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MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

ANALYSIS OF ALTERNATIVE RECOVERY SYSTEMS FOR THE RQ-21A BLACKJACK

by

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March 2018

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BLACKJACK**

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ABSTRACT

The RQ-21A unmanned aerial system must be able to launch and recover independent from any runway or leveled surface. The current RQ-21A STUAS recovery system (SRS) has been deemed deficient by Program Management Authority 263, because it is incapable of recovering the air vehicle at its maximum weight and commonly causes damage to the air vehicle, payloads, and/or the SRS. This project conducted an analysis of alternatives to compare the SRS, VTOL, SideArm, FLARES, and Net Capture recovery systems based on performance, cost, and risks. The VTOL and SideArm are recommended as potential replacements because they outperform the RQ-21A SRS and other alternatives in performance, cost, and risk. Replacing the current SRS with VTOL or SideArm would reduce the amount and frequency of damage to the air vehicle, increase performance, and reduce life-cycle costs. SideArm and VTOL have performance values of 0.809 and 0.766, respectively. FLARES, Net Capture, and the SRS have substantially lower performance values of 0.453, 0.448, and 0.005. The total life cycle costs of the VTOL and SideArm are substantially lower, \$758 and \$759 million, compared to the other systems, which range from \$913 to \$1,034 million.

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LIST OF ACRONYMS AND ABBREVIATIONS

AVO	air vehicle operator
AHP	Analytic Hierarchy Process
AoA	analysis of alternatives
CIP	Component Improvement Program
CONOPS	Concept of Operations
EI	engineering investigation
EOC	Early Operational Capability
FLARES	Flying Launch and Recovery System
FoUAS	family of unmanned aircraft systems
FOUO	For Official Use Only
FST	Fleet Support Team
GCS	ground control systems
IAW	in accordance with
IOC	initial operational capability
ISR	intelligence, surveillance, & reconnaissance
KPP	key performance parameters
LCC	life-cycle cost
LSE	Lead System Engineer
MGTOW	mean ground take-off weight
MTOW	maximum take-off weight
NAVAIR	Naval Air Systems Command
O&S	procurement and operations and support
PBS	Performance Based Specification
PM	project manager
PMA	Program Management Authority
R&D	research and development
SRS	STUAS recovery system
STUAS	small tactical unmanned aerial system
UAS	unmanned air system

UASTD	unmanned aerial systems test directorate
UAV	unmanned air vehicle
USAF	United States Air Force
USMC	United States Marine Corps
USN	United States Navy
VTOL	vertical takeoff and landing

EXECUTIVE SUMMARY

The RQ-21A Small, Tactical Unmanned Aerial System (STUAS) Recovery System (SRS) is deemed deficient by the Small Tactical Unmanned Aircraft Systems Program Management Authority (PMA 263) because it is incapable of recovering the air vehicle at its maximum weight, and commonly causes damage to the air vehicle, payloads, and the SRS. The RQ-21A is a part of the Navy and Marine Corps STUAS, and is an update to the ScanEagle unmanned aerial system. Five recovery systems were selected, the Vertical Take-Off and Landing (VTOL), Flying Launch And Recovery System (FLARES), SideArm, Net Capture, and SRS, and an analysis of alternatives (AoA) was performed. The AoA process aimed to systematically eliminate non-viable recovery systems, and rate the remaining recovery systems by performance, cost, and risk

The sum of all weighted score values for each recovery system was computed during the performance analysis. The SideArm, VTOL, FLARES, Net Capture, and RQ-21A SRS were determined to have score values of 0.809, 0.766, 0.453, 0.448, and 0.005, respectively. Following the cost analysis, the Net Capture was estimated to have the least research and development costs; FLARES was estimated to have the lowest procurement costs; and the VTOL was estimated to have the least operating and support costs. Risk was analyzed for performance and technical/cost. The VTOL posed the least amount of performance risk while Net Capture posed the least amount of cost risk. However, the Net Capture posed the highest amount of performance risk.

Based on the AoA, it was recommended that the VTOL and SideArm be selected for consideration and further research. Both recovery systems outperformed the current SRS. The other systems (SRS, Net Capture, and FLARES) were all determined to be more expensive and less capable than VTOL or SideArm.

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I. INTRODUCTION AND BACKGROUND

A. INTRODUCTION

The RQ-21A “Blackjack” unmanned air vehicle (UAV), also called the Small Tactical Unmanned Aerial System (STUAS), is designed to provide day and night intelligence, surveillance, and reconnaissance capabilities for expeditionary and maritime forces, which is capable of delivering real time intelligence. An RQ-21A measures 8 feet long, has a wingspan of 16 feet and can operate for approximately 16 hours. According to Program Management Authority 263 (PMA-263), the air vehicle’s open-architecture configuration is designed to integrate multi-mission payloads seamlessly ; including day/night full-motion video cameras, an infrared marker, laser range finder, communications relay package, Automatic Identification System receivers, and additional payloads determined by mission requirements (Naval Air Systems Command [NAVAIR] PMA-263 n.d.).

The RQ-21A, which does not require a runway for launch and recovery, makes it possible to deploy with a small footprint from both austere land-based and shipboard environments (Naval Air Systems Command [NAVAIR] PMA-263. n.d.). However, NAVAIR PMA-263 has deemed the RQ-21A STUAS Recovery System (SRS) unsuitable for various reasons including recovery weight and damage sustained during capture.

Currently, the SRS is rated to recover the RQ-21A vehicle at a weight below the maximum weight with which the air vehicle is certified to launch. This limits the payload options that can be integrated on the vehicle. During recovery, the RQ-21A purposefully contacts a recovery wire on the SRS. The SRS does not consistently provide enough energy absorption when the RQ-21A contacts the recovery wire. This in turn results in a violent capture, and pendulum like motion of the RQ-21A. A “violent” capture often damages the airframe, payloads, and SRS; this then creates unscheduled repairs and reduced operational availability.

B. BACKGROUND

The RQ-21A is launched by a pneumatic catapult system. For recovery, a crane-based vertical capture rope system, referred to as the SRS, is utilized (Insitu Inc. 2013). The UAV is recovered when it flies its wing into the rope. The rope travels along the leading edge to the wingtip where carabiner-like clip on the tip secures the RQ-21A to the SRS, as depicted in Figure 1. The rope kinks in a way that prevents the UAV from sliding down.

The remainder of this chapter covers the history, past failures and present status of the RQ-21A and SRS, as well as discussion of alternative recovery systems.



Figure 1. RQ-21A Captured On Shipboard Using SRS. Source: Federation of American Scientists (2000, 1).

1. RQ-21A History

The RQ-21A carries a modular payload, which includes an electro-optical and infrared (EO/IR) turret ball, communications relay, automated identification system

(AIS), and additional payload bays (Insitu Inc. 2013). The RQ-21A is intended to have a small footprint. The shipboard configuration of the SRS supports both United States Navy (USN) and United States Marine Corps (USMC) (embarked) requirements while the land-based configurations support USMC, USN Special Warfare, and United States Air Force (USAF) requirements (Program Executive Officer for Unmanned Aviation and Strike Weapons [PEO(U&W)] 2012).

2. Past SRS Failures

Landing/recovery of UAVs in general remains a significant issue. Work on recovery of Group 2 and 3 UAVs is particularly prevalent due to their size (see Table 1). These UAVs are often too large for a deep stall belly landing, yet still present an opportunity for runway independent recovery. RQ-21 is a group 3 UAV.

Table 1. UAS Group Descriptions. Source: UAS Task Force, (2011).

UAS Group	Maximum weight (lb)	Operating altitude (ft)	Speed (knots)
Group 1	0–20	< 1,200 AGL	100
Group 2	21–55	< 3,500 AGL	< 250
Group 3	< 1,320	< FL 180	
Group 4	> 1,320	> FL 180	Any airspeed
Group 5		> FL 180	

AGL = Above Ground Level, FL = Flight Level

According to an *Initial Operational Test and Evaluation* report for the RQ-21A system, the SRS causes a significant proportion of the failure modes. In fact, “Structural damage to the air vehicle accounted for 23 percent (16 of 68)” of the failure modes experienced. Recovery damage experienced by the air vehicle during capture “ranged from hinge clips to replacement of entire wing and empennage modules” (Operational Test and Evaluation [DOT&E] Director 2015).

According to a listing of maintenance actions performed on the RQ-21A and SRS from July 2015 to July 2017, the failure modes caused by recovery encompassed the following:

- **Air Vehicle Control surfaces:** Broken clips and cracking have been found on flaps, on elevators, on ailerons, and on rudders. This required the removal and replacement of these particular control surfaces.
- **Air Vehicle Electronics:** Damage occurred to antennas, to navigation lights, and to pilot/IR camera lenses. This required removal and replacement of these particular electronics.
- **Air Vehicle Structure:** Damage, such as cracking, occurred to the empennage and to the wings. These structures required removal and replacement.
- **SRS:** Damage, such as tearing, occurred to the capture rope, to the GPS egg, and to the GPS cabling. The GPS components and cabling were required to be removed and replaced.

3. **Review of Alternative Recovery Systems**

The alternative recovery systems evaluated in this report were based on existing systems either currently used or under development for other UAVs. In addition to the current SRS described in the previous chapter, the other four alternative systems under consideration are discussed below.

*a. **Flying Launch and Recovery System (FLARES)***

The FLARES alternative is based on the similarly-name prototype system developed by Insitu. The prototype system lifts an Insitu ScanEagle—which weighs approximately 50 lbs—into the air with a large quadcopter, as seen in Figure 2. For recovery, the same FLARES quadcopter would replace the SRS by suspending the capture rope between the hovering quadcopter and an anchor in the ground (Insitu Inc. n.d.). A minor modification may be necessary for the system to attach/detach from the air vehicle, but it could utilize existing hard points.

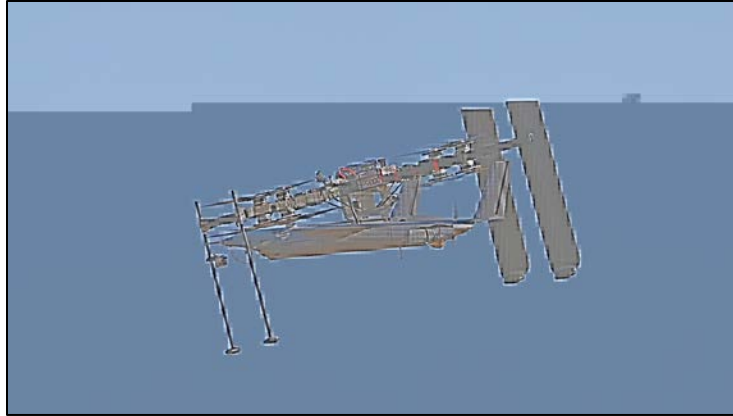


Figure 2. FLARES Carrying a Scan-Eagle during Launch.
Source: Atherton (2015, 1).

b. SideArm

The alternative SideArm system takes its name and design from the SideArm prototype developed by DARPA and Aurora Flight Sciences, seen in Figure 3. Like the SRS, SideArm uses a crane for recovery. However, this system uses a hook located on the top of the UAV to catch an arresting gear. Once engaged, the arresting gear controls the deceleration of the aircraft as it swings up into a net that brings the UAV to a stop. A barb on the nose of the aircraft, in conjunction with the hook, reduces motion as the UAV is lowered to the ground (Defense Advanced Research Projects Agency [DARPA] 2017). A minor modification, that incorporates the hook and the barb on the RQ-21A, may be necessary.



Figure 3. Artist's Rendering of SideArm Operation. Source: Villasanta (2017, 1).

c. Vertical Takeoff and Landing (VTOL)

The alternative recovery system referred to as VTOL is based on the Arcturus JUMP 20 system. The Arcturus JUMP system uses a quadcopter configuration of motors permanently mounted to the aircraft. The JUMP system is capable of vertical takeoff and landing (VTOL). It was demonstrated on the Arcturus T20, seen in Figure 4, which has a gross takeoff weight comparable to the RQ-21A (Arcturus UAV n.d.). The system would use the existing hard point on the aircraft to attach to the system. This kit would be reversible to allow the RQ-21A to function with the existing launch and recovery system.

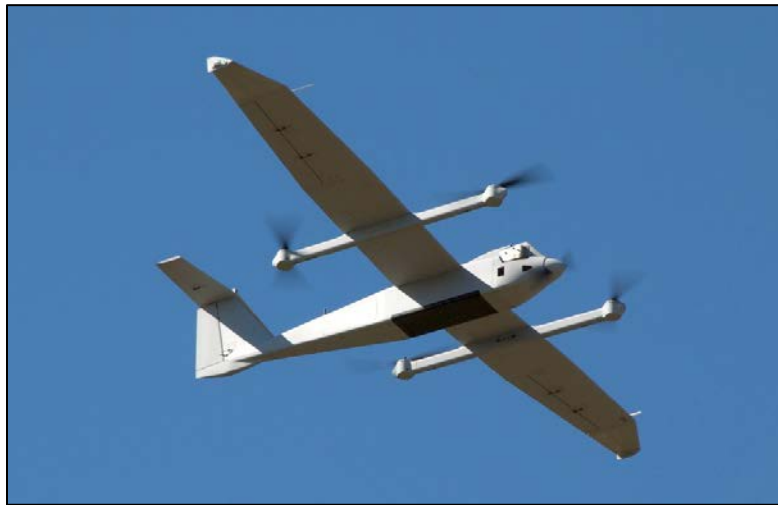


Figure 4. Arcturus JUMP 20 Hovering. Source: Arcturus (n.d., 1).

d. Net Capture

The Net Capture alternative is based on one of several UAV net capture systems, like the one sometimes used with the RQ-2 Pioneer UAV. Instead of a single rope, the Net Capture system uses an angled net to distribute the capture forces across the entire leading edge of the wing, shown in Figure 5. This system would not require any modifications to the air vehicle.



Figure 5. RQ-2 Pioneer Captured by Net. Source: Federation of American Scientists (2000).

C. PROBLEM STATEMENT

The RQ-21A SRS has been deemed deficient by PMA 263, as it is incapable of recovering the air vehicle at its maximum weight, and commonly causes damage to the air vehicle, payloads, and the SRS.

The purpose of this project is to perform an analysis of alternatives (AoA), and from the insight gained, propose a viable and cost-effective recovery solution for the RQ-21A SRS. The recovery system needs to recover the air vehicle while minimizing damage (to the air vehicle and recovery system) within the wind envelopes specified for the baseline recovery system, defined in the RQ-21 performance based specification (PBS) document (Program Executive Officer for Unmanned Aviation and Strike Weapons [PEO(U&W)] 2012).

This project includes information gathered from stakeholders, and from independent sources of comparable systems. The information consists of requirements information, design data, test data, performance data, component and system cost data, maintenance records, and logistics data. Varying amounts of data were available for each system, and missing or incomplete data had to be estimated. When possible, the estimation was done by comparing the proposed alternative to a similar existing system.

Due to time limitations, certain aspects of the problem could not be explored in this report. Items that were in, and out, of the project scope are outlined below.

a. *In Scope*

- Recovery systems.
- Fielded systems and prototypes being used on the current or similarly sized UAVs.
- Reversible, or minor, changes to air vehicle (i.e., removable kits)
- Designs expected to reduce damage due to capture, or increase potential air vehicle capture weight/energy.

b. *Out of Scope*

- Aspects of baseline system not related to recovery.
- Feasibility of necessary modifications to alternative systems.
- Company proprietary information such as cost.
- Classified data.
- Launch systems; only recovery component of a combined launch and recovery system would be evaluated.
- Design changes that do not improve damage due to capture or air vehicle capture weight/energy.

c. *Assumptions*

The following assumptions were made in order to facilitate the timely completion of this Capstone effort. Each of these areas have not been completely investigated and would be appropriate for future investigation or research.

- The team's engineering judgement used in formulating the evaluation criteria weights is similar to that of the stakeholders. (This assumption was validated at the first interim progress review).

- Thirty-three total recovery systems would be acquired, per discussions with PMA-263. This included 31 operational systems and 2 spare systems with each system supporting 5 RQ-21A air vehicles.
- A majority of the damage to the air vehicle is not caused by impact, but rather the forces exerted on the air vehicle during recovery. Thus, force is an adequate proxy measure for the amount of damage experienced during recovery.

d. Limitations and Constraints

The following are the limitations and constraints for the project:

- Actual performance data was not available for damage reduction, percent grade, capture after launch, and approach envelope parameters. For these parameters estimates intended to reflect actual performance were created or derived from other sources of information. Derivation is explained in the Needs Analysis chapter of the report.
- Airframe modification and the extent of those modifications have not been assessed in this analysis.
- The FLARES and VTOL cost data is proprietary and/or competition sensitive.
- The SideArm program information was limited because it was in the early stages of development and testing.

e. Capstone Project Objectives

The first step in the project process, after the problem statement was defined, was to determine project objectives. The objectives guided the research methodology and solution steps.

- To determine which existing systems with similar size and functionality to the SRS would be suitable for inclusion in the AoA.

