Conceptual Design Document

ARES: Aspect-ratio Redesign of Eagle-owl for Stormchasing

University of Colorado
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ASEN 4018

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1. Information

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2. Project Description

Mission Statement: *Aspect-ratio Redesign of Eagle-owl for Stormchasing (ARES) will loosely build on the previous Eagle Owl project by designing, building, and testing a box wing unmanned aircraft with a Flush Air Data Sensing (FADS) system to measure relative wind velocity, with the objective of creating a system that can eventually fly into extreme adverse weather conditions.*

2.1. Project Overview

Small unmanned aircraft systems (UAS) are commonly used to collect data on environmental conditions, especially where humans cannot manually measure necessary data, such as in extreme weather events. One important measurement for meteorological and aerospace research is wind velocity. From a UAS, the wind velocity can be gathered in-flight with a mechanical airdata boom, multi-hole probe (MHP), or flush airdata sensing (FADS) system. The airdata boom and multi-hole probe solutions are effective but require a physical component to extend out from the airframe.[1] Especially in small, lightweight aircraft, these extruding options can have a significant impact on aerodynamic performance and expose the hardware to damage.[2]

The purpose of this project is to design, build, test, and verify a box-wing aircraft with a FADS system to measure pressure and convert those data to relative wind velocity. The Aspect-ratio Redesign of Eagle-owl for Storm-chasing (ARES) aircraft will be a revised model of a previously designed and constructed box wing aircraft: the Eagle Owl. In addition to integrating the FADS system, the revised model will have an improved endurance of at least 2 hours. At the customer's request, a study will be conducted in which the aspect ratio will be increased by at least a factor of 2 to understand the effect this increase has on endurance. ARES will also have improved landing capabilities such that all hardware can remain functional for at least 10 flight cycles.

2.2. Objectives

The objectives of ARES have been split into three success levels for various elements of the project and are shown in Table 1. A Level 1 success is the first stage of accomplishments to be achieved on the way to Level 3, which satisfies all design goals, and will be considered a minimum success.

Level 1 shows the proper design behind the aircraft and its theoretical achievement of the mission goals. In the data capture category, a Level 1 success will show that the FADS system has been integrated and is recording continuous pressure, local temperature, and inertial measurements. In addition, a Level 1 landing will show that the airframe can survive a load that would be seen upon a real landing. Under navigation and control, the airframe would show actuated responses (i.e. movement of the control surfaces) after test data has been fed to the system. Lastly, in the first level of flight, models and simulations will have been successfully created to prove that the design is modeled to complete the specific design objectives. These levels will all be verified separate from the mission flight test, through mostly ground tests, including adding a load to a static airframe and testing a FADS integrated system in a wind tunnel or similar test.

Level 2 successes demonstrate successful aircraft flight, and thus will be more difficult to complete than the ground tests. The Level 2 landing will show that the chosen landing method will allow for consecutive takeoff and landing cycles with only time to recharge. The navigation and control criteria of a Level 2 success will show that the integrated autopilot allows the aircraft to maneuver in a large diameter circle within visual site, as required by the FAA. Furthermore, the Level 2 flight criteria states that the takeoff will not damage and sensor or structure of the aircraft, and steady level flight with altitude disturbances of $\pm$ 3 meters or less is shown. Level 2 successes are tested through demonstration and position data collected during flight.

A Level 3 success indicates the complete success of all requirements and project goals and demonstrates the ability to calculate accurate, calibrated aircraft-relative wind velocity data from pressure and temperature data. In a landing sense, the aircraft will show that it can support 10 consecutive takeoff and landing cycles with only 15 minutes in between to make any repairs. A Level 3 navigation and control success will show that the entire flight (including takeoff and landing) will be controlled by autopilot. Furthermore, in flight, the aircraft will prove an endurance of 2 hours or more with all the systems. ARES will be designed to complete Level 3 objectives, but the lower level tiers are suitable in the event that down scoping is necessary or irreparable damage to the aircraft occurs near the deadline. Overall, a Level 1 success on all categories will provide solutions to the problems presented by the customer: 10 consecutive takeoff and landing cycles, flight endurance of 2 hours, and study relating increase aspect ration to increase endurance. By providing the models and simulations for success of these goals, ARES will have answered the posed problems, allowing future iterations of this mission to prove physical feasibility.

Table 1. Success levels for ARES mission objectives.

	Data Capture	Landing	Navigation & Control	Flight
Level 1	• FADS system integrated and recording continuous pressure data while powered • Record continuous local temperature and inertial measurements to onboard storage while powered	• Airframe can survive a simulated landing cycle outside of a flight test; exact test TBD based on landing system designed	• Control surfaces are actuated in response to RC input and autopilot feedback loop; autopilot verified by feeding in test data on ground	• Provide flight models and simulations to show that the design can complete design objectives
Level 2	• Level 2 objectives are the same as Level 1 objectives	• Landing method allows for consecutive takeoff and landing cycles with only power replacement/recharge	• Autopilot achieved with ability to maneuver the aircraft in a 600m diameter circle while staying within visual sight	• Takeoff with no damage to sensors, structure, or operators • Achieve steady, level flight with no more than 3 m divergences
Level 3	• Calibrate FADS system such that data is converted to aircraft-relative wind velocity to within 1 m/s and 1° of accuracy	• Consecutive takeoff and landing cycles occur a minimum of 10 times	• Full flight with takeoff and landing achieved with autopilot	• Flight endurance is greater than 2 hours with all systems powered

2.3. Concept of Operations

Figure 1 below depicts the concept of operations (CONOPS) for ARES. The purpose of the operation is to demonstrate successful and repeatable takeoff, controlled flight, and landing of ARES to meet requirements FR 3.0, FR 4.0, and FR 6.0, respectively. Additionally, this operation will validate the aircraft's endurance stated in requirement FR 1.0 and data collection during the operation will validate requirement FR 5.0. The upper height bound of 400 feet comes from FAA regulations,[5] and the TBD testing location will be in Colorado. Also by FAA regulations, the aircraft must stay within visual sight, so a circular flight path is most optimal for demonstrating endurance. The image of the aircraft in the upper right corner depicts the aircraft constrained by FR 2.0.

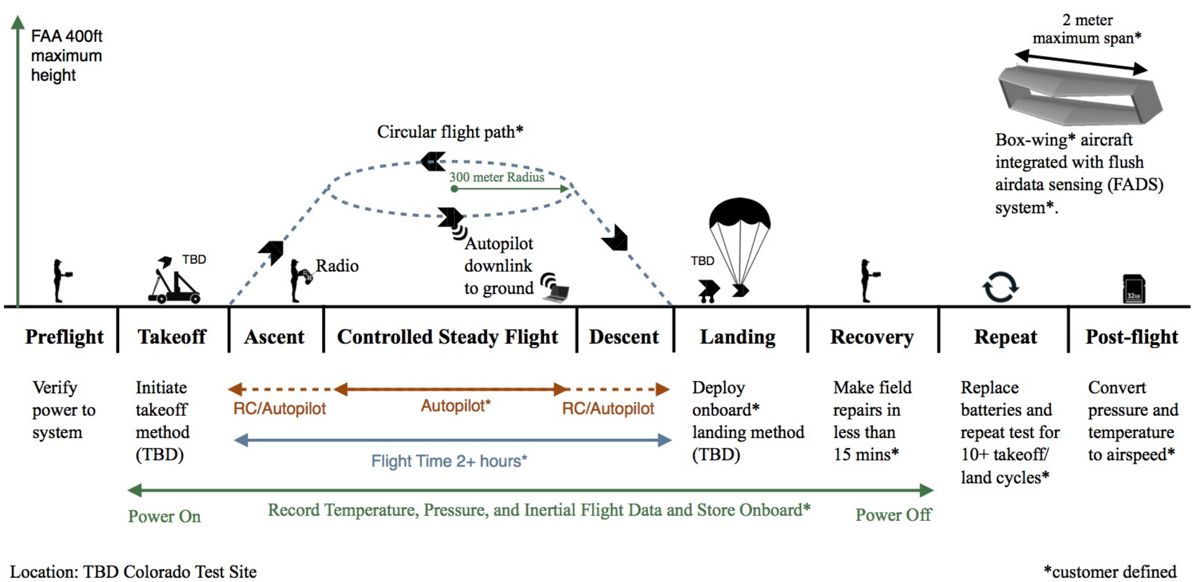
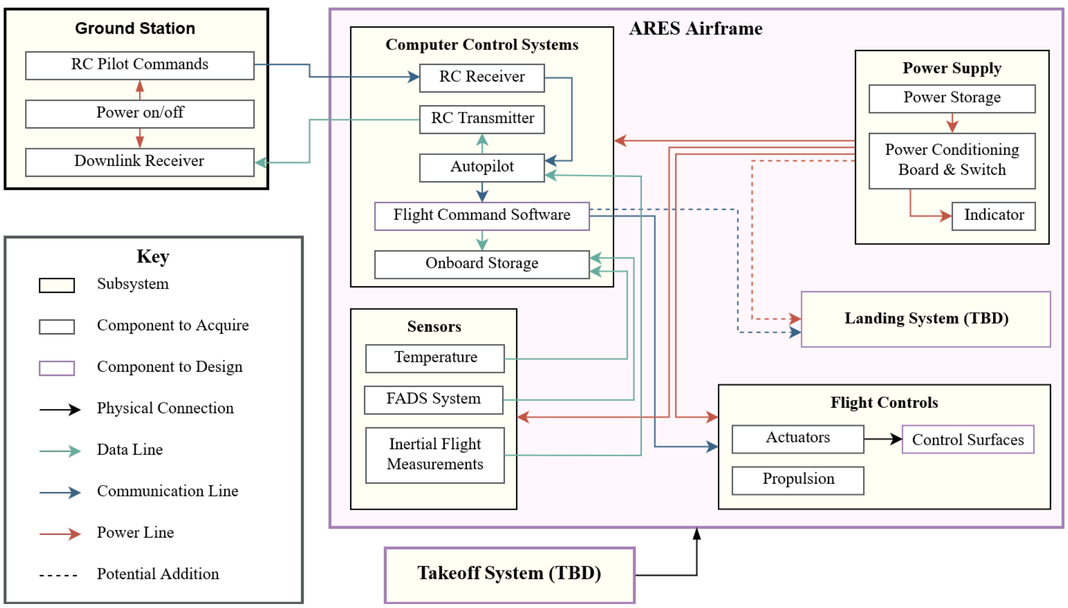


Figure 1. Concept of Operations for ARES.

2.4. Functional Block Diagram

Figure 2 depicts the functional block diagram (FBD) for ARES. The system includes three major systems: the ground station, the aircraft itself, and the takeoff system. The takeoff system may evolve to include separate components from the aircraft, but this is TBD as part of the trade studies conducted in this document and may require power or communication lines. The RC pilot communicates with the aircraft through a wireless transmitter. These commands are sent to the autopilot or onboard flight command software, depending on user setting, and sends the necessary signals to actuators for control surfaces and to the propulsion system. A sensor package including the FADS system, a temperature sensor, and a device to record inertial flight measurements such as attitude and position data all feed data into the onboard storage through the computer control system, which performs appropriate formatting/processing of sensor signals. The autopilot component used will most likely have the inertial flight measurements sensors included. All powered components share the same external power supply whose performance and current storage is shown by a visual indicator.

Figure 2. Functional Block Diagram for the mission hardware interactions of ARES.



2.5. Functional Requirements

FR 1.0: The aircraft shall have a total flight endurance of at least 2 hours while maintaining visual sight with the operator.

FR 2.0: The system shall be an aircraft with a box wing configuration with a span no larger than 72 inches; the effects of increasing aspect ratio from the previous version to increase endurance will be investigated.

FR 3.0: The aircraft shall demonstrate a controlled takeoff.

FR 4.0: The aircraft shall be piloted by an autopilot during the steady flight regime of the mission.

FR 5.0: The aircraft shall simultaneously measure external temperature, inertial flight data, and pressure on the airframe surface at multiple points with a flush airdata sensing (FADS) system. The recorded data shall be stored on-board and converted to relative wind speed after flight.

FR 6.0: The aircraft shall land in a manner such that the aircraft is capable of completing at least 10 takeoff and landing cycles with only 15 minutes on the ground between landing and takeoff.

3. Design Requirements

FR 1.0: The aircraft shall have a total flight endurance of at least 2 hours while maintaining visual sight with the operator.
Motivation: Increasing the endurance is the customer's primary goal and 2 hours is a realistic time frame to fly and obtain wind measurements. The circular pattern will allow the aircraft to stay within sight as per the Federal Aviation Administration regulations[5].
Verification: This will be verified by flying the aircraft in a circular pattern while timing the flight.

- **DR 1.1:** The system shall have an in-flight power system.
  Motivation: An in-flight power system will provide voltage to all aircraft sub-systems requiring a power supply.
  Verification: This will be verified by conducting ground tests and flight tests to prove the embedded systems/hardware can be run, simultaneously, via an on-board power supply.

  - **DR 1.1.1:** The power system shall provide power to the propulsion system, autopilot, GPS, radio controller and flight computer.
    Motivation: Each individual system must have power or the overall aircraft will not have full functionality, if any.
    Verification: An electrical test will be conducted on the ground to show that all aircraft components, requiring power, will be receiving their operational voltage and current required for activation and continued operation.

  - **DR 1.1.2:** The power system shall be rechargeable or replaceable between flights.
    Motivation: The customer desires an aircraft that is capable of landing and taking off a minimum of 10 times with only 15 minutes between flights for maintenance and repairs.
    Verification: This will be verified by starting a timer, removing and recharging/replacing the power system and validating that all sub-system's components, requiring power, are receiving the voltage and current required for activation in under 15 minutes.

  - **DR 1.1.3:** The power system shall have visual indicators to prove when power is being supplied to the aircraft.
    Motivation: The aircraft needs a visual sign that sub-systems are receiving power.
    Verification: This will be verified by demonstrating that an indicator is visible and lit when power is being supplied from the power system before the power system is integrated with the aircraft structure.

- **DR 1.2:** The system shall have an integrated propulsion system capable of producing enough thrust for flight.
  Motivation: The customer requests an aircraft capable of flying, in order to complete atmospheric measurements.
  Verification: This will be verified by measuring the thrust output on a static test stand and ensuring that the thrust produced reaches a minimum of 1/3 the weight of the aircraft.[22]

  - **DR* 1.2.1:** The propulsion system shall be capable of producing enough thrust for the aircraft to reach a range of 10-30 [m/s] flight speeds.
    Motivation: The customer desires an aircraft that is capable of flying between these speeds in order to prove that the aircraft would be applicable in severe weather situations.
    Verification: This requirement will be verified in two ways: first through computer simulations that show the thrust produced can propel the aircraft forward at the desired speed and second through in flight measurements from the IMU.

  - **DR 1.2.2:** The propulsion system shall be integrated to a speed controller.
    Motivation: The propulsion's system must be wired to a speed controller such that the autopilot and radio controller can designate the voltage supplied to the motor.
    Verification: The requirement will be verified by conducting a static test to prove that the Radio Controller/autopilot can communicate a desired voltage to the speed controller which will activate the propulsion's system.

FR 2.0: The system shall be an aircraft with a box wing configuration with a span no larger than 2.0 m*; the effects of increasing aspect ratio from the previous version (prior aspect ratio = 3) to increase endurance will be investigated.
Motivation: The customer believes that increasing the aspect ratio will improve flight efficiency and improve endurance and would like to see how much this modification will affect the performance of the aircraft. Limiting the span ensures easy transport of the aircraft.
Verification: Measuring the wing span and calculating the aspect ratio of the design will ensure it is within the desired parameters.

- **DR* 2.1:** The aircraft's structure shall only consist of two lifting surfaces connected by struts in the middle and walls on the outside such that it appears in a rectangular "box" shape when viewed from the front and rear.
  Motivation: The customer's desire to study the effectiveness of a box wing design.
  Verification: The box wing design will be verified first through a CAD model and then finally through the physical design.

  - **DR 2.1.1:** The air frame shall have no vertical fins or protruded aerodynamic surface.
    Motivation: This would cause the air frame to deviate from the customer requested box design.
    Verification: The design space will be limited by said parameters to ensure the design meets the requirement. All hardware will be inspected after manufacturing.

  - **DR 2.1.2:** The air frame shall have no central fuselage.
    Motivation: The customer's desire to implement sensors in the open area between the top and bottom surfaces and study the box design on an aircraft.
    Verification: The design space will be limited by said parameters to ensure the design meets the requirement. All hardware will be inspected after manufacturing.

  - **DR 2.1.3:** The air frame shall be able to fly without a tail boom or any cantilever type structures attached to increase stability.
    Motivation: This would cause the air frame to deviate from the customer requested box design.
    Verification: The design space will be limited by said parameters to ensure the design meets the requirement. All hardware will be inspected after manufacturing.

  - **DR 2.1.4:** The only exterior modifications on this design shall be flush mechanical control surfaces which do not protrude when not deployed.
    Motivation: This would cause the air frame to deviate from the customer requested box design.
    Verification: The design space will be limited by said parameters to ensure the design meets the requirement. All hardware will be inspected after manufacturing.

- **DR.2.2:** The aircraft shall have a Lift-to-Drag ratio greater than that of previous designs from the Eagle Owl lineage.
  Motivation: The customer's desire to see an improvement in the aircraft's endurance and performance.
  Verification: This will be verified through aerodynamic analysis through methods such as CFD or AVL as well as actual field tests.

FR 3.0: The aircraft shall demonstrate a controlled takeoff.
Motivation: In order for the aircraft to gather relevant airdata and prove Level 2 and 3 flight capabilities, it must be airborne, which means it must somehow take off. This takeoff must be controlled as unpredictable behavior can result in damage to the aircraft or harm to a team member, failing FR 1 and FR 6.
Verification: A test will be conducted to show that the aircraft follows a predicted launch scenario, and sensors will be checked to ensure proper operation. A controlled takeoff will be demonstrated through the verification of the below design requirements.

- **DR 3.1:** The takeoff system shall be able to control the heading of the aircraft after takeoff to within plus or minus 45 degrees of the expected lateral heading.

Motivation: If the lateral heading is not controlled to within the above accuracy, the aircraft has the possibility of takeoff into unfavorable terrain around the takeoff site or possibly harming operators of the takeoff system. Damage to the aircraft or operators will violate FR 6 and DR 3.5
Verification: A test will be conducted to demonstrate that the lateral heading of the aircraft (or similar object) after takeoff matches expectations, through the use of GPS location or other frame-by-frame tracking software.

- **DR 3.2:** The takeoff system shall be able to bring the aircraft to its desired initial velocity before it leaves the takeoff system.
  Motivation: If the takeoff mechanism does not launch the aircraft at near flight speed, the aircraft may be unable to maintain lift and crash. If the aircraft takes off at too high of a velocity, it could produce too much lift, leading to an uncontrollable climb, stall, and a crash. Either scenario could damage the aircraft and the sensors, violating FR 5 and FR 6.
  Verification: Control over the initial velocity of the takeoff will be tested with objects of a similar characteristics to the aircraft before the aircraft is tested and velocity of the aircraft during takeoff will be verified through the IMU on board.
  - **DR 3.2.1:** The takeoff system shall be capable of launching the aircraft at a minimum velocity to maintain lift.
    Motivation: If the takeoff mechanism does not launch the aircraft fast enough, the aircraft may be unable to produce lift and crash. This scenario could damage the aircraft and the sensors, violating FR 5 and 6.
    Verification: The takeoff mechanism shall demonstrate its ability to launch objects similar to the aircraft faster than a calculated minimum initial velocity before being used to launch the aircraft. Further tests will be conducted, with the aircraft's IMU data, to demonstrate the initial velocity in a full flight scenario.
  - **DR 3.2.2:** The takeoff system shall have a maximum velocity such that the aircraft does not enter an uncontrolled climb.
    Motivation: If the takeoff system provides an initial velocity to the aircraft that is too large, it may go into an uncontrollable climb that can lead to a crash. This scenario could damage the aircraft and sensors, violating FR 5 and FR 6, and was a common point of concern in past designs.
    Verification: The takeoff mechanism shall demonstrate its ability to launch objects similar to the aircraft slower than a calculated maximum initial velocity before being used to test the aircraft. Tests will also be conducted with the aircraft to demonstrate the initial velocity during a takeoff scenario by leveraging onboard IMU data.
- **DR* 3.3:** The takeoff system shall be capable of a minimum of 10 consecutive takeoffs.
  Motivation: The aircraft will need to survive 10 takeoff and landing cycles without major repair as a customer requirement (FR 6). The takeoff mechanism will be held to the same standard.
  Verification: The takeoff mechanism will be used to launch the aircraft (or other similar object) 10 times without the need to leave the testing location for repair.
  - **DR 3.3.1:** The takeoff system shall be able to accommodate 10 takeoffs without violating takeoff parameter constraints defined in DR 3.1 and DR 3.2.
    Motivation: Being able to maintain takeoff parameters after several takeoffs is necessary to ensure the safety of the aircraft and the takeoff system operators. In addition, reducing the amount of random variability in testing will allow the isolation and alteration of specific takeoff parameters (heading, takeoff angle, initial velocity) to accommodate specific testing conditions.
    Verification: A test will be conducted to ensure that the repeated takeoffs of an object similar to the aircraft can be accomplished with minimal variability in takeoff parameters. These takeoff parameters will be verified through means discussed in DR 3.1 and DR 3.2. These tests will also be conducted with the aircraft to ensure takeoff parameters have minimal variability.
  - **DR 3.3.2:** The takeoff system shall be able to accommodate 10 takeoff without repairs to the system that last longer than 15 minutes.
    Motivation: The definition of a major repair given by the client is a repair that takes more than 15 minutes or requires leaving the testing location. If repairs are required that last longer than 15 minutes, FR. 6 will be violated.

