Design of a Micro-Scale Deployable Unmanned Aerial Vehicle

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Abstract: Small unmanned aerial vehicles that can be deployed from a tube have a wide range of potential uses, from military reconnaissance to interplanetary exploration. The primary benefits of such designs are stowability and the potential to deploy via mechanisms such as artillery shells, sonar buoy tubes, rockets, and interplanetary probes. The design of a micro-scale, autonomous, unmanned aerial vehicle, deployed from a cylindrical container is presented. The integration of elements unique to deployable aircraft, such as folding control surfaces, retractable empennage, and inflatable wings are explored. The focus point is the design of a small glider with the ability to deploy from a container with a diameter of 5.5 inches and a length of 10.5 inches. These dimensions were chosen to match the payload bay of an ARLISS high power rocket.

Key-Words: Unmanned Aerial Vehicles, Aircraft Design

1. Introduction

This paper presents the design of an Autonomous Tube-Deployable Aerial Vehicle (ATDAV) to participate in the ARLISS Comeback Program. ARLISS (A Rocket Launch for International Student Satellites) is a cooperative venture between Stanford University and AeroPac, a regional amateur rocketry group. Students design rocket payloads to perform various tasks such as collecting atmospheric data or communicating with the ground via radio. In the Comeback Program, teams must design a vehicle capable of navigating independently to a target. Before being placed inside the rocket, the vehicle is given a set of coordinates, to which it must travel after being ejected from the rocket at altitude. The focus of the paper is the configuration design of the aircraft as well as the unique deployment capabilities it requires.

2. Mission Specification

The design requirements for the ATDAV are based on the ARLISS Comeback competition, which states that the vehicle must deploy from the payload bay of a rocket at 10,500 ft AGL and navigate autonomously to a set of GPS coordinates no more than 1 mile from the launch site. The aircraft should be able to land within a circle of radius 25 yards surrounding the coordinates. These requirements necessitate the construction of an aircraft that is not only flight-capable, but can also be compressed into a small space. Most of the design decisions revolve around fitting the aircraft into the rocket cylinder and the ability to transition to flight upon deployment. The uncertain nature of the weather at the time of launch requires that the aircraft be able to operate in a wide range of wind conditions, requiring a high maximum airspeed to penetrate fast winds. This conflicts with the requirement that landing speed should be low to allow the autopilot to accurately place the aircraft in the required landing area. The mission requirements do not require a very maneuverable aircraft. The rocket is limited to a payload of approximately 10 lbs, however the practical limitation on the weight of the aircraft will be far less.

3. A Look at Similar Aircraft

While not commonplace, deployable aircraft do exist for various applications. One of the simpler types is the steering parafoil, which can be deployed like a parachute and guided to a target. Small parafoils, however, are very sensitive to weather conditions and do not have the performance of a fixed wing airplane. Traditional designs for stowable and deployable aircraft utilize primarily mechanical designs, such as folding wings. However, surfaces that fold incur penalties in the form of weight and complexity with each additional fold. Further reducing the stowed volume requires an increasing number of joints. More advanced designs often incorporate inflatable wings in either full or partial-span configurations as a method of maximizing the potential wingspan that can be reasonably stowed.

When compared with other gliders, the ATDAV will be aerodynamically similar to so-called "slope soarers", unpowered radio controlled airplanes that are designed to fly on the windward side of hills. Such models take advantage of the rising air that occurs as it is forced over the hill. Because these aircraft are designed to operate in high wind conditions, they typically have a moderate to high wing loading and a smaller wingspan when compared to other gliders. A number of aircraft of various sizes, both deployable and non-deployable, are shown in Table 1.