- To determine whether if similar systems could be directly included into the current concept of operation (CONOP) for the RQ-21A.
- To determine whether major physical, or functional, pieces of the similar systems are able to be taken in their entirety for use in place of the RQ-21A SRS.
- To determine which system characteristics were most important to the stakeholders.
- To determine whether other existing recovery systems fulfilled those characteristics (identified by stakeholders) as priorities to satisfy needs expressed in the problem statement.
- To determine the performance and cost risks associated with each of the alternatives.
- To determine which of the identified alternatives provided the most value as a potential SRS replacement.

D. TECHNICAL APPROACH

The team performed an AoA in accordance with the USAF, *Office of Aerospace Studies (OAS) AoA Handbook* (Air Force Office of Aerospace Studies, 2016), and *Systems Engineering and Analysis* (Blanchard and Fabrycky, 2011). Figure 6 shows the steps used by the team to gather information leading up to the AoA.

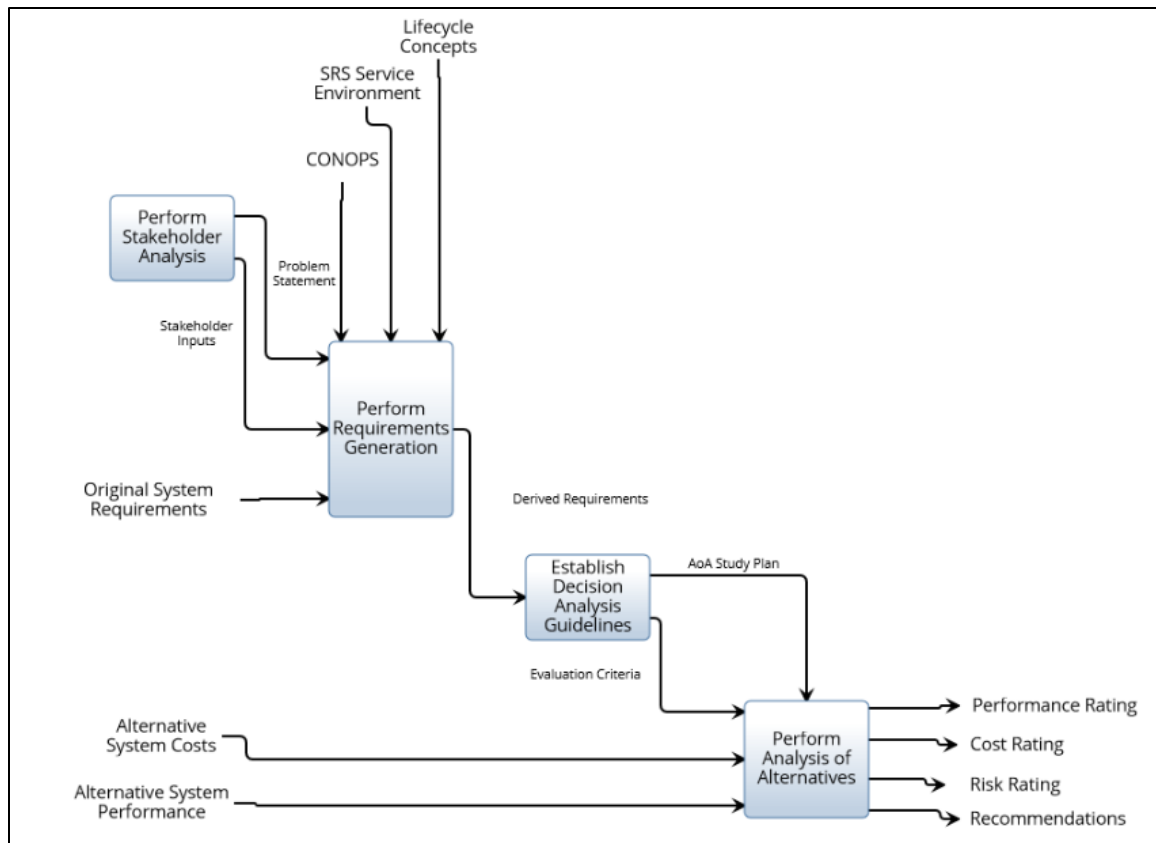


Figure 6. Capstone Team Systems Engineering Process.

1. Stakeholder Analysis

The stakeholder summary is essential to the AoA process. Inputs from the stakeholders were needed to better understand the system and its capability gaps later in the process. The team identified some of the stakeholders, including PMA 263, the air vehicle operator (AVO), and the ground crew. The output from this step was a comprehensive list of stakeholders affected by the recovery system and a plan for communication with each stakeholder or group.

2. Requirements Generation

Requirements generation included the needs analysis and requirements analysis. In order to perform the requirements analysis, the team first identified the stakeholder needs. Through this analysis, the team identified the stakeholder priorities for the system, and whether the current system met them.

The needs analysis established updated requirements for the system. The resulting requirements were then considered for use as a criterion in the performance analysis within the AoA.

3. Guidelines for Decision-Making

This capstone project explored five different alternatives for an improved RQ-21A SRS. Since there are many factors influencing the benefits and costs of each recovery system, it was imperative to establish guidelines for deciding which alternative was best suited for the end application. This project adopted the guidelines for decision-making based on proven systems engineering concepts (Blanchard and Fabrycky 2011) (Air Force Office of Aerospace Studies 2016).

a. Performance Analysis

The performance analysis between the recovery systems was accomplished using a weighted method for decision-making. The summation of the weighted criteria produced a performance value for each recovery system. The performance values were combined with the cost of each recovery system to provide a value ranking.

b. Cost Analysis

The life-cycle cost of each recovery system was estimated; costs included research and development, investments in procurement, operating and support, and disposal cost. The final product of the analysis was a net present value of each recovery system, which was used in the final decision-making.

c. Risk Analysis

There was a risk that the system will not perform as expected or cost more than estimated because of the level of engineering judgement being used for the analysis. Therefore, risk was evaluated for use in the AoA. The output was a set of risk ratings (risk cube) used to inform the final conclusions.

4. Analysis of Alternatives

The AoA was the stage in which the performance, risk, and life cycle cost of each recovery system was analytically compared based on the established guidelines for decision-making. According to the *USAF AoA Handbook* (Air Force Office of Aerospace Studies 2016), “the purpose of the AoA is to help decision-makers understand the trade-space for new material solutions to satisfy an operational capability need.” In this project, there is a need for an adequate recovery system for the RQ-21A air vehicle that shall reduce the damage to the air vehicle upon capture, and enable an increased mean ground take-off weight (MTGOW). The AoA study plan and evaluation criteria were the inputs for this stage of the systems engineering process. As described in the previous chapter, the characteristics of each recovery system were used to evaluate the performance, risk, and life cycle cost of each alternative system. The outcome of the AoA is a preliminary recommendation to the stakeholders on the optimal recovery system alternative based on a performance rating, cost rating, and risk rating. This recommendation should be used to inform follow-on studies, and reduce the field of potential alternatives. The AoA is fully described in Chapters III and IV.

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II. REQUIREMENTS GENERATION

Requirements analysis is performed to determine the needs or conditions required to meet a stakeholder's desires. This analysis is critical to the success or failure of a system or project. The final list of requirements should be directly traceable to identified the stakeholder needs and sufficiently defined for system design.

The first step was to identify the stakeholders. Once complete, a list of questions for the stakeholders was developed. These questions were used to interview the stakeholders and understand their needs with respect to any currently existing system requirements. Table 2 lists the identified stakeholders and the organizations they belong to; all stakeholders were contacted for an interview.

Table 2. List of Identified Stakeholders.

Organization	Description
PMA-263	Acquisition agency responsible for fielding and supporting the RQ-21A System
Unmanned Aerial System Test Directorate (UASTD)	Agency responsible for conducting, monitoring, and evaluating UAS test events
Fleet Support Team (FST)	Field activity of the PMA responsible for supporting fleet usage of the RQ-21A
Fleet Users	End User for the RQ-21A

The questions used for interviewing the stakeholders and subsequent answers to the questions given by each stakeholder are contained in Appendix A. The stakeholders were queried as to the current deficiencies of the fielded system, required improvements, alternatives being considered, timelines for replacement, costs and more.

A. CONCEPT OF OPERATIONS

The USMC published a CONOPS for the USMC family of unmanned aircraft systems (FoUAS) outlining the missions and environments that future UASs are expected to operate in (Glueck and Davis 2014). The operational environment and mission

described for the RQ-21 (called the MQ-21 in the report) and UAVs of similar UAV class (group 2 and 3) informed the AoA.

The global presence of the United States and increasing globalization necessitates UASs that can be operated in practically every environment on Earth. Glueck and Davis also emphasized the concentration of population in the littoral regions. As a component of the overall UAS, the recovery system must be capable of operating in the same broad range of environments as the air vehicle.

The mission for the RQ-21A and similarly sized aircraft consists primarily of ISR. The USMC utilizes UASs for developing battlefield awareness for ground troops, especially expeditionary forces. For a UAS to be effective carrying out this mission, it has to be capable of persistent presence over the battlefield. A recovery system then must be able to capture a UAV designed to carry the fuel and payloads necessary for this mission, in close proximity to the where the UAV flies. In order to maintain persistent presence, the RQ-21A must be able to carry payloads up to 39 lbs, which include a communications relay package and EO/IR turret, and enough fuel for a minimum of 10 flight hours. (PMA-263 and PEO(U&W), 2012)

Chapter IV.III, of Glueck and Davis covers details of the RQ-21 system. It states: “The fully automatic launch and recovery system requires minimal space for takeoff and recovery from an unimproved expeditionary/urban environment or from the deck of an air capable ship.” Because of the requirement for operation on both ships and ground, the UAV must be able to be recovered on uneven terrain and moving (pitching) ships. The recovery system must also function in an area much smaller than similarly sized runway-dependent systems.

B. STAKEHOLDER SUMMARY

1. PMA 263

PMA 263 (Navy and Marine Corps STUAS) is the government agency dedicated to the cost, schedule, performance (CSP), overall system acquisition, and success of the RQ-21A and its sub-systems. The PMA also oversees all fleet related concerns and therefore when appropriate speaks for the fleet. Thus, PMA 263 was among the primary

stakeholders for the SRS AoA providing unique insight into key performance parameters, cost metrics, recovery system concepts, and expertise in the air vehicle and recovery system. PMA 263 has shown a vested interest in this SRS AoA, as an improvement in the recovery system can have far-reaching effects related to programmatic CSP (e.g., reduced cost to repair air vehicle damage, increased operational availability).

The full set of questions and answers from the stakeholder questionnaire with PMA 263 are summarized in Appendix A. Here are the most relevant responses from the stakeholder questionnaire that are summarized for consideration in the needs analysis:

- Several recovery systems are in the early stages of research and development; namely, 1) FLARES, 2) SideArm, and 3) VTOL, and 4) Net Capture.
- The primary issues with the RQ-21A are the limited capture envelopes (i.e., the air vehicle weight and speed upon capture), and the damage caused to the SRS and/or air vehicle during recovery.
- Damage to the recovery system and/or air vehicle can be caused by energy transferred from the bungee rope and hook during capture to the air vehicle.
- The recovery system needs to be able meet the fielding requirements of the SRS, which is 32 units.
- The recovery system should be incorporated with a “turn-table” design element.
- The alternative recovery system needs to have footprint similar in size to the baseline recovery system (SRS) in support of ship-board operation.

From the stakeholder statements, the basic needs of PMA 263 were determined, shown in Chapter II.C.

2. Unmanned Aerial Systems Test Directorate

The UASTD at Webster Outlying Field was contacted because of their experience with the precursor to the SRS (Skyhook) as well as the SRS itself. Although operation of the SRS had only begun at Webster Field in 2017, they have conducted several tests with the Marine Unmanned Aerial Squadrons (VMU-1, VMU-2) and their RQ-21A systems, including the SRS.

a. Test Engineering Team

While Webster Field had only had an SRS for a short period of time, the test engineers have observed its operation by both contractor and fleet operators. The test engineers noted a mishap aboard a ship during testing where the turret-mounted electro-optical and infrared was broken by a part of the SRS during capture.

They also noted that recovery system had a low success rate of capture during shipboard operations. They performed a series of simulated captures using a mobile platform with an SRS on August 5, 2017. The aircraft was given an altitude offset so that it flew above the SRS. The aircraft performed an automated wave-off or missed the capture rope 38 of the 58 of attempts, giving a success rate of 65% as claimed by Andrew Tkaczuk (Test Engineer, UASTD) in discussion with the author, September 23, 2017.

b. Maintenance Team

The maintainers noted that the most serious instances of air vehicle damage sustained during operation at Webster Field were control surfaces (such as ailerons or flaps) breaking or separating from the aircraft. In most cases, the control surfaces had to be replaced, although they were sometimes in good enough condition to be reattached.

They have not experienced any post-capture mast strikes, although they were aware of three occurring in the fleet: two during shipboard operation, and one with a land-based setup. They also noted that a recent “pull procedure” (where a ground crew member uses a rope-and-pulley system to lessen swinging of the air vehicle) implemented in the fleet has reduced the amount of rope wrap that commonly causes damage.

Their main concern was with the SRS itself. Because of the forces experienced during capture and past manufacturing defects, they were required to inspect the SRS boom after every capture. The inspection involves extending the boom horizontally after off-loading the air vehicle, inspecting weldments over the entire length for cracks, marking and measuring any cracks, and retracting the boom. This process takes approximately 15–20 minutes and requires a HMMWV (“Humvee”). Other regular inspections were required at various time intervals.

C. NEEDS ANALYSIS

The final step in the needs analysis was to review the current specification. The PBS for the RQ-21A was obtained from PMA-263. Chapter III of the PBS specifically highlights the RQ-21A performance requirements. The capstone team examined the key performance parameters (KPPs), and the performance requirements that were listed in Chapter III of the PBS, and determined which KPPs and performance requirements were relevant to the recovery system of the RQ-21A. These existing requirements and KPPs can be found in Appendix B. It was noted that there were reoccurring requirements throughout this document and the majority of these requirements could be separated in three categories. The following categories were determined to be of the most importance in accordance with the PBS and stakeholder’s survey: 1) Recovery, 2) Size and Transportability, and 3) Human and System Integration. They will be discussed in the following chapters.

1. Recovery

The most natural metric to evaluate the recovery systems was the ability to successfully recover the air vehicle. Here, these “needs” statements, which have been generated from the stakeholder questionnaire, discuss the desired recovery-related criteria for the recovery system.

The air vehicle and recovery systems are often deployed in areas with a high range of wind speeds, depending on the time of year and sea state.

- The stakeholders need the recovery system to capture the air vehicle within the wind envelopes specified for the baseline SRS in the RQ-21A PBS document (Program Executive Officer for Unmanned Aviation and Strike Weapons [PEO(U&W)] 2012). The relationship between wind speed and the recovery performance of the baseline SRS has not been specified.

The air vehicle occasionally needs to be captured immediately following its launch, for a variety reasons (malfunctioning flight control systems, or abort mission command). The baseline SRS is incapable of capturing the air vehicle immediately following launch because the weight of the vehicle, including a full tank of fuel, is over the designed capture weight.

- The stakeholders need a recovery system to be capable of capturing the air vehicle immediately following launch, regardless of the weight of fuel onboard the air vehicle.

Whether deployed at sea, or land, the SRS is required to perform recovery of the air vehicle on grades of land within the limits specified in the RQ-21A PBS (PEO(U&W) 2012). This is critical to the performance of the SRS because extreme sea states and non-level terrain are frequently encountered by the Navy and Marine Corp.

- The stakeholders need the recovery system to operate within the grade limits specified in the PBS.

The SRS has several deployment modes, whether hitched to the back of a land vehicle or carried by foot soldiers.

- The stakeholders need the recovery system to meet the mounting requirements specified in the RQ-21A PBS, so that it could be deployed with or without a land vehicle (PEO(U&W) 2012).

The air vehicle may approach the SRS from a variety of angles, and the situation has arisen where the air vehicle could not be captured and was waved-off for another recovery attempt because the SRS is stationary. If a pivot mechanism were integrated into the SRS, the issue would be mitigated.

- The stakeholders need the recovery system to be capable of a multi-directional capture mechanism, such as a turn-table, which enables the air vehicle to be captured from a variety of approach angles.

The successful capture rate of the SRS was a need that originated from discussions with the test engineering team. In the test engineering team's operation of the system, they noted that SRS system had a low success rate of capture during shipboard operations. This was a concern for them and was included as a secondary need.

2. Size and Transportability

The size of the recovery system is limited due to the availability of transportation equipment. Because of this, there is already a requirement in the PBS that the recovery system have the appropriate dimensions and weight so that it can be transported via HMMWV. This includes towing of the recovery system. Additionally, some stakeholders identified a benefit to decreasing the size and weight of the recovery system for programmatic and operational reasons. Below is a list of the needs derived from stakeholder input and existing requirements.

- The recovery system needs to have a minimal operational footprint (smaller is better).
- The recovery system needs to be transportable with a single HMMWV (or similar vehicle).
- The recovery system needs to be assembled, and disassembled, in 45 minutes, or less, by at most 10 personnel with the knowledge, skills, and abilities that already exist in the USN and USMC, and/or that are currently used on the legacy SRS (Threshold = Objective).