Verification: If any repairs to the takeoff mechanism are required during testing, the repairs will be timed to ensure that they do not exceed 15 minutes.

- **DR 3.4:** The aircraft shall not require repairs, due to takeoff, that last longer than 15 minutes after a full flight cycle (terminating with landing) has been completed.
Motivation: If the aircraft sustains major damage after takeoff, the aircraft cannot achieve the customers requirement of 10 flight cycles without repairs lasting longer than 15 minutes, violating FR 6.
Verification: Observation during takeoff and examination after landing will determine if any damage to the aircraft was caused during takeoff. If any repairs are required, they will be timed to ensure they do not exceed 15 minutes.

  - **DR 3.4.1:** The takeoff mechanism shall not apply a normal stress that is larger than 17.7 MPa to the aircraft.
  Motivation: Damage to the aircraft due to compression can cause damage to the structure of the aircraft. This damage may be too significant for repairs to be made in 15 minutes, violating FR 6.0. Assuming a worst case scenario material of expanded polystyrene foam, this maximum compressive modulus is 17.7 MPa.
  Verification: Observation during takeoff and examination after landing will search for any evidence of damage during takeoff, caused by compressive forces. If any repairs are required, they will be timed to ensure they do not exceed 15 minutes.

  - **DR 3.4.2:** The takeoff mechanism shall not apply a shear stress that is larger than 0.290 MPa to the aircraft.
  Motivation: Damage to the aircraft due to shear stress can cause damage to the structure, propulsion system, or the sensors of the aircraft. This damage may be too significant for repairs to be made in 15 minutes, which would violate FR 6.0. In a worst case scenario material of expanded polystyrene foam, this maximum shear strength is 0.290 MPa.
  Verification: Observation during takeoff and examination after landing will search for any evidence of damage during takeoff, caused by shearing forces. If any repairs are required, they will be timed to ensure they do not exceed 15 minutes.

  - **DR 3.4.3:** The takeoff mechanism shall not apply an acceleration on the aircraft larger than 3000 g's, to prevent damage to the onboard sensors.
  Motivation: If a force is large enough to cause an acceleration that is larger than the maximum acceleration of the on-board sensors, FR 5.0 and FR 6.0 could be violated. In the case of the LSM303D 3D Accelerometer and 3D Magnetometer that is onboard a standard Pixhawk autopilot, the maximum acceleration it is capable of handling is 3000 g's.
  Verification: Observation during takeoff, examination after landing, and an analysis of gathered data will search for any evidence of damage during takeoff, due to a large acceleration. If any repairs are required, they will be timed to ensure they do not exceed 15 minutes.

- **DR 3.5:** The aircraft shall not be hand launched.
Motivation: The customer has requested the aircraft not be hand launched due to safety concerns for the team members.
Verification: The design space will be limited by this constraint to ensure the requirement is met. During testing the launch system will be demonstrated to show hand launching was not used.

- **DR 3.6:** The aircraft shall not be car launched.
Motivation: The customer has requested that the aircraft not be launched by a car as the customer's program is phasing out this launch method from standard use.
Verification: The design space will be limited by this constraint to ensure the requirement is met. During testing the launch system will be demonstrated to prove a car launch was not used.

- **DR 3.7:** The takeoff system's design shall be capable of transport by 4 people.
Motivation: A maximum of 4 people was chosen to transport the takeoff system under the assumption of 2 vehicles, each with 2 team members, being used to transport the takeoff system and aircraft to the testing site.
Verification: This shall be verified through a demonstration involving 4 people carrying the takeoff system, loading it into 2 cars and assembling the system prior to testing the system in the field.

- **DR 3.7.1:** The takeoff system shall not exceed a mass of 136 kg.
  Motivation: A mass of 136 kg was determined to be the average mass that 4 people can lift.
  Verification: The takeoff system will be weighed before transport to the testing site to verify that it does not exceed a mass of 136 kg.

- **DR 3.7.2:** The takeoff system shall not exceed dimensions of 2m x 1.75m x 1m.
  Motivation: This size will facilitate transportation to the test site and the size constrained to the cargo space of a Ford Explorer, the vehicle used by the customers program.
  Verification: The takeoff system will be measured to verify its dimensions do not exceed those of a Ford Explorer's cargo space.

FR 4.0: The aircraft shall be piloted by an autopilot during the steady flight regime of the mission.
Motivation: The customer has requested the autopilot be used for at least the steady flight maneuvers but ideally also for takeoff and landing to demonstrate the aircraft's ability to be autonomous, such that it can be used in the future to fly inside of super cells.
Verification: The functional requirement will be verified through the performance of each design requirement that is met.

- **DR* 4.1:** The aircraft's autopilot shall demonstrate steady level flight for at least 2 minutes by ensuring that the altitude disturbance is does not exceed ±3 meters.
  Motivation: The original Eagle Owl maintained steady level flight for 1 minute and 45 seconds. In order to create safe takeoff and landing methods, it will be important to prove that the aircraft is capable of stable flight.
  Verification: This will be verified through the onboard barometer integrated in the autopilot which will be post processed to find the altitude changes during flight.

- **DR* 4.2:** The autopilot shall log position and attitude data on board with a speed of at least 1 Hz for the entirety of flight (2 hours).
  Motivation: The autopilot runs through an internal IMU and GPS system which continuously saves these coordinates to perform maneuvers and be autonomously controlled. In order to ensure that the aircraft has the ability to be completely controlled by autopilot, it must first be proved that the autopilot can save and log data for at least the entirety of flight.
  Verification: This will be tested through an on-the-ground demonstration in which a test will be run with the autopilot on for at least 2 hours within the aircraft and then the data will be checked.

- **DR 4.3:** The autopilot shall be powered by an on-board system within the aircraft.
  Motivation: To ensure that the autopilot can in fact run and work on the aircraft during a flight test, it will need to receive its power from within the aircraft.
  Verification: This will be verified with a system level power test in which the autopilot is mounted on/in the aircraft, demonstrates that it receives power and logs data for the entire test. The time the autopilot remains powered will be verified through data time-stamps.

- **DR 4.4:** The aircraft shall be able to receive and complete inputs from customer provided RC ground station.
  Motivation: While the aircraft is in RC mode it will need to use feedback from the ground station's inputs. The ground-station will always be sending inputs, but this will only be necessary while the aircraft's autopilot has been turned off.
  Verification: This will be verified through demonstration by powering on the aircraft with RC and sending an input to the aircraft and observing the performance.

  - **DR 4.4.1:** The autopilot shall be able to switch on and off from RC control inputs.
    Motivation: As the customer's goal is to demonstrate the ability to maneuver the aircraft with an autopilot system, the team may choose to still takeoff and land using RC control. In this sense, the autopilot must be able to be turned on and off accordingly.
    Verification: This will be verified through demonstration such that an RC command will be sent to the autopilot and does not affect the aircraft since the control input has been turned off. Then another RC command will be sent and a visual confirmation of the autopilot turning on by following the RC command.

- **DR 4.5:** The autopilot shall be able to continuously downlink its data during test flights.
  Motivation: Downlinking the flight data will allow the team to quickly get results from experimental tests. It is not a customer requirement that the aircraft has this capability, but it is common for autopilot systems to come with easily integrated downlink features.
  Verification: The functionality of the downlink system will be determined in a ground test with all systems powered. The plane can be physically moved, and the downlink data can be matched to ensure that the output is reasonable. In a flight test, the data can be compared to how the aircraft can be visually seen to be behaving.

- **DR 4.6:** The autopilot shall be able to control the aircraft such that it performs a circular path.
  Motivation: To prove the autopilot has maneuverability the IMU and GPS integrated units will allow for the aircraft to use a heading hold mode or an altitude hold mode.
  Verification: The flight test will be demonstrated using the autopilot for the 2 hour circular pattern. It is important to have the autopilot be able to keep the aircraft within visible range while traversing its path, as per FAA regulations.

- **DR 4.7:** The autopilot system shall be able to send commands to actuators and the propulsion system to move control surfaces and make speed adjustments.
  Motivation: For the autopilot to function, it must be able to respond to sensor data with feedback controls.
  Verification: The integration of the autopilot with the propulsion system and control surfaces will be verified with an isolated subsystem test. The aircraft's autopilot will be fed test data, and it must send appropriate commands to the active components in response to the test data.

FR 5.0: The aircraft shall simultaneously measure external temperature, inertial flight data, and pressure on the airframe surface at multiple points with a flush airdata sensing (FADS) system. The recorded data shall be stored on-board and converted to relative wind speed after flight.
Motivation: Pressure and density, found through the temperature sensor, are needed post flight to calculate the speed of the wind, which is a major requirement of the customer.
Verification: This requirement will be verified by testing the FADS system and all other airdata sensors and ensuring all recorded data match the test conditions post-test.

- **DR 5.1:** An array of pressure sensors shall be integrated flush to the exterior of the airframe.
  Motivation: The FADS system is necessary to calculate wind speed.
  Verification: This will be verified when the tip of each pressure sensor is below or at the surface of the airframe's skin.

  - **DR* 5.1.1:** A minimum of 12 pressure sensors shall be integrated into the airframe.
    Motivation: Multiple pressure sensors are desired to evaluate pressure at different points along the aircraft for windspeed measurements.
    Verification: The design space will be limited by the number of pressure sensors and the requirement will be verified by visual inspection of 12 pressure sensors on the aircraft.

  - **DR 5.1.2:** The pressure sensors shall be distributed with a minimum of 4 on the top wing (two towards each wing tip), 4 on the bottom wing (two towards each wing tip), and 2 on each side panel.
    Motivation: This distribution of pressure sensors is based upon prior research by Roger Laurence.
    Verification: Visual inspection of the hardware in the prescribed distribution will be used for verification.

  - **DR 5.1.3:** The integrated pressure sensors shall be accurate up to 200 Pascals.
    Motivation: In order to calculate wind speed accurately, the error from the pressure sensors must meet this standard. 200 Pascals is the accuracy of pressure sensors used in past research by Roger Laurance.
    Verification: The pressure sensors will be commercial off the shelf (COTS) purchased, and the manufacturer specifications will be used to assess accuracy pre-purchase. Additionally, recorded pressure measurements from test flights can be compared to modeled atmospheric conditions and commercial weather reports.

- **DR 5.2:** A temperature sensor shall be integrated to the aircraft.

Motivation: The temperature sensor is needed to collect ambient temperature data in order to calculate density. Density is needed for the wind speed calculation.
Verification: Before flight and during manufacturing, the temperature sensor will be confirmed visually.

- ◦ **DR 5.2.1:** The temperature sensor shall be accurate to within 0.1 K.
  Motivation: The customer has requested temperature be recorded to at least this accuracy to ensure the sensor is sensitive enough to the expected range of temperatures of the atmosphere at operational flight height.
  Verification: The temperature sensor will be COTS, and the manufacturer specifications will be used to assess accuracy pre-purchase. Additionally, recorded temperature measurements can be compared to other available temperature sensors, or verified using a heat source at a set temperature.

- **DR 5.3:** The pressure sensors and the temperature sensor shall report measurements at the same rate.
  Motivation: Having the wind sensing measurements time synchronized eliminates the error associated with interpolating between points.Each measurement of pressure will have a corresponding temperature measurement, where the correspondence is known based upon equal time stamps.
  Verification: When the COTS pressure and temperature sensors arrive, they will be tested to ensure they take data at the same rate.

  - ◦ **DR* 5.3.1:** The pressure and temperature sensors will record data at a rate of at least 1Hz.
    Motivation: The customer has requested the pressure and temperature data to be recorded to at least this frequency.
    Verification: The recorded time stamps associated with the pressure and temperature measurements will reflect a rate of at least 1 Hz.

- **DR 5.4:** An inertial measurement unit (IMU) and GPS shall be integrated with the autopilot.
  Motivation: Inertial attitude and position are needed for the autopilot to function.
  Verification: On-the-ground testing consisting of physically moving the plane around will confirm that the autopilot is recording IMU and GPS data.

- **DR 5.5:** An on-board computer shall be integrated with the pressure and temperature sensors.
  Motivation: A computer is needed to translate voltage signals to a standard data format, and write the pressure and temperature data to a storage system.
  Verification: The computer will be writing temperature and pressure data to a storage unit and the data will be in a standard format. This will be verified in on-the-ground testing and post flight with a computer.

  - ◦ **DR 5.5.1:** The on-board computer shall be capable of formatting data and writing to a storage unit.
    Motivation: The customer has requested the pressure and temperature data be stored on-board.
    Verification: The pressure and temperature measurements will be recovered from the storage system before and after to integration with the airframe.

  - ◦ **DR* 5.5.2:** The on-board computer shall be capable of recording pressure, temperature, and time measurements at a rate of at least one 1 Hz.
    Motivation: The customer has requested the data rate be at least 1 Hz.
    Verification: The recorded time stamps associated with the pressure and temperature measurements will reflect a rate of at least 1 Hz.

- ◦ **DR 5.5.3:** The on-board computer shall be capable of communicating with a minimum of 12 pressure sensors and 1 temperature sensor.
  Motivation: The computer needs to be able to record from all the pressure sensors and the temperature sensors simultaneously.
  Verification: All of the sensors will be connected to the on-board computer and the functionality will be confirmed.

- **DR 5.6:** An on-board storage system shall be integrated with the on-board computer.
  Motivation: The customer has requested that pressure and temperature measurements be stored on-board. Data from test flights will be available on-board for download.

Verification: This requirement will be met when data that is collected through the computer that is stored on-board.

- ◦ **DR 5.6.1:** The on-board storage system shall be capable of storing a minimum of 2 megabytes (13 sensors x 8bits x 1hz x 2hr flight time x 2 factor of safety).
  Motivation: The storage system needs to be able to store enough data that corresponds to a maximum flight time.
  Verification: The storage system will be stress tested to determine maximum number of measurements that can be stored and a model of the expected storage required per time stamp will generated.

FR* 6.0: The aircraft shall land in a manner such that the aircraft is capable of completing at least 10 takeoff and landing cycles with only 15 minutes on the ground between landing and takeoff.
Motivation: In order to prove reliability and versatility of the aircraft, the customer has required that the aircraft be able to land and take off again without major repairs to the airframe or sensors. Since "major repair" is qualitative, the customer imposed a 15 minutes turn around time to limit the number and types of repairs that can be completed.
Validation: In order to prove that Functional Requirement 6 has been met, the aircraft will be subjected to 10 takeoff and landing cycles during testing allowing only 15 minute breaks on the ground for repairs.

- **DR* 6.1:** The aircraft shall land such that it can takeoff again within 15 minutes.
  Motivation: The customer requires that the aircraft is capable of taking off immediately after landing with minimal damage to the aircraft. Instead of trying to quantify how much damage is "too much" or what field repairs are allowable, a time limit requirement was realized by the customer.
  Verification: The requirement will be verified during testing by starting a 15 minute timer upon landing and performing any necessary repairs in the field before taking off again.

- **DR 6.2:** The landing system shall be attached to the aircraft and not rely on an external device.
  Motivation: The customer wants a landing system that is mounted to the aircraft or carried by the aircraft so that the landing location can be variable and requires no set up. The customer wants the team to focus on the design of the aircraft itself and not on the design of an external landing device.
  Verification: The design space will be limited to a landing system that is connected to the aircraft. This will be verified as soon as the landing system is attached to the aircraft.

  - ◦ **DR 6.2.1:** The landing system shall not exceed 2.5 kg.
    Motivation: The aircraft must be able to carry the weight of the landing system throughout the entire flight. The performance of the aircraft during flight is the most important requirement so the landing system should not be so heavy that it would significantly change the aerodynamics of the aircraft. The AMA limits RC planes to 25 kg so the landing system was restricted to 1/10th the maximum allowable weight of the plane, for a total of 2.5 kg.
    Verification: The entire weight of the landing system including attachment mechanisms will be measured prior to attaching it to the aircraft.

  - ◦ **DR 6.2.2:** The landing system shall not increase the aircraft's total drag coefficient by more than 10%.
    Motivation: The aircraft must be able to carry the entire landing system throughout the flight. The endurance of the aircraft is critical to ARES' success, so the landing system cannot significantly impact the aerodynamics of the aircraft.
    Verification: The aircraft will be modeled and drag will be computed before and after installing the landing system. These values will be compared to ensure the requirement is met.

- **DR 6.3:** The aircraft shall be able to land in an outdoor field.
  Motivation: The aircraft will be flown outdoors above a natural field with no human infrastructure such as roads or runways. Thus, it must be able to land in such a location.
  Verification: This requirement will be met when the landing system is used to land the aircraft in an outdoor field.

  - ◦ **DR 6.3.1:** The aircraft shall be able to land on a surface with 60 cm or less vertical variation in the surface and/or vegetation.[20]

Motivation: This requirement is included as a reasonable upper limit to account for variability in the landing surface at potential landing zones. To show the versatility of the aircraft, ideally it would be capable of landing at multiple landing locations. This upper limit was also set so the customer knows exactly where the aircraft is capable of landing. The values for variation come from a credible study published in the Journal for Environmental Informatics.[20]
Verification: The vertical variability of each predicted landing zone will be measured (by measuring the maximum vertical height of nearby rocks/mounds/vegetation) to ensure it is less than the 60 cm upper limit. The requirement will be met when the aircraft lands in an area as described above.

- **DR 6.4:** The landing system and method shall not put any person in danger at any point. During landing, everyone involved will be a safe distance of 5 meters away as per Academy of Model Aeronautics (AMA) recommendations.
  Motivation: The safety of the ARES team and any bystanders or assistants is of the utmost importance.
  Verification: The landing method will not involve any physical interaction with a person. This will be verified by ensuring that before takeoff, no people are within a 5 meter radius of any potential landing zones.

  - **DR 6.4.1:** The landing system shall have the ability to be entirely autonomous or allow all operator interaction to be via remote control.
    Motivation: Prohibiting all physical interaction between the operators and the landing system allows all operators to remain a safe distance from the aircraft as it lands.
    Verification: The design space will be limited to a landing system that does not involve human interaction. This will be verified when the aircraft lands using the designed method with no physical interaction from the operators.

Note: All requirements including a * are directly driven by the customer.

4. Key Design Options Considered

4.1. Autopilot

As stated in requirement FR 4.0, the aircraft must have the ability to run autonomously with an autopilot and be able to switch on and off with the remote control. An autopilot for this purpose of controlling the box-wing aircraft will posses an Inertial Measurement Unit (IMU), GPS receiver, and a magnetometer and pressure sensor to determine altitude. The IMU measures rotational speed, acceleration, and magnetic field to return altitude and rotational velocity in order to complete the automatic feedback control. IMUs are made up of 9 sensors: a 3-axis accelerometer, 3-axis gyroscope, and a 3-axis magnetometer. The accelerometer measures acceleration along the axes and changes these accelerations into analog voltage which is then translated into binary. The gyroscope measures rotational velocity on the axes and converts it to the tilt or roll angle. The magnetometer measures the local magnetic field components along its axes by internally comparing the local magnetic field to the World Magnetic Field Model to find the altitude. The GPS receiver works by receiving data from four satellites simultaneously to pinpoint its location in 3 dimensions using trilateration: three satellites to to measure distance and one to correct any time error.

The autopilot necessary for application of this mission does not need to possess a magnetometer for precision heading. In order to traverse a circular path, the aircrafts autopilot can use GPS for pinpointing location as a function of time. For a system such as a multi-rotor copter, a magnetometer may even be harmful because of magnetic interference close to the rotors, but for a flying wing this is not a big concern. Thus, within the trade study for autopilots, if a magnetometer is not present on autopilot, it is still a viable option. An autopilot with a magnetometer can be utilized as a failsafe although this is not necessary, and it could possibly increase power consumption or cost of the product.

Each autopilot researched will work as the "processor" behind the actuators that will be used to regulate the control surfaces and the motor(s) for the propulsion system. The autopilots researched do not come with the servos or motors, just the inputs, and those components will be connected later. At this time this research is used to ensure that there are enough servo and motor inputs as necessary for the application of this mission.

With this understanding of how the components in the autopilot run the system, the following autopilot options were researched: Pixhawk 1, Pixhawk 4, ArduPilot MEGA, and Eagle A3 Super 3.

4.1.1. Pixhawk 1

The Pixhawk 1 is a commercial autopilot unit that comes as a full kit called the mRo Pixhawk 2.4.6 Cool Essential Kit. This autopilot kit has GPS, telemetry capability, redundant power supply, and microSD to log data. The Pixhawk has a magnetometer and a GPS running at about 100 W of power consumption. Pixhawks work from multirotor drones to aircrafts, and are compatible with vast UAS sizes. In addition, a boomerang gliding wing aircraft was even recommended as one of the supported configurations as can be seen in figure 4, meaning the code and control logic would only need to be slightly modified. Pixhawks use enabling and disabling channels, and can be customized by these rather than heavy coding. These enable and disable channels will directly affect altitude and feeds to the magnetometer. Pixhawks have a tuning or mixing feature that senses weight and size of vehicle and returns values to provide stability. Pixhawks do utilize Arduino code; although based on the recommendation of a Pixhawk expert from their distributing company, mRobotics.io, it should not be necessary. Servo arms and motors can be directly connected to the outputs of the autopilot, adding even more to the ease of use. The weight of the autopilot is 38 g, costs $259, has 256 KB RAM, and the following dimensions: 50x81.5x15.5 mm.

