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Project Definition Document
ARES: Aspect-ratio Redesign of Eagle-owl for Storm-chasing

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Approvals

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1. Problem Statement

Small unmanned aircraft 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. This can be gathered 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, this can have a significant impact on aerodynamic performance and expose the hardware to damage.[2]

A FADS system employs a similar solution to the MHP in that it takes pressure data at multiple points as inputs and allows for the computation of wind speed, angle of attack, and side slip based on the aggregate data, which can then be combined to get wind velocity. FADS systems differ in that, as opposed to placing the pressure ports along a mechanical probe which attaches to the aircraft, the ports are embedded within the surface of the airframe itself. This greatly reduces the aerodynamic footprint of the sensor and allows the airframe to shield the system from damage.[3] In most cases, a FADS system is also significantly less expensive than the use of a MHP while retaining a similar level of accuracy.

The purpose of this project is to design, build, and verify a box wing aircraft with a FADS system to measure pressure and convert that data to relative wind speed. The Aspect-ratio Redesign of Eagle-owl for Storm-chasing (ARES) aircraft will be an updated model of a previously designed and constructed 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 after at least 10 flight cycles. In past designs, the Eagle Owl did not have a formal landing procedure or mechanism beyond a somewhat guided crash into the ground; as a result, a pressure-measuring probe would have been damaged or destroyed when the airframe tumbled during landing. In response to this, another objective of ARES is to construct the new aircraft such that it can survive at least 10 repeated landings. The final product will be validated in a flight test to demonstrate the full cycle of a future mission.

2. Previous Work

The most important predecessor to Eagle Owl was a variation created by the Research and Engineering Center for Unmanned Vehicles (RECUV). This adaptation was designed and built by Dr. Argrow, Matthew Osborn, and Tom Wormer in 2007. Much of the design was made in the program, Athena Vortex Lattice, and many of the design choices were done so to maximize the lift over drag ratio (L/D). The box shape of Eagle Owl was chosen to isolate the effects of flow separation over the wing bodies. This adaptation was selected to have an aspect ratio of 3 due to the 25% increase in L/D from 2 to 3. Next, a stagger of the top wing ahead of the lower wing was chosen to increase the in-flight stability, and the choice of a larger upper wing further maximized the L/D ratio. A cambered wing was used for both wings because it offers a high coefficient of lift for a minimal increase in coefficient of drag. The aircraft only had two control surfaces which were elevons (ailerons coupled with elevators) located on the upper wing. The motor was precisely installed to account for motor torque and placement off of the center of gravity. The aircraft was flown by radio control (RC) and was hand launched overhead. The criticisms of this design, which this team would like to overcome, were that the flying wing had a tendency to climb fast in altitude with an increase in throttle and that the system had difficulty returning to steady flight after a strong banked turn.

Another notable variation from the original Eagle Owl design is that of a 2012-2013 senior project: Small Combined Unmanned Aircraft (SCUA).[4] SCUA consisted of multiple box-biplane units designed to take off together and separate in midair in order to accomplish multiple mission objectives simultaneously. Both individual pieces could sustain controlled flight individually. Each one of these units was identical and used a design that borrowed heavily from the original Eagle Owl to accomplish its unique project requirements. The propulsion systems used a propeller in the rear powered by a motor which was supplied by a few batteries held in carbon fiber housing. The aircraft was hand launched using an underhanded method. The units were operated by an RC pilot via a receive only radio frequency (RF). The wiring and other small electronics were pressed into the foam in a flush fashion, for aerodynamic purposes, into the body of the aircraft itself. Lastly, the units were controlled by two elevons and had a stagger between the upper and lower wing, similar to Eagle Owl.

