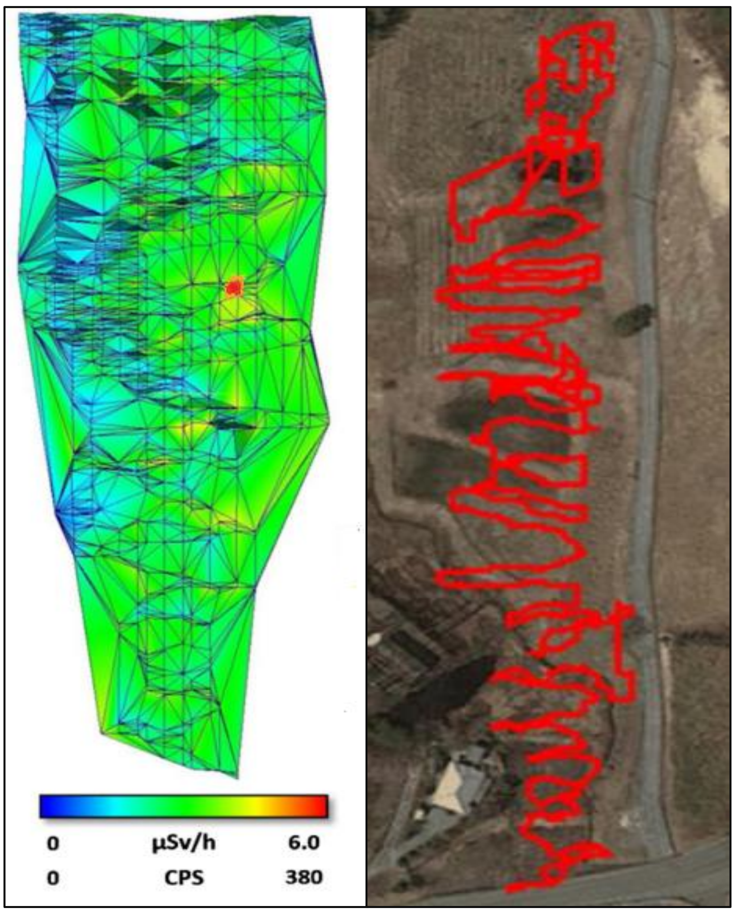

Figure 15. 3-D radiation strength map (left) of a vehicle search pattern (right) [41]

should provide real-time and planned vehicle locations on a map, similar to existing autopilot software suites. Lastly, the software should provide command options for both

vehicle navigation and payload functions, such as starting and stopping spectrum collection, controlling camera gimbals and articulator arms, and being able to toggle between autonomous and controlled movement.

Analysis of Feasibility and Utility

After progressing through concept development, applicable scenarios, a task and physical decomposition of the system, and design considerations, the overarching query remains whether the system would be practical to employ and what utility it could provide to the radiological search mission and other mission areas. The concept system's abilities can be fundamentally evaluated through sizing and endurance estimations for multirotor and fixed-wing UVs. Ground vehicles are more forgiving with payload capacity, and therefore will not be analyzed due to the several COTS options that meet example payload requirements [42], [43], [44].

Air vehicle sizing and performance will be centered on assumptions founded upon similarly sized UAS specifications and incorporating handheld detector weights where appropriate. Assumptions are made for component sizes, efficiency ratings, air speeds, and mass fractions based on AFIT professor knowledge, existing literature, and existing COTS systems [45], [45], [46]. Mass fractions (MF) are typically tracked for vehicle payloads and for power sources (i.e. battery, fuel), and provide thresholds for vehicle estimates. The mass fractions for unmanned vehicles typically fall within the same range, with the fuel mass fraction ranging from 0.2 to 0.3 and the payload ranging from 0.1 to 0.3 [45]. Mass fractions can be estimated using Equation 2.

$$MF_{component} = \frac{W_{component}}{W_{takeoff}} \tag{2}$$

Incorporating handheld detectors would be the worst-case scenario for payload weight and size due to the additional weight from ruggedized cases and integrated power supplies, but it also gauges the feasibility of employing handheld detectors on UV platforms. Custom-designed detectors can be a fraction of the weight but typically do not include power sources, hardening, or user interfaces for handheld operation. Example payloads will be used for multirotor sizing, whereas fixed-wing vehicles will use mass fractions and total takeoff weight to determine system endurance.

Electric Multirotor Sizing

Multirotor sizing is estimated from derived power equations related to current draw and battery capacity that can maintain the vehicle in a constant hover. The power required for each prop (P_{prop}) is dependent on vehicle mass (*m*), the area and efficiency of the prop (A_{prop}, η_{prop}), the number of motors (n_{motors}), and the density of air (ρ_{air}) (Equation 3) [45], [46].

$$P_{prop} = \frac{2 \cdot A_{prop} \cdot \rho_{air}}{\eta_{prop}} \cdot \left(\sqrt{\frac{m \cdot g}{2 \cdot A_{prop} \cdot \rho_{air} \cdot n_{motors}}} \right)^3 \tag{3}$$

The power required for each prop to maintain hover determines the current required for each motor (I_{motor}), which also depends on the battery voltage ($V_{battery}$) and the motor efficiency (η_{motor}) (Equation 4) [46].

$$I_{motor} = \frac{P_{prop}}{V_{battery} \cdot \eta_{motor}} \tag{4}$$

The total current (I_{total}) required for vehicle operation is found using the total number of motors (n_{motors}) and additional current requirements ($I_{auxilary}$) (Equation 5) [46].

$$I_{total} = I_{motor} \cdot n_{motors} + I_{auxilary} \tag{5}$$

In order to determine the UV's endurance (E), the usable battery capacity (C_{usable}) has to be calculated by using the rated capacity of the battery (C_{rated}), the efficiency of the battery ($\eta_{battery}$), the permissible battery discharge depth (f_{usable}), and the number of batteries ($n_{batteries}$) (Equations 6-7) [46].

$$C_{usable} = C_{rated} \cdot \eta_{battery} \cdot f_{usable} \cdot n_{batteries} \tag{6}$$

$$E = \frac{C_{usable}}{I_{total}} \tag{7}$$

Sizing was calculated for electric DoD UAS Group 1 and Group 2 multirotor vehicles. The Group 1 multirotor was estimated to carry a FLIR IdentiFINDER R400-NG, which has a NaI(Tl) scintillator for dose rate measurement and radioisotope identification and a G-M tube for high radiation field dose rate equivalence. This payload adds 1.2 kilograms to the overall mass with dimensions of 24.9 centimeters × 9.4 centimeters × 7.6 centimeters and an 8-hour runtime on internal batteries [19]. A Tarot T960 hexacopter frame with Tarot 5008-340KV motors were used for mass and power estimates. Including two 10 ampere-hour 6-cell lithium polymer (LiPo) batteries to the

system, the overall mass is 9 kilograms, which is within the threshold for Group 1 UAS. Hovering at this weight produces an overall endurance of 20 minutes. A summary of the input data and results can be found at Table 10.