Table 2. Pixhawk 1 Pros & Cons

Pros	Cons
Continuous downlink between autopilot and controller Easily modifiable to custom aircraft Flight heritage at CU	Slower processing speed than PX4 Mixing causes slow feedback enabling instability with turbulence

4.1.2. Pixhawk 4

The Pixhawk 4 is a newer version of the commercial autopilot. It possesses the same features as the Pixhawk 1 in that the IMU contains an accelerometer, gyroscope, magnetometer, barometer and GPS positioning. The main notable difference between the Pixhawk 1 and Pixhawk 4 are in the power consumption and processing speed. The power module output for the two autopilots are very similar, with PX1 having 3.3-6 V and PX4 containing 4.9- 5.5 V. However, the important voltage difference between the two are in the servo rail inputs. For the PX1 it is 7 V and for the PX4 it is up to 36 V, which can translate into having stronger servos (thus more maneuverability with control surfaces) for the aircraft. Furthermore, the Pixhawk 4 weighs 15.8 g, costs $211, has 512 KB RAM, and the following dimensions: 44x84x12 mm.

Table 3. Pixhawk 4 Pros & Cons

Pros	Cons
Continuous downlink between autopilot and controller Fast processing speed Flight heritage at CU	Power consumption

4.1.3. ArduPilot MEGA

The ArduPilot MEGA (APM) 2.8 Flight Controller Board is the official hardware component of an open-source software package for autopilots. The ArduPilot software works with other hardware packages as well, including the Pixhawk family of autopilots. It is most notable for its ease of user interaction and its ability to work with many vehicles: multi-rotors, planes, and tilt-rotors. The ArduPilot software is versatile and work with a variety of Ground Control Station (GCS) software to allow for autonomous takeoff, flight, and landing. The ArduPilot MEGA is easily customizable and contains software for multiple airframes. Software packages already exist for control surfaces such as flaperons and specific pre-programmed servo functions for elevon-controlled aircraft. The ArduPilot MEGA regulates 16 W of power, weighs 100 g, costs $100, and has the following dimensions: 50.5x45x13 mm.

Table 4. ArduPilot MEGA Pros & Cons

Pros	Cons
Continuous downlink between autopilot and controller Can easily tune features to be used for specific uses Best interface for ArduPilot software	Does not have box-wing designs GPS component is separate

4.1.4. Eagle A3 Super 3

The Eagle A3 Super 3 is an RC stabilizer/autopilot package from Motion RC. Its main purpose is to assist an RC pilot control their plane, but it can be modified to perform simple maneuvers on its own. The RC assistance would still be helpful during test flights or RC portions of the flight to reduce the chance of a catastrophic accident. The Eagle A3 programming software comes with configurations for flying wing designs and other unconventional control surface setups but does not have one for a box wing specifically. The Eagle A3 itself is just $67, and the total cost of the setup including receivers and radio is about $150. The system works off of 4.8 to 8.4 V for 32-bits of data precision using a 3-axis accelerometer and 3-axis gyroscope. The controller weighs in at 10 g and measures 43x27x14 mm.

Table 5. Eagle A3 Super 3 Pros & Cons

Pros	Cons
Lightweight	Limited autopilot maneuvers
Supports custom aircraft	No supported downlink
Assists RC flights	

4.1.5. Vertone Autopilot

The Vertone Autopilot is a fully-functional autopilot developed by Embention, a Spanish UAV company. Using a 3-axis accelerometer, 3-axis gyros, a 3-axis magnetometer, and support for external sensors and data processing, this autopilot could also take the place of a separate microcontroller. Its built-in temperature, pressure, and voltage sensors, as well as a GPS receiver, let it provide full functionality right out of the box. The system includes many systems for data downlinking and controlling. It has support of many aircraft types and is designed to also work with custom aircraft. It can support a wide variety of control surfaces, including elevons. Dozens of pre-programmed flight patterns are included with the package, and more can be installed easily as it is designed to allow for customization towards custom aircraft. It is a larger unit at 190 g and 63x39x67.9 mm. Its power draw ranges between 5 and 15 W off of 6.5-36 V, depending on settings for downlink and data quality. Unfortunately, this system is also very expensive at over $1700, not including international shipping and other fees. The company which develops this device is also relatively small, so there could be issues with lead times and support.

Table 6. Veronte Autopilot Pros & Cons

Pros	Cons
Flying wing support	Very expensive
Supports custom aircraft	Heavy
Support external sensors	Large
Extensive included software	Small, international company

4.2. Wing Design

As stated in requirement FR 2.0, the aircraft design must be a box wing configuration with a span no larger than 2 meters and have the possibility of increasing aspect ratio. As per customer request, the air frame must not include any additional fins or a tail, a fuselage, or any other external aerodynamic feature, meaning it consists solely of two wings separated by connecting walls on the left and right wing tips and only one strut in the middle to connect the top and bottom. Wings are needed on the aircraft to produce lift; therefore, multiple wing design options must be considered. When shapes are considered, especially for increasing aspect ratio, simple geometric shapes have to be utilized to allow for easier analysis. Similarly, many properties of the shapes have to be evaluated such as the aerodynamics, structural properties, and other characteristics.

The following designs all incorporate some kind of wing stagger, meaning that the bottom wing is farther aft than the top wing in all designs. There are multiple reasons for this design choice. Primarily, shifting back the lower wing will increase longitudinal stability. While we cannot have an actual tail on our aircraft, having the lower wing farther back will effectively increase the moment arm on any force it produces. This means that if there is a positive elevation angle disturbance on the aircraft, the lower wing will have more lift than nominal, and the longer moment arm will result in a larger restoring torque applied to the aircraft. This larger restoring torque directly relates to static longitudinal stability. Additionally, the wings will not affect each other as much if they are staggered. Lastly, a study on lift over drag was conducted for the previous iteration of the Eagle Owl, and it was found that more stagger resulted in a higher lift to drag ratio (L/D). This is important for ARES' design because a high aerodynamic efficiency will be needed to achieve the two hour flight time. While the group will do a trade study on how much stagger is needed later on in the design process, a study like this would require advanced computational techniques beyond the scope of this document.

4.2.1. Pentagon

The pentagonal wing design is very easily described by the name. It carries 5 angles and is most notable for heritage, as it is the wing shape of the Eagle-Owl. A pentagon shape for the wing looks like the following.

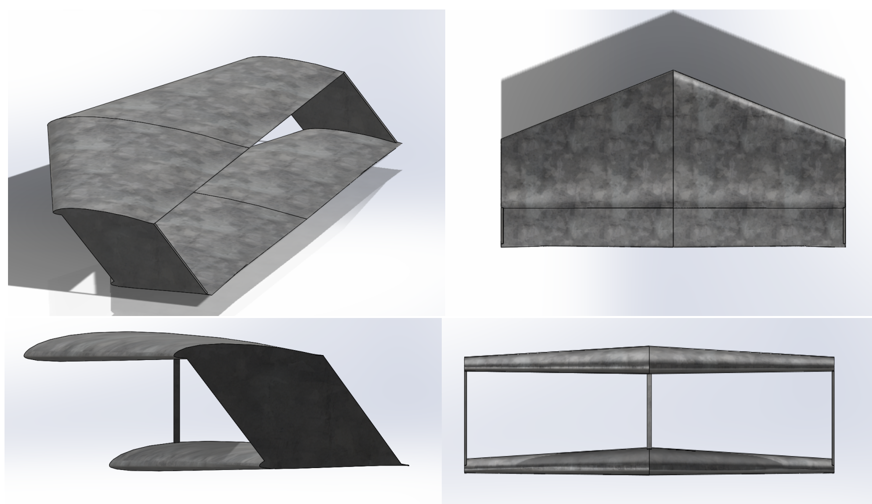


Figure 3. Sample Pentagon Design

Table 7. Pentagon Planform Pros & Cons

Pros	Cons
Flight Heritage	Difficult to increase AR while maintaining pitch/yaw
FADS research available	Excess surface area
Structurally sound	Shallower lift curve due to sweep

4.2.2. Boomerang

The boomerang wing design is also known as a swept back wing. It carries front and rear sweep. This wing shape has beneficial characteristics including increased yaw and pitch stiffness as well as ability to easily increase the aspect ratio and therefore increase L/D. Due to the shape, the overall surface area is equivalent to that of a rectangle, therefore making the shape efficient for increasing span without having excess surface area.

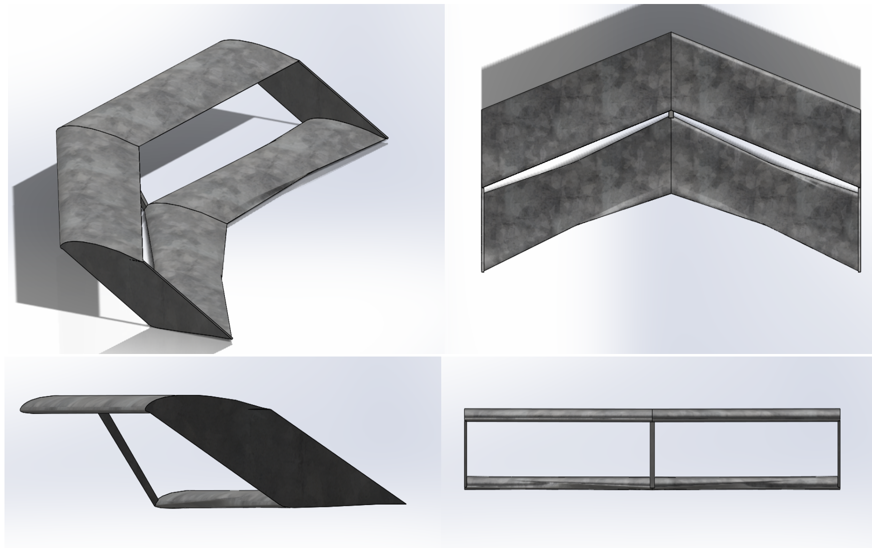


Figure 4. Sample Boomerang Design

Table 8. Boomerang Planform Pros & Cons

Pros	Cons
More yaw stiffness	No flight heritage
Easier to increase AR	Less structural integrity
Better pitch stiffness	Even shallower lift curve
More pitch control authority available	Slightly harder to manufacture

4.2.3. Rectangle

The rectangular wing design is a surface with 4 corners and is very well defined. The surface area is very adaptable and has heritage, especially with biplanes from early studies of aviation. Although a simple shape, rectangles are very well known for being structurally strong as well as simple to manufacture and analyze. Since a rectangle only has 90 degree angles, the calculations and ability to modify the wing are simplified.

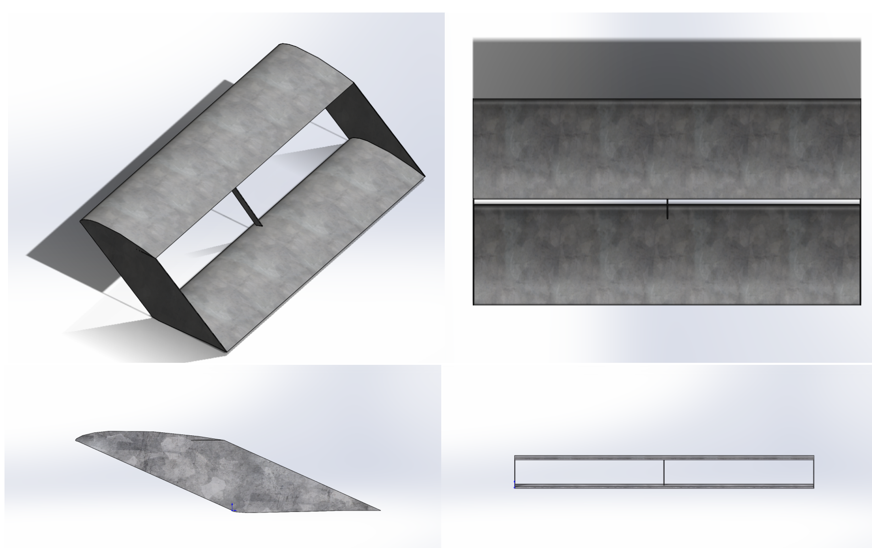


Figure 5. Sample Rectangle Design

Table 9. Rectangle Planform Pros & Cons

Pros	Cons
Structurally strong	Less stable in pitch and yaw
Simple to manufacture	More induced drag
Simple to increase AR & L/D	
Easy to analyze	

4.2.4. Diamond

The diamond wing design is easily describable for the horizontal diamond shape that is created from the inverted boomerang lower wing. The diamond planform consists of a boomerang shape on top with an inverted boomerang design on the bottom. This design was considered due to its superior longitudinal stability over the boomerang design.

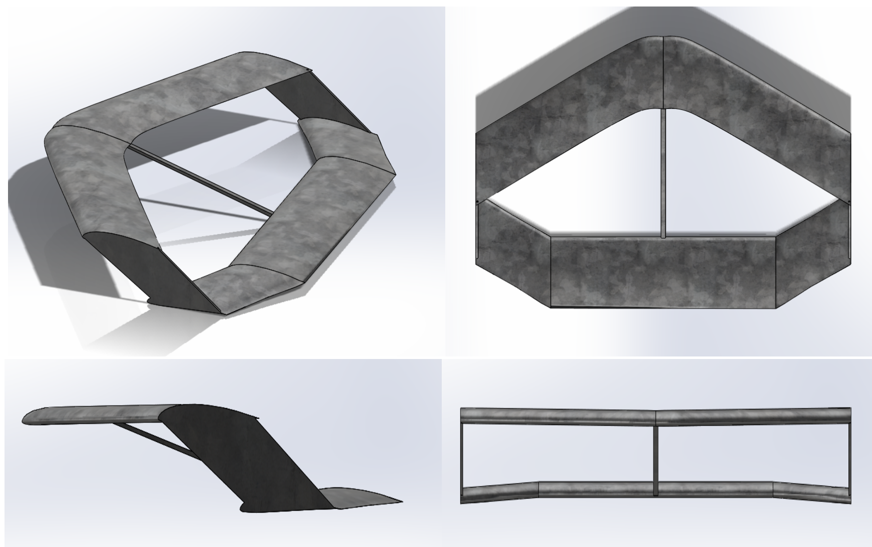


Figure 6. Sample Diamond Design

Table 10. Diamond Planform Pros & Cons

Pros	Cons
Most pitch stiffness	Structurally weaker
Strong yaw stiffness	More difficult to make
Minimal wing interference	

4.2.5. Boomerang Top Rectangular Bottom

The final design option was the Boomerang Top Rectangular Bottom wing design (BTRB). This design was made to be a compromise between the rectangle simplicity, the boomerang yaw stability (from sweep), and the diamond longitudinal stability. As shown in the CAD models, the design has a top wing with sweep, and a bottom wing with a rectangular planform.

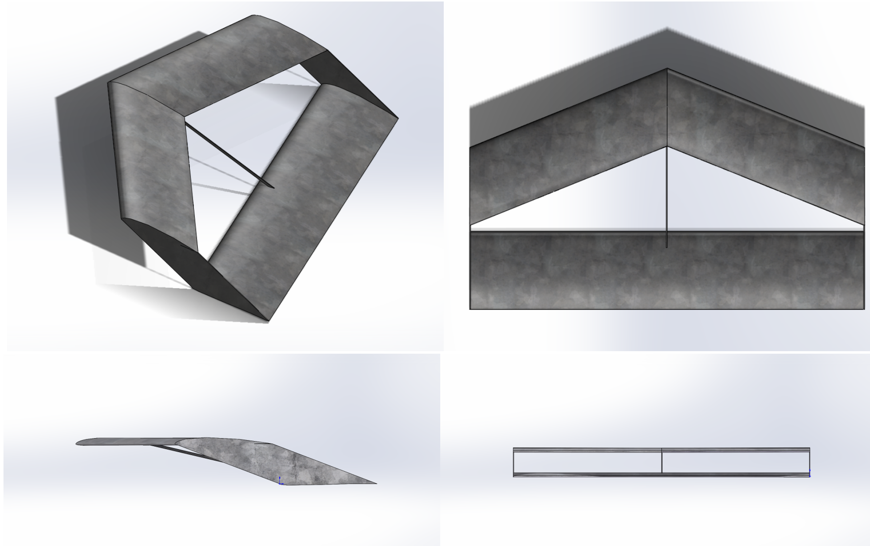


Figure 7. Sample BTRB Design

Table 11. BTRB Planform Pros & Cons

Pros	Cons
Easier to make than diamond	Significant stress on strut
Strong yaw stiffness	Separate planform designs
Good stability	Spar will have to be longer

4.3. Propulsion

Functional Requirement 1.0 states that the total flight endurance for the aircraft must be at least 2 hours. This requirement is the over-arching goal of the customer for this aircraft, and as such the propulsion system will play a big part in meeting this requirement. Common propulsion systems for RC aircraft are primarily propeller based, so for the purpose of this trade study, three different propeller configurations will be considered. The first is a traditional pusher design, where the propeller is located on the stern of the aircraft. The second is a traditional tractor, or puller, design, where the propeller is located at the bow of the aircraft. The final design option is a push/pull configuration, where there is both a pusher and puller integrated into the aircraft. To eliminate variability in all the designs, the motor(s) are mounted at the center of the span, either at the leading edge or trailing edge of the upper wing.

4.3.1. Pusher Configuration

The pusher configuration is a propeller propulsion system that is located on the stern of the aircraft. This means the propeller is located behind its respective engine indicating the draft shaft is in compression. The pusher configuration works by providing thrust at the stern, ”pushing” the aircraft along.

Pusher configurations are increasing in popularity for RC aircraft because the location allows for the wing to experience undisturbed, free-stream air. This reduces the skin friction drag on the wing[27]. However, wing mounted pushers produce vibrations because the propeller is subject to a pressure difference from the wake from the upper surface of the wing and the wake from the lower surface[26]. This vibration leads to acoustic noise and potential signal noise in data. Finally, this same pressure difference due to the different wakes can reduce the efficiency of the propulsion system[26]. In order to counter this effect, pusher systems tend to be installed a distance from the stern edge of the wing. This requires additional mass to provide structure to support the motor.

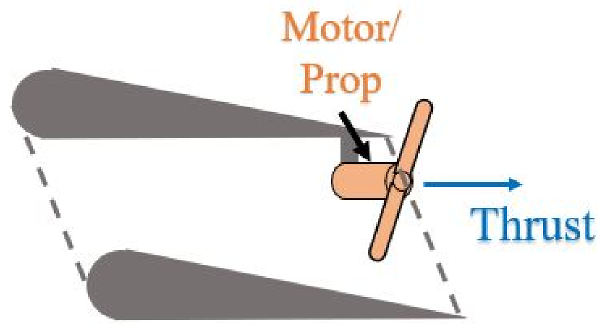


Figure 8. Pusher Configuration.

Table 12. Pusher Configuration Pros & Cons

Pros	Cons
Reduces drag on wing	Vibrations
Flight heritage	Weight
	Acoustic noise
	Decreased thrust due to turbulent flow from aircraft body

4.3.2. Puller/Tractor Configuration

The puller, or tractor configuration, is where the propeller is located on the bow of the aircraft. This means the propeller is fore of its respective engine, indicating the drive shaft is in tension. The puller configuration works by providing thrust at the bow, ”pulling” the aircraft along.

Puller/tractor configurations are at least 12% more efficient under the same thrust output when compared to pusher configurations[24]. This is due to the pressure difference from wake decreasing the efficiency of pushers. Pullers experience undisturbed, free-stream air during flight, and as such perform better. However, the puller configuration disturbs the air behind the propeller, and the resulting turbulence reduces the performance of the wing[25]. This effect can be reduced if the propeller is located inline with a fuselage, but since the aircraft will have no fuselage, the decrease in performance must be taken into account. Puller configurations increase maneuverability of the aircraft because the weight of the engine is at the front of the aircraft[25]. This impacts the center of gravity, improving the stability of the aircraft.

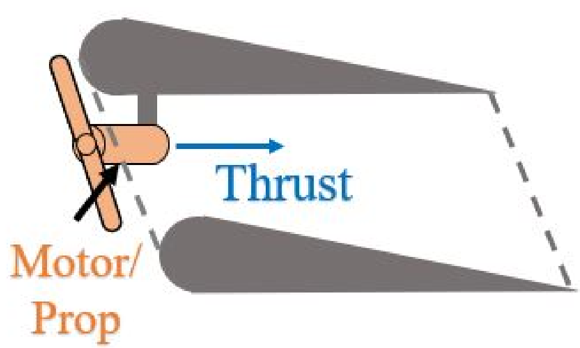


Figure 9. Puller Configuration.

Table 13. Puller Configuration Pros & Cons

Pros	Cons
Weight placement at center of gravity	Limited heritage on swept wing RC aircraft
Increases dynamic flight stability	Increases drag on body
Extremely common configuration in commercial/private aviation	Propeller exposed during landing
Increased thrust/power efficiency due to only free stream effects	

4.3.3. Push/Pull Configuration

The push/pull configuration involves two inline propellers that rotate in opposing directions. The aft propeller is in the push configuration, and the fore propeller is in the pull configuration. The propellers can be split between the bow and stern or co-located somewhere in between. The propellers rotate in opposite directions to offset the moment from the rotating drive shafts.