The main instrumentation carried by ARES will be a FADS system. A FADS system is a collection of pressure sensors that are placed flush with the surface of the airframe, exposed directly to the airstream. A FADS system is often placed into a modified nosecone in a conventional aircraft. Other pressure sensors, such as MHPs, are difficult to calibrate due to their direct exposure to the external flowfield while FADS can use the natural shape of the aircraft to "clean up" the incoming data and makes calibration easier.[6] FADS systems are often used in supersonic aircraft, where a probe on a boom in front of the aircraft can destabilize flight. The effects of these systems were being studied by NASA in the late 1990s. FADS systems have also been shown to provide (after mathematical regression) wind speed data to within 1 m/s and angle of attack and sideslip angles to within 1° of true, even while mounted on a small UAS.[2]

3. Specific Objectives

Success levels for various elements have been defined for ARES. A level 1 success is the first stage of accomplishments to be achieved on the way to level 3, which satisfies all goals to design for. Level 1 demonstrates that the box wing aircraft includes the necessary instrumentation, is flight capable, and can achieve steady level flight during cruise with an autopilot. Level 2 successes improves on these characteristics, includes an autopilot with maneuverability, and a 1 hour endurance with all systems powered. An endurance of 1 hour was chosen because this matches the goal of old Eagle Owl project. Additionally, level 2 adds in that the aircraft must perform at least 10 consecutive takeoff and landing cycles. 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. ARES will be designed to complete level 3 objectives, but the lower level tiers are suitable in the event that down scoping is necessary. Most objectives can be verified through inspection during and after flight tests. Verification of the FADS system's accuracy will need to be conducted by a to be determined (TBD) method, but potential options include wind tunnel testing or flying a predictable pattern in known conditions while measuring the nearby wind with an anemometer.

	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	• Landing method is prearranged and controlled such that damages can be repaired in the field. • Landing method allows for consecutive takeoff and landing cycles	• Maintain steady, level flight for at least 2 min (flight time of previous Eagle Owl) • Steady, level flight achieved with autopilot • Remote controlled where needed	• Takeoff with no damage to sensors, structure, or operators • Achieve a TBD cruise altitude that must be less than 400 feet[5]
Level 2	• Level 2 objectives are the same as level 1 objectives	• Consecutive takeoff and landing cycles occur a minimum of 10 times	• Autopilot achieved with ability to maneuver in a TBD diameter circle while staying within visual sight	• Flight endurance is greater than 1 hour (endurance goal of the previous Eagle Owl)
Level 3	• Calibrate FADS system such that data is converted to aircraft-relative wind velocity to within 1 m/s and 1° of accuracy.	• Accurate landing in a recovery zone within TBD meters	• Full flight with takeoff and landing achieved with autopilot	• Flight endurance is greater than 2 hours with all systems powered

Table 1. Success levels for ARES mission objectives.

The deliverables for ARES are the aircraft, the takeoff system, and a landing system (should the takeoff or landing method evolve to include separate components from the aircraft). All necessary software and flight test data will be delivered with final simulations, trade studies, and models, including a model of predicted flight performance and a comparison to Eagle Owl.

4. Functional Requirements

4.1. Requirements

The requirements listed below provide a high level overview of the customer's expectations for the project. By describing the desired behavior of the system instead of the specific hardware involved, different solutions may be examined in order to satisfy the customer's goals. Because the purpose of the project is to improve the aerodynamics of the previously designed Eagle Owl, the values from the customer (listed below) are roughly double the aerodynamic performance of the previous aircraft.

R.1: *The aircraft shall have a total endurance of at least 2 hours and be capable of traversing a circular flight path while staying within visual sight.* Increasing the endurance is the customer's primary goal. By flying in a large circular pattern, the onboard sensors can be calibrated, and the aircraft will stay within sight as per the Federal Aviation Administration[5] regulations. With the visibility constraint, the customer states that a circular pattern is the most efficient for demonstrating endurance.

R.2: *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 (prior aspect ratio = 3) to increase endurance will be investigated.* The customer believes that increasing the aspect ratio will improve flight efficiency and improve endurance. Limiting the span ensures easy transport of the aircraft.

R.3: *The aircraft shall demonstrate a controlled takeoff and must not cause any mission critical, debilitating damage or injury to the structure, sensors, or operators.* Due to the size of the aircraft, hand and car takeoffs pose safety risks.