Table 10. Group 1 electric multirotor endurance estimate

Payload mass [kg]	1.2
Mass w/out batteries/payload [kg]	5.3
Gravity [m/s²]	9.86
Air density [kg/m³]	1.2
Prop diameter [in]	18
Prop diameter [m]	0.46
Prop efficiency	0.8
Motor efficiency	0.8
# battery cells	6
Rated battery capacity [Ah]	10
Battery voltage [volts]	22.2
Battery mass [kg]	1.32
# batteries	2
Battery efficiency	0.9
Permissible battery discharge	0.8
Usable battery capacity [Ah]	14.4
# motors	6
Motor mass [g]	168
Auxiliary current [A]	5
Total mass [kg]	9
Power required per prop [W]	115.9
Current required per motor [A]	6.5
Total current [A]	44.2
Endurance [min]	**19.6**

The Group 2 multirotor was estimated to carry an Ortec Micro-Detective-DX, which uses an HPGe semiconductor and electromechanical Stirling-cycle cooler for dose rate measurement and high-resolution identification. This payload adds 6.8 kilograms to

the overall mass with dimensions of 37.3 centimeters × 14.6 centimeters × 27.9 centimeters and a 5-hour runtime on its lithium-ion battery pack [19]. A Tarot T960 hexacopter frame with T-Motor-U7-420KV motors were used for mass and power estimates. Including three 10 ampere-hour 6-cell LiPo batteries to the system, the overall mass is 16.7 kilograms, which is 6 kilograms below the Group 3 UAS threshold. However, it should be noted that the total mass exceeds the recommended 15-kilogram design threshold for the frame [47]. This estimate, although not advisable for design purposes, provides a best-case operating endurance using the lightweight frame and heavy payload. Even with these risky operating parameters, hovering at this weight only produces an endurance of 13 minutes. A summary of the data and results can be found at Table 11.

Table 11. Group 2 electric multirotor endurance estimate

Payload mass [kg]	6.8
Mass w/out batteries [kg]	5.9
Gravity [m/s²]	9.86
Air density [kg/m³]	1.2
Prop diameter [in]	18
Prop diameter [m]	0.46
Prop efficiency	0.8
Motor efficiency	0.8
# battery cells	6
Rated battery capacity [Ah]	10
Battery voltage [volts]	22.2
Battery mass [kg]	1.32
# batteries	3
Battery efficiency	0.9
Permissible battery discharge	0.8
Usable battery capacity [Ah]	21.6
# motors	6
Motor mass [g]	255
Auxiliary current [A]	5
Total mass [kg]	16.7
Power required per prop [W]	285.3
Current required per motor [A]	16.1
Total current [A]	101.4
Endurance [min]	**12.8**

Hybrid-electric Multirotor Sizing

Group 1 and Group 2 electric multirotors provide short endurance flights, which limits their application to cover small search areas. Therefore, an estimate was completed of a Group 2 hybrid-electric multirotor that uses a gasoline generator to charge a LiPo battery to power the motors. The gasoline provides a higher specific energy while the battery provides a simpler and more reliable method for throttling power to the six

electric motors. The same Ortec Micro-Detective-DX payload was used, but this time a GAIA 160 Elite Pro 2.4 kilowatt hybrid-electric drone was used as a baseline system [48]. The same power equation (Equation 3) was used to determine the power required per prop, which was then totaled for the entire system. The gas generator can supply a constant 2.4 kilowatts of power at a fuel burn rate of 2.5 liters per hour. This allows for an endurance of 58 minutes when flying with 3 liters of fuel and retaining 20% of fuel at the end of mission. Results from the estimation are detailed in Table 12.

Table 12. Group 2 hybrid-electric multirotor endurance estimate

Payload mass [kg]	6.8
Mass fraction payload	0.30
Generator system mass [kg]	4.2
Mass w/out payload [kg]	13.7
Gas density [kg/L]	0.76
Fuel capacity [L]	3
Mass of fuel [kg]	2.3
Mass fraction fuel and batteries	0.2
Gravity [m/sec^2]	9.86
Air density [kg/m^3]	1.2
Prop diameter [in]	29
Prop diameter [m]	0.74
Prop efficiency	0.8
Motor efficiency	0.8
# battery cells	6
Rated battery capacity [Ah]	5
Battery voltage [volts]	22.2
Battery mass [kg]	0.85
# batteries	2
# motors	6
Auxiliary current [A]	5
Total mass [kg]	22.8
Power required per prop [W]	282.8
Power required system [W]	2232
Fuel burn rate (2.4kW) [L/hr]	2.5
Endurance [min]	**57.6**

Fixed-wing Sizing

Fixed-wing sizing was completed for a Group 1 electric vehicle and a Group 2 gasoline-powered vehicle. The maximum takeoff weights ($W_{takeoff}$) for the electric and gasoline UVs are the maximum allowable for Group 1 and Group 2 vehicles, which are 9 kilograms and 25 kilograms respectively. Vehicle airspeeds (v) were varied for both vehicles so high and low endurance estimates can be compared. The lift-to-drag ratios (L/D) were also varied in order to provide endurance ranges. The endurance equation is similar to the multirotor endurance equation, but the battery power equation incorporates the takeoff weight, the vehicle air speed, the lift-to-drag ratio, and the summated propulsion efficiencies ($\eta_{propulsion}$) from the electronic speed controller, the propeller, and the motor (Equations 8-9) [45].

$$E = \frac{C_{usable} \cdot V_{battery}}{P_{battery}} \tag{8}$$

$$P_{battery} = \frac{W_{takeoff} \cdot v}{L/D \cdot \prod \eta_{propulsion}} \tag{9}$$

For the fixed-wing vehicles, specific payloads were not chosen for mass. Instead, a mass fraction of 15% of the takeoff weight was used for the allowable payload mass in order to estimate the endurance. The endurances for the Group 1 electric vehicle range from 41 to 69 minutes when flying at a constant angle of attack at the given cruise airspeeds. A summary of the estimated endurances and ranges can be seen in Table 13.