The rear engine in the push/pull configuration operates in the disturbed air from the fore engine, which can reduce its efficiency to 85% of the forward engine[24]. The advantage for this aircraft is it provides the ability to mount two propellers on the aircraft's center line, therefore avoiding the increased drag that comes with the twin wing-mounted engines for the same thrust product.

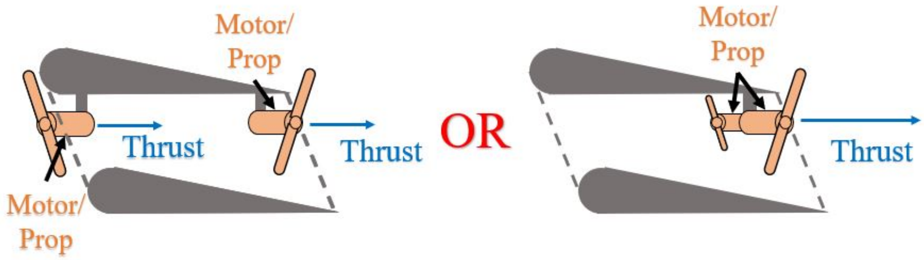


Figure 10. Push/Pull Configuration.

Table 14. Push/Pull Configuration Pros & Cons

Pros	Cons
Thrust provided along the center line	Weight, cost, and power of two motors
Weight from engines can be divided longitudinally	Rear motor efficiency drop

4.4. Takeoff System

As stated in FR 3.0, the aircraft must be able to demonstrate a controlled takeoff. Control is defined by the ability to limit the lateral heading, launch angle, and initial velocity to specified parameters. To this end, a takeoff mechanism must be chosen that satisfies these requirements. In addition, FR 6.0 states the necessity of the aircraft to be able to land and takeoff 10 times consecutively with only fifteen minutes on the ground between landing and takeoff. While some damage to the aircraft due to takeoff is allowed, any repairs to the aircraft taking longer than fifteen minutes after landing is prohibited by customer requirement, so the launch mechanism cannot damage the aircraft to this extent. Two common methods of launching RC drones include hand launching and car launching. Both methods are eliminated by customer request, due to the safety issues involved with hand launching and the progression of the customer's program away from car launching.

Five takeoff methods were researched: an independent vertical rotor, a tiltrotor design allowing for vertical takeoff, a rail system using bungee cords, a rail system using compressed air, and a conventional takeoff. These are evaluated and described in this section.

Several other methods of takeoff were discussed, but did not merit a place in a trade study. The first of these methods was a trebuchet system, where a counterweight would swing a lever and launch the aircraft. While evidence was found to support the possibility of manufacturing this system, it was decided that the launch process posed an unacceptable risk to the aircraft due to the unpredictable and uncontrollable nature of the launch[6]. The second method to be discussed consisted of a tall standing structure that would drop the aircraft from a high height. The aircraft motors would be spun up prior to release from the structure and after release would use the rotors to pick up initial velocity as it falls to the ground. Assuming constant acceleration due to gravity, thrust from the motors equal to at least 1/3 the weight of the aircraft, and a necessary velocity of 25m/s for flight, this structure would need drop the aircraft from approximately 24m high. Therefore, this method was discarded due to the height required for the structure in order for the aircraft to reach flight speed before it hit the ground. It was also found that there is little to no evidence to show other RC launches had used this system in the past. A third method considered was similar to the bungee and pneumatic rail systems, but was powered by bottle rockets instead[7]. This method was discarded after research into the number of rockets needed and the cost of these rockets. Assuming a worst case scenario where the aircraft is 25 kg, the aircraft would need a minimum of 42 bottle rockets to achieve an initial velocity of 25 m/s. If we assume the aircraft must take off a minimum of 30 times for all testing the number of rockets needed would cost more than $3000. This is assuming a worst case scenario, but this cost is much to large to have this option be feasible to trade.[8,9]

4.4.1. Independent Vertical Rotor

An independent vertical rotor system is a vertical takeoff method that provides vertical thrust to the ARES aircraft for launch capabilities. This rotor would be independent of the main horizontal thrust motors as depicted in the upper left of figure 11. On the ground, the vertical rotor, in a puller configuration, is spun up and the vertical thrust pulls ARES off the ground. Once the aircraft reaches an altitude of approximately 50 feet the horizontal motors will be spun up to provide horizontal velocity to the aircraft, shown in the upper right of figure 11. ARES will begin to attain lift from the wings as its velocity increases. Once ARES reaches the aircraft's flight speed the vertical rotor will be powered off and the aircraft will continue until it reaches cruise altitude with the use of the horizontal motors, depicted on the bottom of figure 11.

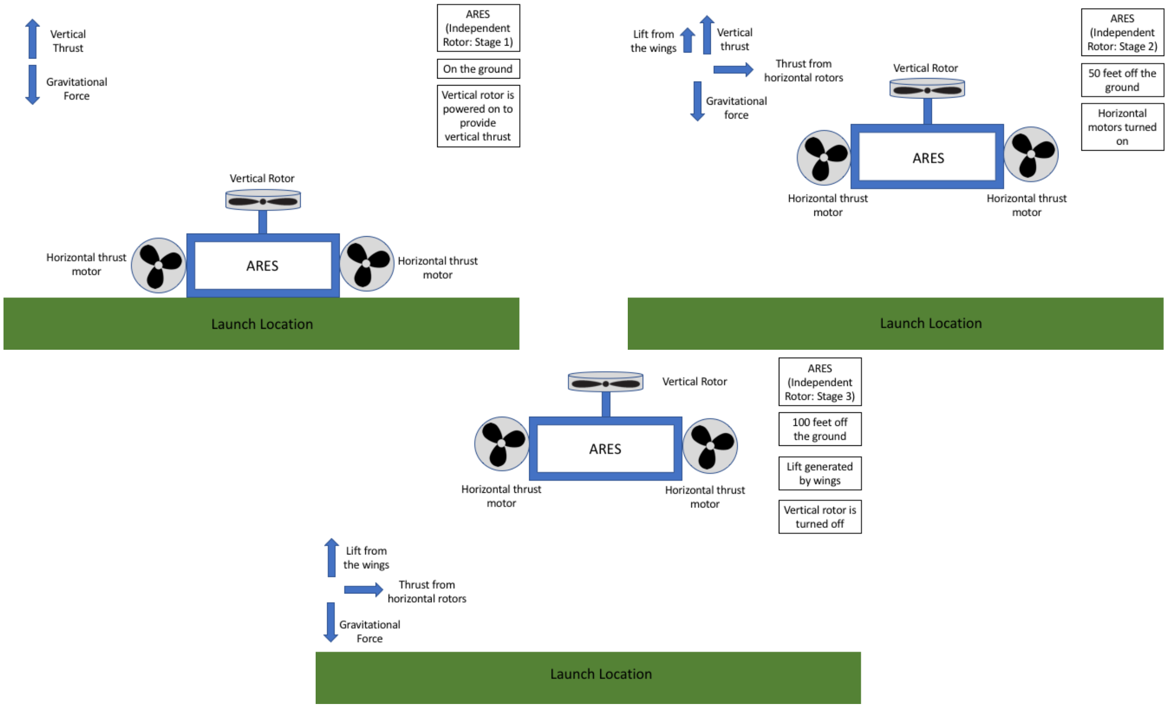


Figure 11. Independent Vertical Rotor Diagram

Table 15. Independent Vertical Rotor Pros & Cons

Pros	Cons
Ability to provide for takeoff and landing due to the vertical thrust capability Takeoff can be done on any terrain Internal to the aircraft (no external mechanism is necessary) Initial velocity is controlled by pilot Adds no additional transport difficulty	Strong winds may cause challenging takeoff Increased drag due to additional rotor Increased weight (reducing flight performance) Increased power consumption (reducing flight time) Stability changes (due to change in center of mass) Additional cost from extra rotor(s)

4.4.2. Tiltrotor

This is another vertical takeoff method similar to the independent rotor method. When the aircraft is on the ground the motors are angled towards the ground and provide vertical thrust by pushing air downward, a pusher configuration. This is depicted in the upper left of figure 12. The aircraft will rise until it reaches an altitude around 50 feet in which the motor/motors will be rotated to 45 degrees from the ground, shown in the upper right of figure 12. This will increase the aircraft's velocity, which allows for the wings to start providing lift to the aircraft in combination with the vertical thrust from the motors at 45 degrees. Once the aircraft reaches its flight speed the motors will be rotated to be 90 degrees from the ground, shown on the bottom of Figure 12. The aircraft will be at a speed large enough to provide lift from the wings to sustain altitude and the vertical thrust from the motors will not be necessary.

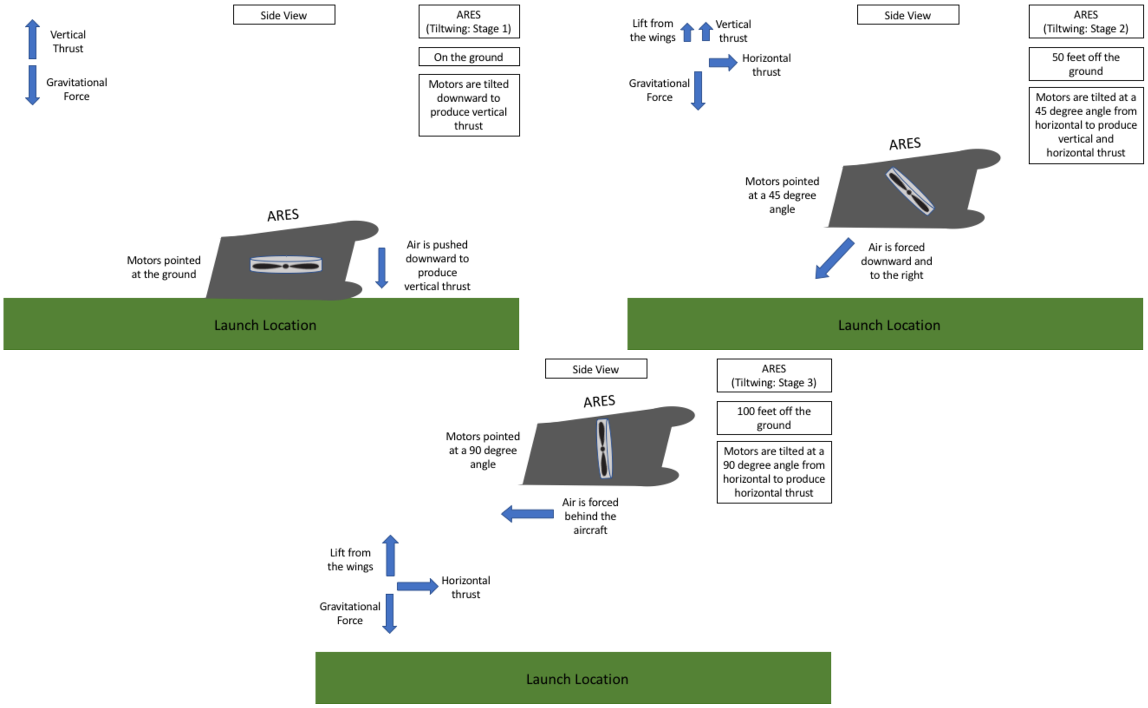


Figure 12. Tiltrotor Diagram

Table 16. Tiltrotor Pros & Cons

Pros	Cons
Ability to provide for takeoff and landing due to the vertical thrust capability	Strong winds may cause challenging takeoff
Takeoff can be done on any terrain	Rotation of motors is incredibly complex to control
Internal to the aircraft (no external mechanism)	Challenging to integrate a rotating motor system onto the aircraft
Control-able by pilot during launch	Difficult to control stable thrust transition
Adds no additional transport difficulty	Adds additional moving parts - power draw and mechanical complexity

4.4.3. Bungee Cord Rail System

This system looks similar to a crossbow; rails allow for the aircraft to move up an inclined ramp to provide an initial velocity and a slight initial altitude. Two rails are built on the sides of the ramp with space in the center to allow a string or other item to be pulled along. Bungees will be used to provide velocity to the aircraft so the aircraft can move up the rails. The bungees are staked to the ground and attached to a flight string that is looped at its far end to allow for connection to a hook deployed on the bottom of the aircraft. The aircraft will be pulled back and locked into place at the bottom of the ramp to apply tension to the bungees. This process is shown in Figure 13. When the locking mechanism is released the bungees will pull the aircraft up the rails and off of the ramp. Once the aircraft has enough speed to attain lift from the wings the flight string will be released from the hook and the aircraft will continue to climb until the aircraft reaches its cruise altitude. The force to move the aircraft in this system could also be done through the use of an electric winch. This would be more costly but improve safety for the team. This will be studied further in the preliminary design review if this system is found to be the best option.

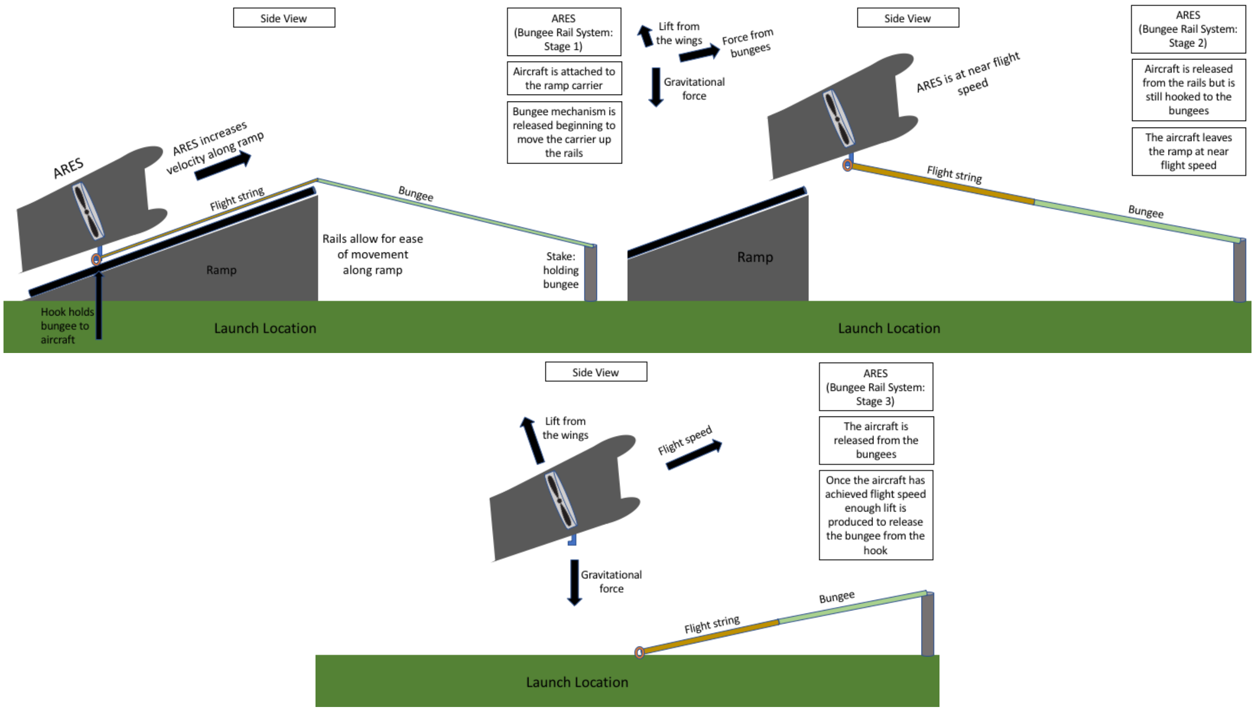


Figure 13. Bungee Rail System Diagram

Table 17. Bungee Cord Rail Systems Pros & Cons

Pros	Cons
Significant flight heritage Provides well defined heading (due to rails) No aerodynamic effects on the aircraft during flight Headings are easily reproducible Bungees are a low cost way to provide force	Must be launched on a relatively flat surface The ramp system may need to disassemble for transport Additional manufacturing time to build ramp system Requires a number of additional moving parts and mechanisms that could fail

4.4.4. Pneumatic Rail System

This system is similar to the bungee rail system but instead of bungees being used to provide movement along the rails, compressed air is used. A compressed air tank sits at the base of the ramp and is connected a PVC pipe that sits in between the rails. A carrier rod is placed inside the PVC pipe with a flight string attached to the end. The flight string connects to a hook on the bottom of the aircraft. This system is depicted in the upper left of figure 14. Compressed air is pushed through the PVC pipe and the carrier rod is therefore pushed out of the pipe pulling the aircraft along with it. Once the carrier rod leaves the PVC pipe the aircraft will also be pulled off the end of the ramp system, shown in the upper right of Figure 14. The aircraft will have attained lift due to the now nonzero free stream velocity, provided by the launch system, and the aircraft will climb, releasing the string from the hook. The aircraft will then ascend to its cruise altitude to complete its mission, depicted in figure 14.

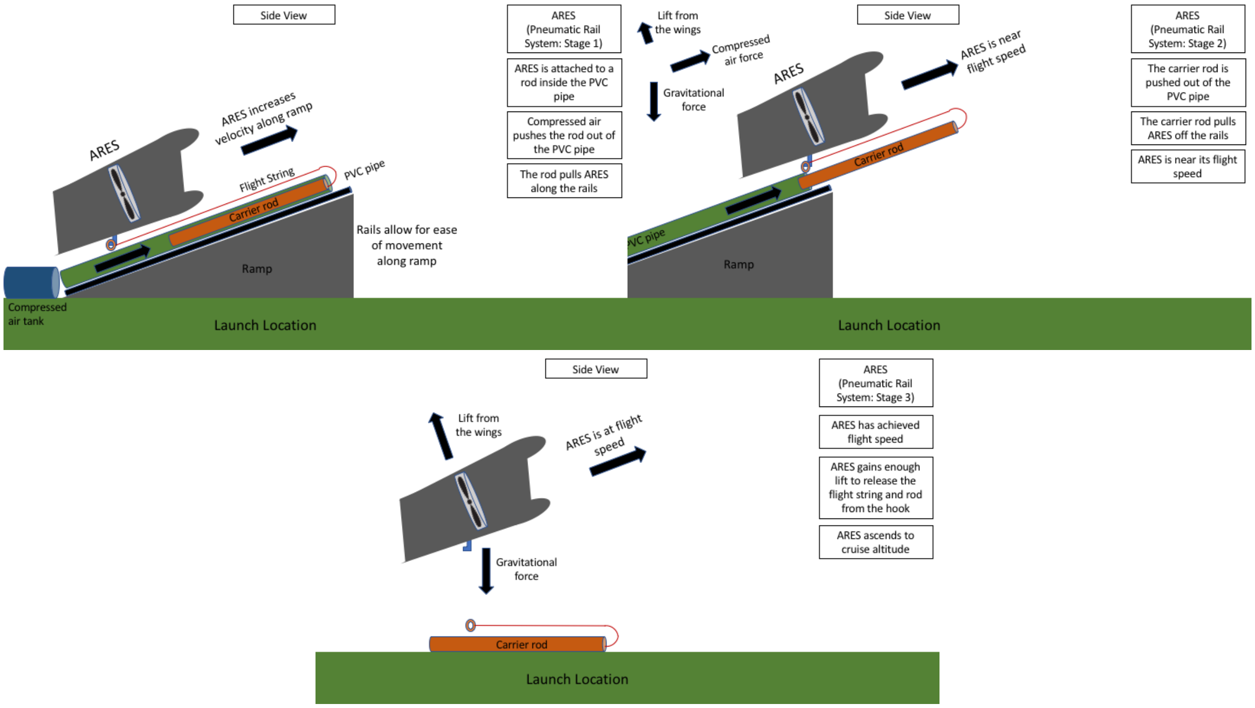


Figure 14. Pneumatic Rail System Diagram

Table 18. Pneumatic Rail Systems Pros & Cons

Pros	Cons
Has some flight heritage (not as common as the bungee system)	Provides a large initial impulse on the aircraft structure
Provides well defined heading through rail system	Must be launched on a relatively flat surface due to ramp system
No aerodynamic effects on the aircraft during flight	The ramp system is large and may need to fold or disassemble for transport
Large initial velocity	Calibration complexity of pneumatic tank
	Heading is not as well controlled due to large impulse from compressed air

4.4.5. Conventional Takeoff

This system is a basic/conventional takeoff where the aircraft has wheels or landing gear allowing the aircraft to travel across the ground until enough velocity is attained to ascend. This is shown in figure 15. The engine will be started on a relatively flat ground and the aircraft will gain velocity and begin to travel along the ground. Once the aircraft has achieved enough velocity to fly the pilot will increase the throttle and the aircraft will begin to climb off the ground. This climb will continue until the aircraft reaches its cruise altitude. In the case that the landing systems trade does not come to find that wheels are the best option, the system could be built similar to a U2 recon in which the wheels are not attached and remain on the ground after launch.