R.4: *The aircraft shall be piloted by an autopilot during the controlled flight regime of the mission (circular path).* The customer has requested the autopilot be used for at least the controlled maneuvers but ideally also for takeoff and landing.

R.5: *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.* Pressure and density, found through the temperature sensor, are needed post flight to calculate the speed of the wind.

R.6: *The aircraft shall land in a manner such that the aircraft is capable of completing at least 10 takeoff and landing cycles in immediate succession without requiring repair of the airframe or sensors.* 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 repair (this excludes expected minor field repairs such as replacement of a broken propeller).

4.2. Concept of Operations

The image 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 R.3, R.4, and R.6, respectively. Additionally, this operation will validate the aircraft's endurance stated in requirement R.1 and data collection during the operation will validate requirement R.5. The upper height bound of 400 feet comes from FAA regulations,[5] and the TBD location will be in Colorado. Finally, the image of the aircraft in the upper right corner depicts the requirements stated in R.2.

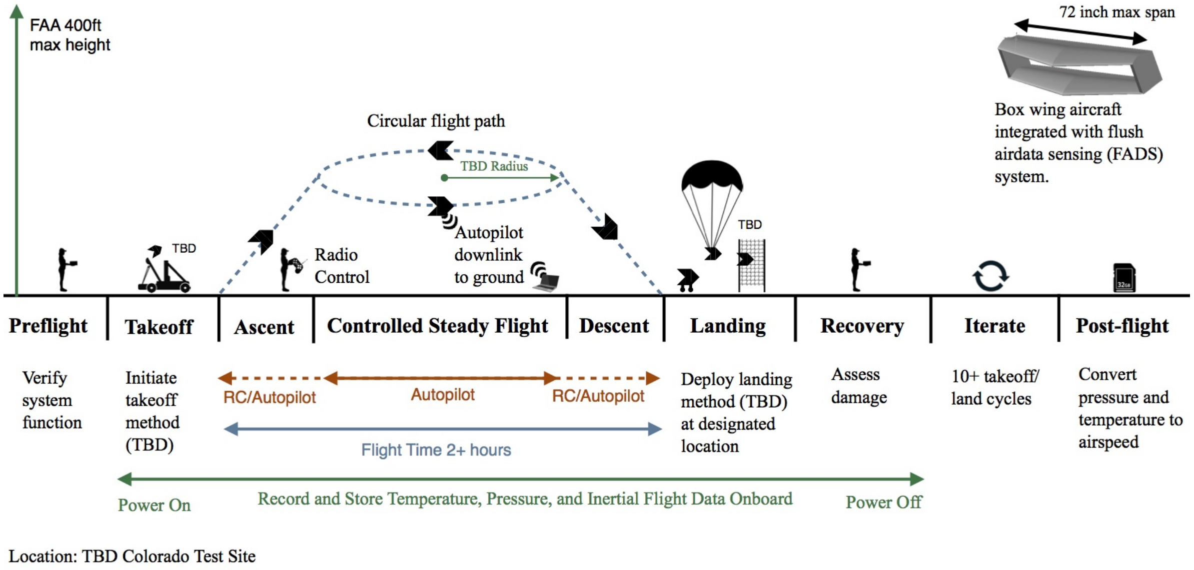

Figure 1. Concept of Operations for ARES.

4.3. Functional Block Diagram

The image below 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 landing system may evolve to include separate components from the aircraft, but this is TBD 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 TBD 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.