Table 13. Group 1 electric fixed-wing endurance estimate

Airspeed [m/s]	16	20	16	20
L/D	6	6	8	8
Mass fraction battery	0.3	0.3	0.3	0.3
Mass fraction payload	0.15	0.15	0.15	0.15
Battery mass allowable [kg]	2.73	2.73	2.73	2.73
Payload mass allowable [kg]	1.36	1.36	1.36	1.36
Total mass [kg]	9	9	9	9
Gravity [m/s²]	9.86	9.86	9.86	9.86
Prop efficiency	0.8	0.8	0.8	0.8
Motor efficiency	0.8	0.8	0.8	0.8
# battery cells	6	6	6	6
Rated battery capacity [Ah]	10	10	10	10
Battery voltage [volts]	22.2	22.2	22.2	22.2
Battery mass [kg]	1.32	1.32	1.32	1.32
# batteries	2	2	2	2
Battery efficiency	0.9	0.9	0.9	0.9
Permissible battery discharge	0.8	0.8	0.8	0.8
Usable battery capacity [Ah]	14.4	14.4	14.4	14.4
Power required thrust [W]	239.0	298.8	179.3	224.1
Power required from battery [W]	373.5	466.9	280.1	350.1
Endurance [hr]	0.9	0.7	1.1	0.9
Endurance [min]	**51.4**	**41.1**	**68.5**	**54.8**

The endurance estimate for gasoline engine requires the brake specific fuel consumption ($BSFC$) (Equation 10). A representative vehicle that is under the 25-kilogram Group 2

$$E = \frac{L/D \cdot \eta_p}{v \cdot BSFC} \cdot ln\left(\frac{1}{1 - MF_{fuel}}\right) \tag{10}$$

threshold is the Silver Fox, which has a $BSFC$ of 395 grams per kilowatt-hour [49]. The estimated endurances for a gasoline-powered vehicle using this $BSFC$ range from 12 to 24 hours with a payload near 2 kilograms (Table 14).

Table 14. Group 2 gasoline fixed-wing endurance estimate

Airspeed [m/s]	20	30	20	30
L/D	6	6	8	8
Mass fraction fuel	0.25	0.25	0.25	0.25
Mass fraction payload	0.15	0.15	0.15	0.15
Fuel [kg]	3.25	3.25	3.25	3.25
Payload [kg]	1.95	1.95	1.95	1.95
Total mass [kg]	13.0	13.0	13.0	13.0
Prop efficiency	0.8	0.8	0.8	0.8
BSFC [g/kW-hr]	395	395	395	395
Endurance [hr]	**17.7**	**11.8**	**23.6**	**15.8**

Feasibility for Current Radiological Search Operations

At a minimum, the conceptualized system would serve useful for a portion of current operations. Executing the entire operation from the initial search through completing source disposal is unlikely. This is due to the potential unfavorable scenarios and environmental conditions that could be encountered, especially when weighing the limited performance of certain vehicles such as the electric multirotor endurance and payload capacity. Incorporating the system into a portion of operations is very feasible. For instance, conducting an initial search of a large area would be extremely useful for responding personnel, especially if the terrain is difficult to navigate by foot or is not accessible by vehicle. Once the initial search area has been decreased, unmanned platforms could provide an excellent asset for surveillance by providing immediate feedback to personnel on the ground. However, confirmation activities using the unmanned system may have limited applicability. In most permissible scenarios, human operators are best suited to finish ground operations including spectrum collection and follow-on activities. Non-permissible environments may warrant the full utilization of

the radiological search system, especially when strong sources or nefarious activity and entrapments are involved. Nevertheless, utilizing the system in place of human operators is dependent on system-mitigated hazards and efficiently accomplishing the tasks expected of human teams.

When considering the estimated endurances for the vehicle power plant configurations, there are performance constraints for some vehicles and optionality for others. The fixed-wing is able to execute the mission using both electric and gasoline power plants. The endurance and payload capacity are much higher for the gasoline engine, but the overall size of the vehicle is increased. The larger size could decrease vehicle maneuverability, forcing the vehicle to fly at a higher and safer operating altitude. This is not ideal for detecting radiation. Therefore, detector sensitivity, operating altitude, and airspeed should be assessed when selecting the fixed-wing vehicle and detector payload. On the other hand, multirotor vehicles are limited to hybrid-electric setups in order to provide sufficient endurance while carrying a detector payload. This would supply enough power to ingress, collect a spectrum, and egress from any estimated source location. Battery-powered multirotors offer limited endurance and are too risky for incorporating into the radiological search system.

An important aspect of evaluating system feasibility is the cost of the system, which depends on design decisions and other factors that are not the focus of this research. Regardless of having a tangible price, the same comparison needs to be made concerning the cost of the system against the utility it provides the user. The procurement cost and recurring costs will not be worthwhile for some agencies based

upon their scope of responsibility and the probability that they will have to respond to a lost or stolen radiological source. The typical small-town police department would not benefit from this system as both the probability of response is low and there is most likely a federal or state asset that is the principal agency for this type of emergency response. Agencies that would benefit from this system would be those responsible for large metropolitan areas, have a high-threat environment including radiological material, cover high-density areas of NRC Category 1 and Category 2 radioactive materials, and those that are deemed principal responding agencies per governing policy. State and local agencies that could realistically benefit from an unmanned search system include large metropolitan area police departments and high-volume ports. Federal applicability ties directly to existing policy and emergency response plans that define who is responsible for specific emergency scenarios and jurisdictional areas, such as the Federal Bureau of Investigation, the DOE and national laboratories, the Department of Homeland Security, and the DoD. For example, the Radiological Assistance Program (RAP) under the DOE is one of many organizations formed to assist with radiological emergency responses. The United States is split into nine geographic regions that are covered by separate RAP teams [50]. These teams could benefit from an unmanned radiological search system as part of their equipment suite to cover the array of radiological response missions they are responsible for.