3. Human and System Integration

The recovery system shall be similar in size, shape, material, and function as the current capabilities; the level of skill to operate the SRS should not change.

- The recovery system needs to be lifted by a two-man crew.

- The crew needs to have the knowledge, skills, and abilities that exist in the USN and USMC.

D. REQUIREMENTS

Stakeholder discussion summaries, and questions and answers, is shown in Chapter II.B.I, and Appendix A. The above needs and concerns were transformed into the following eight requirements.

1. Recovery

a. Wind Conditions (Wind over Deck)

The recovery system shall be capable of capturing the RQ-21A air vehicle within the wind envelopes specified for land-based SRS, shown in Figure 7, and ship-based SRS, shown in Figure 8. This requirement has been derived from the wind envelopes specified in the RQ-21A PBS (PEO(U&W) 2012). Accordingly, for the recovery system shipboard wind envelopes, all wind values refer to “relative winds, or Wind over Deck (WOD), which are the result of natural winds plus ship-motion-created winds” (PEO(U&W) 2012). This requirement was taken from the existing SRS specification.

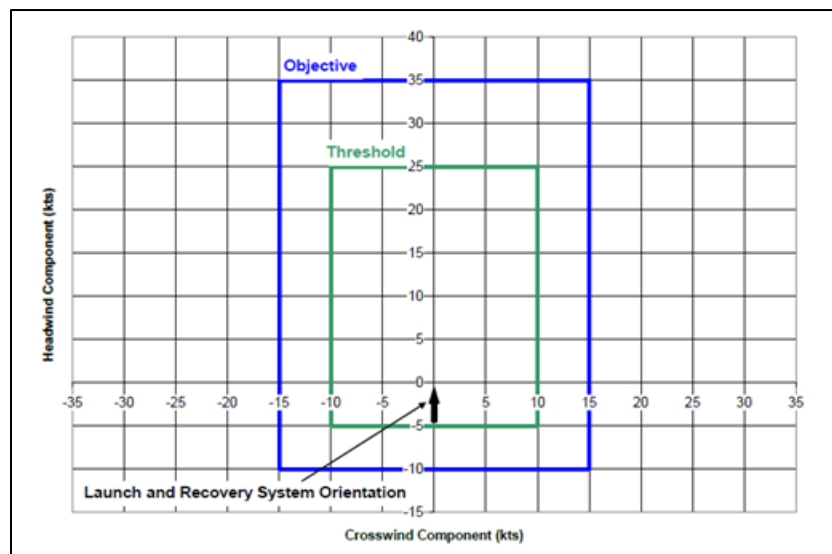


Figure 7. Land-Based Launch and Recovery Wind Envelopes. Source: RQ-21A PBS PEO (U&W) (2012).

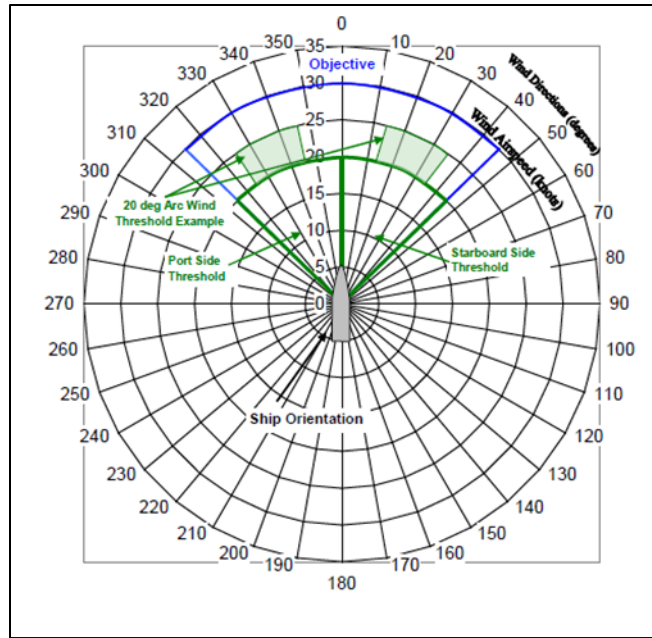


Figure 8. Ship-based Launch and Recovery Wind Envelopes, Source: PEO (U&W) (2012).

b. Immediate Capture After Launch

The recovery system shall be capable of capturing the air vehicle immediately following the air vehicle launch, at which time the air vehicle shall have a maximum gross take-off weight (MGTOW) of 135 lbs / 185 lbs as an objective. The team derived this requirement from stakeholder needs.

c. Capture Rate

The recovery system shall have a safe (no-damage) capture rate of 95% as a threshold. This requirement was also derived from stakeholder needs.

d. Shock Absorption

The recovery system shall have sufficient shock absorption to safely capture the air vehicle at upwards of 22.3kJ (based on 125 lbs. aircraft weight at 28 m/s capture speed) as a threshold. The recovery system shall have sufficient shock absorption to safely capture the air vehicle at upwards of 24kJ (based on 135lb aircraft weight at 28 m/s capture speed) as an objective. This requirement was derived from stakeholder needs.

e. Grade of Land Required (Land and Shipboard)

The recovery system shall be “capable of successfully...recovering the air vehicle during combined maximum ship motions of +3 degrees to -3 degrees of pitch and +5 degrees to -5 degrees of roll” as the threshold values and “+5 degrees to -5 degrees of pitch and +8 degrees to -8 degrees of roll” as the objective values (PEO(U&W) 2012). This requirement was taken from the existing SRS specification.

2. Size and Transportability

a. Grade of Land Required

The recovery system shall be “designed to enter (approach), negotiate (up or down), and leave (depart) a solid surface (i.e., one (1) piece) ramp having a slope of 20 degrees,” according to the requirements for the baseline SRS specified in the RQ-21A PBS (PEO(U&W) 2012). This value will be used as the threshold.

3. Human and System Integration

a. Personnel Support

Any recovery system that is not mounted on wheels shall be capable of two-man lift, according to the RQ-21A PBS (PEO(U&W) 2012). This value will be used as the threshold.

b. Recovery Envelope

The recovery system shall incorporate a turn-table mechanism to expand the recovery envelop of the recovery system from any orientation within 360° of its center vertical axis. This value will be used as a threshold and was derived by the team from stakeholders needs.

III. ANALYSIS OF ALTERNATIVES OVERVIEW

A. OVERVIEW

The AoA process aimed to systematically eliminate non-viable alternatives, and rate the remaining alternatives by performance, cost, and risk. No systems were deemed technically infeasible in relation to the SRS. All alternatives were considered viable and included in the performance, cost, and risk analyses. A description of each alternative recovery system was covered in Chapter I.3.b, and is summarized below.

1. **RQ-21A SRS** – The current system.
2. **FLARES** – A hypothetical system based on the Insitu system of the same name which uses a multi-copter to suspend a rope attached to the ground. Captures aircraft in a similar manner to the SRS.
3. **VTOL** – A hypothetical system based on to the Arcturus JUMP 20 VTOL system. Attached to air vehicle lift aircraft to launch altitude and lower aircraft for landing.
4. **Net Capture** – An existing system which uses a net that the aircraft flies into in order to capture.
5. **SideArm** – A prototype system which uses a crane to suspend a device similar to an inverted arresting gear.

B. CRITERIA SELECTION AND WEIGHTING

1. Criteria Selection

In order to screen the alternatives, a performance analysis was conducted. The list of requirements to be used as criteria in the performance analysis decision matrix was established to make the most effective use of the limited resources and data available to the team. The team accomplished this reduction by filtering potential criteria (requirements) based on three attributes: pass/fail, unique/distinct, and derivable data.

These attributes were meant to identify criteria that could discriminate between the recovery systems with the data available or derivable by the team. Table 3 lists how each requirement was rated against the attributes below.

a. *Pass/Fail Criteria*

Some requirements identified by the team were binary, where a system would either satisfy the requirement or not. In these cases, there was no way to exceed the requirement, and failure would not be acceptable. Since an alternative must pass the requirement to be a viable system, these would not be useful for comparing recovery systems. All the systems being evaluated passed these criteria and none were eliminated.

b. *Distinct Criteria*

On several occasions, the stakeholder needs were translated into overlapping requirements. However, there were other requirements that appear different, but are dependent on each other. For instance, the requirements for operational availability and damage on capture are similar. The frequency and severity of damage to the aircraft on capture directly affects operational availability of the system. If requirements are dependent on each other or closely related, then the set will only be addressed by a single criterion. Discussion of requirements consolidation appears in Table 3.

c. *Derivable Data*

Many of the systems evaluated contained proprietary data, were not specifically designed for the RQ-21A, or were not designed for UASs similar to the RQ-21A in size. Performance data on such systems could not be obtained over the duration of this project with the resources available. Therefore, the team had to estimate performance data in order for the team to include some criteria in the performance analysis. The criteria selected required enough available data to estimate each alternative's performance for an RQ-21A-sized aircraft.

2. Chosen Criteria

The eight requirements derived in Chapter II.D, were evaluated against the desired attributes discussed above. Table 3 shows all the requirements, and indicates which attributes each requirement passed. The numbering for each requirements corresponds to the designation from Chapter II.D, of this report.

Table 3. Criteria Selection Breakdown

#	Requirement	Pass/Fail	Distinct	Derivable
1.a	Wind Over Deck	X	X	
1.b	Capture After Launch	X	X	X
1.c	Capture Damage	X	X	X
1.d	Capture Weight/Energy	X	X	X
1.e	Grade of Land (Recovery)	X	X	X
2.a	Grade of Land (Transport)	X		X
3.a	Two-Man Lift		X	X
3.b	Approach Envelope	X	X	X

Requirements 2.a and 3.a, “Grade of Land (Transport)” and “Two-Man Lift,” did not pass all three attributes and hence did not pass as individual requirements. However, requirements 2.a and 3.a, were combined to create a single criterion named “Footprint,” which meets all three attributes and will be used as a requirement going forward. “Turntable” was derived from a suggestion by a stakeholder, but it was very narrow and prescriptive. The intent of the stakeholder was to increase the angle that the UAV could approach the recovery system, so this was changed to “Approach Envelope.” “Grade of Land (Recover)” was also changed to “Grade/Sea State” since the recovery system would also be used on ships. Table 4 reflects these changes.

Table 4. Selected Criteria.

#	Requirement	Selected	Pass/Fail	Distinct	Derivable
1.b	Capture After Launch	Y	X	X	X
1.c	Capture Damage	Y	X	X	X
1.d	Capture Weight/Energy	Y	X	X	X
1.e	Grade/Sea State	Y	X	X	X
2.a & 3.a	Footprint	Y	X	X	X
3.b	Approach Envelope	Y	X	X	X

The criteria listed in Table 4 will be utilized for the alternative system performance evaluation. The team consulted the stakeholders during an interim review and they concurred with the use of these criteria.

3. Criteria Weighting

Once the criteria were selected, they were weighted by importance. An abbreviated pairwise comparison was used by the team members to assign criteria importance weighting. Stakeholder concurrence with the team's weights was obtained at the first interim progress review.

Criteria were rated against each other on a scale ranging from "Absolutely More Important" (seven times as important) to "Absolutely Less Important" (1/7 as important). The capstone team chose to use seven divisions on the scale to make the survey easy and intuitive.

The pairwise comparison, shown in Figure 9, was laid out in a grid with rows of criteria being compared. The criterion used to compare all of the other criteria was system footprint, which was rated in importance to each of the other criteria. Only five comparisons were made, and only footprint was paired with any other criteria.

Rate the importance of "Footprint" compared to the following criteria in regards to system performance.

	Absolutely More Important (7)	Much More Important (5)	More Important (3)	About Equally Important (1)	Less Important (1/3)	Much Less Important (1/5)	Absolutely Less Important (1/7)
Capture Weight/ Energy is...	☐	☐	☐	☐	☐	☐	☐
Capture Damage is...	☐	☐	☐	☐	☐	☐	☐
% Grade / Sea State is...	☐	☐	☐	☐	☐	☐	☐
Capture after Launch is...	☐	☐	☐	☐	☐	☐	☐
Approach Envelope is...	☐	☐	☐	☐	☐	☐	☐

Figure 9. Example of Pairwise Comparison Survey.

First, the responses from the team member survey in Figure 9 were inverted (for example “7” was changed to “1/7”). Then, the responses to the survey were tabulated and averaged, shown in Table 5. Next, the weights were calculated, shown in Table 6.

Table 5. Tabulated and Average Comparison Responses.

Footprint/ Criteria Importance ratio	Footprint	Weight / Energy	Damage	% Grade / Sea State	Capture After Launch	Approach Envelope
Participant 1	1	1/7	1/7	3	1	3
Participant 2	1	1/7	1/7	3	1	3
Participant 3	1	1/5	1/3	1	1	3
Participant 4	1	1/5	1/7	1	1/3	3
Participant 5	1	1/3	1/7	1	1/3	3
Participant 6	1	1/7	1/5	1/3	1/7	3
Participant 7	1	1/3	1/5	1	1/3	3
Participant 8	1	1/5	1/7	3	1/3	3
Average	1.00	0.21	0.18	1.67	0.56	3.00

The responses from team members were averaged before calculating the requirement weights, shown in Table 6. The top row of values correlates to the survey responses, while the leftmost column are their inverses. Each criterion weight is calculated by simply dividing each criterion's inverse by the sum of all the inverse values. The weights for each requirement were used in the performance analysis to create a weighted average score that takes into account each requirement's relative importance to the system's suitability.

Table 6. Criteria Weighting Calculations.

		Criteria #	Footprint	Weight / Energy	Damage	% Grade / Sea State	Capture after Launch	Approach Envelope
Criteria #		1	2	3	4	5	6	Weights
Footprint	1	1.00	0.21	0.18	1.67	0.56	3.00	0.072
Weight / Energy	2	4.70	1.00	0.85	7.84	2.61	14.11	0.34
Damage	3	5.53	1.18	1.00	9.21	3.07	16.58	0.40
% Grade / Sea State	4	0.60	0.13	0.11	1.00	0.33	1.80	0.043
Capture after Launch	5	1.80	0.38	0.33	3.00	1.00	5.40	0.13
Approach Envelope	6	0.33	0.07	0.06	0.56	0.19	1.00	0.024

IV. ANALYSIS OF ALTERNATIVES

A. PERFORMANCE ANALYSIS

This chapter highlights the methodology used and results of the performance analysis for the RQ-21A SRS AoA.

The first step in conducting the performance analysis was to gather technical data on the six chosen requirements for the RQ-21A SRS, and the alternative recovery systems. Performance data for the RQ-21A Mark 4 launcher and the RQ-21A SRS was used to create a baseline (in terms of performance) with which to compare the proposed recovery systems. Comparison is done by dividing the value for the system by the control value, which is based on the either maximum or minimum value for that requirement. Each calculation is shown in tables below the discussion. For those criteria which had no available data, such as the damage reduction criteria, values were estimated based on the performance of similar systems. The criteria chosen in Chapter III.C, above are listed here, and will be discussed in more detail below. Values listed in parenthesis represent the threshold for that criterion:

- System footprint (less than the SRS value of 207.3 square feet)
- Capture weight (at least 135 pounds)
- Damage (less than the SRS value of 5.38 Gs(G-force))
- Percent grade/sea state (more than the SRS value of 5 degrees)
- Capture after launch (less than the SRS value of 5 minutes)
- Approach envelope (more than the SRS value of 20 degrees)

1. Size and Footprint

Three of the recovery systems also function as launch systems, and thus do not have the RQ-21 launch system footprint included in the total for that system. The recovery systems that require the Mark 4 launcher (RQ-21A SRS and Net Capture) had

the launcher and recovery system square footage included in their footprint values. A smaller recovery system footprint is preferred.

The RQ-21A SRS stowed footprint is 15.3 feet by 5.1 feet, and the launcher's footprint is 17.83 feet by 7.25 feet. Therefore, the total footprint of the RQ-21A SRS is 207.3 square feet.

The FLARES is a quadcopter system that ships in six crates. Each crate measures 6.75 feet by 2 feet. The FLARES functions as both launch and the recovery, so a launcher was not included in the footprint value. The footprint of the FLARES is 81 square feet.

The VTOL system would require substantial airframe modifications, which were not accounted for in this AoA. If this system is chosen for further consideration, it is recommended that the stakeholders evaluate the extent of these modifications. Since the VTOL is part of the air vehicle, there is effectively no recovery system footprint. The footprint of the VTOL was recorded as zero square feet.

The Net Capture system was estimated to have a stowed footprint consisting of two crates sized five feet by two feet. Since the net system does not function as a launch system, the footprint of the Mark 4 launcher was added. This makes the footprint of the Net Capture system 149.3 square feet.

The SideArm is designed to fit in an ISO standard 20-foot shipping container and functions as both a launch and recovery system. Though the SideArm is designed to recover substantially larger air vehicles, the decision was made not to adjust the size of the system for purposes of this AoA. Reducing its dimensions would negate the interoperability of the SideArm system. The SideArm system's stowed footprint is 20 feet by 8 feet, totaling 160 square feet. Table 7 shows the relative footprint values of each recovery system.