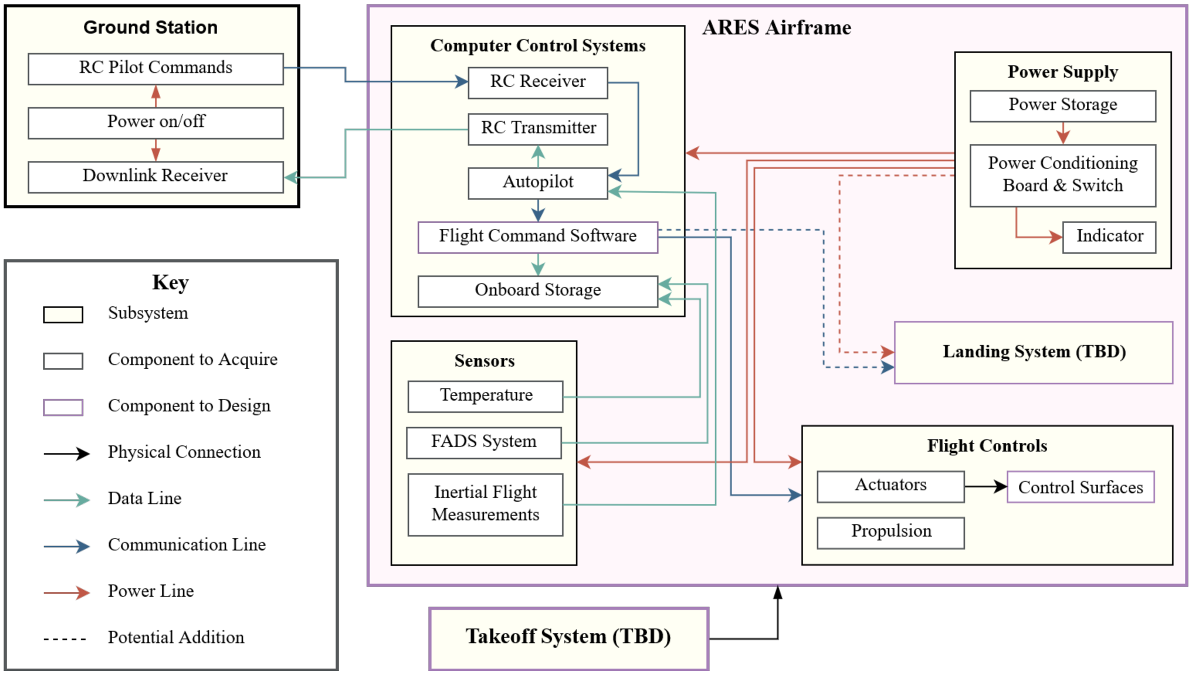

Figure 2. Functional Block Diagram for the mission hardware interactions of ARES.

5. Critical Project Elements

5.1. Technical Elements

T.1 Aircraft Redesign: A critical objective of ARES is to improve the endurance of the aircraft. The main difficulty in achieving this lies in redesigning the Eagle Owl aircraft while maintaining structural integrity and retaining aerodynamic stability. Without improved endurance, ARES will not meet customer requirements. The consequences of structural weakness or instability could be failure of the aircraft during flight testing.

T.2 Takeoff Method: A takeoff method or system will be developed for this project in order for the aircraft to fly. The challenge in determining the takeoff method or system used, is the box wing design of the aircraft. The aircraft does not have a fuselage, removing common takeoff methods with proven flight heritage and requiring a new system or method for this purpose. If a suitable takeoff method or system is not developed, the aircraft cannot fly.

T.3 Reusability: The aircraft will not have a runway available for landing and therefore a suitable landing system or method will be explored to allow for the reusability of the aircraft. A suitable method will be challenging to implement due to the uniqueness of the airframe's box wing design. This open air configuration minimizes structural integrity and necessitates the absence of a fuselage. If a suitable landing system is not used, then the FADS system, other avionics components, or the aircraft structure could be damaged upon landing. This would render the aircraft incapable of a minimum of 10 or more takeoff and landing cycles, a customer requirement.

T.4 FADS System Integration: The aircraft will record pressure data during flight with the integrated FADS system.

The challenge of this integration will be ensuring the flush placement of the FADS sensors allows for precise measurements during flight while providing protection for the sensors and components during takeoff and landing. This is critical to the project because the FADS system is a top priority for the customer's future intentions for the aircraft.

T.5 Autopilot System Integration: The autopilot, in collaboration with other systems, will control the aircraft's trajectory to achieve customer requirements. This will be challenging because control algorithms for the autopilot must be defined and calibrated specifically for the custom control surfaces used on ARES. If the autopilot is improperly integrated, the aircraft will be incapable of controlled flight and would not meet success objectives.