Table 1 – Selected data of similar aircraft

		Weight (lb)	Wingspan (ft)	Wing area (in^2)	Wing loading (oz/in^2)
Dynaflite BOT	Radio control sailplane	2.55	9	1070	0.04
Mistral - heavy	Radio control slope glider	9.79	9	1066	0.15
Big Blue	Research	17.6	6	850	0.33
ILC Apteron	Inflatable flying wing	7.04	4.8	574	0.20
Shuriken Slope	Radio control slope glider	3.10	4.56	360	0.14
GLOV	Reconnaissance UAV	39.6	4.5	372	1.71
RQ-11	Miniature reconnaissance UAV	4.18	3.9	292	0.23
SkyFly 2	Radio control electric airplane	1.21	3	186	0.10
Wasp III	Miniature reconnaissance UAV	0.95	2.22	176	0.09

4. Configuration Selection

An early rendering of the configuration of the ATDAV is shown in Figure 1. One of the primary design challenges for this vehicle is the requirement to fit into a small container. To accomplish this, the empennage is attached to a retractable tailboom, allowing it to collapse into the fuselage (Figure 1). The T-tail was chosen so that the horizontal stabilizer sections are able to fold down past the tailboom, thereby maximizing their size. Inflatable wings are used to maximize the deployed span for a given stowed size. High wings and dihedral will provide inherent roll stability.

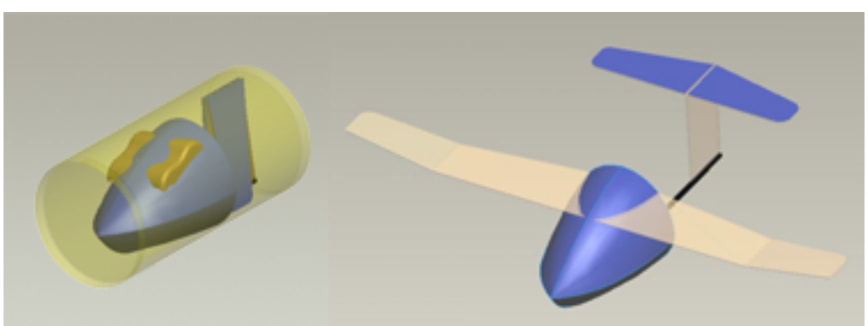

Figure 1 – Early rendering of the ATDAV in stowed and deployed configurations.

5. Fuselage Design

Figure 2 shows details of the fuselage exterior, while Figure 3 shows the internal layout of the fuselage. The main constraint for the fuselage is the overall size. The collapsed aircraft needs to fit in a standardized ARLISS deployment tube. This tube has an inside diameter and length of 5.5 and 10.5 inches, respectively. The inflatable wings will be rolled and placed alongside the fuselage inside of the cylinder. This empennage will be situated on a boom, which will be spring-loaded to allow automatic deployment in midair, and as a result the fuselage must contain a housing for the spring and tailboom assembly. These parts will be made of rolled fiberglass and carbon fiber tubes designed to mate together in order to provide the tailboom with a maximum amount of rigidity. The fuselage must be large enough to contain the autopilot, receiver, an inflation system for the wings, and a significant amount of ballast to adjust the center of gravity to its optimal location. The inflation system consists of a CO_2 cartridge and other items that are explained below.

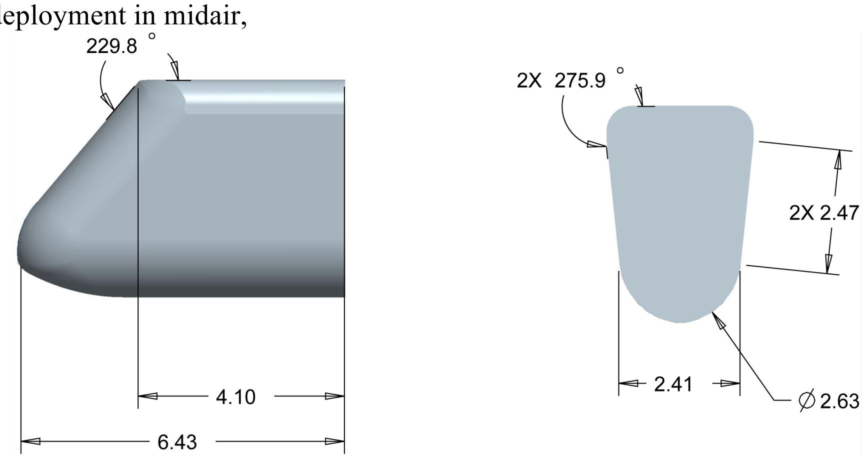

Figure 2 – Side and rear view of the fuselage (all dimensions in inches)