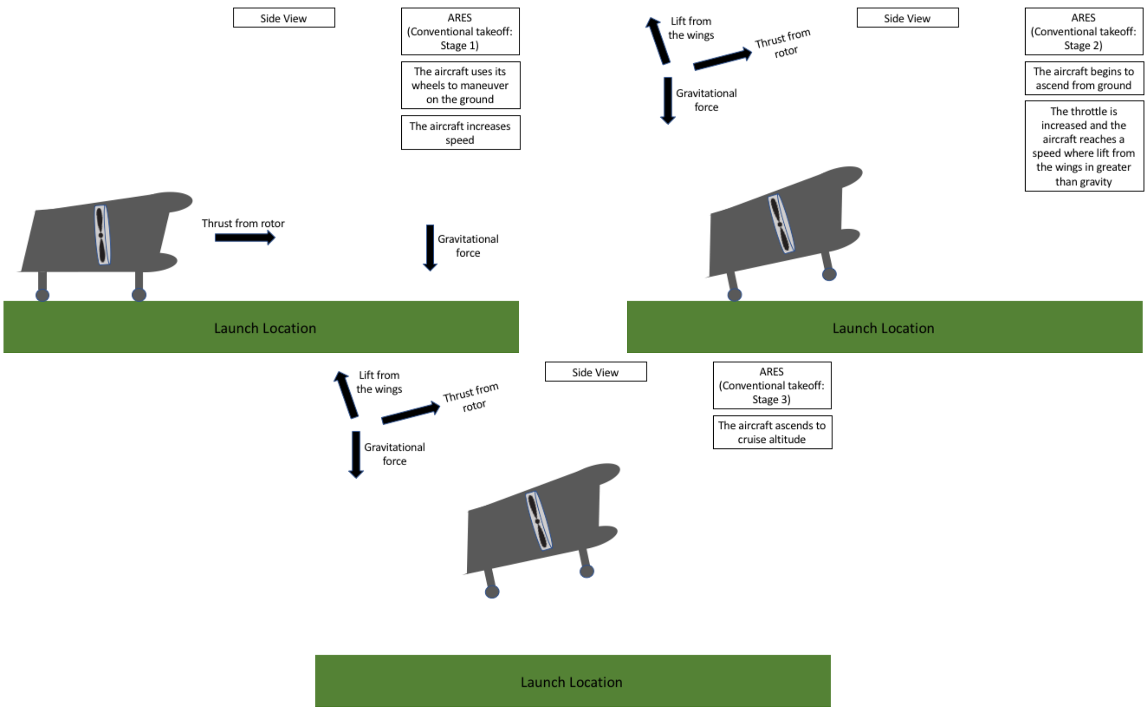


Figure 15. Conventional Takeoff Diagram

Table 19. Conventional Takeoff Pros & Cons

Pros	Cons
Very low complexity (attachment of wheels)	Must be launched on a relatively flat surface for wheels
Easy to manufacture	No rudder will make yaw control during take-off challenging
Accommodates both takeoff and landing systems	Will have slight detrimental affects to the aircraft stability and center of mass
No additional transport needs	Additional drag caused by additional surface area from the wheels and struts
	Difficult to launch in windy conditions

4.5. Landing System

In order to satisfy requirement FR 6.0, the aircraft must be able to land with minimal damage to all systems. Additionally, for simplicity and ease of use, the customer requires that ARES is able to land without the use of any external systems, meaning all required landing equipment must be carried on board the aircraft for all phases of flight. In order to keep the aircraft from sustaining major damage, this landing system must enable the aircraft to touch down in a controlled manner and cannot cause any forces or impulses that would result in major damage. For operator safety, the all interaction from team members shall be through remote control signals sent to the aircraft, allowing all team members to be at least 5 meters away from the landing zone. The following designs are considered as possible candidates for the landing system: parachute, conventional landing gear, skid or controlled crash landing, and vertical landing. Each is described in detail below.

4.5.1. Parachute

The first landing system option is a parachute. This fabric parachute will be packed aboard the aircraft in such a way that it minimizes its effects on the flight performance, and when the aircraft needs to land, it will be deployed from a suitable altitude as the thrust is cut. The parachute will have suitable time to fill completely as the aircraft begins to fall, and it will create enough drag (vertically) that the aircraft falls to the ground smoothly and in a controlled fashion.

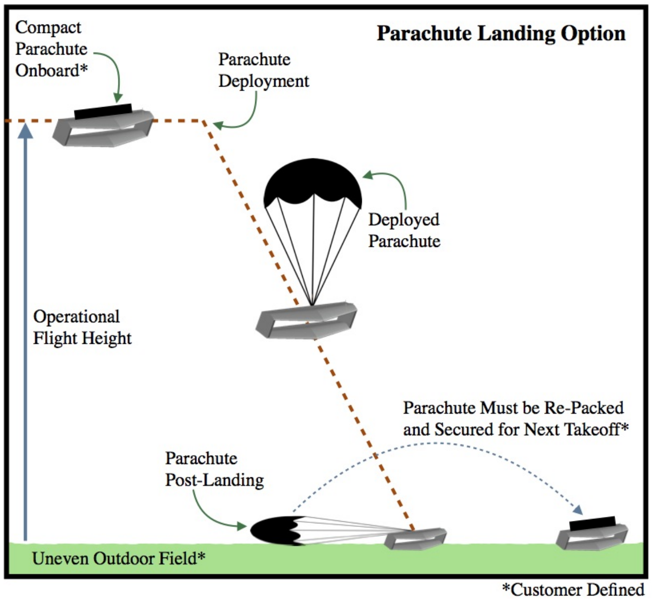


Figure 16. Parachute Landing System Operation

Parachutes are a relatively reliable system that allow for a way to land the aircraft in the event control is lost in the air, the signal to the remote control is lost, the autopilot malfunctions, and other unexpected issues. They allow for landing on nearly any terrain and can be remotely deployed to keep all operators out of danger. The main concerns involved with parachutes involve windy conditions that can take the aircraft far from the desired landing zone or drag it across the ground after touchdown, the inherently unpredictable landing location, and if there is an issue with deployment, there is no safe way to land the aircraft. The full pros and cons list is below.

Table 20. Parachute Pros & Cons

Pros	Cons
Easy to design/purchase	Must repack before takeoff
Lots of flight heritage	May be damaged by winds
Provides failsafe for loss of control	Material may rip on ground
Deployable at high altitude	Unpredictable landing location
Easily testable	Major damage if it fails
Allows for landing on most terrain	
Options for folding to limit drag	
Can place on wing to make cg ideal	

4.5.2. Landing Gear

Next on the list of options for potential landing systems is conventional landing gear. This consists of at least three fixed struts with wheels attached that allow the aircraft to touch down and roll to a stop.

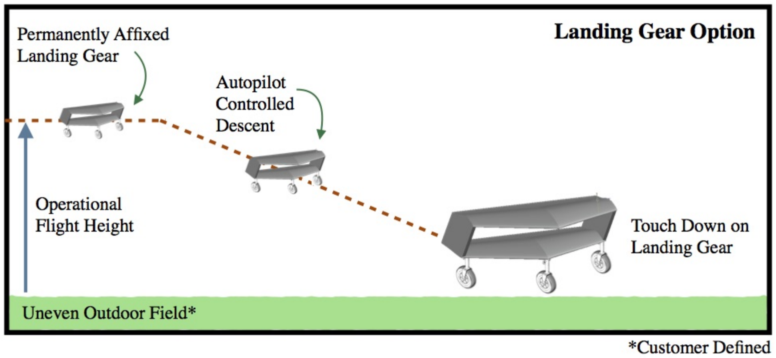


Figure 17. Landing Gear System Operation

The most common configuration of landing gear is the ”tricycle” configuration, in which one wheel is near the nose, and two others are aft and coaxial with each other.[18] This allows the aircraft to remain fully supported when in contact with the ground. This tricycle style forces the rear wheels to touch down first, causing a forward pitching moment that decreases lift. Similarly, it allows for the nose to rise to a desired angle of attack on takeoff, if a conventional takeoff is chosen as the desired system. Thirdly, this configuration allows for the best maneuverability when on the ground. The wheel and tire selection plays a critical role in the landing gear design as well. Most other design issues with landing gear involve the taxi and takeoff stages, which do not concern the ARES mission.

The challenge here is to design gear that allows for landing on the rough terrain where ARES will be tested. In order to comply with DR.6.3.1, the landing gear must be robust enough to traverse wide variation in the terrain and vegetation. The average height of vegetation is $\approx$60 centimeters, and the acceptable height of rocks and roughness is $\approx$15 centimeters.[20] This drives the minimum wheel diameter to be 15 centimeters. Wheels of this size are impractical due to the fact that they will not be able to stow inside of the wing during flight, and will therefore add extreme amounts of drag to the aircraft. This issue can be counteracted by using skids to land (such as on a helicopter or float plane), but then the stability of the aircraft becomes a huge factor. The friction induced by landing on a non-rolling surface would be almost guaranteed to cause the aircraft to flip/tumble. In order to reduce complexity of the system as much as possible and because of the unique fuselage-less design, the gear must remain fixed in the downward position through all phases of flight.

Table 21. Landing Gear Pros & Cons

Pros	Cons
Lots of prior design / heritage	Cannot land in rough terrain
Not a complex design	Mechanical component
Minimal impact to body on landing	Causes large amounts of drag
Predictable landing location	No fuselage for convenient integration
	Fixed position changes aerodynamics

4.5.3. Skid/Crash Landing

The third solution in question is for the aircraft to simply descend until it impacts the ground. In this case, the aircraft frame will be hardened to be able to withstand impact with the ground. Likely, some sort of low altitude stall will occur and the aircraft will use some sort of skid plate on the bottom to prevent damage to the bottom wing. A nose shaped strut on the leading edge may be used to prevent the aircraft from flipping over upon impact.

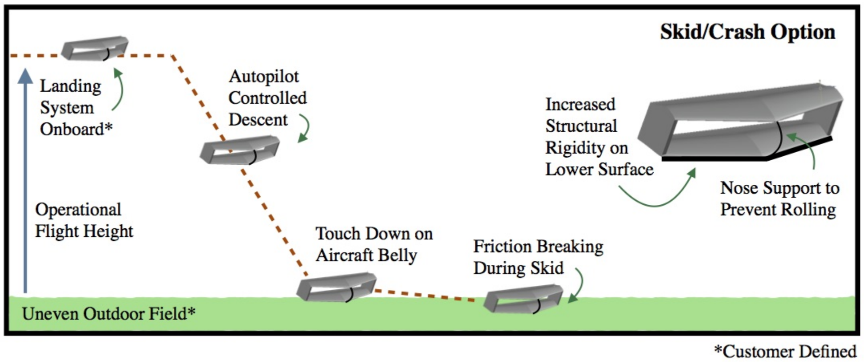


Figure 18. Skid/Crash Landing System Operation

Table 22. Skid Landing Pros & Cons

Pros	Cons
Minimal extra design	Strong material could be heavy
No mechanical components Minimal extra drag	Need to improve structural integrity
Allows for landing on most terrain Leaves design space very open	Difficult to stall/flare close to ground
Tons of RC and Eagle Owl heritage	

4.5.4. Vertical Landing

The last solution that was considered is a vertical landing system that uses propulsion to lower the aircraft to the ground. The aircraft will use a vertically oriented propulsion system to counteract its weight as it descends to the ground. This will either be a supplemental propulsion system that remains vertically oriented, or the aircraft will orient its main propulsion system vertically by pitching itself or through thrust vectoring.

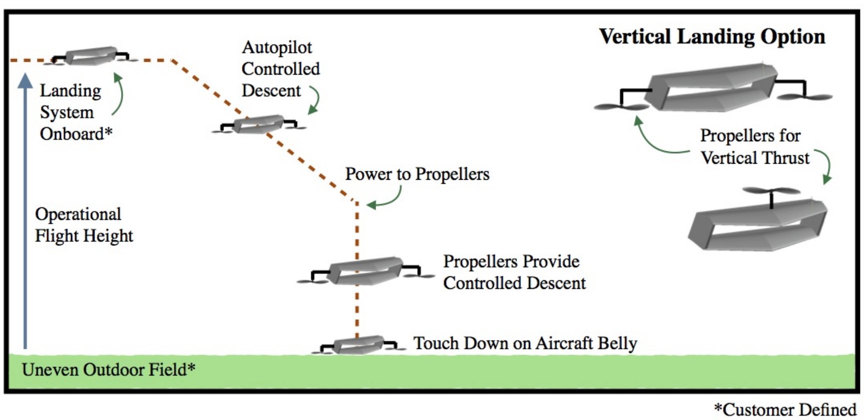


Figure 19. Vertical Landing System Operation

In order to offset almost the entire weight of the aircraft for a vertical landing, the propulsion system will have to provide as much thrust as the weight of the aircraft. This could be up to 55lbs (25kg). Generally, the static thrust provided by a propulsion system should be around $\frac{1}{3}$ of the aircraft's total weight in order to climb.[22] This means that in order to achieve a vertical landing, the propulsion system will have to provide three times as much thrust as it would regularly.

This fact is supported with a quick back of the envelope calculation. As mentioned above, the thrust T, must equal weight W for a vertical landing system. Generally, T is equal to drag, D, and the lift L is equal to W. Therefore, the ratio of lift to drag is exactly proportional to the needed thrust increase. This value can be calculated using: $L/D = \frac{1}{2}\sqrt{\frac{\pi AR\epsilon}{CD_0}}$.[23] Using the best case scenario for this calculation, the CD_0 needs to be at a maximum, and the AR and efficiency need to be minimum. These values are chosen to be 0.25, 6, and 0.25, which give a L/D of 3.760. Therefore, the propulsion system would have to be designed to provide 3.76 times as much thrust to integrate this design.

Table 23. Vertical Landing Pros & Cons

Pros	Cons
Predictable landing location Gentle touch down Can double as takeoff system Possible high-altitude deploy	Heavily affects other subsystems Requires large amount of propulsion Extremely complex system Difficult to stop horizontal motion Unnecessarily over-scopes project Difficult to control

5. Trade Study Process and Results

5.1. Autopilot Trade Study

5.1.1. Metrics

Each metric in the trade for the autopilot selection was ranked on a 1-5 scale, with 1 being the worst performer and 5 being the best. The study for the autopilot was conducted on the following features: power consumption, weight, cost, flight heritage, customization (i.e. complexity for our design), and size. After each definition of the metric a table will be provided to show what categories fell under each level

Power: The power was given a weight of 15% due to its level of importance in this study. A customer requirement is for the aircraft to have an endurance of 2 hours, and in order to accomplish this, power needs to be conserved. First, by integrating an autopilot, more power can be conserved than from RC, since the autopilot will eliminate human error of overcorrecting, which overall wastes power. However, even more, the autopilot cannot draw an excess amount of power that will drain its on-board power system in less than two hours. Generally, most small autopilots for the purposes of UAS have similar power draws that are not intensely high, and are about the same as a household fan or stereo.

Table 24. Power Scoring Definition

Estimated Power Consumption (W) :	1-40	41-90	91-130	131-170	171-210
Score:	5	4	3	2	1

Weight: The weight of the autopilot has been given a weight of 15% as well because of the design of the aircraft. Since the UAS is a box wing with no fuselage, its main weight is coming from its material and propeller system. Due to this design, an autopilot can drastically increase this weight, hurting the overall performance and the customer requirement of 2 hour endurance. However, the reason why this percentage is not a devastatingly high number is due to the fact that most of the autopilots have very similar weights, on the scale of less than 100g.

Table 25. Weight Scoring Definition

Estimated Weight (g):	1-30	30-60	60-90	90-120	120-200
Score:	5	4	3	2	1

Cost: The metric of cost was decided to be 10% as this will not have a large effect on the system. There are some very expensive autopilots, and there are cheaper commercial autopilots. Since the high end autopilots start at around $1000 the team was constrained to the cheaper, open source, commercial autopilots. Most of the commercial autopilots vary with similar price ranges so this metric can be chosen to have a low value.

Table 26. Cost Scoring Definition

Estimated Cost ($) :	30-150	150-270	270-390	390-510	510-up
Score:	5	4	3	2	1

Flight Heritage: Flight heritage is defined as being successfully used on previous missions. This metric was chosen at 35% as a customer desire is to utilize an autopilot that has been used on previous Integrated Remote and In Situ Sensing (IRISS) UAS projects. For this reason, it was necessary for the metric to be chosen as a high value. The Pixhawk autopilots, specifically Pixhawk 1, have been used on the past IRISS drones, meaning that there are multiple resources through Research and Engineering Center for Unmanned Vehicles (RECUV) for questions and and help when integrating the autopilot with the system.

Table 27. Flight Scoring Definition

Flight Heritage:	Yes	No
Score:	5	1

Customization: Customization was chosen to be at 20% due the complexity of having to integrate an autopilot that is not best suited for the unconventional design of ARES. The Pixhawks and the ArduPilot MEGA are both configurable autopilots with open source code already developed; however, there is not code specifically for a rectangular box wing aircraft design. This will add a level of complexity for the team to tune the autopilot, yet by choosing an autopilot that has flight heritage, ARES will have resources.

Table 28. Customization Scoring Definition

Development Complexity Standard:	COTS ready-to-fly autopilot supporting mission necessities	Almost ready-to-fly kit with minor modifications	Typical autopilot kit with tuning capabilities	Large complex kit without flight heritage	Significant design and tuning work for integration of autopilot to system
Score:	5	4	3	2	1

Size: The last metric scored is the dimensions of the autopilot, which corresponds slightly to the level of integration complexity. This metric was defined at only 5% because all of the autopilots are relatively small and easy to integrate within the aircraft.

Table 29. Dimensions Scoring Definition

Dimensions (mm):	under 40 mm^3	between 40-100 mm^3	over 100 mm^3
Score:	5	3	1

5.1.2. Scoring

Considering all these components and metrics used for the trade of the autopilot, the following table shows the overall calculated scores for each specific autopilot. These scores are all calculated using the categories shown in tables 24-29 and the data for each autopilot given in section 4.1.

Table 30. Autopilot Trade Study Matrix

Category	Weight	Pixhawk 1	Pixhawk 4	ArduPilot MEGA	Eagle A3	Vertone Autopilot
Power Consumption	0.15	3	3	5	5	5
Weight	0.15	4	5	2	5	1
Cost	0.10	4	4	5	4	1
Flight Heritage	0.35	5	5	1	1	1
Customization	0.20	4	4	3	3	2
Dimensions	0.05	3	3	3	3	3
Total Score	**1**	**3.83**	**4**	**3.16**	**3.5**	**2.16**

5.2. Wing Design Trade Study

In order to decide which wing design to use, a weighted system was created that used the metrics of manufacturability, stability, overall compatibility, and structural integrity. These metrics were defined based on the consideration of what factors would be most crucial to the development of the overall aircraft design and its accompanying testing and analysis. Manufacturability is crucial to this as, without a doubt, many of the prototype iterations are sure to crash and in order to stay on schedule a new model will have to built as quickly and carefully as possible. Building a relatively simple model versus an extremely complex design can save valuable project time, which is why this metric was established. Next, the stability was created as a trade study criteria as it affects the complexity of the control surface implementation and aerodynamic analysis. A more stable design will require less work and optimization in the future which is a very desirable factor. Overall compatibility with the other subsystems is also a very key metric to consider in the trade study as it eases the implementation of other crucial mission components which is extremely beneficial from a systems engineering standpoint. Lastly, structural stability was used as a deciding factor due to the design constraints given by the customer which mandate that the structure shall consist of only a single strut in the middle and walls in the exterior which connect two wings. These constraints severely limit the available structural support that can be added to the design so it is imperative that the wing design itself is relatively strong. Ultimately, all of the metrics used to conduct the trade study were chosen with practicality and flexibility in mind. The significance of each one was reflected in their respective weightings.

The effect of wing configuration to L/D was discussed; however, there are too many unknown variables to quantitatively score each design. For example, it is too difficult to distinguish the differences in the effect of air flow interference from the bottom wing with different designs, including swept back, swept forward, and rectangular configuration. It is known that the sweep angle flattens the lift curve, but the sweep angle is a variable which cannot be compared in different wing designs. Also, one of the largest contributions to L/D is the choice of airfoils. The airfoil selection process is too early on at this stage and different airfoils might be suitable for different wing configurations. Overall, the only available method of quantifying the L/D is to either conduct computational modeling such as CFD analysis, or experimental data collection, such as wind tunnel experiment with scaled model. Due to the time constraint, these methods are unrealistic for the CDD.

The weighting for each metric consisted of 25% for manufacturability, 35% for stability, 20% for overall compatibility, and 20% for structural integrity. Stability was weighted the heaviest because it consisted of a consideration of stability about all three axes as well as the fact that a baseline stability is required for sustainable flight even with the implementation of control surfaces. Therefore, the inherent stability of the design is easily the most important aspect of wing design. Next, manufacturability was given its weight based on the thought that, as stated earlier, the prototypes are expected to crash and be damaged beyond repair relatively frequently. Therefore, the difficulty of manufacturing is incredibly important as it affects how often the designs can be tested; however, it does not affect flight itself as stability does.

Structural integrity and compatibility can both be improved upon or built around in the future and do not affect sustainable flight or the time constraint as much as the previous metrics do. When it comes down to it, if there is an issue in either of these areas a solution can ultimately be engineered albeit at the expense of convenience and time which are not as critical to the mission as the plane not being able to fly or be built from the start. For example, if the design is found to be weak in a certain area this can be fixed but if the plane has a poor static margin it will not be able to fly practically, even with control surfaces. Overall, the metrics were given their weights based on their impact on flight and the mission and ability to be compensated for in the future.