Table 7. Recovery System Footprint Values (Smaller is Better).

	RQ-21A SRS	FLARES	VTOL	Net Capture	SideArm	Control (SRS)
Value (ft ²)	207.3	81	0	149.3	160	207.3

2. Recovery Weight

The RQ-21A is intended to have a maximum takeoff weight of 135 lbs. Presently, the RQ-21A takeoff weight is restricted by the maximum recovery weight of the SRS (125 lbs), making the SRS unsuitable for use for a 135-lb item. The 135-lb threshold takeoff weight was used as the control value for this criterion. A higher recovery weight is preferred.

The FLARES is designed for the smaller ScanEagle air vehicle, which weighs 49 lbs. To account for the larger RQ-21A, the lift capability needs to be increased. Since design data for an upgraded FLARES vehicle was not available, the performance value of a similar system (VTOL) was used. The VTOL system is an electric propeller-driven air vehicle of similar size to that of the anticipated upgraded FLARES. The estimated recovery weight of the upgraded FLARES is 210 lbs (per VTOL specifications).

The VTOL is of comparable size and weight to the RQ-21A. The VTOL is capable of taking off and landing at 210 lbs, and this value was used as the recovery weight value.

The recovery weight of the Net Capture SRS currently used by the RQ-2 air vehicle is 392 lbs. The RQ-2 is of comparable size to the RQ-21A. The Net Capture recovery weight will remain 392 lbs. Similarly, the SideArm has been recorded recovering 400 lbs. Table 8 shows the relative recovery weight scores of each alternative.

Table 8. Recovery Weight Values (Larger is Better).

	RQ-21A SRS	FLARES	VTOL	Net Capture	SideArm	Control (Threshold)
Value (lbs)	125	210	210	392	400	400

3. Damage Reduction (Force)

The most highly weighted evaluation criterion was damage reduction. Air vehicle damage was not attributed to the impact experienced by the air vehicle, but rather the forces exerted on the air vehicle during recovery, that is: force is used as a proxy for damage reduction in the performance calculations. These high forces are a result of the abrupt halt experienced by the RQ-21A. Table 8 shows the stopping forces the air vehicle experiences when being captured by each recovery system (assuming equal speeds and estimated stopping distance for each system). The unit of measurement most aviation-minded readers are accustomed to is G-force (Gs), or the force due to gravity. It is used to communicate the values of negative acceleration for each recovery system. To calculate the forces experienced during capture, stopping distance and an assumed capture speed of 40 mph were used in a standard deceleration equation. A larger stopping distance and therefore, lower negative acceleration, is preferred.

Continuing to use the RQ-21A SRS will provide no damage reduction. The force experienced by the RQ-21A when using the SRS was estimated to be 5.38 Gs and is set as the control value. The FLARES has an estimated stopping distance of 15 feet. Assuming a capture speed of 40 mph, the negative acceleration forces were calculated as 3.59 Gs. The VTOL is part of the air vehicle and therefore the air vehicle does not experience any substantial horizontal forces during recovery. Negative acceleration forces for the VTOL system were estimated as 1.10 Gs. The Net Capture recovery system has an estimated stopping distance of 10 feet. Negative acceleration forces were calculated as 5.38 Gs. For the SideArm, stopping distance is approximately 30 feet. Negative acceleration forces were calculated as 1.79 Gs.

Table 9 shows the relative damage reduction scores (forces) of each recovery system.

Table 9. Damage Reduction Values (Force) (Smaller is Better).

	RQ-21A SRS	FLARES	VTOL	Net Capture	SideArm	Control (SRS)
Value (Gs)	5.38	3.59	1.10	5.38	1.79	5.38

4. Land Grade / Sea State

The FLARES and VTOL are airborne recovery systems and therefore can hover above any grade of land or sea state. To quantify the allowable land grade/sea state for these two systems, the land grade/sea state of the steepest terrain the systems might hover above was used. It was estimated that the average slope of a mountain is 60 degrees. Using the steepest-slope logic, the value for the FLARES and VTOL was recorded as 60 degrees. The Net Capture recovery systems allowable land grade/sea state is the grade at which the net can safely stand and recover the 15.7-foot wingspan of the RQ-21A, and was estimated to be 45 degrees. The remaining estimated land grade/sea states for each recovery system are shown in Table 10. A larger land grade/sea state is preferred.

Table 10. Land Grade/Sea State Values (Larger is Better).

	RQ-21A SRS	FLARES	VTOL	Net Capture	SideArm	Control (FLARES/VTOL)
Value (deg)	5	60	60	45	10	60

5. Capture after Launch

To evaluate the recovery systems ability to capture an air vehicle immediately after launch, the time required to setup for recovery for each alternative was compared. A shorter time to capture after launch is preferred. In order to simulate a worst case (longest time) situation, the assumptions for this criterion are as follows:

- An air vehicle was recovered just prior to the launch of the subject air vehicle and, if possible, remains on the recovery system.
- The subject air vehicle is at maximum takeoff weight.

This criterion represents the number of minutes it takes to prepare a recovery system for recovery of an air vehicle. The RQ-21A SRS cannot recover an air vehicle at maximum takeoff weight and requires the air vehicle to circle above the system for an estimated five minutes to burn enough fuel to arrive within the allowable weight limit.

The FLARES vehicle, after launching the RQ-21A air vehicle, must return to the ground to allow for the attachment of the recovery cable, and then regain altitude before recovering the air vehicle. This process was estimated to take 2 minutes.

The VTOL is part of the air vehicle and is ready for recovery at any moment after launch. For this reason, the time required to prepare the VTOL recovery system is 0 minutes.

The Net Capture recovery system requires the removal of any previously recovered air vehicles prior to the recovery of another. It was estimated to take approximately 2.5 minutes to remove an air vehicle from the net and prepare for the next recovery.

The SideArm is used for launch and requires the connection of an adapter prior to recovery. It takes 48 seconds (0.8 minutes) to maneuver the arm, connect the adapter, and reposition the arm for recovery. Table 11 shows the relative time to capture after launch for each recovery system.

Table 11. Time to Capture After Launch (Smaller is Better).

	RQ-21A SRS	FLARES	VTOL	Net Capture	SideArm	Control (SRS)
Value (min)	5	2	0	2.5	0.8	5

6. Approach Envelope

The FLARES can approach from any direction, and therefore has a lateral approach envelope of 360 degrees. The VTOL would be part of the RQ-21A air vehicle, and for analysis purposes has a lateral approach envelope of 360 degrees. The remaining lateral approach envelopes for each recovery system are shown in Table 12. A larger lateral approach envelope is preferred.

Table 12. Lateral Approach Envelope Values.

	RQ-21A SRS	FLARES	VTOL	Net Capture	SideArm	Control (FLARES/VTOL)
Value (deg)	20	360	360	20	10	360

7. Analysis and Results

Criteria values in tables 7–12 were normalized so they could become unit-less values that could be summed and used to compare alternatives. This was done by dividing the values in each table by the control values which were the largest values obtained. In the cases where a smaller value was better (footprint, damage, capture time), the value was subtracted from 1 so that the normalized table always represents that a better performing system has a larger value.

For the grade and approach envelope criterion, the best-case value was used as the control. RQ-21A SRS values were set as the control for footprint, damage reduction, and capture after launch. For takeoff weight, the RQ-21A SRS did not meet the original required threshold value, hence, the threshold value was used as the control. Since the RQ-21A SRS did not meet the threshold value, it was assessed a score of zero for the weight criterion.

After computing the normalized ratios (scores), the criteria importance weights (gained from team pairwise comparisons) were added, and each score value was multiplied by the weight of that particular criterion. Finally, the sum of all weighted score values for each recovery system was computed. The computed scores indicate which recovery system has the best performance. The performance analysis table, found in Appendix C, shows all values used in the performance analysis, including original recovery system performance, performance adjustments, and score values.

Table 13 shows the score values, criteria weights derived previously (Table 5), and the combination of the two weighted score values. Using the score values in Table 13, the recovery systems were ordered from highest to lowest (highest being the best).

Table 13. Performance Data Values and Weighting.

<i>Criteria Values</i>	RQ-21A SRS	FLARES	VTOL	Net Capture	SideArm		
Footprint	207.3	81.0	0.0	149.3	160.0		
Weight	125	210	210	392	400		
Damage (G reduction)	5.38	3.59	1.10	5.38	1.79		
Grade/Sea State	5	60	60	45	10		
Capture after Launch	5.0	2.0	0.0	2.5	0.8		
Approach Envelope	20	360	360	20	10		
<i>Normalized Values</i>	RQ-21A SRS	FLARES	VTOL	Net Capture	SideArm	WEIGHTS	Rank of Weights
Footprint	0.000	0.609	1.000	0.280	0.228	0.072	4
Weight	0.000	0.286	0.286	0.970	1.000	0.340	2
Damage (G reduction)	0.000	0.419	1.000	0.000	0.838	0.400	1
Grade/Sea State	0.083	1.000	1.000	0.750	0.167	0.043	5
Capture after Launch	0.000	0.600	1.000	0.500	0.840	0.130	3
Approach Envelope	0.056	1.000	1.000	0.056	0.028	0.024	6
<i>Weighted Data</i>							
Footprint	0.000	0.044	0.072	0.020	0.016		
Weight	0.000	0.097	0.097	0.330	0.340		
Damage (G reduction)	0.000	0.168	0.400	0.000	0.335		
Grade/Sea State	0.004	0.043	0.043	0.032	0.007		
Capture after Launch	0.000	0.078	0.130	0.065	0.109		
Approach Envelope	0.001	0.024	0.024	0.001	0.001		
<i>Sum:</i>	0.005	0.453	0.766	0.448	0.809		
	SRS	FLARES	VTOL	Net Capture	SideArm		
<i>Rank:</i>	5	3	2	4	1		

8. Sensitivity Analysis

Due to the amount of derived data used in the performance assessment, an analysis was performed to assess the relative sensitivity of individual criterion weights to

the end result of the performance analysis. This analysis gauged how easily the performance analysis was effected by the criteria weighting process.

The analysis was accomplished by setting the weight of each criterion to 1.0 so that 100 percent of the final score is derived from that one criterion. This creates two points for each recovery system from which to perform a linear regression. A summary of the analysis results is shown in Figure 10, and the detailed charts are in Appendix D.

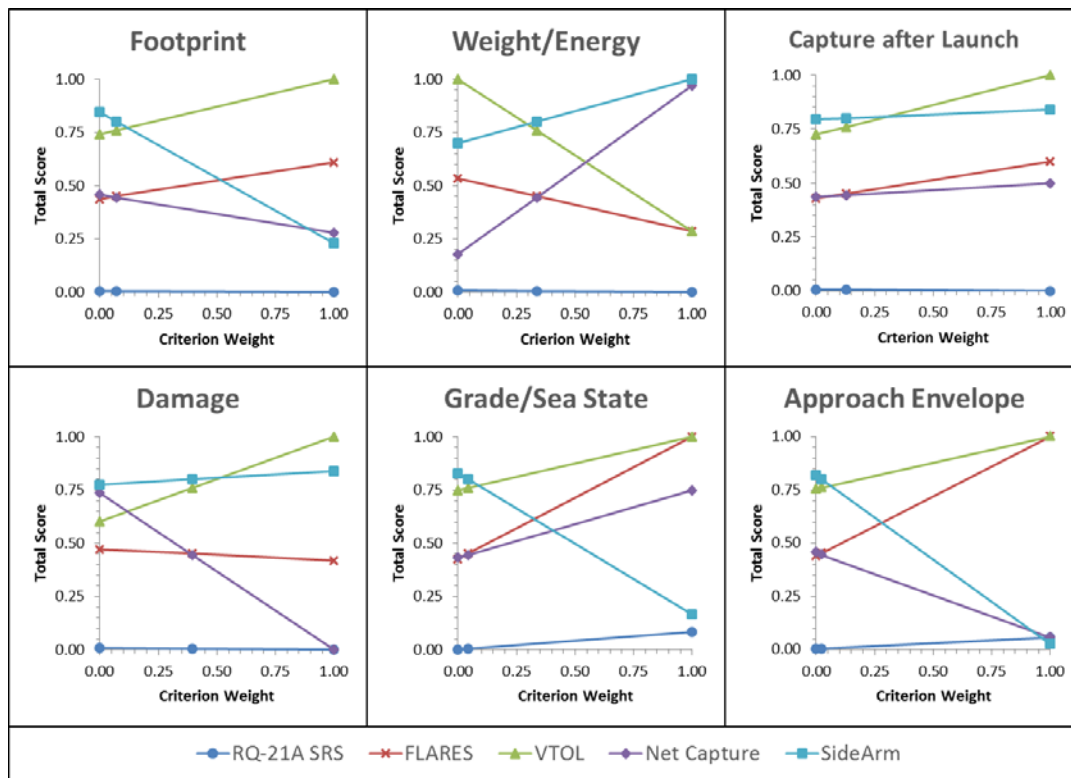


Figure 10. Sensitivity Analysis.

As many of the criterion have the top performing systems change close to the criterion weight, having accurate data and weights is very important. This is especially true for damage and capture weight data, which the team had difficulty obtaining, as these were rated as the two most important criteria. The most notable examples are Net Captures increase in the weight/energy chart, and decrease in the damage chart. While changes in weights are not likely to affect the final result, changes in the performance

data might. Gathering more complete and accurate data is recommended before making a final decision based on this AoA. A more detailed summary of the sensitivities follows.

a. *Footprint*

SideArm dropped to second place after only a slight change in criterion weight. However, after that, the top two (VTOL and SideArm) remained until Footprint accounts for about 50 percent of the total score. Since Weight/Energy and Damage were deemed so important to system performance, it would be very unlikely that Footprint could change enough to significantly affect the end result.

b. *Weight/Energy*

Weight/Energy already made up a significant portion of the performance analysis, and the total scores changed significantly as that portion changed. It took an increase of weight of about 0.15 to change the result at all. Because SideArm and VTOL had such close total scores, it only took a small decrease in criterion weight for them to switch places. However, they remained in the top two for any weight less than the original of 33.7%.

Weight/Energy was one of the more difficult criteria to measure due to the lack of complete test data available to the team. While the total scores did not seem very sensitive to the criteria weight, it was more sensitive to the actual performance of the systems.

c. *Capture after Launch*

All alternatives shared a positive correlation with the Capture After Launch criterion, but they all were small. An increase of about 0.2 would be required to see any change in the final result, and no decrease would be able to make a difference. It is unlikely that this criteria weight could increase enough for this to happen.

d. *Damage*

Damage was the other major contributor to the total score, and the total score was less sensitive to this criteria. It would take an increase or decrease of 0.2 to change the

final outcome. Both of these scenarios would be unlikely due to both its importance to system performance and the importance of the other criteria (especially Weight/Energy)

e. Grade/Sea State

Like Footprint, only a small change in Grade/Sea State was needed to have the top two swap places. A much larger change was needed to make a significant difference to the total score. This criterion would have to change from one of the least to one of the most important criteria to affect the final outcome.

f. Approach Envelope

Approach Envelope was similar to Footprint and Grade/Sea State. It would also have to change to significantly impact the final outcome, which is just as improbable.

B. COST ANALYSIS

Cost-effectiveness is another component of the AoA process. A cost analysis was performed on each recovery system. This chapter covers the methodology used in creating and comparing the cost of each of the recovery systems. When looking at the cost criteria, the main comparison used was life-cycle cost (LCC). The LCC was broken into research and development (R&D), procurement and operations and support (O&S) costs. For procurement, it was assumed that 33 total recovery systems would be acquired. This included 31 operational systems and two spare systems with each system containing five RQ-21A air vehicles.

Cost estimates were built using historical data, build-ups, analogous systems and cost projections for each recovery system. Factors were used to adjust for the capability, complexity and scaling differences between the recovery systems. Engineering judgement was used for a majority of these adjustments. A detailed cost estimate break out for each recovery system is provided in Appendix E.

1. Constraints / Limitations

There were constraints and limitations for the cost analysis. Some of the proposed recovery systems were in the development phase, and/or the availability of cost data

could not be obtained over the course of this project. The FLARES and VTOL cost data is proprietary and/or competition sensitive. The SideArm program information was limited because it was in the early stages of development and testing. However, cost data was available for the RQ-21A SRS (historical parts pricing, contract data, & subject matter expert estimates). The VTOL Wing Upgrade Kit feasibility study created for the RQ-21A system is also available. Due to the limited amounts of cost data, the cost-effectiveness of the AoA is a general rough order of magnitude comparison of the proposed recovery systems.

2. Calculations

a. VTOL

The cost estimate for using a VTOL recovery method was based on a feasibility study that was performed for the RQ-21A. This feasibility study, “RQ-21A Blackjack Launch and Recovery Equipment Upgrade,” was performed on developing and producing a VTOL wing upgrade kit for the RQ-21A, and the effect it would have on reducing maintenance costs. According to the feasibility study; “approximately 90% of the composite damage attributed to air vehicle recovery will be eliminated by using a VTOL kit,” and “avionics repairables will see a demand decrease of ~15% due to reduced impact loads on sensitive electronics” (PMA-263 2017). The study used RQ-21A aviation depot level repairable (AVDLR) and aviation fleet maintenance (AFM) funds to determine the possible life-cycle maintenance cost savings, which they determined to be 33%. The AVDLR and AFM fund profile from the feasibility study is shown in Table 14. This method for calculating the life-cycle maintenance cost savings was used for the remaining recovery systems. A linear factor was used to correlate the damage reduction (90%) to the reduction in life-cycle maintenance cost (33%), as shown in Figure 11.