5.2. Logistical Elements

L.1 RC Pilot: An RC pilot may be required during takeoff and landing prior to the use of the autopilot system. If RC piloting is used, at least 1 team member is required to attain RC pilot training in order to control the aircraft. RC pilot training and licensing will need to be completed as soon as possible in order to reduce schedule risk during testing. Without an RC Pilot, the aircraft will not be able to demonstrate performance characteristics or prove data collection capabilities.

5.3. Budgetary Elements

Components needed for mission success, including autopilot, sensor packages, and structural materials, may be expensive. In the case these items are damaged during testing or risk-reduction prototyping, budgetary constraints may occur. However, the team does not believe these are considered critical at this time.

6. Team Skills and Interests

Team Member	**Skills & Interests**	**Relevant CPEs**
Cody Goldman	Controls, wind tunnel testing, aerodynamic modeling, propulsion, management, embedded software	T.1, T.5, L.1
Alejandro Corral	Structural design, mechanical design, manufacturing, testing, CAD modeling, RC piloting, aerodynamic design	T.1, T.2, T.3, T.4, L.1
Ryan Davis	RC pilot training, testing, GPS navigation, autopilot system, data acquisition and analysis	T.2, T.3, T.4, T.5, L.1
Thomas Kisylia	Aerodynamics analysis, propulsion implementation and analysis, avionics, structures, flight dynamics and navigation.	T.1, T.2, T.3, T.4
Erika Polhamus	Systems engineering: writing SoW, requirements design, interface control documents, systems architecture, signal mapping	T.2, T.3, T.4
William Butler	Systems engineering, PCB design and population, aerodynamic analysis, wind tunnel testing, manufacturing, test engineering	T.1, T.2, T.3, T.4
Alec Stiller	Welding, machining/manufacturing, 3D printing, laser cutting, CAD modeling, flight software, algorithm development.	T.1, T.2, T.4, T.5
Yuma Yagi	DBF experience, aircraft performance and stability and aerodynamic analysis (XFOIL, AVL, XFLR5), auto-pilot system	T.1, T.2, T.3, T.5
Matthew Alexander	Mechanical design, CAD modeling and documentation, additive manufacturing, laser cutting, RC pilot training	T.1, T.2, T.3, L.1
Connor Myers	Machining/manufacturing, PCB development, electronics, software, RC pilot training	T.2, T.3, T.4, T.5, L.1
Elliott Davis	Embedded flight software, PCB development, electronics, manufacturing and RC pilot training	T.1, T.4, T.5, L.1
Carson Brumley	Systems engineering, requirements, integration, model testing, airframe manufacturing, structure design, materials, landing system	T.1, T.3, T.4

7. Resources

Critical Project Elements	Resource/Source
T.1 Aircraft Redesign	Dr. Donna Gerren, experience mentoring DBF and similar plane projects; Dr. John Evans, valuable resource for CFD modelling; Dr. Dale Lawerence, expert in control theory and aircraft stability
T.2 Takeoff Method	Dr. Donna Gerren; Matt Rhode, experience designing mechanical systems and is an expert in manufacturing/machining
T.3 Reusability	Dr. Donna Gerren; Matt Rhode; Bobby Hodgkinson, mechanical design and machining experience
T.4 FADS System Integration	Roger J. Laurence, PhD student involved in prior research of FADS model; Trudy Schwartz, electronics and avionics experience
T.5 Autopilot System Integration	Dr. Dennis Akos, interest and experience with autopilot integration; Trudy Schwartz
L.1 RC Pilot	Boulder Aeromodeling Society, provides training and flight locations for RC tests

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] Boerhave, G., Guadyn, D., Hennig, G., Milliken, J., Trussell C., Varhus, J., Ziegler, M., “SCUA: Small Combined Unmanned Aircraft,” CU Boulder AES Senior Projects, 2012-2013.

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

[6] Whitmore, S., Cobleigh, B., and Haering, J. E., “Design and calibration of the X-33 Flush Airdata Sensing (FADS) system,” 36th AIAA Aerospace Sciences Meeting and Exhibit, Dec. 1998.