The last issue that this system would introduce is logistical requirements on the owning organization. Like the initial procurement cost of the system, the cost for maintenance and replacement parts should be measured against the utility of the system.

Maintenance issues can be time consuming and costly, which depends on the complexity of the system and the necessity to procure specialty tools or equipment. If maintenance is completed by the owning organization, maintenance hours on this system would decrease hours spent on other serviced equipment and potentially impact other mission areas. Increased manpower or dedicated maintenance technicians may be necessary, which also increases the overall cost. If a separate maintenance contract is determined to be the optimal route, this requires continual funding to ensure the system maintains operational readiness. The aforementioned costs will help decision-makers determine the realistic acquisition and implementation of this system.

Utility to Other Missions

It is crucial to look at the applicability and extension of the radiological search system to other mission areas. Expanding the operational reach of the system to other mission areas would also increase the overall value for government and private entities. This increase in the asset's value could result in more emphasis on mission application, funding, maintenance, and development of future systems and system payloads. Providing a niche-solution to the radiological search mission will only attract niche customers. An infrequently used equipment set makes it challenging for the end user to reorient on system functionality and could lead to mechanical maintenance issues due to inactivity. Therefore, expanding the applicability of the system should be beneficial in terms of utility and cost effectiveness. Some consequences of expanding the mission coverage could include optional sizing of ground and air vehicles, the inclusion of a

water-borne platform, and a more flexible vehicle architecture that can interface with numerous payloads.

In order to promote a flexible system that can apply to other missions, some modifications will need to be made. The system architecture is currently geared toward a radiological search mission with three specific vehicle options that all serve a certain purpose and accomplish certain tasks. There is some flexibility built into the system with separate modems for autopilot, video, and payloads. However, the promoted sizing for both the vehicle chassis and the power plant configurations are geared toward lifting a 6.8-kilogram payload for the multirotor and ground UVs as well as providing increased endurance for the fixed-wing UV by integrating a combustion engine. These narrowed solutions serve the purpose of meeting the intent established in the CONOPS. In order to provide a more comprehensive system, a new CONOPS and system architecture should be developed with a more holistic approach to incorporate current and emerging missions. As previously discussed, this would necessitate the customization of some hardware components such as the communication modem and processor suite in addition to on-board and GCS software. These additions would provide the capability for multiple vehicles to interchange payloads and the ability to reprogram system software to be compatible with a variety of components and data types.

Summary

The radiological search system has been characterized starting with the system CONOPS and resulting in the physical framework to meet the capabilities and assumptions determined by the CONOPS. Following the characterization of the system,

a feasibility analysis considered the potential benefits and disadvantages that the system presents and must be evaluated when determining the overall utility of the system to the mission area. The analysis determined that the system could apply to current radiological search operations but may be limited to certain portions of the mission and constrained to specific organizations. Lastly, it was concluded that the system could be applied to other missions, but it may need to be modified to provide enhanced flexibility and a more refined product.

V. Conclusions and Recommendations

Overview

Within the counter-WMD mission space, radiological and nuclear terrorism is an imminent and constant threat to United States national security. Developing and employing new technologies is crucial for safeguarding this nation, and a radiological search system is a potential solution to assist and strengthen the radiological search mission space. It would provide more execution options to responding personnel and the ability to remove the human element from hazardous situations.

Review of Findings

A CONOPS was developed by incorporating mission needs and constraints for radiological search operations. Utilizing the radiological search CONOPS, use cases and a functional decomposition were derived that account for the necessary tasks to complete radiological search missions. A physical architecture was created in order to allocate physical components to satisfy task completion. After completing the hierarchical decomposition, it is evident that the system necessitates a multidimensional construct with multiple vehicle platforms and distinct detector payloads that are governed by scenario or mission criteria. Each detector technology can be optimally applied to select portions of the radiological search mission, such as initial search operations or gamma spectrum collection. Similarly, certain vehicle platforms are ideal for or are limited to specific segments of the mission. In order to cover the gamut of radiological search mission tasks, the system needs multiple vehicle options and interchangeable detector

payloads with an adaptable system framework. The conceptual system was found to be feasible in terms of constructability and operability based upon currently available technologies, but it may have limited application to the mission area. Hybrid-electric power plants would be a necessity for multirotor endurance and payload capacity, whereas fixed-wing vehicles could safely operate with battery or gasoline-powered options. In order to maximize the utility and effectiveness of the system to other DoD mission areas, the system needs to be expanded to provide more optionality for payload integration, vehicle selection, and software flexibility. This includes a universal system architecture and software suite that can adapt to emerging technologies and mission areas.

Study Limitations

The research was scoped to cover system application to radiological and nuclear material search and spectroscopy activities in the next two to five years. Assumptions guided the creation of the CONOPS, as user requirements for the system do not exist. The research did not incorporate consequence management surveying following accidents or terrorism activity involving nuclear or radiological materials. Content was limited to publicly available information and did not dwell at a higher-level of classification. Tactics, techniques, and procedures for the system were not covered, as the focus was characterizing the system and its operational feasibility and utility of the system to the radiological search mission. Lastly, research was limited by funding and time constraints.

Future Research

There are multiple avenues for future research involving unmanned systems to accomplish radiological search missions. Options align with a continuation of the Systems Engineering "V" concept by conducting a detailed system design, developing custom hardware or software for the vehicles and GCS, or completing a cost analysis of system procurement and lifecycle operating costs for the end user. Utilizing a decision-based engineering design framework will provide rigor to the engineering design process and ensures that value theory is applied to system development [51]. These additional areas would provide more tangible findings and insight to the system's utility when weighed against acquisition and recurring costs.

Another research opportunity is refining or building a new architecture to expand the radiological search system to multiple mission areas. The application of the system to other missions was briefly discussed in Chapter IV. This would include additional ground and air vehicles, waterborne vehicles for maritime operations, a custom communication and processing package, and custom system software for both the GCS and UVs. An extended application to current mission areas with the flexibility to cover emerging missions would greatly increase the utility and value of the system.