Table 14. Total: \$1,034.1M, RQ-21A Blackjack Launch and Recovery Equipment Upgrade AVDLR and AFM Fund Profile.

“As is”	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
AVDLR (\$M)	25.2	35.0	36.5	37.5	38.6	39.6	40.6	41.6	42.6	43.6	44.6	45.6	46.6
AFM (\$M)	25.4	35.0	36.5	37.5	38.5	39.6	40.6	40.6	42.6	43.6	44.6	45.6	46.6

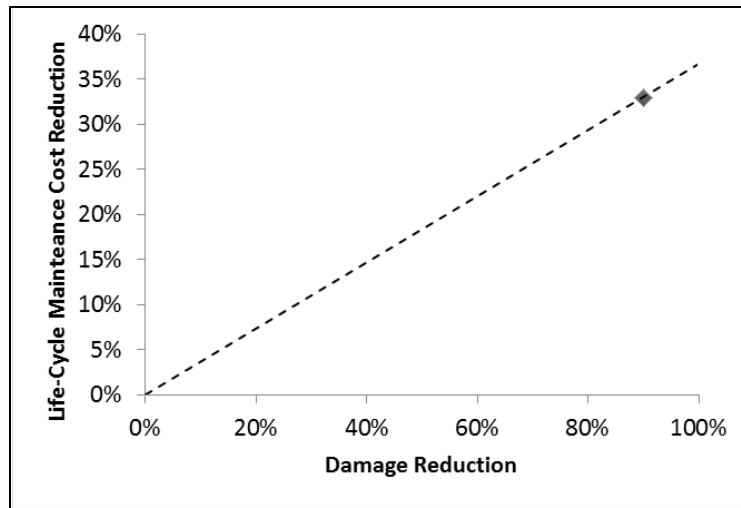


Figure 11. Damage Reduction Maintenance Savings Factors.

The RQ-21A SRS feasibility study included contractor labor and materials for development. The feasibility study used subject matter expert rough order of magnitude (ROM) estimates for ship integration costs, developing the take-off stands for the VTOL, software modifications; as well as Rockwell and Quattro Composites portions for structural and navigation modifications to the RQ-21A. Prototype costs included three RQ-21A air vehicles (~\$900K each), for a total of \$2.9M. Testing costs were estimated to be \$2.7M, and included land and sea development and operational tests. The estimate total for R&D was approximately \$18.2M, shown in Table 15.

The VTOL kit from the feasibility study was approximately \$200K. The 155 operational kits (31 systems) and 64 spare kits (two spare systems) procurement costs are estimated to be \$47.1M, shown in Table 15.

From the feasibility study it was determined that a 90% reduction in composite damage would result in a 33% reduction in life cycle maintenance costs. The savings for AVDLR and AFM are approximately \$170.8M and \$170.5M, respectively. The total AVDLR and AFM savings would reduce the funding to \$692.9M, shown in Table 15. The total life-cycle estimate for the VTOL is approximately \$758.1M.

Table 15. VTOL Cost Estimate.

Development/ including Takeoff Stands, SE for Ship Integration & Tech Pubs	\$ 5.1 M
Prototypes	\$ 2.9 M
Rockwell	\$ 1.3 M
Quattro	\$ 5.2 M
Test	\$ 2.7 M
Software	\$ 1.1 M
R&D	\$ 18.2 M
Procurement	\$ 47.1 M
AVDLR	\$ 517.5 M
Damage Reduction Savings	- \$ 170.8 M
AFM	\$ 516.6 M
Damage Reduction Savings	- \$ 170.5 M
O&S Total	\$ 692.9 M
Total	\$ 758.1 M

b. FLARES

The RQ-21A SRS feasibility study was used as an analogy to the FLARES. Due to the complexities in FLARES versus a traditional VTOL kit, along with the increased size of the RQ-21A versus the SCANEAGLE (which FLARES was originally designed for) factors were applied to some of the development cost estimates. These factors affected contractor labor and materials, ship integration costs, software modifications; as

well as Rockwell and Quattro composites portions of the structural and navigation modifications. Prototype costs were assumed to equal production unit costs; and it was assumed that three prototypes would be acquired. The estimated total R&D costs are approximately \$33.1M, shown in Table 16.

Using subject matter expert (SME) advice, a cost build up for the FLARES was developed. This build up included 8 motors, along with their controllers, radios, battery, recovery rope, and the composite materials required for the frame. The composite was estimated using composite parts from the RQ-21A, and included a size factor (3.0). To support 31 systems (one system includes five air vehicles), along with two spare systems, 33 FLARES would be acquired. Thus, the procurement costs were estimated to be \$4.9M, shown in Table 16.

Our performance evaluation for damage reduction, shown in Table 12, estimated that a 42% reduction in composite damage could be achieved using the FLARES. Using the same method from the VTOL cost analysis in Chapter IV.2.a (see Figure 11); there was a possibility of 15% reduction in life cycle maintenance costs. AVDLR and AFM could save approximately \$79.5M and \$79.4M, respectively. The total AVDLR & AFM savings would reduce the funding to \$875.3M, shown in Table 16. The total life-cycle estimate for the FLARES was approximately \$913.3M.

Table 16. FLARES Cost Estimate Summary.

Development/ Including SE for Ship Integration & Tech Pubs	\$ 9.8 M
Prototypes	\$ 0.4 M
Rockwell	\$ 2.6 M
Quattro	\$ 15.5 M
Test	\$ 2.7 M
Software	\$ 2.2 M
R&D	\$ 33.1 M
Radios/Battery	\$ 1.3 M
Motors	\$ 0.1 M
Piccolo Controller & Ground Control Station	\$ 0.3 M
Composite	\$ 3 M
Recovery Rope	\$ 0.2 M
Procurement	\$ 4.9 M
AVDLR	\$ 517.5 M
Damage Reduction Savings	- \$ 79.5 M
AFM	\$ 516.6 M
Damage Reduction Savings	- \$ 79.4 M
O&S Total	\$ 875.3 M
Total	\$ 913.3 M

c. SideArm

The development costs were estimated using the DARPA TERN contract awarded to Aurora. The SideArm has successfully demonstrated the ability to capture a 400 lb air vehicle using an arresting gear capture method. An adjustment (1.5) was made to the development contract costs because of the RQ-21A tail boom and hook modifications that would be required. The SideArm had a specific air vehicle that was developed to be used on that recovery system. Thus, the RQ-21A would require adding a tail boom, hook, and subsequent testing; which adds more scope and complexity. Prototype testing assumed 3 structures, and 3 RQ-21A air vehicles are needed. The structure prototype was estimated using procurement unit costs. Testing and ship integration costs were used

from the VTOL upgrade kit feasibility study. The estimated total for R&D was approximately \$12.4M, shown in Table 17.

The crane and the launch/recovery rail were estimated using the current SRS mast with an added complexity factor (1.5). The SideArm launch/recovery rail is more complex than the current SRS mast with more hydraulic components and integrated launcher. The arresting gear assembly cost was taken from the RQ-2B Pioneer system. A factor (0.3) was applied due to the size difference. Thirty-three arresting gear recovery systems and 219 modification kits (33 systems with five air vehicles each) would be acquired. The estimated total procurement costs were approximately \$30.7M, shown in Table 17.

The performance evaluation, shown in Table 12, estimated that a 84% reduction in composite damage could be achieved for the SideArm. Using the same method from the VTOL analysis in Chapter IV.2.a (see Figure 11), there is a possibility of a 31% reduction in life-cycle maintenance costs; for a savings of \$159M in AVDLR and \$158.7M in AFM. The total AVDLR & AFM savings would reduce the funding to \$716.4M, shown in Table 17. The total life-cycle estimate for the SideArm was approximately \$759.5M.

Table 17. SideArm Cost Estimate Summary.

Development/ Including SE for Ship Integration & Tech Pubs	\$ 4.6 M
Prototypes	\$ 5.1 M
Test	\$ 2.7 M
R&D	\$ 12.4 M
Launch/Recovery Rail (including hydraulics)	\$ 14.3 M
Arresting Gear Assembly	\$ 0.3 M
Crane	\$ 9.5 M
Boon & Tail Hook (Qty 219)	\$ 6.6 M
Procurement	\$ 30.7 M
AVDLR	\$ 517.5 M
Damage Reduction Savings	- \$ 159 M
AFM	\$ 516.6 M
Damage Reduction Savings	- \$ 158.7 M
O&S Total	\$ 716.4 M
Total	\$ 759.5 M

d. Net Capture

The Net Capture development costs were estimated using the SideArm with adjustments (0.5) for scaling differences, and simplification of the capture area that a net would require versus an arresting wire. Modification of the RQ-21A air vehicle was not needed. Prototype testing assumed three net capture structures would be built and that the cost for the prototype structures would be the same as the procurement structure costs. Testing and ship integration costs were used from the VTOL upgrade kit feasibility study. The estimated total for R&D was approximately \$5.4M, shown in Table 18.

Net recovery was the simplest design concept out of the recovery systems being investigated. A procurement estimate was created for the structure and net assembly. Cost for the capture net was taken from average pricing on IHS Haystack, a defense parts and logistics database. The twin goal post structure was assumed to be analogous to the mast structure for the RQ-21A SRS. Thirty-three Net Capture assemblies would be acquired, and thus the estimated procurement costs were approximately \$9.8M, shown in Table 18.

The performance evaluation concerning damage reduction, shown in Table 12, estimated that there was no reduction in composite damage for the Net Capture. Thus, the total AVDLR & AFM values would remain \$1034.1M, as shown in Table 18. The total life-cycle estimate for the Net Capture is approximately \$1,049.4M.

Table 18. Net Capture Cost Estimate Summary.

Development/ Including SE for Ship Integration and Tech Pubs	\$ 1.1 M
Prototypes	\$ 0.9 M
Test	\$ 2.7 M
R&D	\$ 5.4 M
Net	\$ 0.3 M
Structure	\$ 9.5 M
Procurement	\$ 9.8 M
AVDLR	\$ 517.5 M
Damage Reduction Savings	- \$ 0 M
AFM	\$ 516. M
Damage Reduction Savings	- \$ 0 M
O&S Total	\$ 1034.1 M
TOTAL	\$ 1049.4 M

e. Current SRS

The current SRS is already operational so no development costs were applied. For procurement, it was assumed that the current SRS/Launcher unit costs were approximately \$500K per bill of materials for the system. Acquiring 33 total systems, the procurement cost estimate was \$16.5M. O&S costs were the same as the total AVDLR & AFM value of \$1034.1M shown in Table 18. The total estimate for the current SRS is approximately \$1,051M as shown in Table 19.

3. Analysis and Results

Table 19 summarizes the results of our cost and performance evaluations for each recovery system. Net Capture was estimated to have the least R&D cost, FLARES was

estimated to have the least procurement cost, and VTOL was estimated to have the least O&S costs. Figure 12 combines the cost evaluation outputs with the performance evaluation output into a cost-benefit graph. It shows that the VTOL and the SideArm recovery systems had the highest scores from the performance evaluation while also having the lowest estimated life-cycle cost. These two are the non-dominated systems and would be a logical choice in terms of performance and cost. Again, it is worthy to note that the cost estimates are only a rough order of magnitude comparison of the proposed recovery systems. One of the underlying cost drivers is damage caused to composite parts and the associated costs with repairing and replacing those components. There are other factors that could affect these estimates, but if the damage reduction ratings hold, the overall cost savings should not differ from what is shown in Figure 12.

Table 19. Cost Analysis Outputs.

System	R&D (\$M)	Procurement (\$M)	O&S (\$M)	Total Life Cycle Cost (\$M)	Performance Evaluation Output
*Current SRS	-	\$17	\$1,034	\$1,051	0.005
FLARES	\$33	\$5	\$875	\$913	0.45
VTOL	\$18	\$47	\$693	\$758	0.759
SideArm	\$12	\$31	\$716	\$759	0.801
Net Capture	\$5	\$10	\$1,034	\$1,049	0.445

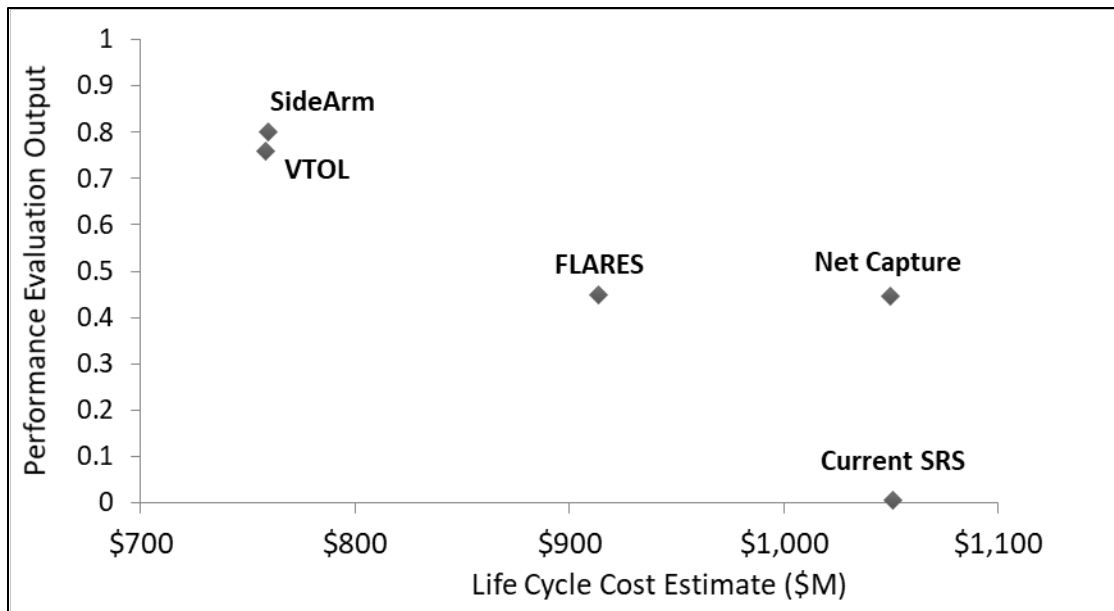


Figure 12. Cost-Benefit Graph.

C. RISK ASSESSMENT

A risk assessment was conducted on all of the recovery systems. The intent of the risk analysis is to examine the severity of the risk by considering the likelihood of an event occurrence, and identifying the possible consequences in terms of performance and cost. The risk assessment was qualitative, and engineering judgement was used based on the cost and performance analysis. The risk reporting matrix, shown in Figure 13, was used to measure and report the performance and technical/cost risk of each recovery system.

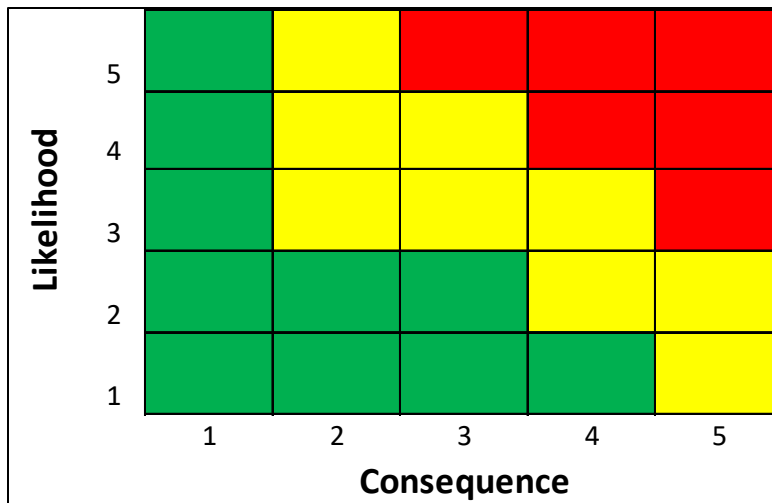


Figure 13. Sample Risk Matrix.

The rankings used in the cost analysis and performance analysis were used to populate this risk reporting matrix. The capstone team examined the likeliness and severity (consequence) of each risk, and provided another ranking indicating which recovery system poses the most and least amount of risk. The level of each risk was reported as low (green), moderate (yellow), or high (red). Table 20 defines the levels of likelihood criteria.

Table 20. Levels of Likelihood Criteria.