No scoring guide was used for the compatibility metric as this was decided upon by averaging the scores given to each design by all sub teams based on how that particular configuration would work with their subsystems.

In order to fairly conduct this trade study, various assumptions were made for each metric. For the manufacturability, it was assumed that all designs were to be built and designed using the same programs, tools, and machines so that the score was based completely on the complexity of the design and the difficulty of how hard it would be to create. Additionally, it was assumed all designs were to be made of foam and a carbon honeycomb skeleton as previous Eagle Owl designs were. For the stability, the results were obtained by assuming all shapes had the same stagger and gap purely due to the fact that both of these parameters require extensive research to accurately design and create similar aerodynamic characteristics in both shapes. On top of this, an aspect ratio of 2.7226 (twice that of the last Eagle Owl iteration), a leading edge sweep angle, Λ, of 25°, a trailing edge sweep angle, ϕ, of 10°, and a chord length of 20 in. were assumed for all shapes.

For the overall compatibility, no assumptions were made as this was evaluated purely on how compatible the wing designs would be with the system designs chosen from the other trade studies. Lastly, for the structural integrity, the gap and stagger were assumed to be equal for all configurations as was done for the stability and so therefore the wall connections and struts were varied per design to get a sense of how they compared with one another.

5.2.1. Metrics

Each of these respective metrics were given a score between 1 and 5 with a score of 1 indicating the lowest possible performance in the category and 5 indicating the best possible performance. For the manufacturability, the designs were ranked based on their overall complexity which entailed how many unique and challenging characteristics were present, how much the manufacturing team would have to learn in order to successfully create a prototype, and how long it would take a team of minimally experienced aircraft manufacturers to create such a design in its entirety using a hot wire foam cutter and standard carbon honeycomb matrix. For example, the rectangle planform was considered to be the simplest design as it contained no front or back sweep nor taper whereas the diamond configuration was the most complex due to its prevalence of both characteristics which would require the manufacturing team to devote more time to creating the various pieces that would make it up. For stability, the wing design sub team used a conceptual check of the designs about all three axes to get a rough estimate of their respective pitch, yaw, and roll stability. This study was conducted purely using an intuitive approach as the team did not have enough time, information, or resources to conduct an in depth computational or experimental analysis on each design. Therefore, pitch stiffness was governed by an approximation of the static margin of each design based on the relative location of the design's center of gravity and aerodynamic center. If the aerodynamic center was more rearward than the potential center of gravity for one design than another, it would be given a higher score. For yaw stability, the only consideration was if a planform had forward sweep or not. If it did, then it would gain an additional point whereas if it didn't the score would not be affected. For roll stability, the only aspect that could be used was the span length relative to the pentagon; if a design had a longer span than the baseline pentagon, it would gain a point as it had a larger moment of inertia about the body x-axis whereas if it was smaller then the score would not be affected. Next, for the overall compatibility, the wing design sub team drew up CAD designs of the planform candidates and communicated with the landing, takeoff, autopilot, and propulsion sub teams and had them each assign a score for each respective design. The scores among all sub teams were then averaged for the final compatibility score. Lastly, for structural integrity, each design was given a score based on how the angle available surface area of the connecting walls and the angle and length of the center strut. A higher angle and less surface area, as is expected with the diamond, is much less structurally sound than a rectangle planform which had identical chord lengths on the top and bottom meaning it had more room for the connecting walls. For this, as was mentioned earlier, it was assumed that all designs had the same gap and center line stagger distance in order to fairly compare all designs.

The following table provides descriptions for each manufacturing score.

Table 31. Manufacturability Scoring Guide

Metric	**Simple; Minimal Learning and Time Needed**	**More Complex; Some Learning and Time Needed**	**Moderate Complexity**	**Somewhat Complex; More Learning and Time Needed**	**Complex; A Lot of Learning and Time Needed**
Manufacturability	5	4	3	2	1

Stability will be defined on a 1 to 5 scale as well. While it will be fairly difficult to evaluate a design for stability, the following table describes each score.

Table 32. Stability Relative Scoring Definition

Metric	**Best Stability for Pitch, Roll, and Yaw**	**Good Stability in Pitch, Roll, and Yaw**	**Moderate Stability in Pitch, Roll, and Yaw**	**Poor Stability for Pitch, Roll, and Yaw**	**Worst Stability for Pitch, Roll, and Yaw**
Stability	5	4	3	2	1

Overall compatibility of the design is based on the average score of how compatible all other systems are with a specific wing design. Once again, this was the average of the rank provided by each of the four subsystem teams (launch, landing, autopilot, and propulsion). Due to the fact that the other subsystem teams assigned the score, no scoring definition was needed by the wing design team. The scores themselves are assigned in the scoring section.

The structural integrity scores are based upon the central strut, the side connection strength, and the thickness of the planform itself. The central strut length is the largest variable that will determine its strength. All wall connections will be similar dependent mostly on the stagger of the planforms. However planform shape will determine overall structural integrity also due to its ability to resist folding. Therefore the structural integrity scores are described in the following table.

Table 33. Structural Integrity Relative Scoring Definition

Metric	**Best Spar Connection and Planform Shape**	**Good Spar Connection and Planform**	**Moderately Stable Spar Connection and Planform**	**Less Stable Spar Connection and Planform**	**Min. Stable Spar Connection and Planform**
Structural Integrity	5	4	3	2	1

5.2.2. Scoring

Manufacturability: Based on the manufacturing scoring guide, the pentagon design earns a 3. While the design is fairly complicated, there is some flight heritage which will speed up the manufacturing process. The rectangular wing design is very quick to manufacture compared to wings that have sweep angles. Therefore, it will be very simple and quick to make relative to other designs and earns a score of 5 for manufacturability. The Swept back wing gets the score of 2 because both top and bottom planforms are swept and they could have different airfoils, angle of attack, or geometric twist, which will increase the time to manufacture. The diamond wing gets the score of 1 due to added complexity. The bottom wing design is complicated, and it leads more time on manufacturing. On the other hand, the BTRB has a rectangular planform on the bottom, so there will be less time required to manufacture this design overall. Thus it is scored at a 2 because of the complex top wing, along with the fact that a different process will be used to construct the bottom, different planform wing.

Stability: For stability, the main concern is the longitudinal stability. This was largely because the previous Eagle Owl had no roll stability, but the control surfaces allowed for the roll direction to be controlled. Also, while yaw is important, the vertical connectors between the two planforms will help provide yaw stiffness, so all designs will be semi stable in yaw already. The scores were assigned based on the fact that pitch stiffness is dominated by the relative locations of the center of mass and the aerodynamic center. So if an aircraft has a large tail, the overall aerodynamic center will be drawn back, while the center of mass will only shift a small amount. This drastically increases pitch stiffness. With this information in mind, the following scores were assigned for stability. The strongest pitch stiffness is in the diamond wing design because the swept forward wing on the bottom shifts the aerodynamic center aft more than any other design. Thus the score is 5. The next most stable is the BTRB design. The BTRB is very stable because the boomerang design on top will shift the center of mass forward, and the lower rectangular planform will act as a horizontal stabilizer. Additionally, this design is stable in yaw because of the wing sweep. The wing sweep helps increase yaw stiffness because if a yaw angle is applied, more of one side of the wing will be exposed to the freestream flow, and the increased drag on the more exposed wing will cause a correcting moment. For this reason, the BRTB design earns a 4 for stability. The boomerang design also gets a 4 for stability. This is because while it is very stable in yaw, the pitch will be less stable than the boomerang because of the shifted forward center of lift from the lower wing. The rectangular design has the smallest static margin of all the designs, since the aerodynamic center cannot be moved by sweeping. Also, this design has no yaw stability attained by a swept back design. Therefore the score for the Rectangular planform must be 1. Lastly, the pentagon design earns a 2 for stability because while there is some yaw stability, the longitudinal stability may suffer from the fact that the center of mass will not be much farther ahead of the aerodynamic center. Also, there is a design restriction because the front sweep angle is limited by the fact that the shape is a pentagon, so there is less freedom to change the sweep angle and modify stability.

Overall Compatibility: The overall compatibility metric for the boomerang design was given a 3.75. This averaged score was largely affected by the fact that many autopilots are developed for designs much like the boomerang. The value for the rectangle design was a 3.5, because all systems either scored it a 3 or a 4. The diamond design scored a 2.25, mainly because it would be difficult to launch and land. Lastly, the BRTB design scored a 3.625, because all systems would work reasonably well. Lastly, the pentagon design scores a 4.75 in compatibility, largely because of flight heritage and because many subsystem leads developed their systems with something like the pentagon design in mind.

Structural Integrity: A critical component of ARES structural integrity is the central strut. The plane damage is critical when this strut fails to support the force during the mission, including takeoff and landing. Therefore longer the strut is, the lower the structural integrity. Also, the wing side supports are major components of the structure because they must withstand the load during the flight. Additionally, wing sweep will lower the structural integrity because there will be a smaller area in the center to support the forces and moments applied to the aircraft. Therefore the rectangular wing will have the best structural integrity of all designs. So the rectangle earns a 5 for structural integrity. When comparing the three wing designs with sweep angles, the longest strut is needed by the diamond wing, and the diamond wing also has a boomerang shape on top and bottom, earning it a 1 for structural integrity. The next longest is for the BTRB, but the bottom wing has a rectangular planform, which is structurally better. Therefore, the BTRB gets a 3. On the other hand, Swept back has shorter strut but bottom wing structural integrity is not as good as the BTRB. Therefore they both acquire 3 for the score. Lastly, the pentagon design was assigned a 4 because the distance between the aft of the top wing and the tip of the bottom wing will be small in the horizontal direction. This means that the strut may be shorter and this will increase the overall structural stability of the design. Also, more than half of the design choices use swept back wings, which have less structural integrity than the pentagon design. Also, many of the other designs are less structurally stable than the pentagon design, so having a 4 will allow more room to compare the less strong designs.

Table 34 shows the trade study matrix with the overall scores calculated.

Table 34. Wing Design Trade Study Matrix

Category	**Weight**	**Pentagon**	**Swept Back**	**Rectangular**	**Diamond**	**BTRB**
Manufacturability	0.25	3	2	5	1	2
Stability	0.35	2	4	1	5	4
Overall Compatibility	0.2	4.75	3.75	3.5	2.25	3.625
Structural Integrity	0.2	4	3	5	1	3
Total Score	**1**	**3.2**	**3.25**	**3.3**	**2.65**	**3.225**

5.3. Propulsion Trade Study

5.3.1. Metrics

Each considered propulsion system is assignned a numerical assessment for each of the metrics listed below. The scoring systems goes from 1 to 5, with a score of 1 meaning least ideal and a score of 5 meaning most ideal. "Ideal" is defined for each metric below. The metrics are weight, cost, motor/propeller protection, flight heritage, and motor efficiency. The numerical values which dictate the score for each propulsion system are determined through research for a specific motor: the Power 46 BL, 670Kv[28]. This motor is commercially used by a 5 foot span RC aircraft, the Hanger 9 Pulse XT 40. While the Power 46 motor may not be the motor chosen by this group for the propulsion system for ARES, it provides a baseline for which to evaluate the propulsion design options. Table (5.3.1) below describes the weight associated with each metric, which will help determine the final overall score for each propulsion system. The weight and efficiency of the propulsion system were each given a weight of 0.25 because these two metrics play the most significant role in the endurance of the aircraft. The motor/propeller protection metric was given a weight of 0.2 because in order to meet FR.6, the aircraft must be able to demonstrate the ability to survive takeoff and landing at least 10 times. Cost is weighted lower than motor/propeller protection at 0.15 because this metric does not directly support any of the functional or design requirements. Rather, this metric is important due to the budgetary constraints for the project. The likelihood of breaking the propulsion system during the design phase is high, so a cost effective motor can eliminate the financial burden of needing to replace the propulsion system. Finally, the flight heritage metric is also given a weight of 0.15, as this metric again does not specifically influence any functional or design requirements. The more flight heritage a propulsion system has, the more resource and documentation is available to use as guidance in the design process for ARES.

Table 35. Weighting of Propulsion Trade Metrics

Metric:	Weight	Cost	Motor/Prop Protection	Heritage	Efficiency
Weight:	.25	.15	.20	.15	.25

Weight - Weight is an important metric because the amount of thrust needed to propel the aircraft is directly proportional to the amount of mass in the system. Therefore, a propulsion system that weighs less (i.e. less mass) increases the efficiency of the system and correlates to less power required to propel the system. Since a primary goal for this project is to increase endurance, propulsion systems that weigh less will be more favored. The propulsion system placement also affects how the center of gravity is calculated on the aircraft and the weight of the motor is directly coupled with the stability of the aircraft. Meaning the weight of the motor not only affects the endurance, but it affects the in flight stability of the aircraft as well. The weight of each propulsion system will be scored using the following table.

Table 36. Weight Scoring Definition

Estimated Weight, (kg):	0.1 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0
Score:	5	4	3	2	1

Cost - The price of the propulsion system is important due to the budgetary limits of the project. The design process employed in this project will result in many iterations of the aircraft crashing or sustaining significant damage. A cheaper propulsion system is important as it can be replaced with reduced impact on the budget. The price of each proposed propulsion system will be scored using the following table.

Table 37. Cost Scoring Definition

Estimated Cost, ($):	50 - 99	100 - 149	150 - 199	200 - 249	255+
Score:	5	4	3	2	1

Propeller/Motor Protection - This metric was selected because the endurance of the aircraft is directly tied how well the propulsion system can survive impact with the ground and the placement of the propulsion system on the aircraft is directly tied to the type of propulsion system chosen (i.e. pusher, puller, or both). The weight was selected because the customer requirement to take-off and land in 10 consecutive cycles (FR 3.0/6.0) is dependent upon if the propeller and motor remain intact after each cycle. The weight given is higher than other metrics because the survivability of this project is valued by the team and customer. The protection of the propeller system will be scored relative to each other, based upon how propeller/motor(s) will be distributed on the aircraft.

Table 38. Propeller/Motor Protection Scoring Definition

Protection from ground impact	Protection by air frame	Can be protected with design	No protection
Score:	5	3	1

Flight Heritage on Swept Wing RC Aircraft - This metric is selected because successful past RC projects imply a successful propulsion system. It is important to evaluate which propulsion designs have worked well in the past, especially if one design stands out more than others. This metrics weight reflects the fact that not all RC projects can be compared to this one, and just because one system could prove to be historically popular, it might not be the best solution for this project. This flight heritage of the propulsion system will be scored relative to each other, based upon if the system has been used in past projects.

Table 39. Flight Heritage Scoring Definition

Flight Heritage: Used in past swept wing RC aircraft (SCUA, Eagle Owl, Other?)	Used	Not Used
Score:	5	1

Motor Efficiency - This metric was chosen because Motor/Propeller Efficiency will directly impact the endurance of the aircraft. With the primary goal for this project being to increase endurance, the propulsion system should consume as little power as possible to maintain flight. The on-board propulsion system will be the source of primary power consumption, so optimizing this trait will be crucial for adequate endurance. The motor efficiency is also heavily dependent upon the configuration the motor is placed in, so the trade study will expose which configurations are efficient based upon the airflow reaching the wing. ($\eta_{eff} = W_{out}/W_{in}$)

Table 40. Motor Efficiency Scoring Definition

Designed Motor Efficiency, (%):	90 - 100	70 - 89.99	< 69.99
Score:	5	3	1

5.3.2. Pusher Scores

Weight: **3.5** - The weight of the Power 46 used in a Pusher configuration, which requires 1 motor, was given a score of 3.5 because the weight of the motor is 290g and the motor will be located at the rear of the aircraft. The team has defined given criteria for the score associated with the total weight of the motor, shown in Table 36. The motor, if in pusher configuration, would be located at the rear of the aircraft which would move the center of gravity closer to the aerodynamic center making the aircraft less stable and less responsive.

Cost: **5** - The Power 46 is $89.99, as listed on HorizonHobby.com, and as a result the motor in Pusher Configuration has earned a score of 5. This score is driven by the fact that the team does not want to spend more than $100 on an item that is very exposed on the aircraft and can easily break upon landing if not mounted correctly. Due to the Pusher style of propulsion only requiring 1 motor at the rear the price can be kept under that threshold.

Propeller/Motor Protection: **3** - It is extremely difficult to protect a motor from ground impact due to the uncertainty of how and where an aircraft may intentionally or unintentionally land. However, a pusher configuration places the motor at the rear of the aircraft and as such the motor may be protected based upon how the team decides to design the mounting system for the propulsion system. Due to the fact that the motor is not in direct impact with the ground, but the propeller may be, the team has chosen to give the Pusher configuration a score of 3 for propeller/motor protection.

Flight Heritage on Swept Wing RCs: **5** - The Pusher configuration has numerous successes on past swept wing RCs and on many of the prior Eagle-Owl designs. The team would like to build off of the successes of past projects in order to increase the likelihood of our designs success, but also to build off of much of the research that those projects have already done. Using the fact that a pusher configuration has been used on many different swept wing RCs and that it is the only choice thus far on the Eagle-Owl, the team has given it a 5.

Motor Efficiency: **3** - The pusher configuration is given a score of 3 because this configuration is inherently less efficient than the tractor design, but more efficient than the push/pull design. Due to the location of the propeller, the propulsive efficiency is decreased due to a pressure difference between the wake from the top of the wing and the wake from the bottom of the wing it is mounted on. This requires an increase in power draw to compensate in thrust. This can lead to a drop in efficiency up to 12%-15% from the tractor design with the same thrust output[24]. However, the pusher design is more efficient than the push/pull design, where two inline motors draw significantly more power.

5.3.3. Puller Scores

Weight: **4** - The Puller Configuration was given a score of 4 in the weight metric because the Power 46 motor weighs 290g, and only one is required. The team has chosen the weight to be important in the Puller Configuration because the weight of the motor at the front of the aircraft will bring the center of gravity closer to the leading edge, increasing stability. And the configurations weight is only one range worse than the option SCUA decided upon.

Cost: **5** - Much like the pusher configuration, the puller configuration would only require one motor and the Power 46 is $89.99 on HobbyHorizon.com. This price falls within the first range the team has chosen due to the fact that the team does not want to pay a significant amount ($100) for something that is directly exposed to damage during each flight cycle.

Propeller/Motor Protection : **3** - The puller configuration would place the propeller and motor at the front of the aircraft, which would make the propulsion system in the direct line of impact with the ground during each flight cycle. Due to the requirement (FR 6.0), the aircraft must complete 10 launch and land cycles with minimal damage which is heavily dependent upon if the propulsion system can survive each cycle and be capable of producing the desired thrust. Based upon the fact that the puller configuration exposes the motor to a significant amount of damage, the team has given the configuration a 3. This score comes from the fact that the team can design methods to protect the motor and many options in the RC industry already exist to protect the propeller i.e. Folding Propellers.

Flight Heritage on Swept Wing RCs: **1** - Flight heritage for this project is extremely important and the team has decided to dedicate a portion of the trade study to Flight Heritage because we do not want to ignore the successes of past projects. Due to the fact that a puller configuration is not evidently used on prior Senior Project RCs or on any of the prior Eagle-Owls, the team has scored the puller configuration with a 1.

Motor Efficiency: **5** - The puller configuration is given a score of 5 because the position of a puller implies it is subject to undisturbed or free-stream air. While tractors can reduce wing efficiency behind them because the flow behind the propeller is disturbed and reduces the lift produced by the wing, this is outweighed by the inefficiency of the push configuration which is documented to be 85% of a puller configuration[24]. Additionally, the puller configuration draws significantly less power than two inline motors which are part of the push/pull design.

5.3.4. Push/Pull Scores

Weight: **2.5** - The push/pull configuration is given a score of 2.5 because this configuration requires two motors, which for the Power 46 combine to weigh 580g. This design option is also less desirable because if the push/pull configuration is distributed with one conventional tractor and one conventional puller, the weight distribution would be such that the net mass moves the center of gravity towards the center of the chord, reducing stability. If the push/pull configuration is such that both motors are located on the aft side of the aircraft, the center of gravity would be pulled significantly back, which will heavily reduce stability.

Cost: **3** - The push/pull configuration would require two motors, which increase the cost of the design option from $89.99 to $179.98 (determined using the Power 46). This lowers the appeal of the push/pull option because the likelihood of the propulsion system breaking during the design is high. A lower cost for the propulsion system would ease the financial burden of replacing components, and as such the push/pull design option is given a 3.

Propeller/Motor Protection: **3** - The push/pull design can be integrated into the aircraft such that the fore and aft propellers are contained between the two wings. This provides moderate protection from the impact with ground, but requires design considerations. The propellers cannot be completely protected from the ground in the push/pull configuration, especially if the combination is of a conventional puller and pusher. As such, the push/pull configuration is given a 3.

Flight Heritage on Swept Wing RCs: **1** - Similar to the tractor configuration, the push/pull design is not evidently used on prior Senior Project RCs or on any of the prior Eagle-Owls. Therefore, the team has scored the push/pull configuration with a 1.

Motor Efficiency: **1** - The push/pull configuration is given a score of 1 because it consumes the most power out of the considered design options. The push/pull design includes two motors which are inline on the aircraft. The fore motor disturbs the air behind it, which reduces the efficiency of the afte motor by up to 15%. This leads to another slight increase in power draw in order to keep thrust up. While the thrust is significantly higher than a single pusher or puller configuration, this drop in efficiency on the rear motor becomes less appealing than two parallel pushers or pullers. As such, the push/pull configuration is deemed the least appealing design option considered in terms of power draw for thrust output.