In Chapter IV's design considerations, employing handheld detectors on system vehicles was considered for increasing the flexibility of the overall system and avoiding a mission stoppage if conditions change. It would be beneficial to compare commonly used handheld detectors to COTS and GOTS detectors designed for vehicle applications. Detectors can be evaluated on performance in different radiation field configurations,

vehicle emplacement options and limitations, integration with system hardware and software, and expected procurement and lifecycle costs.

Appendix A. Subsystem Physical Allocation Matrices

Table 15. Fixed-wing vehicle physical allocation matrix

Legend Allocated - ↗		Navigation Module					Payload Module						Power Module									Self-Destruct		Vehicle				
	System Summary	**Module Summary**	Autopilot	Autopilot Modem	GPS/ Compass	Pitot sensor	**Module Summary**	Camera	Gimbal	Payload Modem	Radiation detector	Video transmitter	**Module Summary**	Battery	Fuel tank	Gas generator	Ignition	Ignition power switch	Optical kill switch	Power distribution board	Wiring	**Module Summary**	Self-destruct package	**Module Summary**	Airframe	ESC	Propeller	Servo
Analyze spectrum data																												
Auto land	↗	↗											↗											↗				
Auto takeoff	↗	↗											↗											↗				
Calculate target coord																												
Capture video	↗						↗	↗					↗															
Collect rad data	↗						↗				↗		↗															
Collect rad spectrum																												
Combine rad data/telemetry																												
Conduct BIT	↗	↗	↗										↗															
Connect to GCS	↗	↗		↗			↗			↗		↗	↗															
Connect to vehicle																												
Construct MP																												
Create rad map																												
Display MP status																												
Display rad data																												
Display rad map																												
Display rad spectrum																												
Display radionuclide																												
Display target coord																												
Display telemetry																												
Display video																												
Follow search pattern	↗	↗											↗											↗				
Initiate search																												
Load MP	↗	↗	↗	↗																								

Legend Allocated - ↗		Navigation Module					Payload Module						Power Module									Self-Destruct		Vehicle				
	System Summary	**Module Summary**	Autopilot	Autopilot Modem	GPS/ Compass	Pitot sensor	**Module Summary**	Camera	Gimbal	Payload Modem	Radiation detector	Video transmitter	**Module Summary**	Battery	Fuel tank	Gas generator	Ignition	Ignition power switch	Optical kill switch	Power distribution board	Wiring	**Module Summary**	Self-destruct package	**Module Summary**	Airframe	ESC	Propeller	Servo
Loiter	↗	↗											↗											↗				
Navigate waypoints	↗	↗											↗											↗				
Perform autopilot functions	↗	↗	↗	↗									↗											↗				
Perform controlled movement	↗	↗											↗											↗				
Perform GCS activities																												
Perform rad measurement	↗						↗				↗		↗															
Perform rad search activities	↗	↗	↗	↗			↗	↗		↗	↗	↗	↗											↗				
Perform vehicle activities	↗	↗	↗	↗			↗	↗		↗	↗	↗	↗											↗				
Perform vehicle data comm	↗	↗	↗	↗			↗			↗			↗															
Process																												
Provide data comm w/ vehicle																												
Provide I/O w/ GCS operator																												
Provide video	↗						↗	↗				↗	↗															
Receive cmd	↗	↗		↗			↗			↗			↗															
Receive MP status																												
Receive rad data																												
Receive spectrum data																												
Receive telemetry																												
Receive video																												
Report MP load status	↗	↗	↗	↗									↗															
Send cmd																												
Send rad data	↗						↗			↗			↗															
Send spectrum data																												
Send telemetry	↗	↗		↗									↗															
Send video	↗						↗					↗	↗															
Store rad data																												
Store spectrum data																												
Store target coord																												
Store telemetry																												
Store video																												
Trigger self-destruct actuator	↗	↗	↗	↗									↗									↗	↗					
Write MP																												

Table 16. Ground vehicle physical allocation matrix

Legend Allocated - ↗		Navigation Module				Payload Module							Power Module				Self-Destruct		Vehicle					
	System Summary	Module Summary	Autopilot	Autopilot Modem	GPS/Compass	Module Summary	Camera	Gimbal	Payload Modem	Radiation detector	Spectrum collector	Video transmitter	Module Summary	Battery	Power distribution board	Wiring	Module Summary	Self-destruct package	Module Summary	Articulator arm	ESC	Ground vehicle chassis	Motor	Servo
Analyze spectrum data																								
Auto land	↗	↗											↗						↗					
Auto takeoff	↗	↗											↗						↗					
Calculate target coord																								
Capture video	↗					↗	↗						↗											
Collect rad data	↗					↗				↗			↗											
Collect rad spectrum	↗					↗					↗		↗											
Combine rad data/telemetry																								
Conduct BIT	↗	↗	↗										↗											
Connect to GCS	↗	↗		↗		↗			↗			↗	↗											
Connect to vehicle																								
Construct MP																								
Create rad map																								
Display MP status																								
Display rad data																								
Display rad map																								
Display rad spectrum																								
Display radionuclide																								
Display target coord																								
Display telemetry																								
Display video																								
Follow search pattern	↗	↗											↗						↗					
Initiate search																								
Load MP	↗	↗	↗	↗																				

Legend Allocated - ↗		Navigation Module				Payload Module							Power Module				Self-Destruct		Vehicle					
	System Summary	**Module Summary**	Autopilot	Autopilot Modem	GPS/Compass	**Module Summary**	Camera	Gimbal	Payload Modem	Radiation detector	Spectrum collector	Video transmitter	**Module Summary**	Battery	Power distribution board	Wiring	**Module Summary**	Self-destruct package	**Module Summary**	Articulator arm	ESC	Ground vehicle chassis	Motor	Servo
Loiter	↗	↗											↗						↗					
Navigate waypoints	↗	↗											↗						↗					
Perform autopilot functions	↗	↗	↗	↗									↗						↗					
Perform controlled movement	↗	↗											↗						↗					
Perform GCS activities																								
Perform rad measurement	↗					↗				↗	↗		↗											
Perform rad search activities	↗	↗	↗	↗		↗	↗		↗	↗	↗	↗	↗						↗					
Perform vehicle activities	↗	↗	↗	↗		↗	↗		↗	↗	↗	↗	↗						↗					
Perform vehicle data comm	↗	↗	↗	↗		↗			↗				↗											
Process																								
Provide data comm w/ vehicle																								
Provide I/O w/ GCS operator																								
Provide video	↗					↗	↗					↗	↗											
Receive cmd	↗	↗		↗		↗			↗				↗											
Receive MP status																								
Receive rad data																								
Receive spectrum data																								
Receive telemetry																								
Receive video																								
Report MP load status	↗	↗	↗	↗									↗											
Send cmd																								
Send rad data	↗					↗			↗				↗											
Send spectrum data	↗					↗			↗				↗											
Send telemetry	↗	↗		↗									↗											
Send video	↗					↗						↗	↗											
Store rad data																								
Store spectrum data																								
Store target coord																								
Store telemetry																								
Store video																								
Trigger self-destruct actuator	↗	↗	↗	↗									↗				↗	↗						
Write MP																								