Likelihood	Level	Likelihood	Probability of Occurrence
	1	Not Likely	~ 10%
	2	Low Likelihood	~ 30%
	3	Likely	~ 50%
	4	Highly Likely	~ 70%
	5	Near Certainty	~ 90%

1. Performance Risk

The level and type of severity for performance risk is defined utilizing criteria shown in Table 20. In terms of performance risk, the assessment was based on the two

performance parameters that were weighted the highest; damage reduction and the recovery weight capability of each recovery system. Using these criteria, the VTOL poses the least amount of performance risk. The SideArm also posed minimal risk to performance, but ranks lower than the VTOL due to lower damage reduction capabilities. Both the FLARES and Net Capture posed medium risks, as these recovery systems may not significantly reduce the risk of damage to the RQ-21A. The Net Capture posed the most risk of all four recovery systems, with the potential to still cause damage to the RQ-21A. The performance risk-reporting matrix, shown in Figure 14, was the result of the defined thresholds in Tables 21 and 22.

Table 21. Consequence Severity Criteria.

Consequence	Level	Performance
	1	Minimal or no Consequence to technical performance
	2	Minor reduction in technical performance
	3	Moderate reduction in technical performance
	4	Significant degradation in technical performance
	5	Severe degradation in technical performance

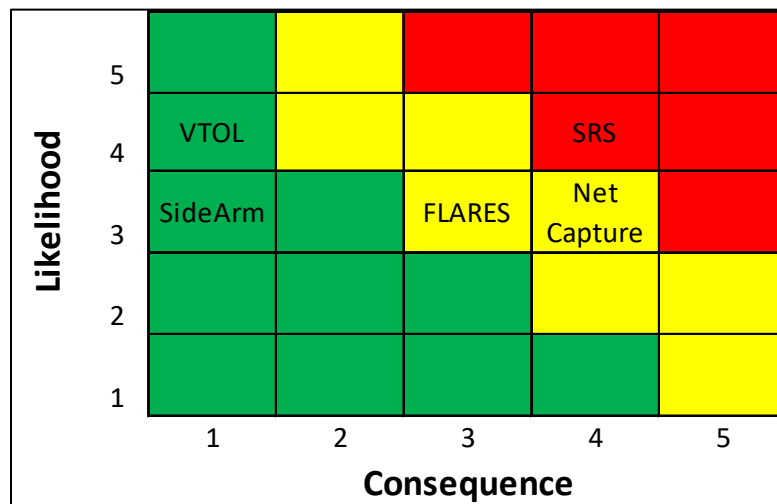


Figure 14. Performance Risk Matrix.

2. Technical/Cost Risk

The level and type of severity for cost risk is defined utilizing criteria, shown in Table 21. The cost-associated risks were estimated based on technology maturity of each recovery system and the technical risk they impose. Figure 15 is the cost risk-reporting matrix based on technical risks. It was assessed that the FLARES and SideArm posed the highest cost overrun risks. FLARES was evaluated as the highest technical/cost risk due to uncertainties related to known development costs and testing of the added VTOL-like quadcopters, structural, software, and navigation modifications. While FLARES is being developed for the smaller ScanEagle UAV, developing the same system for the much heavier RQ-21A will encompass all the complexities associated with VTOL systems, engine issues, and hover control, which has the potential to drive up R&D costs should the modifications not work as intended. Therefore, it is highly likely that there will be cost overruns greater than 15% for FLARES. The SideArm also falls into the same risk category as it is still in the early developmental stages, and may potentially incur greater R&D costs for incorporation for the RQ-21A since the airframe will require an addition of a hook on top of the UAV and a tail boom. Although there will not be any significant modification needed to the SideArm crane system, necessary modifications to the UAV adds greater technical risk which translates to greater cost risk. Therefore, we estimate that the SideArm will also have similar cost overruns to FLARES.

The VTOL was assessed as a medium technical/cost risk even though this system will require substantial modification to the RQ-21. The VTOL wing upgrade kit has already been developed, and has been proven for four similar class UAVs by the same manufacturer thus reducing some uncertainties. For RQ-21A, still some uncertainties do exist. The airframe will require significant modifications to add the wing mounted quadcopters which may potentially impact the performance of the aircraft. The motors for the VTOL system will need to be made stronger to handle the weight and harsh environment of sand and sea spray. Taking all these factors into consideration, the technical/cost risks are not the lowest among the alternatives. Due to engine issues that can arise and the difficulty of hover control, this can lead to increased development costs, as shown in Chapter IV.B. The Net Capture posed the lowest amount of cost overrun risk

due to the fact that this system has been tested and proven for UAVs larger than the RQ-21A. The Net Capture does not require any modification to the RQ-21A and therefore it also poses the lowest technical risk thru supporting the lowest R&D cost estimates.

Table 22. Consequence Severity Criteria.

Consequence	Level	Cost
	1	Minmal or no impact
	2	< 5% of Budget
	3	< 10% of Budget
	4	< 15% of Budget
	5	> 15% of Budget

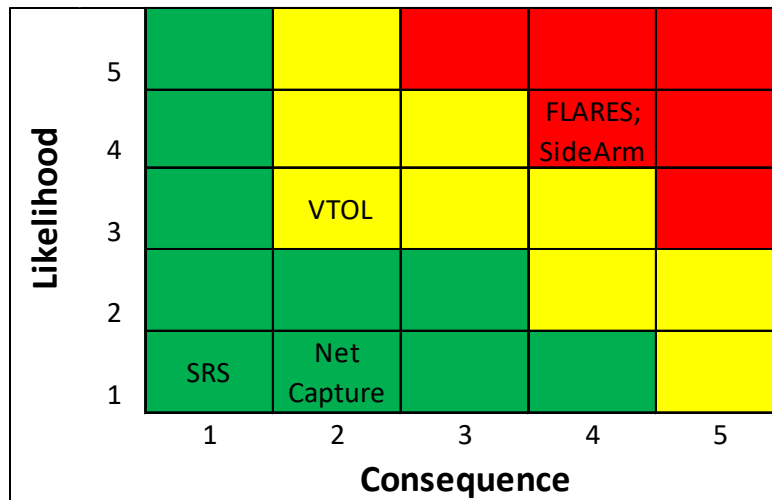


Figure 15. Cost Risk Matrix.

D. SUMMARY OF RESULTS

SideArm was determined to be the best performing system at a reasonable price. However, since SideArm is still in early development, there is a risk that the system could cost more to develop and operate than estimated, and that modifications to get the reduced footprint cannot be accomplished. This system may not be the best alternative for the PMA if schedule is a concern, again due to its current development status.

The VTOL performs well (0.766 versus SideArm's 0.809), while costing slightly less over its life cycle (\$758M versus SideArm's \$759M). The cost/performance is close to SideArm. VTOL is a lower overall risk than SideArm since it has been demonstrated a fielded system.

The other systems (Current SRS, Net Capture, and FLARES) were all determined to be more expensive and less capable than VTOL or SideArm. Net capture was also a high performing system but was eliminated due to the high cost associated with the estimated damage to the aircraft during capture. If this could be reduced significantly in development or improved cost estimation, then Net Capture could be included in the most viable alternatives.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This AoA's cost and performance analysis shows the SideArm and VTOL are by far the two highest performing recovery systems of the alternatives presented in this report. The other systems overall performance was far worse, while also at a much higher estimated cost. The VTOL, poses less overall risk, especially in the risk of a cost overrun. However, it requires more modifications to the RQ-21 system than the SideArm does.

The team believes the best option is to continue to pursue both of these options and better quantify the two systems, primarily in the damage and cost areas. There was uncertainty pertaining to the most consequential evaluation criteria: damage caused to the UAV during recovery and the maximum safe capture energy. Although the calculations used to estimate these two areas is logical, any test data that could be obtained could verify the methodology used or provide additional data for analysis. There was also uncertainty in the extent of the modifications needed to fit these systems onto the RQ-21. Gaining clarity in these areas will help solidify the performance and cost results presented.

The process and data provided by this AoA should serve as a solid foundation on which the PMA can expand. If further testing is accomplished and additional information is collected, the PMA can use the AoA process provided and re-calculate performance and cost information. This additional future work will reduce uncertainties. The AoA process could also be expanded to include additional factors if pertinent data became available, thus providing additional value to the stakeholders.

B. RECOMMENDATIONS

Based on the analysis, the capstone team recommends the SideArm and VTOL for further consideration and research. The SideArm and VTOL are the best recovery systems based on performance, cost, and risk; and outperformed the RQ-21A SRS baseline system. The final decision should depend on the level of risk which can be accepted, scheduling and cost priorities.

If the final priority of the PMA is to find the most viable solution with the lowest cost and a performance increase over the current SRS then the VTOL system should be chosen. If the priority of the sponsor is to choose the system with a lower price than the current SRS with the highest performance, then the SideArm system should be chosen. Further, a technology demonstration and risk reduction program including both alternatives should be initiated to mature the designs for damage resistance, and cost reduction. Testing and analysis should then be executed to determine which alternative offers the better performance, least damage, and lowest life cycle cost.

Both VTOL and SideArm require physical modifications to be compatible with the RQ-21 air vehicle. This endeavor did not investigate either the modifications or any other effort needed to integrate the recovery system with the air vehicle. Full investigation of the necessary changes is recommended.

C. AREAS FOR FUTURE WORK

There is a lack of complete data which necessitated assumptions when determining cost and performance; see Chapter I.C.1, for assumptions. Further research and testing is necessary to create a more accurate assessment of all recovery systems.

The performance analysis could be improved by gathering data on damage and allowable aircraft weight. Testing would provide insight into how the aircraft is affected by the different modes of capture and the types and frequency of damage sustained. Characterizing energy dissipation is key to accurately predicting values for both performance criteria.

Cost is closely related to the same performance criteria, because maintenance costs incurred by aircraft damage make up a large portion of life-cycle costs. Additionally, actual procurement cost data would increase the accuracy of the life-cycle cost estimate, albeit a much smaller one compared to maintenance. The key with the cost issues is LCC (inclusive of the procurement cost and the repair costs). Another important aspect is understanding what the cost drivers are and controlling them.

APPENDIX A: STAKEHOLDER QUESTIONS AND ANSWERS

(1) Are there any alternative SRS that are currently being investigated?

Yes, there are alternative SRS being investigated, however these are all in very early stages of research and development, with very low-levels of maturity. The more near-term improvement to the SRS relates to the manufacturing process, which should enable a larger capture envelop, higher factor of safety, and more consistent quality builds that improve the air vehicle life span. The manufacturing improvement will transition from a welded-design to an extruded design.

The alternative SRS include: 1) Flying-launch and recovery system (FLARES) by Insitu, 2) the SideArm prototype co-developed by DARPA and Aurora Flight Sciences, and 3) the VTOL.

Insitu offers the Flares system for the smaller SCANEAGLE (smaller than the RQ-21A), this system would need to be significantly scaled up to work for RQ-21. The system is still quite a ways away even for the SCANEAGLE.

Without changing the basic winglet hook system, there really is not much else out there.

(2) What are the problems with the SRS?

The primary issues with the current SRS are the limited capture envelop and the capture damage. For instance, if the air vehicle is launched at 135 lbs., it must burn-down 10 lbs of fuel before it is able to be retrieved by the SRS. Thus, an immediate recovery of the air vehicle after launch is not possible. The capture damage caused by the SRS is related to the air frame strength and the SRS strength. The SRS suffered some early system design failures, which limited the weight of the air vehicle and the speed upon capture.

The recovery process involves the aircraft engaging the rope and hook, the aircraft slows down, and then engages the bungie. Once it reaches point of maximum payout, it travels back towards the point-of-capture. Now all this energy is going back

into the aircraft. The damages to the air vehicle can be caused by a mass strike (aircraft impacts the SRS) or if the aircraft becomes entangled in rope, which has been shown to damage the tail of the air vehicle.

(3) What actions have already been taken to correct known issues?

The fleet users are currently using an “tug-rope” attachment, with a capture point tagged on the rope, to provide a secondary relief force to the aircraft from an operator tugging on the rope upon capture.

(4) Do you have a priority for updating/correcting the system?

The priority is capture damage, secondary is to increase envelop expansion. The key piece there is the energy requirement.

(5) PMA: When do you want this replacement system fielded?

We do not currently have an ECP in place, since we are only in concept development for the alternative SRS, thus no deadline.

(6) What is your primary interest in the project?

System engineer responsible for launch and recovery systems, technical execution, 4.8.1 Systems Engineering competency.

(7) How many are currently fielded, are in reserve?

We currently have 14 SRS fielded, 1 test SRS at Webster Field.

(8) What are your “needs” or requirements for an improved or alternative SRS?

The KPPs associated with current system. Transportability is big. The physical size is big and limits mobility.

(9) What are you spending on the maintenance of the system?

[These numbers were not available during the phone call.]

(10) What are the costs associated with the current SRS?

[These numbers were not available during the phone call.]

(11) Have you performed an analysis on an improvement program? Do you have cost numbers on this effort?

The extruded design is only a small cost increase; it is about less than 5–10% increase of entire system cost. 20–Year system, improved from couple of year.

(12) Are there any rigid guidelines concerning ship- or land-mounts for the SRS?

There is no difference in how the system is deployed. Same system, same operator. Towable by HUMVEE. You may want to look into a system with a turn-table and reduced in size for ship-board operation. Right now with the current requirements there is one shipboard system.

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APPENDIX B: RELEVANT KPPS AND PERFORMANCE REQUIREMENTS FROM THE PBS

Expeditionary—Air Transportability (KPP)

- The entire UAS, which includes wheeled vehicles, trailers and all other support equipment shall be transportable by sealift, and airlift C-17, or C-5. [KPP]
- The entire UAS, including wheeled vehicles, trailers and all other support equipment shall be transportable by C-130 intra-theater transport aircraft. [Threshold]
- For tactical movement on the battlefield, the entire UAS, shall be transportable by CH-53s. [KPP]

Expeditionary—Transport by Small Vehicle (KPP)

- The entire UAS shall be transportable by High Mobility Multi-Purpose Wheeled Vehicles (HMMWV). [KPP]

Expeditionary—Shipboard Compatibility (KPP)

- The entire UAS and all of its sub-systems and ancillary equipment required to support all phases of operation (e.g., AV, GCS, payloads, launch/recovery device, communications systems, spares, and support equipment) shall be shipboard compatible during storage, maintenance and operation. [KPP]
- The UAS shall operate from air-capable L Class ships (amphibious). [KPP]
- The UAS shall be capable of successfully launching and recovering the AV during combined maximum ship motions of +3 degrees to -3 degrees of pitch and +5 degrees to -5 degrees of roll. [KPP]
- The UAS operations and systems shall not interfere with the operations of manned aircraft on the ship. [Threshold]

- The UAS storage, maintenance, and operations footprint shall not adversely impact the ship's mission. [Threshold]
- The UAS storage, maintenance, and operations footprint shall be compatible with the existing Class 1 Aviation Facility aboard the ship, which includes allocated spare parts stowage, aviation workshop and hangaring facility. [Threshold]
- The shipboard integrated UAS shall be mission capable launch through recovery at the combination of maximum wind, pitch and roll limits specified herein. [Threshold]
- The UAS shall be capable of successfully launching and recovering the AV during combined maximum ship motions of +5 degrees to -5 degrees of pitch and +8 degrees to -8 degrees of roll. [Objective]

Expeditionary—Performance Requirement

- Every individual part or component of the system shall have provision which allows two (2) men to lift the item to waist level, excluding wheeled and/or towed components. [Threshold]
- All UAS wheeled and/or towed equipment shall have provision to enable crewmen the ability to maneuver the item in the field with a HMMWV or ECV. [Threshold]
- All equipment (ALRE or SE) that is mobile and or towed shall be designed to enter (approach), negotiate (up or down), and leave (depart) a solid surface (i.e., one (1) piece) ramp having a slope of 20 degrees. Ground clearance, angles of approach, ramp break-over, and departure shall be selected accordingly. The length of the incline will be 1.2 times the wheel-base of the equipment or greater.[Threshold]