5.3.5. Scoring Summary

The table below (table 41) shows the results of the propulsion trade study in a matrix. Based on the metrics outlined above and their weights, each design is given a total score that will be used to help determine a baseline design.

Table 41. Propulsion System Trade Study Matrix

Category	Weight	Pusher Design	Puller Design	Push/Pull Design
Weight	.25	3.5	4	2.5
Cost	.15	5	5	3
Motor/Prop Protection	.20	3	3	3
Flight Heritage	.15	5	1	1
Motor Efficiency	.25	3	5	1
Total	**1**	**3.725**	**3.750**	**2.075**

5.4. Takeoff System Trade Study

5.4.1. Metrics

Each system defined in the previous section will be given a numerical score for the metrics described below. These scores will be defined based on research and back of the envelope calculations. The six metrics chosen were: Damage risk to the aircraft, manufacturing complexity, integration complexity, cost, flight performance, and safety. These metrics were chosen based off of the design requirements set out under FR 3.0 and the other functional requirements. A score of 1 is considered the worst score whereas a 5 is considered the best possible score, Since there are six metrics, they would be equally weighted at about 15%, and these weights were modified to reflect the relative importance of each metric to the project. The weights for each metric was defined below in Table 5.4.1 Therefore, it was weighed equally to damage risk and split between the two categories of complexity. Cost was weighted at 10% because it is less important to the launch mechanism individually and is included in every aspect of the project. Finally, flight performance was rated as a standard aspect of the project.

Table 42. Weighting of Trade Metrics

Metric:	Damage Risk	Manufacturing Complexity	Integration Complexity	Flight Performance	Cost	Safety
Weight:	.30	.20	.20	.15	.10	.05

Damage Risk - Damage risk was chosen in order to meet functional requirement 6.0, providing 10 flight cycles without major repairs. If the aircraft sustains significant damage from the launch mechanism, most success objectives greater than level 1 will not be able to be met. Therefore, this metric was determined to be the most important of those applied to the launch system. This category was defined by the number of failure modes possible during a launch. The definition of each score is defined in Table 43. This is seen as the most important metric due to its affect on the rest of the project.

Table 43. Damage Risk Scoring Definition

Damage Risk (Failure Modes):	1	2	3	4	4
Score:	5	4	3	2	1

Manufacturing Complexity - The manufacturing complexity was chosen as a metric in order to assure that none of the options traded would cause significant schedule risk. This metric was determined to be the second most important due to the complexity and scope of the project. The simpler the team can make the side work on this project, allows for greater time to be spent on the design of the aircraft. This metric was defined by how many man-hours would be required to manufacture the system. Table 44 defines each score below.

Table 44. Manufacturing Complexity Scoring Definition

Manufacturing Complexity (Man Hours):	0-40	40-80	80-120	120-160	160
Score:	5	4	3	2	1

Integration Complexity - The integration complexity metric relates to how difficult the launch mechanism is to integrate with the other systems on the aircraft. The more systems affected by the launch system, the more difficult the project becomes. Therefore, this metric was defined by the number of other systems on the aircraft the launch mechanism would affect. The scores for this metric are defined below in Table 5.4.1. This metric was determined to have the same weight as manufacturing complexity in order to assure a simple but effective solution was found. The less systems on the aircraft required to integrate with the launch system the simpler the launch mechanism will be.

Table 45. Integration Complexity Scoring Definition

Integration Complexity (Systems Affected):	0	1	2	3	3
Score:	5	4	3	2	1

Flight Performance - Flight performance was chosen because any adverse drag or stability caused by the launch mechanism will affect the endurance of the aircraft and its ability to complete FR 1.0. This metric was seen as the third most important due to its affect on the first functional requirement, but was not seen to be as important as complexity or risk of damage to the aircraft. This design metric was defined by the approximate surface area added to the aircraft in cm^2, which would affect drag on the aircraft. The scores for this metric are defined in Table 5.4.1.

Table 46. Flight Performance Scoring Definition

Flight Performance (Added Surface Area) [cm^2]:	0	50	100	150	200
Score:	5	4	3	2	1

Cost - The cost of the launch mechanism is an important metric due to the likelihood of multiple aircraft prototypes being necessary. Even with the use of proper engineering techniques their is still a good chance that we will have multiple aircraft crashes. The less money that is spent on the launch mechanism means more money can be spent on aircraft production. The weighting of this metric was found to not be as important as the cost of one aircraft is not seen to be critical. This metric is based on the approximate monetary cost of the system and the scores are defined in Table 5.4.1.

Table 47. Cost Scoring Definition

Cost ($):	0	250	500	750	1,000
Score:	5	4	3	2	1

Safety - Finally, safety was chosen as a metric to assure any injury to the team is avoided. This metric was not seen to be as prominent to the project as the above metrics and therefore was given the least weight. This category was defined by the number of failure modes that could potentially harm team members and the scores are defined in Table 5.4.1.

Table 48. Safety Scoring Definition

Safety [Failure Modes]:	0	1	2	3	3
Score:	5	4	3	2	1

5.4.2. Independent Vertical Rotor Scores

Damage Risk: **3** - There were three modes of failure identified for the independent vertical rotor: power failure; controls failure; the transition between vertical and horizontal flight. These three modes denote a score of 3 in the damage risk category. If the power to the rotor fails while in flight, the aircraft will drop a potentially large distance before the horizontal propellers can be activated and take effect. This would likely result in a crash. If the controls to the vertical rotor fail, it is unlikely that the transition from vertical to horizontal flight can be completed successfully, resulting in a crash. If the transition from vertical to horizontal flight cannot be completed for any other reason, then a crash is almost certain to occur. Almost any crash will cause damage to the aircraft.

Manufacturing Complexity: **5** - This method only requires the purchase of additional motors and their attachment to the airframe, so very little actual manufacturing would be required.

Integration Complexity: **1** - This is because integrating the rotor would require interfering in four systems: structure; power; controls; propulsion. This shows the difficulty in adapting the rotor to work well with the other systems.

Cost: **1** - Using the rule of thumb that the thrust of a propulsion system must be approximately 1/3 of the aircraft's weight to climb, this means that the vertical rotor would need to provide at least three times the lift of the horizontal motors. Assuming the same type of motor is used for both horizontal and vertical thrust, this means that three times the motors are required simply for the vertical flight. Assuming an average cost of $90 per motor, and only one spare motor, the vertical rotor system would add at least $360 to the cost of the aircraft.

Flight Performance: **1** - Assuming a propeller diameter of 55cm, and a propeller height of 1cm, each extra rotor would add 55cm^2 of surface area to the aircraft. This would result in at least 165cm^2 of extra surface area.

Safety: **5** - Because the vertical rotor would be operated by remote control, the operators can be far from the aircraft during activation and takeoff. This possible distance means that there will be almost no risk to the operators.

5.4.3. Tiltrotor Scores

Damage Risk: **2** - There were four major failure modes identified for the tiltrotor system. The first of these being power failure to the rotors, if power were to cut to the rotors the aircraft would lose altitude and crash. The second mode is due to instability of the aircraft during transition from vertical to horizontal thrust. During this phase of flight the changing thrust of the aircraft increases the likelihood the aircraft becomes unstable and the pilot loses control of the aircraft. The third mode is controls failure. If the controls fail to the rotor or the rotor transition system the thrust and position of the motors would be fixed, potentially causing a crash. The last mode of failure is due to the rotation mechanism. If the rotation mechanism fails to rotate the rotors the aircraft will not be able to attain a ground speed and therefore will not be able to provide its own lift.

Manufacturing complexity: **5** - This launch system would require the purchase of additional motors, due to the additional thrust necessary for takeoff, and the purchase or manufacturing of a rotation mechanism. If this rotation mechanism were to be manufactured the team does not for see the manufacturing taking more than 40 man-hours to complete.

Integration Complexity: **1** - The integration of this system would be incredibly challenging due to its connections with multiple aircraft systems. This is because integration of the transitioning rotors would require interfering with five systems: structure, power, controls, mechanical, and propulsion. The rotors are going to need to be integrated with the structure of the aircraft and must have some form of mechanical integration to rotate or transition the rotors. The rotors will also need connections to power and the control system in order to vary the thrust of the motors. This shows the difficulty in adapting the rotor to work well with the other aircraft systems.

Cost: **4** - Additional motors are going to be required in order to provide the additional thrust needed for a vertical takeoff scenarios. Defined above in the vertical rotor scoring, a common propulsion system must be able to thrust up to a 1/3 of the aircraft's weight in order to climb. This is considering the lift force from the wings and without this the motors must be able to thrust up to the full weight of the aircraft. This requires the purchase of a minimum of 3 motors versus 1 in a non-vertical takeoff scenario. With the addition of an extra motor as a spare, the predicted cost of these extra motors based on research is $90 per motor, bringing the cost up to $270.

Flight Performance: **2** - Through research of possible propulsion options and previous work on the Eagle Owl, a propeller diameter of 55cm and a propeller height of 1cm was determined to be appropriate for calculations. Due to this, each extra rotor would add an additional 55cm^2 of surface area to the aircraft. This would result in at least 110 cm^2 of additional surface area.

Safety: **5** - As the vertical rotor can be operated by remote control, the operators can be a safe distance from the aircraft during activation and takeoff. This distance between the aircraft and the operator means that there will be almost no risk to the operators, even in the case of crash during launch.

5.4.4. Bungee Rail System Scores

Damage Risk: **4** - There were two failure modes found in the bungee rail system. The first would occur when any of the bungees providing the initial thrust to the aircraft snapped or came loose from its base in some way. The elastic potential energy could be transferred from the bungee to the structure of the aircraft, causing damage that may not be solvable in the field. The second failure mode would occur if the bungees failed to come loose from the hook on the airframe, essentially tethering the aircraft (with a great deal of velocity) to the ground, causing a crash.

Manufacturing Complexity: **4** - The manufacturing complexity involved in the bungee rail system mainly revolves around the construction of the ramp used to direct the aircraft. Since the ramp should be fairly straightforward to construct, it was estimated that the ramp will require around 40hrs to construct. After that, the attachment of the bungees and any other additions will push the construction into the 40-80hrs range.

Integration Complexity: **4** - The bungee rail system will affect the structure of the aircraft in the hook attached to the airframe. This will be the only system affected.

Cost: **4** - Based on worst case scenario price estimations on material and manufacturing materials for the ramp, it is estimated to cost $150.[10 11] A worst case scenario for the cost of the bungees is $200, so the total cost is approximately $350.[12]

Flight Performance: **5** - Because the bungee rail system will be almost entirely contained on the ground, there will be very little effect on the drag on the aircraft. The surface area of the hook used to attach the bungee cords will certainly be fewer than 10cm^2.

Safety: **4** - As stated before, there is a risk of a bungee cord snapping when stretched. Unfortunately, it will be more difficult for the operators of this launch mechanism to keep their distance during takeoff preparations. Therefore, the is one mode of failure that can affect the safety of the team members.

5.4.5. Pneumatic Rail System Scores

Damage Risk: **4** - There were two methods of failure identified in the pneumatic rail launch mechanism. The first lies in a difficulty in releasing the correct pressure of air at the correct time. This can dramatically alter the initial velocity of the aircraft, leading to a crash due to a lack of lift or due to an uncontrollable ascent. The second mode of failure can happen if the aircraft fails to disengage from the hook attaching it to the carrier rod. The weight of the rod will destabilize the aircraft and cause a crash.

Manufacturing Complexity: **3** - The manufacturing of the pneumatic rail system is broken into two parts. The first is the construction of the ramp, which is expected to take around 40hrs to build. The second part is implementing the compressed air tank into the ramp to provide the thrust for takeoff. This is likely to be complex in its implementation due to the danger inherent in highly pressurized gas, and is expected to take at least 30hrs. In addition, calibration will need to be performed to find what pressure of gas corresponds to what initial velocity. This calibration will require a great deal of testing, so this process is estimated to take 20hrs. Therefore, the complete manufacturing time for this launch mechanism is estimated at 90hrs.

Integration Complexity: **4** - This launch mechanism will only affect the structure of the aircraft. The hook attaching the carrier rod to the airframe will be the only addition to the aircraft itself.

Cost: **4** - Based on worst case scenario price estimations on material and manufacturing materials for the ramp, it is estimated to cost $150.[10 11] A suitable air tank costs $110, so the total cost is approximately $260.[13]

Flight Performance: **5** - As the only addition to the aircraft after launch will be the hook used to attach the aircraft to the carrier rod, the extra surface area will certainly be fewer than 10cm^2, giving this metric a solid score of 5.

Safety: **4** - A possible way in which the operators could be injured by this launch mechanism would be due to a broken seal in the compressed air system. A seal or hose could suddenly burst, exposing a team member to the violent decompression. Unfortunately, this launch method will require the operators to be near the apparatus to set up the launch, and so distance cannot be used to mitigate the risk.

5.4.6. Conventional Takeoff Scores

Damage Risk: **3** - There were three major failure modes identified for the conventional takeoff system. The first of these is the chance of the aircraft falling on its side or nose during the takeoff process. This could occur due to instability in rough ground or strong winds. The second failure mode is the chance that the aircraft is taken of course due to its lack of yaw control. A rudder cannot be used in this design due to customer requirements and therefore during takeoff the aircraft will not have a way to control yaw. Strong gusts of wind or bumps could take the aircraft off course and into rough terrain or obstacles, potentially damaging the aircraft. The last mode of failure is the possibility of the wheels or struts becoming damaged during takeoff. If the aircraft hits rocks or other objects during takeoff the wheels or struts could break off from the structure causing the aircraft to fall over and possibly sustain damage.

Manufacturing complexity: **5** - This takeoff system would require the purchase of the wheels and struts to attach the wheels to the aircraft body. The only manufacturing necessary would be the attachment of the struts to the body and this is not expected to take more than 40 man-hours.

Integration Complexity: **4** - The integration of this system would be relatively simple but it will need to be attached or somehow connected to the aircraft structure. This means only one system will require integration work.

Cost: **5** - The only cost for this system would be the purchase of the wheels and struts. Three wheels will be needed in order to assure the aircraft is stable during takeoff and therefore three struts will need to be purchased. Based on research the wheel size is expected to be between 8-12 cm, depending on the final weight of the aircraft, with a thickness of 2 cm. Through this research it was also found that the struts should provide at least 8 cm of clearance from the ground to protect the aircraft and propulsion systems. With these sizes defined the each wheel is expected to cost $15 each and the struts are expected to cost $10, therefore staying well under $250.[14]

Flight Performance: **3** - Based on the above research done on the wheel size the surface area of the 3 wheels and the 3 struts in combination is going to be 96 cm^2.[14]

Safety: **5** - For the same reason as the vertical takeoff systems, their is very little chance of harm to the operators. The aircraft will be remote controlled during the takeoff sequence and therefore the operators can be a long distance away. Even in the case of a crash the damage to the operators is incredibly low.

5.4.7. Scoring Summary

The overall results of the trade study described above are shown in table 49 below. For the takeoff system trade study, the bungee rail system scored the highest overall based on all chosen metrics.

Table 49. Takeoff Method Trade Study Matrix

Category	Weight	Independent Vertical Rotor	Tiltrotor	Bungee Rail	Pneumatic Rail	Conventional Takeoff
Damage Risk	.30	3	2	4	4	3
Manufacturing Complexity	.20	5	5	4	3	5
Integration Complexity	.20	1	1	4	4	4
Flight Performance	.15	1	2	5	5	3
Cost	.10	4	4	4	4	5
Safety	.05	5	5	4	4	5
Total	**1**	**2.9**	**2.75**	**4.15**	**3.95**	**3.90**

5.5. Landing System Trade Study

5.5.1. Metrics

Each system will be given a numerical assessment for each of the metrics listed below. A 1 is considered least ideal and 5 is most ideal where ideal is defined for each metric below. The numerical values will be assigned based on research and without comparing the option in question to the other options. Table 50 shows the weights of the 5 metrics chosen and the reasoning for these choices is described under each metric.

Table 50. Metric Weights

Metric:	Damage Risk	Integration Complexity	Reliability	Weight	Aerodynamic Effects
Weight:	.30	.25	.20	.15	.15

Damage Risk - Damage Risk was chosen as a metric because in order to meet Requirement 6, the aircraft must be able to repaired in the field within 15 minutes and then be launched again. Repairing the aircraft in the field with limited tools, supplies and time will be very difficult, so the landing system must minimize the damage to the aircraft. This metric is the most important because the aircraft will not be able to fly again if the it gets seriously damaged upon landing. We will take into account the damage associated with the worst case landing scenario.

Table 51. Damage Risk Scoring Definition

Damage:	No Damage	Field Repairs < 15 Mins	Field Repairs > 15 Mins	Shop Repairable	Irreparable
Score:	5	4	3	2	1

Integration Complexity - Complexity was chosen as a metric because the customer has very clearly stated that the focus of the project is to improve endurance and integrate the FADS system, not to improve launch or landing. This means that the landing system should be as simple as possible to design and implement. We also want to keep the landing system design very simple in order to keep the scope of the project to a realistically achievable amount of work. In this case, we will quantify the complexities associated with integrating the landing system with the other systems. The scores for this metric are designated as follows:

Table 52. Integration Complexity Scoring Definition

Number of Affected Systems:	1	2	3	4	>5
Score:	5	4	3	2	1

Reliability - Reliability is a slightly less important factor than Complexity because the scope of the project is not in question. The reliability of the landing system includes not only the heritage of the system in an RC application but also the systems ability to perform 10 times without failure. Again, from R.6 the landing system must work 10 times, meaning the entire system needs to be strong enough to withstand 10 landing impacts. The reliability will be appraised in terms of the total number of failure modes that are possible in which the the fewest number of failure modes is ideal.

Table 53. Reliability Scoring Definition

Number of Failure Modes:	1	2	3	4	5
Score:	5	4	3	2	1

Weight - The weight of the landing system has been chosen as a metric because of requirement DR.6.2, which states no external landing system may be used. Due to this, the aircraft is responsible for carrying the entirety of the chosen landing system. The focus of ARES is to significantly improve endurance of the Eagle Owl, and any extra weight impairs progress toward that goal. The weight of each proposed landing system will be estimated with back of the envelope calculations and the system will be scored based on its estimated weight.

Table 54. Weight Scoring Definition

Estimated Weight (kg):	0-0.49	0.5-0.99	1-1.49	1.5-1.99	>2
Score:	5	4	3	2	1

Aerodynamic Effects - The reasoning for including aerodynamic effects as a metric is similar to that of the weight metric. Increasing the aircrafts drag will directly hinder its endurance and could put the project in jeopardy. Also similar to the weight metric is the scoring criteria for the aerodynamic effects; the drag effects will be researched and estimated for each system, and they will be scored based on the expected surface area that would cause drag.

Table 55. Aerodynamic Effects Scoring Definition

Estimated Surface Area (cm^2):	<49	50-99	100-149	150-199	>200
Score:	5	4	3	2	1

5.5.2. Parachute Scores

Damage Risk **3** - We could optimize the damage to the aircraft by trading the size of the packed parachute. We want the parachute to be small because the aircraft must carry it during flight. The smaller the parachute, the faster and more vertical the descent will be while a larger parachute will drift more horizontally due to winds aloft. So how big should the parachute be? It depends on force the aircraft can take upon landing since the faster the descent, the more risk of damage. In an ideal case, using a parachute would reduce the horizontal velocity making the vertical velocity component the only cause of damage. It should gently set the aircraft down on the ground with very little impact velocity. It is worth mentioning in this section that another possible benefit of a parachute is that it can be used as a safety measure if something goes wrong during testing. For example, if we lose controls or autopilot functionality during flight, the parachute could safely land the aircraft from any altitude. The worst case scenario involves the aircraft losing control and then the parachute not deploying, causing the aircraft to fall out of the sky from potentially very high altitude. Although a parachute can be deployed if we lose control, it was given a score of 3 because in the worst case scenario, the plane could fall from a very high altitude.

Complexity **3** - Attempting to design and build an effective parachute would be unnecessarily complicating our project so we would not go down this route. If we buy an already made parachute to the specifications we need, the complexity is reduced to integrating the attachment points onto the airframe structure and attaching the packed parachute to the upper wing changing its aerodynamics. Some way to deploy the parachute would also be needed which gives a total of 3 affected systems corresponding to a score of 3.

Reliability **3** - The likely failure modes of using a parachute includes: failure to deploy, failure to remain attached and potential to rip or tear. 3 failure modes corresponds to a reliability score of 3.