Table 17. Multirotor vehicle physical allocation matrix

Legend Allocated - ↗		Navigation Module					Payload Module							Power Module									Self-Destruct		Vehicle			
	System Summary	Module Summary	Autopilot	Autopilot Modem	Distance Sensor	GPS/Compass	Module Summary	Camera	Gimbal	Payload Modem	Radiation detector	Spectrum collector	Video transmitter	Module Summary	Battery	Fuel tank	Gas generator	Ignition	Ignition power switch	Optical kill switch	Power distribution board	Wiring	Module Summary	Self-destruct package	Module Summary	ESC	Multirotor frame	Propeller
Analyze spectrum data																												
Auto land	↗	↗												↗											↗			
Auto takeoff	↗	↗												↗											↗			
Calculate target coord																												
Capture video	↗						↗	↗						↗														
Collect rad data	↗						↗				↗			↗														
Collect rad spectrum	↗						↗					↗		↗														
Combine rad data/telemetry																												
Conduct BIT	↗	↗	↗											↗														
Connect to GCS	↗	↗		↗			↗			↗				↗														
Connect to vehicle																												
Construct MP																												
Create rad map																												
Display MP status																												
Display rad data																												
Display rad map																												
Display rad spectrum																												
Display radionuclide																												
Display target coord																												
Display telemetry																												
Display video																												
Follow search pattern	↗	↗												↗											↗			
Initiate search																												
Load MP	↗	↗	↗	↗																								

Legend Allocated - ↗		Navigation Module					Payload Module							Power Module									Self-Destruct		Vehicle			
	System Summary	**Module Summary**	Autopilot	Autopilot Modem	Distance Sensor	GPS/Compass	**Module Summary**	Camera	Gimbal	Payload Modem	Radiation detector	Spectrum collector	Video transmitter	**Module Summary**	Battery	Fuel tank	Gas generator	Ignition	Ignition power switch	Optical kill switch	Power distribution board	Wiring	**Module Summary**	Self-destruct package	**Module Summary**	ESC	Multirotor frame	Propeller
Loiter	↗	↗												↗											↗			
Navigate waypoints	↗	↗												↗											↗			
Perform autopilot functions	↗	↗	↗	↗										↗											↗			
Perform controlled movement	↗	↗												↗											↗			
Perform GCS activities																												
Perform rad measurement	↗						↗				↗	↗		↗														
Perform rad search activities	↗	↗	↗	↗			↗	↗		↗	↗	↗	↗	↗											↗			
Perform vehicle activities	↗	↗	↗	↗			↗	↗		↗	↗	↗	↗	↗											↗			
Perform vehicle data comm	↗	↗	↗	↗			↗			↗				↗														
Process																												
Provide data comm w/ vehicle																												
Provide I/O w/ GCS operator																												
Provide video	↗						↗	↗					↗	↗														
Receive cmd	↗	↗		↗			↗			↗				↗														
Receive MP status																												
Receive rad data																												
Receive spectrum data																												
Receive telemetry																												
Receive video																												
Report MP load status	↗	↗	↗	↗										↗														
Send cmd																												
Send rad data	↗						↗			↗				↗														
Send spectrum data	↗						↗			↗				↗														
Send telemetry	↗	↗		↗										↗														
Send video	↗						↗						↗	↗														
Store rad data																												
Store spectrum data																												
Store target coord																												
Store telemetry																												
Store video																												
Trigger self-destruct actuator	↗	↗	↗	↗										↗									↗	↗				
Write MP																												

Table 18. Ground control station physical allocation matrix

Legend Allocated - ↗	**System Summary**	Antenna tracker	Autopilot Modem	GCS computer	GCS software	GPS base station	Payload Modem	Radiation processing & mapping software	Video receiver
Analyze spectrum data	↗							↗	
Auto land									
Auto takeoff									
Calculate target coord	↗							↗	
Capture video									
Collect rad data									
Collect rad spectrum									
Combine rad data/telemetry	↗			↗	↗			↗	
Conduct BIT									
Connect to GCS									
Connect to vehicle	↗		↗				↗		
Construct MP	↗			↗	↗				
Create rad map	↗			↗				↗	
Display MP status	↗			↗	↗				
Display rad data	↗			↗				↗	
Display rad map	↗			↗				↗	
Display rad spectrum	↗			↗				↗	
Display radionuclide	↗			↗				↗	
Display target coord	↗			↗				↗	
Display telemetry	↗			↗	↗				
Display video	↗			↗					↗
Follow search pattern									
Initiate search	↗			↗	↗				
Load MP									

Legend Allocated - ↗	**System Summary**	Antenna tracker	Autopilot Modem	GCS computer	GCS software	GPS base station	Payload Modem	Radiation processing & mapping software	Video receiver
Loiter									
Navigate waypoints									
Perform autopilot functions									
Perform controlled movement									
Perform GCS activities	↗	↗	↗	↗	↗	↗	↗	↗	↗
Perform rad measurement									
Perform rad search activities									
Perform vehicle activities									
Perform vehicle data comm									
Process	↗			↗	↗			↗	
Provide data comm w/ vehicle	↗	↗	↗	↗	↗		↗	↗	
Provide I/O w/ GCS operator	↗			↗	↗			↗	↗
Provide video									
Receive cmd									
Receive MP status	↗	↗	↗						
Receive rad data	↗	↗					↗		
Receive spectrum data	↗	↗					↗		
Receive telemetry	↗	↗	↗						
Receive video	↗	↗							↗
Report MP load status									
Send cmd	↗	↗	↗	↗	↗		↗	↗	
Send rad data									
Send spectrum data									
Send telemetry									
Send video									
Store rad data	↗			↗					
Store spectrum data	↗			↗					
Store target coord	↗			↗					
Store telemetry	↗			↗					
Store video	↗			↗					
Trigger self-destruct actuator									
Write MP	↗		↗	↗	↗				

Appendix B. System Use Cases

Description:
This Use Case encompasses deployment of the Rad Search System vehicle(s) and ingress to the search area.