Launch and Recovery—Performance Requirement

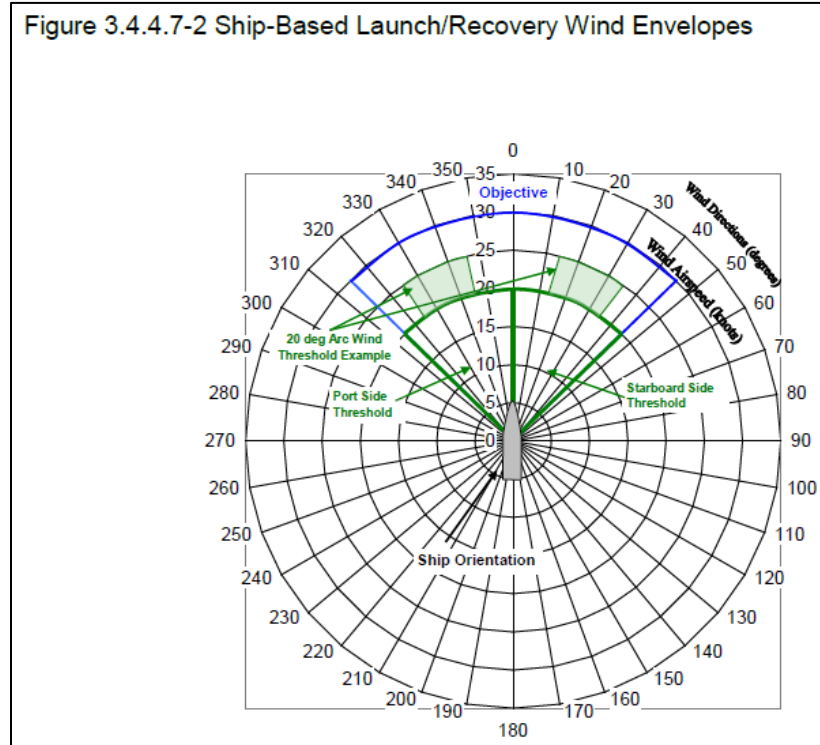
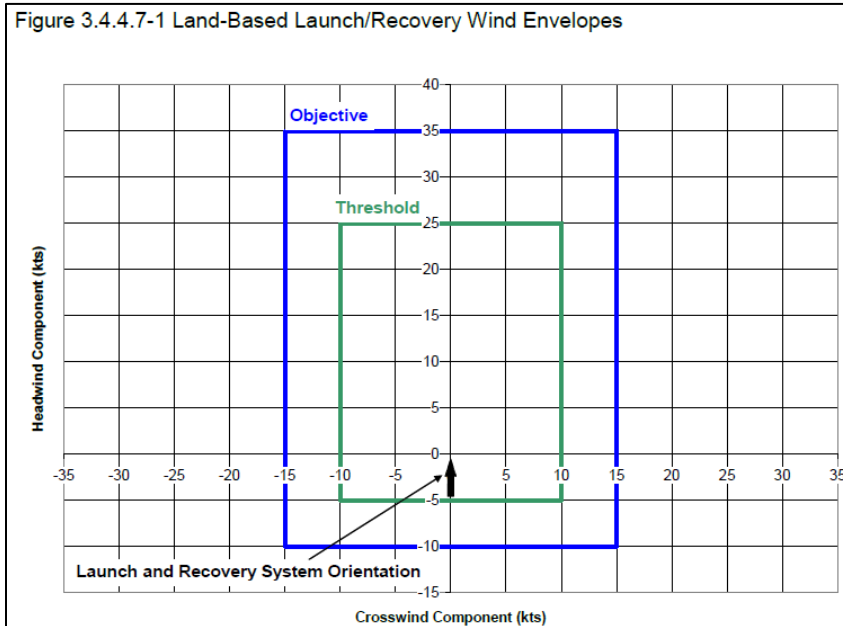
- The launch and recovery equipment shall meet all UAS expeditionary and transportability requirements specified throughout this document. [Threshold]
- All launch and recovery equipment that is not mounted on wheels shall be lightweight, portable, and capable of two-man lift. [Threshold]
- The UAS design shall provide the operator an unobstructed view of the launch and recovery equipment and area(s) at all times. [Threshold]
- The UAS shall provide a capability to communicate launcher or AV “alignment relative to the ship” or “launch heading” to the operator for navigation implementation. [Threshold]
- The UAS recovery rate shall be no less than 95%. [Threshold]

Operating Environments—Performance Requirement

- The UAS shall be able to launch and recover the AV from austere, unprepared, grass or dirt surfaces where terrain surface characteristics or space available or both prevent rolling take-off and landings. [Threshold]
- The UAS shall be able to launch and recover the AV from an urban environment where terrain surface characteristics or space available or both prevent rolling take-off and landings. [Threshold]

Launch and Recovery Wind Envelope—Performance Requirement

The environmental Wind Envelopes are provided in Figures 3.4.4.7-1 and 3.4.4.7-2.



Land-Based Operational Performance in Wind—Performance Requirement

- IAW Figure 3.4.4.7-1, the UAS shall have the capability to launch in a headwind component up to and including 25 knots without inducing any damage. [Threshold]
- IAW Figure 3.4.4.7-1, the UAS shall have the capability to launch in a headwind component up to and including 35 knots without inducing any damage. [Objective]
- IAW Figure 3.4.4.7-1, the UAS shall have the capability to recover in a headwind component up to and including 25 knots without inducing any damage. [Threshold]
- IAW Figure 3.4.4.7-1, the UAS shall have the capability to recover in a headwind component up to and including 35 knots without inducing any damage. [Objective]
- IAW Figure 3.4.4.7-1, the UAS shall have the capability to launch with up to a 10 knots crosswind component without inducing any damage. [Threshold]
- IAW Figure 3.4.4.7-1, the UAS shall have the capability to recover with up to a 10 knots crosswind component without inducing any damage. [Threshold]
- IAW Figure 3.4.4.7-1, the UAS shall have the capability to launch with a tailwind component of up to 5 knots without inducing any damage. [Threshold]
- IAW Figure 3.4.4.7-1, the UAS shall have the capability to recover with a tailwind component of up to 5 knots without inducing any damage. [Threshold]

Shipboard Operational Performance in Wind—Performance Requirement

- For the following shipboard launch and recovery wind envelope requirements, all wind references refer to relative winds (the result of natural winds plus ship-motion-created winds). These relative winds are referenced to the ship centerline, and will be referred to as Wind Over Deck (WOD).
- The AV shall not over-fly the ship structure forward of the flight deck during any phase of launch or recovery (e.g., launch, initial climb-out, approach, recovery, wave-off, and missed approach). [Threshold]
- IAW Figure 3.4.4.7-2, in the shipboard environment, the UAS shall have the capability to launch with WODs from zero (0) to 20 knots from 360 to 045 degrees for launches from starboard side and zero (0) to 20 knots from 315 to 360 degrees for launches from port side. [Threshold]
- IAW Figure 3.4.4.7-2, in the shipboard environment, the UAS shall have the capability to recover with WODs from zero (0) to 20 knots from 360 to 045 degrees for recoveries from starboard side and zero (0) to 20 knots from 315 to 360 degrees for recoveries from port side. [Threshold]
- IAW Figure 3.4.4.7-2, in the shipboard environment, the UAS shall have the capability to launch with WODs from zero (0) to 25 knots for a 20 degree arc of WOD angle on each of the starboard and port side portions of the forward quadrant (e.g., from 015 to 035 degrees for starboard side launches and from 325 to 345 degrees for port side launches). [Threshold]
- IAW Figure 3.4.4.7-2, in the shipboard environment, the UAS shall have the capability to recover with WODs from zero (0) to 25 knots for a 20 degree arc of WOD angle on each of the starboard and port side portions of the forward quadrant (e.g., from 015 to 035 degrees for starboard side recoveries and from 325 to 345 degrees for port side recoveries). [Threshold]

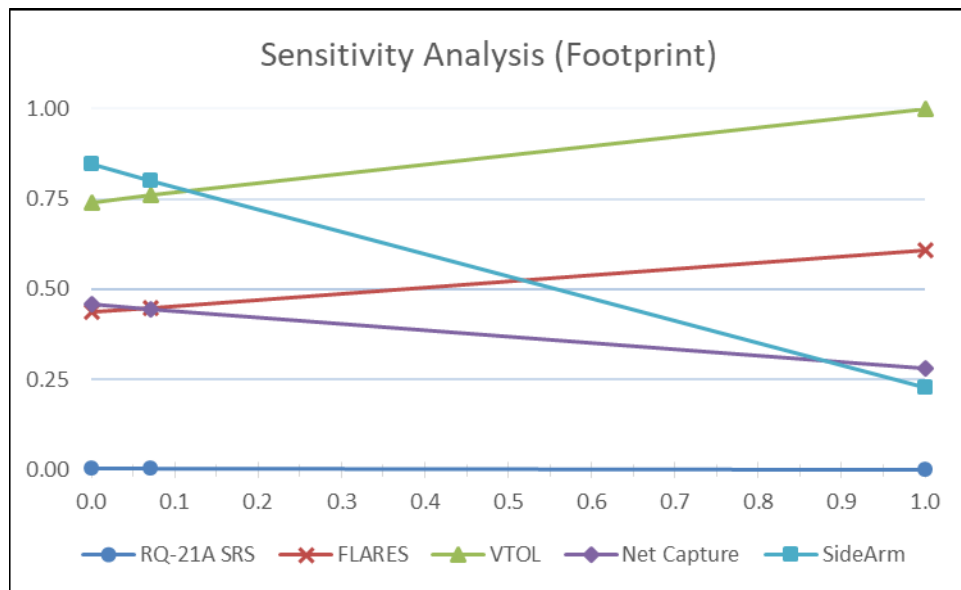
APPENDIX C: PERFORMANCE ANALYSIS

	RQ-21A SRS	FLARES	VTOL	Net Capture	Sidearm	
Footprint (smaller is better) score (higher is better)	207.3 ft^2 0.0000	81 ft^2 0.6093	0 ft^2 1.0000	149.3 ft^2 0.2799	160 ft^2 0.2282	= stowed dimension control: 207.3
Recovery Weight (higher is better) comparable	125 lb	49 lb	210 lb	392 lb	400 lb	
score (higher is better)	125 lb 0.0000 *	210 lb 0.2857	210 lb 0.2857	392 lb 0.9699	400 lb 1.0000	control: 400.0
Damage Reduction (higher is better)	10 ft	15 ft		10 ft	30 ft	= stopping distance
	172.1 ft/s/s	114.7 ft/s/s		172.1 ft/s/s	57.4 ft/s/s	= deceleration rate
(lower G is better)	5.38 G's	3.59 G's	1.10 G's	5.38 G's	1.79 G's	= G Force experienced by air vehicle
score (higher is better)	0.0000	0.4190	1.0000	0.0000	0.8381	control: 5.38
Grade/Sea State (higher is better)	5 degrees	60 deg	60 deg	45 deg	10 deg	
score (higher is better)	0.0833	1.0000	1.0000	0.7500	0.1667	control: 60.0
Capture after Launch (lower is better)	5 minutes	2 min	0 min	2.5 min	0.8 min	
score (higher is better)	0.0000	0.6000	1.0000	0.5000	0.8400	control: 5.0
Approach Envelope (higher is better)	20 degrees	360 deg	360 deg	20 deg	10 deg	
score (higher is better)	0.0556	1.0000	1.0000	0.0556	0.0278	control: 360.0
			= estimated value		* = Does not meet threshold	

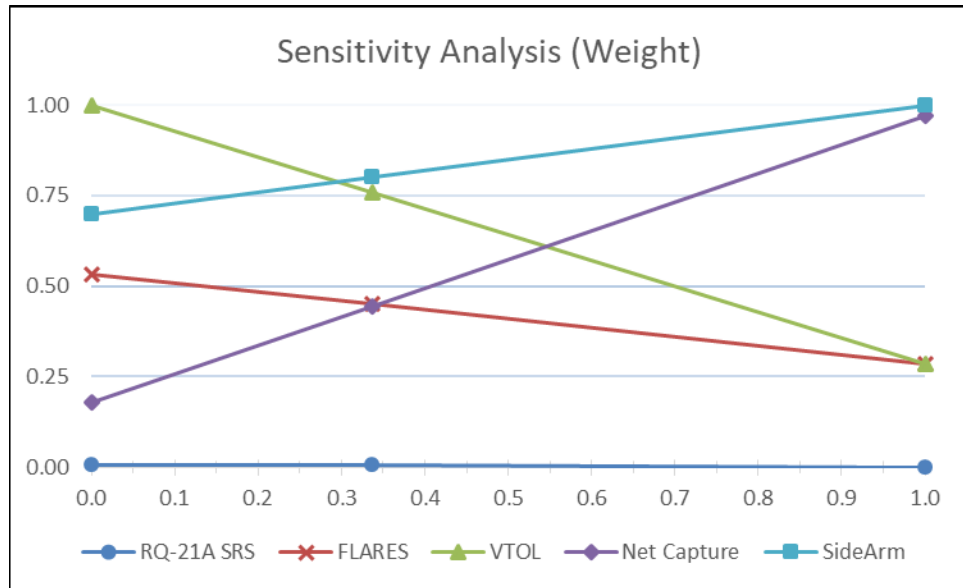
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APPENDIX D: SENSITIVITY DATA AND DETAIL CHARTS

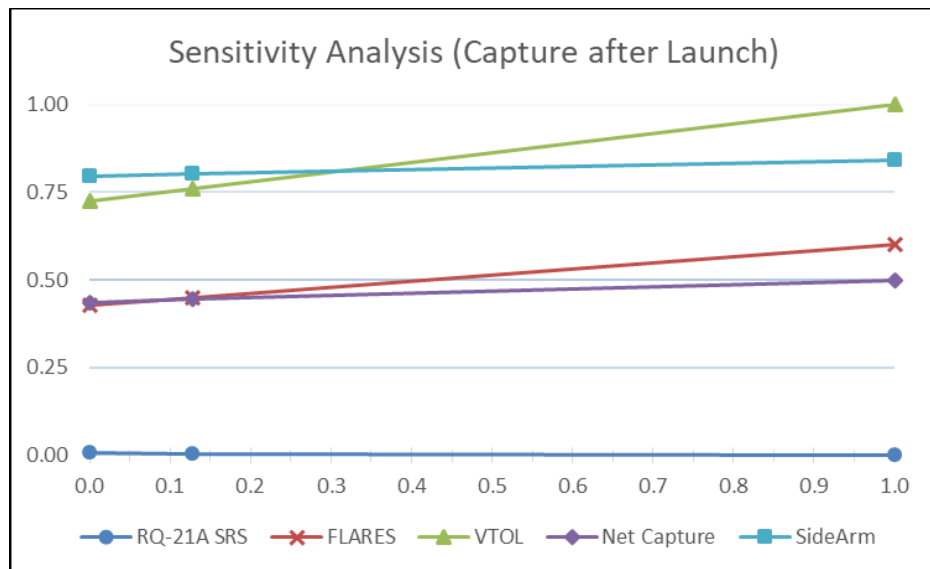
Footprint	RQ-21A SRS			FLARES			VTOL			Net Capture			SideArm		
Criteria Weight	0.00	0.07	1.00	0.00	0.07	1.00	0.00	0.07	1.00	0.00	0.07	1.00	0.00	0.07	1.00
Total Score	0.01	0.00	0.00	0.44	0.45	0.61	0.74	0.76	1.00	0.46	0.44	0.28	0.85	0.80	0.23
Slope	-0.01			0.17			0.26			-0.18			-0.62		



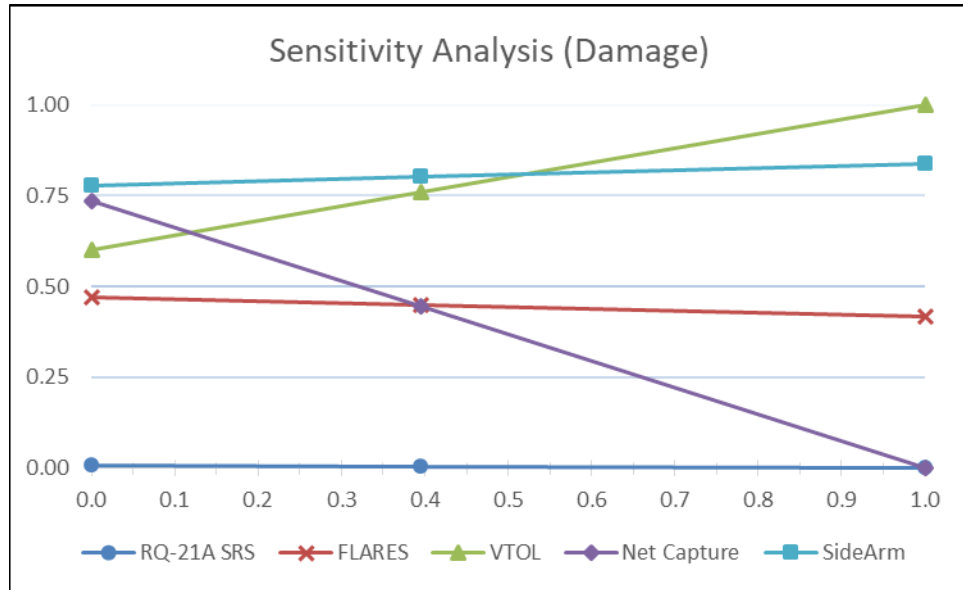
Weight/ Energy	RQ-21A SRS			FLARES			VTOL			Net Capture			SideArm		
Criteria Weight	0.00	0.34	1.00	0.00	0.34	1.00	0.00	0.34	1.00	0.00	0.34	1.00	0.00	0.34	1.00
Total Score	0.01	0.00	0.00	0.53	0.45	0.29	1.00	0.76	0.29	0.18	0.44	0.97	0.70	0.80	1.00
Slope	-0.01			-0.25			-0.71			0.79			0.30		