Weight **3** - The maximum height (h [meters]) from which the aircraft can be dropped without becoming damaged determines the maximum parachute descent velocity (V [m/s]). From the known survivable drop height, the maximum velocity can be calculated from: $V = 2gh$ where g is gravity in $[m/s^2]$.[15] From the maximum descent velocity (V [m/s]), the air density ($[kg/m^3]$), the total weight (W [Newtons]) of the aircraft+parachute and the coefficient of drag (Cd) of the parachute you can determine the parachutes optimal surface area (S $[m^2]$) from: $S = 2W/Cd(v2)$[15]. Using these equations with a maximum weight of 25 kg (AMA restriction) (=245 Newtons), a coefficient of drag of 0.75 (a typical nylon RC parachute that is circular with no holes or slits), an average air density of $0.96kg/m^3$ in Boulder and assuming the maximum safe drop height is 2 meters, the optimal surface area of the parachute would be $S = W/Cd(gh) = 34.7m^2$. Which gives a radius of 3.32 meters. Nylon fabric with a surface area of $34.7m^2$ and thickness of 1 mm weighs 40 grams assuming nylon has a density of $1.15kg/m^3$[16]. From some rough estimates online, the material needed for a parachute of this size would cost between 100 and 140 dollars. Or purchasing an already made parachute that can support 22.5 kg and already has lines and deployment solution (1 kg) for about 350 dollars.[17] Taking the least complex means of obtaining a parachute, the estimated weight would be 1 kg corresponding to a score of 3.

Aerodynamic Effects **3** - Following the same methodology described above in the weight section, the surface area of the parachute was estimated. Based on common drone/RC packing methods, a parachute of this size could be packed into 2278 cm^3 which is about the size of a half gallon of milk.[16] It is important to note that the surface area of the parachute can be made extremely minimal as it can be packed in such a way that it conforms to the shape of the aircraft. Assuming the parachute will be attached to a rectangular upper wing with aspect ratio = 6 and maximum span of 2 meters, we can calculate the area $(area = span^2/aspectratio)$[23] to be 3333 cm^2. Back solving from volume for the thickness of the folded parachute gives a thickness of 0.683 cm. Meaning that the total effective surface area (thickness times span) that contributes to drag is 137 cm^2 which corresponds to a score of 3. Again, this is a worst case scenario with many assumptions since the surface area will vary drastically with the size of the parachute and the dimensions of the wings.

5.5.3. Landing Gear Scores

Damage Risk **2** - The risk of damage with landing gear is high. During landing, the forward component of velocity must remain high enough to provide lift to the aircraft to keep it from crash landing. This velocity can cause damage to the aircraft as it impacts the ground, especially if the wheels are not large enough to deal with the terrain. In the event of a failure, the aircraft could sustain major structural and sensor damage. Additionally, if the aircraft loses control mid air, there is no way to land safely as the landing gear requires a controlled, steady approach. Despite its heritage and its history of flight, conventional landing gear imposes a large amount of risk to ARES through stability concerns due to the fact that we have neither a tail nor a fuselage. The aircraft would be extremely likely to tumble upon landing unless the wheels are large enough in diameter to traverse very rough terrain. The worst case scenario would be if the landing gear fails or if the landing gear gets stuck in a rut causing the aircraft to flip upside and get damaged. Rolling about the aircraft's x-axis would most likely break of a wing which would not be able to be repaired in the field. Thus a damage risk score of 2 was given to the landing gear.

Complexity **3** - The complexity of a landing gear system is relatively low, especially if the gear is fixed in the downward position. Most of the analysis goes into structural aspects to ensure the gear will stay firmly attached as the aircraft touches down on the rough terrain. However, due to the shape of the aircraft, the complexity is increased somewhat in order to make sure it can interface correctly with the box wing design. The lack of a fuselage or tail boom somewhat complicates the design. Additionally, adding landing gear has a significant effect on the control of the aircraft and the way it flies. Not only does the landing gear change the stability of the aircraft, landing the plane will be taxing on the pilot/autopilot. In order to land, the pilot/autopilot must fly the plane close to the ground and then handle it during touch down which is very difficult and could pose many risks. Therefore, the structures, aerodynamics, and autopilot subsystems would be affected corresponding to a complexity score of 3.

Reliability **4** - Due to its flight history and the relatively simple design, using landing gear as the recovery system is extremely reliable. The risk of the gear failing on landing is low and if designed correctly, the gear will allow the aircraft to land with no issues. The two likely failure modes are: the gear not being large enough to deal with terrain or the gear failing to remain attached to the aircraft, causing the aircraft to crash at high velocity. Two failure modes corresponds to a score of 4.

Weight **3** - As described above, the aircraft would need three wheels with 15 cm diameters. Wheel weight = 633g (211g x3 wheels), strut weight = 100g ($2g/cm^3$ * $8.19cm^3$ (4in*1in*1/8in) * 6 struts), Total weight = 733g.[21] If two 4x1x1/8 carbon fiber struts are used for each wheel, the total weight will be between 0.5 and 1kg. Using the higher estimate to account for errors, the landing gear gets a score of 3.

Aerodynamic Effects **1** - The drag induced by adding landing gear is also a huge concern. Adding fairings to the wheels has been shown to significantly reduce drag in the longitudinal direction, but because of the design of ARES, the lateral drag is of much more importance, and the necessary diameter wheels will increase this by a large amount.[23] In the worst case scenario, assuming a square cross section viewed from the side the 3 minimum required 15 cm wheels will have a surface area of about 251 cm^2, resulting in a score of 1.

5.5.4. Skid/Crash Landing Scores

Damage Risk **4** - Planning for a skid landing includes ensuring all sensors are protected and that the entire system is able to land in this fashion. This system will include strengthening the entire airframe so that in the event of a rollover on landing, the aircraft will not sustain major damage. There really is no worst case scenario in terms of damage risk for this solution. Even if the plane loses power and falls from a high altitude, the plane should be structurally sound enough to prevent major damage. The damage risk score is a 4 since we believe that if the aircraft does flip over there may be some damage that needs to be repaired in the field.

Complexity **5** - The system to allow for skid landing will only affect the structural component of the aircraft. This system may include a nose piece to assist in a controlled rollover, but the component will be small enough to not affect the aerodynamics of the plane or any other systems. One affected system means a score of 5.

Reliability **4** - Like using landing gear, this system has only two likely failure mode: a crash landing that is not controlled or the lower surface material getting punctured. In the event the control system does not operate as desired, the aircraft will tumble upon landing and could cause some damage. Two failure modes corresponds to a score of 4.

Weight **4** - In order to calculate the weight added, it is assumed that the entire bottom of the aircraft is protected by a carbon fiber plate. Assuming this plate is 1/16in (0.15875cm) thick at most and covers half the total span, this would result in a total volume of . Multiplied by the assumed density of 2g/cm3, this results in a total added weight of 794g. The weight score for the skid/crash land system is a 4.

Aerodynamic Effects **4** - The maximum possible aerodynamic effect is incurred with the addition of a nose piece. The additional material used to strengthen the aircraft would not add any surface area but instead would be shaped into the airfoil itself. The nose piece can be no more than 2.5cm in width, and assuming there is a 25cm separation between upper and lower wings, this results in an added surface area of 62.5 cm2. Therefore, the score for aerodynamic effects is 4.

5.5.5. Vertical Landing Scores

Damage Risk **2** - In the event that the vertical landing system fails, the aircraft will fall out of the air with little to no control. This landing is likely to take place at a relatively low altitude, so most damages should be able to be repaired. However, it is likely that a fall such as this will cause damages not repairable in the field. From this worst case scenario a score of 2.

Complexity **1** - The other systems affected by the vertical take off system are: propulsion, structures, controls/autopilot, aerodynamics, power.

Reliability **2** - The likely failure modes of the vertical landing system include: the propulsion system fails, controls fail, power fails, or the propulsive impulse breaks the structure. Since there are 3 likely failure modes, the score is a 3.

Weight **2** - This system will likely include an extra motor and propeller at a minimum. Appropriate motors for this purpose are generally close to 1.5kg, so that weight will be assumed for this purpose. Additionally, enough thrust will need to be provided by a large propeller, but because these can be made of a lightweight composite, they can be considered to weigh less than 0.5kg. Therefore, the score is a 2.

Aerodynamic Effects **4** - In the ideal case, the only exposed portion of this system will be the vertically oriented propeller, which will likely have a height of 1 cm. The diameter of this propeller will be approximately 55 cm, in order to be able to provide the thrust needed as described above. This results in an exposed surface area of 55 cm^2 and thus a score of 4.

5.5.6. Scoring Summary

A summary of the analysis above is provided in Table 56 in which the totals were calculated using the weighting scheme from Table 50.

Table 56. Landing System Trade Study Summary

Category	Weight	Parachute	Landing Gear	Skid/Crash Land	Vertical Landing
Damage Risk	0.3	3	2	4	2
Complexity	0.25	3	3	5	1
Reliability	0.2	3	4	4	2
Weight	0.125	3	3	4	2
Aerodynamic Effect	0.125	3	1	4	4
Total	**1**	**3**	**2.65**	**4.25**	**2**

6. Selection of Baseline Design

6.1. Autopilot Selection

The trade study results show that the Pixhawk 4 is the best selection for the purposes of this mission. As seen from table 30 the Pixhawk 1 recieved a score of 3.83, Pixhawk 4 of 4, ArduPilot MEGA of 3.16, Eagle A3 of 3.5, and the Vertone Autopilot of 2.16. For this mission, it was clear that the Vertone Autopilot was too large and expensive. The downfall of the ArduPilot MEGA and Eagle A3 were that they do not have any flight heritage, and thus the team would have far less resources when trying to tune and integrate them. The Pixhawk 1 and Pixhawk 4 had very close scores, which is expected since they are very similar autopilots, both with flight heritage, and the only main difference is in processing speed. Overall, the Pixhawk 4 won because it's a little lighter than the Pixhawk 1, showing that integration into a UAV with no fuselage will be easier.

6.2. Wing Design Selection

The wing design trade study finished with the following results: Pentagon (3.2), Boomerang (3.25), Rectangle (3.3), Diamond (2.65), and BTRB (3.225). The details of the trade study are summarized in table 34. While there is not a clear and distinct winner, it is clear that the Diamond wing design can be eliminated. Its complexity, combined with its structural flaws and incompatibility with other systems make it a poor choice to satisfy the objectives. All other options however, are highly dependent on the stability parameter. Given that a single point difference in the stability parameter can alter the total score by 0.35 points, examining this metric becomes very important. For example, if the stability of the pentagon design were a 3 instead of a 4, it would be the winner of the study. Similarly, if the stability of the BTRB or the boomerang design were a 5 instead of a 4, they would win the trade study. While the stability metric was evaluated with specific stability ideas in mind, it has a lot of potential error given that no CFD simulations were run for each design. For this reason an error of 1 point is not totally unrealistic. So if the error is 1 point, the winners of the trade study could be the pentagon design, the BTRB, the boomerang, and the original winner, the rectangle design. With this in mind, we do not want to eliminate these designs at this point, due to the uncertainty in the stability weighting. Therefore, we will select our baseline design to be the rectangular planform, with the possibility of the wings having sweep of some kind. Additionally, the wings may adopt pentagon planforms if the outcomes of further analysis dictate them to be the better design. However, we will tentatively select the rectangular planforms as our baseline design, while eliminating the boomerang and diamond wing designs. It is important to note that in further analysis, the lift to drag ratio will play a major part in exact planform selection, along with stability determined from more in depth analysis. For now however, the rectangular planform is our baseline design.

6.3. Propulsion System Selection

The results of the propulsion trade study are summarized in Table 41. The puller design narrowly proved to be the baseline design, scoring a 3.750 to the pusher design's 3.725. Both of these options heavily outweighed the push/pull design, which scored a 2.075. While this eliminates the push/pull design entirely, the margin of victory for the puller design is small enough to discuss the differences between the puller versus pusher. The pusher design scored lower than the puller design, in the weight metric, because the effect the configuration has on the aircraft's stability is notable due to the motor having to be mounted on the rear of the aircraft, moving the center of gravity rearward. For flight heritage, the pusher design has been used exclusively on past RC projects such as SCUA and Eagle-Owl. However, the puller design won again when it comes to motor efficiency, due to the pusher design experiencing disturbed and turbulent air from the wing wake. The determined weights for each metric put an emphasis on the weight of the system and on the motor efficiency, and since the puller design won in both of these metrics, it is determined to be the best choice for the baseline design. The team will focus on the puller propulsion method, however, due to the similar total scoring between the pusher and puller methods, both may be a design solution that needs to be considered in the future.

6.4. Takeoff System Selection

The final results of the takeoff system trade study are summarized in Table 49. The baseline design was found to be the bungee rail system. This system scored the highest with a final score of 4.15 whereas, the independent vertical rotor scored a 2.6, the tiltrotor scored a 2.55, the pneumatic rail system scored a 3.95 and the conventional takeoff system scored a 3.9. The pneumatic rail system and the conventional takeoff system scored closely to the bungee rail system. The only parameter that could cause a different winner to be chosen due to a change in score of 1 is the damage risk metric, as it has a significant weight. With that being said the scores given in this metric were discussed heavily and the team feels that the scores given correspond well to the launch systems in the trade. In the case of the bungee system chosen the bungees could be replaced by an electric winch. This would increase the cost of the system, changing the score to be a 3 versus a 4 and the safety of the system would be increased to a 5. With the inclusion of this change the bungee rail system would still score higher than the other takeoff methods with a score of 4.10. The team also believes this is the most feasible design choice as it has the most flight heritage without a significant complexity. The feasibility of the other two designs is somewhat in question, the conventional takeoff requires short grass with little roughness of terrain. This may not be a guarantee, the CU South Boulder Campus may not offer such whereas the Boulder Aeromodeling field likely would, making this design less feasible in some situations. The pneumatic rail system requires the compressed air system to be calibrated to a specific force across multiple trials. This will be challenging as seen in the demonstrations by Matt Rhode. Matt had difficulties calibrating the compressed air in his work and the team expects the same would occur in this situation. Through this analysis the team is confident that the bungee rail system is the best choice as the baseline design for the takeoff system.

6.5. Landing System Selection

The results of the landing system trade study are summarized in Table 56 above. The skid/crash landing system won as the best solution since it scored the highest on the metrics we deemed most important to the project goals. We intend to use this approach of descending to low altitude and skidding into the ground to land the aircraft. To accomplish this, the aircraft frame will be hardened to be able to withstand impact with the ground, some sort of skid plate on the bottom will be used to prevent damage to the bottom wing and a nose shaped strut on the leading edge may be used to prevent the aircraft from flipping over upon impact.

6.6. Baseline Design

Using all of the trade studies and selection processes outlined above led to a baseline design that can fulfill all requirements listed in section 3. This baseline will consist of a box wing aircraft that has a rectangular planform on both wings, allowing for maximum structural strength and manufaturability. This aircraft will take off using a bungee and rails system to control initial velocity, heading, and angle of attack, and will be propelled using one or more tractor motors mounted along the leading edge of one of the wings. During flight, the aircraft will be controlled by a Pixhawk 4 autopilot that will allow it to fly a circular pattern as it takes data using its FADS system. After the aircraft completes its two hour endurance requirement, it will descend and land using a skid style landing where it lands on its belly and uses its strength and low speed to remain safe. If it is found that this landing puts the forward propeller(s) in danger, a folding propeller system can be studied to minimize the chance of damage. Another major component that will require more study is the dual rectangular planform wing design. Due to the fact that the studies in this document were not able to achieve the full amount of necessary accuracy and the scores are so close, this aspect of the baseline design is especially subject to change. Despite these minor uncertainties, the baseline laid out here will be able to fulfill the requirements to their full amount.

References

[1] Data, B. A., "Flush Airdata Sensing," *Basic Airdata* Available: http://www.basicairdata.eu/knowledge-center/measurement/flush-airdata-sensing/.

[2] Laurence, R. J., and Argrow, B., "Flight Results from a Small UAS Distributed Flush Airdata System," 9th AIAA Atmospheric and Space Environments Conference, Feb. 2017.

[3] Quindlen, J., and Langelaan, J., "Flush Air Data Sensing for Soaring-Capable UAVs," 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, May 2013.

[4] Wang, X., J. Schwan, H.-W. Hsu, E. Grn, and M. Hornyi (2016). *Dust charging and transport on airless planetary bodies.* Geophys. Res. Lett., 43, 61036110, doi:10.1002/2016GL069491.

[5] Dorr, Les. "Fact Sheet Small Unmanned Aircraft Regulations (Part 107)." FAA Seal, Federal Aviation Administration, 23 July 2018.

[6] Anderson, C., "Trebuchet drone launcher," *DIY Drones* Available: https://diydrones.com/profiles/blogs/trebuchet-drone-launcher.

[7] "Launching and Flying Foam RC Rocket Gliders — Make:" *Make: DIY Projects and Ideas for Makers* Available: https://makezine.com/2016/07/26/launching-flying-rc-rocket-gliders/.

[8] "Plugged Engines," *Estes Rockets* Available: https://www.estesrockets.com/rockets/engines/plugged-engines.

[9] "Estes Engine Chart." *Estes Rockets* Availabile: http://www2.estesrockets.com/pdf/Estes_Engine_Chart.pdf

[10] Metals, O., "6060 ALUMINUM RECTANGLE BAR (METRIC SIZE) 10MM X 5MM 60 LONG - PACK OF 6 BARS," OnlineMetals.com Available: https://www.onlinemetals.com/merchant.cfm?pid=22572step=4showunits=inchesid=1637top_cat=60.

[11] Geisler, R., "Estimating Total Welding Costs," Fabricating and Metalworking Available: http://www.fabricatingandmetalworking.com/2012/04/estimating-total-welding-costs/.

[12] "Bungee and Shock Cord — US Netting," US Netting the netting experts Available: https://www.usnetting.com/rope/bungee-shock-cord/.

[13] "2-1/2 Bore Double Acting Air Cylinder 6 Stroke," Zoro the fox Available: https://www.zoro.com/velvac-air-cylinder-air-2-12-in-bore-clevis-100123/i/G5262704/feature-product?gclid=EAIaIQobChMI8e7Ct8nU3QIVQrnACh0P0waLEAQYASABEgLGi_D_BwE.

[14] "Sullivan SkyLite Wheel w/Aluminum Hub 4-1/2," *Tower Hobbies* Available: https://www.towerhobbies.com/cgi-bin/wti0001p?I=SULQ3853P=FRgclid=EAIaIQobChMIp8XD1YLV3QIVCIFpCh2TqgUKEAC

[15] Potvin, J., "Building a Model Rocket Parachute Recovery System," *Building a Model Rocket Parachute Recovery System* Available: http://www.pcprg.com/rocketre.htm.

[16] Zwicker, M. L., and Sinclair, R. J., "Pack Density Limitations of Hybrid Parachutes," *AIAA Aerodynamic Decelerator Systems (ADS) Conference* Available: https://airborne-sys.com/wp-content/uploads/2016/09/Pack-Density-Limitations-of-Hybrid-Parachutes.pdf.

[17] Zen Cart Team, "Iris Ultra 96 Standard Parachute - 50lbs @ 20fps," *How to make a Parachute* Available: https://fruitychutes.com/buyachute/iris-ultra-standard-chutes-c-29/iris-ultra-96-standard-parachute-50lbs-20fps-p-145.html.

[18] Chai, S. T., and Mason, W. H., "Landing Gear Integration in Aircraft Conceptual Design," *Multidisciplinary Analysis and Design Center for Advanced Vehicles* Available: http://www.dept.aoe.vt.edu/ mason/Mason_f/M96SC.html.

[19] Ablog, D., Fuget, M., Ko, S., and Tsujita, K., "Optimization of Landing Gear Fairings," *Optimization of Landing Gear Fairings* Available: http://web.stanford.edu/ kei5328/fairingOpt/LandingGearReport.pdf.

[20] "Measuring Spatial and Vertical Heterogeneity of Grasslands Using Remote Sensing Techniques," *JOURNAL OF ENVIRONMENTAL INFORMATICS* Available: http://www.jeionline.org/index.php?journal=myspage=articleop=downloadpath[]=pdf_38.

[21] https://www.aliexpress.com/item/6-inch-Big-RC-Airplane-Wheel/32828147210.html

[22] "Estimate Propeller's Static Thrust," *RC Planes Online* Available: https://rcplanes.online/calc_thrust.htm.

[23] Anderson, J. D., "Fundamentals of Aerodynamics", New York, NY: McGraw-Hill Education, 2017.

[24] Yip, Long P., "Wind-Tunnel Investigation of a Full-Scale Canard-Configured General Aviation Airplane.," NASA Technical Paper 2382., March 1985.

[25] Aviator's Database. "Tractor Configuration."

[26] Taylor, M. B., "Pusher Propeller Efficiency and Problems.," Aerocar.

[27] Raymer, Daniel P., "Aircraft Design: A Conceptual Approach. AIAA Education Series.

[28] www.horizonhobby.com/airplanes/motors/power-60-brushless-outrunner-motor–400kv-eflm4060a

[29] Fiorenzani, Tiziano. HOW DO DRONES WORK? PART 9 - IMU (Inertial Measurement Unit). LinkedIn,

[30] MicroControllerShop.com. The MicroController and Embedded System Store, microcontrollershop.com

[31] Pixhawk 4. Basic Concepts PX4 User Guide, docs.px4.io/en/flight_controller/pixhawk4.html.

[32] MRo Pixhawk 2.4.6 Essential Kit! MRobotics.io, store.mrobotics.io/Genuine-PixHawk-Flight-Controller-p/mro-pixhawk1-minkit-mr.htm.

[33] MRo Pixhawk. Basic Concepts PX4 User Guide, docs.px4.io/en/flight_controller/mro_pixhawk.html.

[34] DavidBuzz, et al. PX4 Vs ArduPilot - When to Choose What. ArduPilot Discourse, 21 Jan. 2017, discuss.ardupilot.org/t/px4-vs-ardupilot-when-to-choose-what/14262.