Preconditions:
Successful completion of Perform Setup Use Case
GPS Lock

Primary Flow:
1. Ground Control Station Operator initiates Launch mode through Ground Control Station
2. Ground Control Station changes Vehicle mode to Launch
3. Vehicle enters Launch mode
4. Vehicle transmits telemetry to Ground Control Station(s)
5. Ground Control Station(s) receives and displays telemetry data
6. Ground Control Station(s) stores telemetry data
7. Ground Crew launches Vehicle
8. Vehicle establishes controlled movement or stable flight
9. Vehicle maneuvers toward search area
10. Ground Control Station Operator observes received data on Ground Control Station
11. Once Vehicle arrives at Search Insertion point, it enters Search mode
12. End Use Case

Alternate Flow:
At any time:
  a. If bad Vehicle health, Ground Control Station Operator enters RTL command on Ground Control Station
  b. Ground Control Station sends RTL command to Vehicle
  c. Vehicle enters RTL mode
At any time:
  a. Operator initiates <<include>> Plan Mission Use Case
  b. Vehicle ingresses to new Search Insertion point
At any time:
  a. If vehicle compromise is evident, execute <<extend>> Perform Self-Destruct Use Case

Postconditions: Vehicle arrives at Search Insertion point and enters Search mode

Involves:
GNSS
Ground Control Station Operator
Ground Crew

Figure 16. Deploy and ingress use case

Description:
This Use Case covers the RTL actions required to return the vehicle to home location or specified location with recovery.

Preconditions: Vehicle has entered RTL mode

Primary Flow:
1. Vehicle maneuvers toward home/recovery point
2. Vehicle arrives at home/recovery point
3. Vehicle executes auto-land maneuver
4. Ground Control Station Operator and Ground Crew recovers Vehicle
5. End Use Case

Alternate Flow: At any time:
a. If bad vehicle health, Ground Control Station Operator enters RTL command on Ground Control Station
b. Ground Control Station sends RTL command to Vehicle
c. Vehicle enters RTL mode
At any time:
a. Ground Control Station Operator initiates Plan Mission Use Case
b. Vehicle ingresses to new Search Insertion point
At any time:
a. If vehicle compromise is evident, execute <<extend>> Perform Self-Destruct Use Case

Postconditions: Vehicle is safely recovered by Ground Crew

Involves:
GNSS
Ground Control System Operator
Ground Crew

Figure 17. Egress and recover use case

Description:
This Use Case covers confirmation activities

Preconditions: Target has been located and a Vehicle has entered Confirmation mode

Primary Flow:
1. Vehicle transmits telemetry data, rad data, and video to Ground Control Station(s) and Off-Board C2
2. Ground Control Station(s) receives and displays telemetry data, rad data, and video
3. Ground Control Station(s) stores telemetry data, rad data, and video
4. Vehicle navigates to and hovers or remains near target
5. Ground Control Station sends collect rad spectrum data command
6. Vehicle receives and initiates rad spectrum collection
7. Vehicle transmits rad spectrum data
8. Ground Control Station(s) receives, stores, and displays rad spectrum data
9. Ground Control Station Operator terminates rad spectrum collection
10. Ground Control Station processes rad spectrum data and displays radionuclide identification
11. Ground Control Station Operator initiates RTL
12. Ground Control Station sends RTL command to Vehicle
13. Vehicle enters RTL mode
14. End Use Case

Alternate Flow:
At any time:
 a. If bad vehicle health, Ground Control Station Operator enters RTL command on Ground Control Station
 b. Ground Control Station sends RTL command to Vehicle
 c. Vehicle enters RTL mode
At any time:
 a. If vehicle no longer required due to deployed sensor package, Ground Control Station Operator enters RTL command
 b. Ground Control Station sends RTL command to Vehicle
 c. Vehicle enters RTL mode
At any time:
 a. Ground Control Station Operator initiates <<include>> Plan Mission Use Case
 b. Vehicle ingresses to new Search Insertion point or Confirmation coordinates
At any time:
 a. If vehicle compromise is evident, execute <<extend>> Perform Self-Destruct Use Case
 b. Vehicle self-destructs

Postconditions: Vehicle hovers or remains near target for > 5 minutes and rad spectrum is stored and displayed on Ground Control Station(s) with suspected radionuclide identification; Vehicle enters RTL mode

Involves:
GNSS
Off-Board C2 Operator
Target

Figure 18. Perform confirmation use case

Description:
This Use Case covers execution of search patterns

Preconditions: Vehicle arrives at insertion point and has transitioned to Search mode; Mission Plan is loaded by GCS

Primary Flow:
1. Vehicle transmits telemetry data, rad data, and video to Ground Control Station(s) and Off-Board C2
2. Ground Control Station(s) receives and displays telemetry data, rad data, and video
3. Ground Control Station(s) continuously combines telemetry and rad data and displays as a radiation strength map
3. Ground Control Station(s) stores telemetry data, rad data, and video
4. Vehicle follows search pattern according to Mission Plan
5. Ground Control Station Operator and Off-Board C2 monitor rad data, navigation data, and video
6. Vehicle completes search pattern according to Mission Plan
7. Ground Control Station determines target(s) coordinates from received rad data and telemetry data
8. Ground Control Station Operator commands change to Confirmation mode
9. Ground Control Station sends Confirmation mode change
10. Vehicle enters Confirmation mode
11. End Use Case

Alternate Flow:
At any time:
  a. If bad vehicle health, Ground Control Station Operator enters RTL command
  b. Ground Control Station sends RTL command to Vehicle
  c. Vehicle enters RTL mode
At any time:
  a. If vehicle no longer required due to deployed sensor package, Ground Control Station Operator enters RTL command
  b. Ground Control Station sends RTL command to Vehicle
  c. Vehicle enters RTL mode
At any time:
  a. Ground Control Station Operator initiates <<include>> Plan Mission Use Case
  b. Vehicle ingresses to new Search Insertion point (may be used to further loiter or investigate target location)
At any time:
  a. If vehicle compromise is evident, execute <<extend>> Perform Self-Destruct Use Case
  b. Vehicle self-destructs

Postconditions: Target is identified through radiation sensor data and telemetry data and target coordinates are calculated and displayed on Ground Control Station(s); Vehicle transitions to Confirmation mode

Involves:
GNSS
Off-Board C2 Operator
Target

Figure 19. Perform search use case

Description:
This Use Case covers the activities required to perform commanded self-destruct.