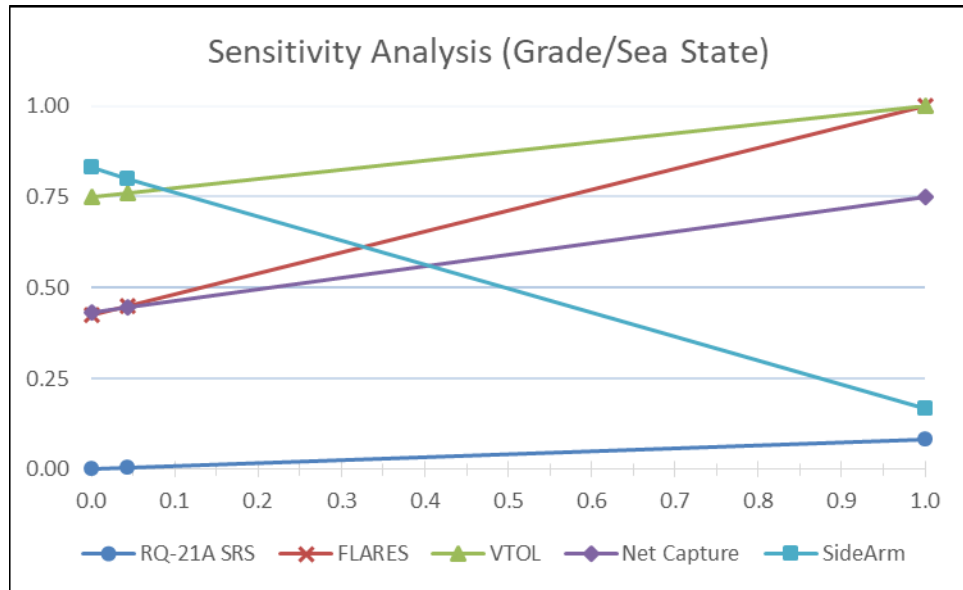
Capture after Launch	RQ-21A SRS			FLARES			VTOL			Net Capture			SideArm		
Criteria Weight	0.00	0.13	1.00	0.00	0.13	1.00	0.00	0.13	1.00	0.00	0.13	1.00	0.00	0.13	1.00
Total Score	0.01	0.00	0.00	0.43	0.45	0.60	0.72	0.76	1.00	0.44	0.44	0.50	0.80	0.80	0.84
Slope	-0.01			0.17			0.28			0.06			0.04		



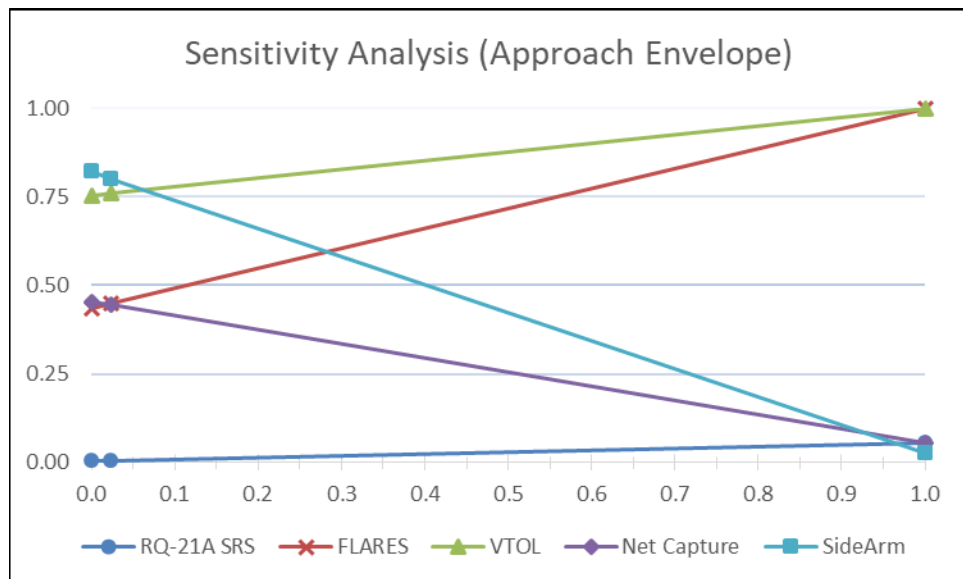
Damage	RQ-21A SRS			FLARES			VTOL			Net Capture			SideArm		
Criteria Weight	0.00	0.40	1.00	0.00	0.40	1.00	0.00	0.40	1.00	0.00	0.40	1.00	0.00	0.40	1.00
Total Score	0.01	0.00	0.00	0.47	0.45	0.42	0.60	0.76	1.00	0.74	0.44	0.00	0.78	0.80	0.84
Slope	-0.01			-0.05			0.40			-0.74			0.06		



Grade/ Sea State	RQ-21A SRS			FLARES			VTOL			Net Capture			SideArm		
Criteria Weight	0.00	0.04	1.00	0.00	0.04	1.00	0.00	0.04	1.00	0.00	0.04	1.00	0.00	0.04	1.00
Total Score	0.00	0.00	0.08	0.43	0.45	1.00	0.75	0.76	1.00	0.43	0.44	0.75	0.83	0.80	0.17
Slope	0.08			0.57			0.25			0.32			-0.66		



Approach Envelope	RQ-21A SRS			FLARES			VTOL			Net Capture			SideArm		
Criteria Weight	0.00	0.02	1.00	0.00	0.02	1.00	0.00	0.02	1.00	0.00	0.02	1.00	0.00	0.02	1.00
Total Score	0.00	0.00	0.06	0.44	0.45	1.00	0.75	0.76	1.00	0.45	0.44	0.06	0.82	0.80	0.03
Slope	0.05			0.56			0.25			-0.40			-0.79		



APPENDIX E: COST ESTIMATE BREAKOUT

Current SRS				
System Element	Cost	Rationale	Factor	Total
Procurement	\$500,000	31 recovery systems plus 2 spares	33.00	\$16,500,000
AVDLR	\$517,527,849	From the funding profile, see funding tab.		\$517,527,849
AFM	\$516,601,970	From the funding profile, see funding tab.		\$516,601,970
Total				\$1,050,629,820
Procurement	\$16,500,000			
O&S	\$1,034,129,820			
Cost Risk	☒ Low	Low cost risk, is currently operational on RQ-21A.		
	☐ Medium			
	☐ High			
Notes				
1	Current SRS and Launcher costs approximated from system bill of materials.			

FLARES				
System Element	Cost	Rationale	Factor	Total
8 FTE for 2 yrs.	\$3,496,554	Labor, Fully burdened KTR. Analogous from VTOL estimate, See VTOL Tab. A factor applied as this recovery solution is more complex than the traditional VTOL wing kit upgrade.	2.00	\$6,993,107
Material		11.02% of labor, Same as VTOL estimate, See VTOL TAB	0.11	\$770,640
G&A		21.85% of labor, Same as VTOL estimate, See VTOL TAB	0.22	\$1,527,994
Hardware/ Prototypes	\$148,300	Three prototypes, 3*(Procurement Costs), See Procurement below	3.00	\$444,900
Rockwell	\$1,290,000	SME ROM, Comms/Navigation. Analogous from VTOL estimate, See VTOL Tab. A factor applied as this recovery solution is more complex than the traditional VTOL wing kit upgrade.	2.00	\$2,580,000
Quattro	\$5,160,000	SME ROM, Composites. Analogous from VTOL estimate, See VTOL Tab. A factor applied as this recovery solution is more complex than the traditional VTOL wing kit upgrade.	3.00	\$15,480,000
Test	\$2,687,500	CT: 50hrs 5FTE, DT: 100 hrs. (70 land, 30 sea), OT: 50 hrs.; 500k / wk. Analogous from VTOL estimate, See VTOL Tab.	1.00	\$2,687,500
Pubs	\$265,186	2 yrs. 1/2 person at tech pub writer rate	1.00	\$265,186
Software	\$1,075,000	SME ROM, Analogous from VTOL estimate, See VTOL Tab. A factor applied as this recovery solution is more complex than the traditional VTOL wing kit upgrade.	2.00	\$2,150,000
SE for ship integration	\$107,500	SME ROM, Analogous from VTOL estimate, See VTOL Tab. A factor applied as this recovery solution is more complex than	2.00	\$215,000

		the traditional VTOL wing kit upgrade.		
Radio/ Battery	\$40,000	Navigation, GPS, Datalink, Battery ROM	1.00	\$40,000
8 motor set up	\$350	Use brushless motors Turnigy CA120 150kv Brushless Outrunner (100 cc equivalent)	8.00	\$2,800
Piccolo controller	\$8,000	http://www.cloudcaptech.com/ products/detail/piccolo-ii http://www.cloudcaptech.com/ products/auto-pilots Online Research	1.00	\$8,000
Piccolo GCS	\$2,500	http://www.cloudcaptech.com/ products/auto-pilots Online research	1.00	\$2,500
Composite	\$45,000	Used SRS Wings (\$8k each) and Fuselage (\$27k) Composite Costs as a ROM for composite required for this system, See PBOM TABS for costs	2.00	\$90,000
Recovery Rope	\$5,000	Same as SRS, WAG	1.00	\$5,000
Procurement Total		31 recovery systems plus 2 spares	33.00	\$4,893,900
Damage Reduction		From Performance Analysis	0.42	
AVDLR	\$517,527,849	From the funding profile, see funding tab. Applied a reduction factor	0.15	\$438,018,321
AFM	\$516,601,970	From the funding profile, see funding tab. Applied a reduction factor	0.15	\$437,234,688
Total				\$913,261,236
R&D	\$33,114,328			
Procurement	\$4,893,900			
O&S	\$875,253,009			
Cost Risk	[] Low	High Cost Risk. While this recovery system is being		

	[] Medium	developed for the smaller SCANEAGLE UAV, developing this system for the much heavier RQ-21A and all the complexities with VTOL systems, engine issues and hover control, there are great cost overrun risks.		
	[X] High			
Notes				
1	VTOL estimate is sourced from “RQ-21A Blackjack Launch and Recovery Equipment Upgrade” See General, Funding, Readiness & Additional Info TABS			
2	Flares was used on the 49-lbs ScanEagle while RQ-21A is approximately 147-lbs			

VTOL				
System Element	Cost	Rationale	Factor	Total
8 FTE for 2 yrs.	\$3,496,554	Labor, Fully burdened KTR. See Funding TAB	1.00	\$3,496,554
Material		11.02% of labor. See Funding TAB	0.11	\$385,320
G&A		21.85% of labor. See Funding TAB	0.22	\$763,997
Hardware/ Prototypes	\$967,500	Three Air Vehicles for prototypes, 3*900k. See Funding TAB	3.00	\$2,902,500
Rockwell	\$1,290,000	SME ROM, Comms/ Navigation. See Funding TAB	1.00	\$1,290,000
Quattro	\$5,160,000	SME ROM, Composites. See Funding TAB	1.00	\$5,160,000
Test	\$2,687,500	CT: 50hrs 5FTE, DT: 100 hrs. (70 land, 30 sea), OT: 50 hrs.; 500k / wk. See Funding TAB	1.00	\$2,687,500
Pubs	\$265,186	2 yrs. 1/2 person at tech pub writer rate. See Funding TAB	1.00	\$265,186
Software	\$1,075,000	SME ROM. See Funding TAB	1.00	\$1,075,000
SE for ship integration	\$107,500	SME ROM. See Funding TAB	1.00	\$107,500
Takeoff stands	\$32,250	SME ROM. See Funding TAB	1.00	\$32,250
Procurement Total	\$215,000	Upgrade kits for 31 systems, 5 Air vehicles per system & 64 spares, 200k * ((31*5)+64 Attrition AVs). See Funding	219.00	\$47,085,000

		TAB		
Damage Reduction		From Upgrade kit estimate (90% damage reduction), See FUNDING TAB.	0.9	
AVDLR (Aviation Depot Level Repairable)	\$517,527,849	From the funding profile, see funding tab. It was determined that this wing kit could save 33% on Life Cycle Maintenance cost	0.33	\$346,743,659
AFM (Aviation Fleet Maintenance)	\$516,601,970	From the funding profile, see funding tab. It was determined that this wing kit could save 33% on Life Cycle Maintenance cost	0.33	\$346,123,320
Total		Value includes prototyping and feasibility study in FY19		\$758,117,786
R&D	\$18,165,807			
Procurement	\$47,085,000			
O&S	\$692,866,979			
Cost Risk	☐ Low	Medium Cost Risk. “The VTOL kit has been developed and is proven for 4 other platforms by the same manufacturer. For RQ-21A, the motor will need to be stronger to handle the weight and harsh environment of sand and sea spray.” See Funding TAB. Cost Risk isn’t low due to engine issues that can arise and the difficulty of hover control which can lead to increased development costs.		
	☒ Medium			
	☐ High			
Notes				
1	“It is estimated that approximately 90% of the composite damage attributed to air vehicle recovery will be eliminated by using a VTOL kit. Further benefits estimate that avionics repairables will see a demand decrease of ~15% due reduced impact loads on sensitive electronics.” See General Tab			
2	The VTOL Kit is assumed to add 25 to 35-lbs per AV			
3	Estimate is sourced from “RQ-21A Blackjack Launch and Recovery Equipment Upgrade” See General, Funding, Readiness & Additional Info TABS			

SIDEARM				
System Element	Cost	Rationale	Factor	Total
Aurora's DARPA TERN Contract	\$2,811,232	DARPA TERN Contract that Aurora was awarded, and eventually successfully tested this concept with a 400-lbs UAV. An adjustment is made for modifications of the RQ-21A (1.5) as it isn't designed to be captured by this method (arresting gear).	1.5	\$4,216,848
Hardware/ Prototypes	\$730,500	Three prototypes, 3*(Procurement Costs), See Procurement below.	3.00	\$2,191,500
Hardware/ Prototypes	\$967,500	Three AV's for developing the tail hook	3.00	\$2,902,500
Test	\$2,687,500	CT: 50hrs 5FTE, DT: 100 hrs. (70 land, 30 sea), OT: 50 hrs.; 500k / wk. Analogous from VTOL estimate, See VTOL Tab.	1.00	\$2,687,500
Pubs	\$265,186	2 yrs. 1/2 person at tech pub writer rate	1.00	\$265,186
SE for ship integration	\$107,500	SME ROM, Used from VTOL estimate, See VTOL Tab. A factor applied as this recovery solution is more complex than the traditional VTOL wing kit upgrade.	1.50	\$161,250
Launch/ Recovery Rail (including hydraulics)	\$288,000	Analogous to SRS Mast, factor	1.50	\$432,000
Arresting Gear Assembly	\$35,000	Pioneer RQ-2B (450lb) from Haystack price https://airandspace.si.edu/collection-objects/pioneer-rq-2a-uav ARRESTING ASSEMBLY	0.30	\$10,500
Crane	\$288,000	Same as SRS Mast, \$288k	1.00	\$288,000
Boon & Tail Hook	\$30,000	ROM	1.00	\$30,000

Procurement Total		31 recovery systems plus 2 spares, & 219 tail hook kits (31x5 air vehicles, plus 64 spares)		\$30,676,500
Damage Reduction		From Performance Analysis	0.84	
AVDLR	\$517,527,849	From the funding profile, see funding tab. Applied a reduction factor	0.31	\$358,508,792
AFM	\$516,601,970	From the funding profile, see funding tab. Applied a reduction factor	0.31	\$357,867,405
Total				\$759,477,482
R&D	\$12,424,784			
Procurement	\$30,676,500			
O&S	\$716,376,197			
Cost Risk	☐ Low	High Cost Risk. This system is still in early development stages and has risks for cost overruns.		
	☐ Medium			
	☒ High			
Notes				
1	This system is listed as having a 2–4 man operation			
2	System successfully captured a 400-lbs UAV, we would need to modify it for our needs to the 200-lbs range.			

NET CAPTURE				
System Element	Cost	Rationale	Factor	Total
Development Costs	\$2,811,232	Analogous to DARPA TERN Contract that Aurora was awarded, and eventually successfully tested arresting gear capture concept with a 400-lbs UAV. An adjustment is made for the scaling differences as well as simplification of the capture area that a net would require vs an arresting wire.	0.5	\$1,405,616
Hardware/ Prototypes	\$298,000	Three prototypes, 3*(Procurement Costs), See Procurement below.	3.00	\$894,000
Test	\$2,687,500	CT: 50hrs 5FTE, DT: 100 hrs. (70 land, 30 sea), OT: 50 hrs.; 500k / wk. Same as VTOL	1.00	\$2,687,500
Pubs	\$265,186	2 yrs. 1/2 person at tech pub writer rate. Same as VTOL	1.00	\$265,186
SE for ship integration	\$107,500	SME ROM, Used from VTOL estimate, See VTOL Tab. A factor applied as this recovery solution is more complex than the traditional VTOL wing kit upgrade.	1.50	\$161,250
Net	\$10,000	Estimate based on pricing in Haystack	1.00	\$10,000
Twin Masts	\$288,000	Analogous to SRS	1.00	\$288,000
Procurement		31 recovery systems plus 2 spares	33.00	\$9,834,000
Damage Reduction		From Performance Analysis		
AVDLR	\$517,527,849	From the funding profile, see funding tab. Applied a reduction factor		\$517,527,849
AFM	\$516,601,970	From the funding profile, see funding tab. Applied a reduction factor		\$516,601,970

Total				\$1,049,377,372
R&D	\$5,413,552			
Procurement	\$9,834,000			
O&S	\$1,034,129,820			
Cost Risk	☒ Low	Low cost risk, has been tested and proven for larger UAVs than RQ-21A.		
	☐ Medium			
	☐ High			
Notes				
1	This system will need to be modified for a smaller range in capture weight from 400-lbs to 200-lbs			

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