Preconditions: Vehicle is navigating in a location away from the Ground Control Station Operator

Primary Flow:
1. Operator initiates Ditch mode on Ground Control Station
2. Ground Control Station sends Self-Destruct mode change to Vehicle
3. Vehicle initiates Self-Destruct mode
4. Vehicle processor sends command to A/P to crash
5. Vehicle processor sends command to embedded self-destruct actuator
6. Embedded self-destruct actuator initiates and destroys processor
7. Vehicle crashes
8. End Use Case

Postconditions: Vehicle is successfully crashed and system is inoperable by other personnel

Figure 20. Perform self-destruct use case

Description:
This Use Case covers the setup and mission planning for use of the Rad Search System

Preconditions:
Tasking received
Search area defined
Desired radionuclide(s) specified

Primary Flow:
1. Ground Crew and Ground Control Station Operator unpacks equipment
2. Ground Crew and Ground Control Station Operator inventories equipment
  2a. If necessary equipment missing - end Use Case
3. Ground Crew and Ground Control Station Operator assembles equipment
4. Ground Crew and Ground Control Station Operator initiate connection between Ground Control Station and Vehicle(s)
5. Ground Control Station sends connect signal to Vehicle(s)
6. Vehicle(s) makes connection to Ground Control Station
  6a. If connection fails, go to step 4. If fail 3x, end Use Case
7. Vehicle(s) begins transmission of rad data, rad spectrum data, telemetry data, and video
8. Ground Control Station displays rad data, rad spectrum data, telemetry data, and video
9. Ground Control Station stores rad data, rad spectrum data, telemetry data, and video
10. Ground Control Station Operator initiates function checks through Ground Control Station
11. Ground Control Station initiates function checks on Vehicle(s)
12. Vehicle(s) performs function checks and sends results to Ground Control Station
13. Ground Control Station displays results of function checks
14. Ground Control Station Operator confirms successful function checks.
  14a. If function check unsuccessful, go to step 10. If fail 3x, end Use Case.
15. <<Include>> Perform Mission Plan
  15a. If Mission Plan unsuccessful, repeat step 15. If fail 3x, end Use Case
16. End Use Case

Postconditions: System properly configured; mission planning complete; system ready for deployment

Involves:
Ground Control Station Operator
Ground Crew
GNSS

Figure 21. Perform setup use case

Description:
This Use Case covers actions associated with planning or re-planning a mission. It can be completed either pre-, or post-launch.

Preconditions: Vehicle has passed function checks and has established comm with Ground Control Station(s)

Primary Flow:
1. Ground Control Station Operator enters Mission Plan information into Ground Control Station
2. Ground Control Station converts Mission Plan to machine language form
3. Ground Control Station Operator initiates Write Mission Plan function on Ground Control Station
3. Ground Control Station sends machine language Mission Plan to Vehicle(s)
4. Vehicle(s) puts Mission Plan into active memory
5. Vehicle(s) sends indication of successful Mission Plan
6. Ground Station displays indication of successful Mission Plan load
7. End Use Case

Postconditions: Successful receipt of Mission Plan by Vehicle(s)

Figure 22. Plan mission use case

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Vita

Captain Sam B. Harriger graduated from the United States Air Force Academy in 2011 where he received his commission and a Bachelor of Science in Environmental Engineering. After commissioning, Captain Harriger served in several Civil Engineering positions at Beale Air Force Base, California, including wastewater environmental compliance, aircraft beddown planning, and construction project management. He also deployed to southwest Asia, where he led five teams across seven countries providing runway rubber removal, airfield paint striping, and large area maintenance shelter construction. Captain Harriger's most recent assignments include serving as the 377th Explosive Ordnance Disposal (EOD) Flight Commander and as the EOD Section Chief at the Defense Nuclear Weapons School at Kirtland Air Force Base, New Mexico. In 2018, he was selected to attend the Air Force Institute of Technology at Wright Patterson Air Force Base, Ohio as part of the Graduate Engineering Management program. Following graduation and earning a Master of Science in Engineering Management, Captain Harriger is deploying to Africa to serve as a United Nations Staff Officer.

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14. ABSTRACT

Nuclear and radiological terrorism is a persistent threat to United States national security. The research and development of new technological capabilities is vital to bolstering emergency response and prevention capabilities in support of national security initiatives. This research characterized the applicable trade-space for a system of unmanned vehicles deployed for search, detection, and identification of radiological source material. Exploration included the development of a CONOPS, a functional decomposition and physical allocation, design considerations, and an analysis of feasibility and utility. The concept system comprises of a ground control station, ground vehicle, hybrid-electric multirotor, and fixed-wing vehicle with an open architecture permitting the exchange of payload components. Payload options include a Geiger-Müller detector or scintillator for large area search and a scintillator or high purity germanium semiconductor for radioisotope identification. Endurance estimates revealed that a hybrid-electric multirotor is capable of carrying a 6.8-kilogram payload for 58 minutes. Similar estimates indicated that a battery-powered fixed-wing vehicle can provide a minimum of 41 minutes of endurance with a payload mass fraction of 15% (1.36-kilogram payload), whereas a gasoline-powered vehicle with the same payload mass fraction (1.95-kilogram payload) can operate for 12 hours. Electric multirotors are limited to a maximum endurance of 20 minutes, which is insufficient for radiological search missions. The system concept proves effective to the radiological search mission and can be expanded to other mission areas through its open architecture.

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