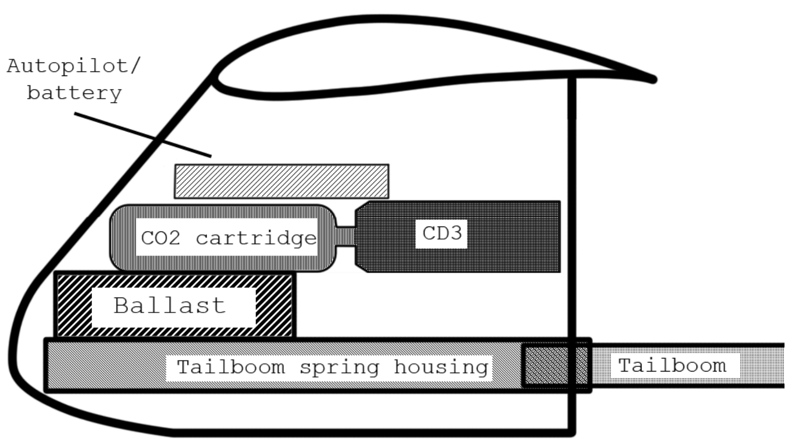

Figure 3 – Internal layout of the fuselage

6. Wing Design

6.1 Airfoil Selection

The airfoil must combine a moderate lift-to-drag ratio (L/D) with a high maximum lift coefficient (C_{Lmax}) to provide a balance between cruise efficiency and a slow landing speed. From these requirements, as well as its history in inflatable wing designs, the Eppler 398 airfoil was selected. The drag of this airfoil is rather high. However, the mission range is only one mile from a deployment altitude of over 10,000 ft AGL, hence cruise efficiency is not critical. In fact, the higher drag will facilitate a steeper descent towards the target landing area. On the other hand, the ATDAV cannot use high lift devices due to its inflatable wing design, hence an airfoil with a high clean C_{Lmax} is imperative.

6.2 Wing Planform Selection

Unlike most gliders, our wing planform is untapared, as we wish to obtain the largest wing area for a given span. Although it is not desirable, our flexible wing may have some twist as a result of the aerodynamic forces acting on it. The inflatable wing design makes it impossible to incorporate geometric twist as a design feature. If the wing is designed with washin (tips up), the tips will operate at higher lift coefficients and as a result, they may deflect upwards. Conversely, if the wing is designed with washout (tips down) the tips may unload during flight and deflect downwards. Either type could cause unwanted amounts of tip deflection, and downward deflection caused by negative twist could reduce the amount of dihedral and create stability problems. The internal pressure provided by the inflation system should provide enough rigidity to keep this twisting to a minimum. Unlike geometric twist, aerodynamic twist could be implemented in the design of an inflatable wing. This, however, would be limited by the ability of the PVC fabric membrane to cover the compound curves introduced by such a design. The ATDAV wing was designed with neither geometric nor aerodynamic twist.

6.3. Dihedral Angle

The aircraft is inherently stable in roll due to its high wing configuration. Based on designs of similar aircraft, a dihedral angle of about 7° is used to further increase the roll stability. The easiest way to incorporate a dihedral in inflatable wings is a moderate deflection of the wing beginning at the roots.

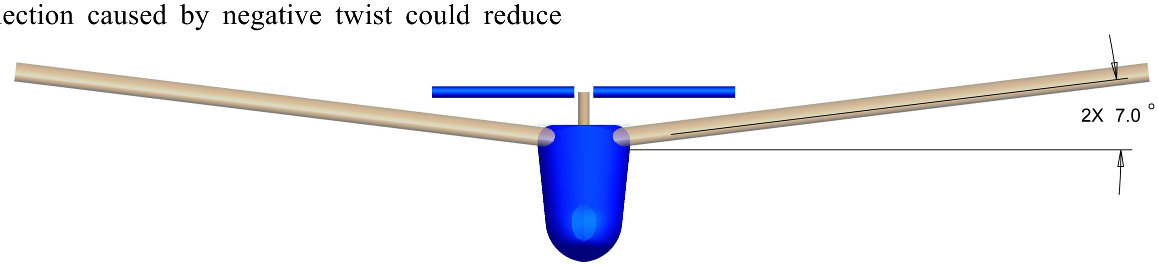

Figure 4 – Front view of the aircraft showing 7º of dihedral.

6.4 Inflatable Wing Design

The most technically challenging component of the ATDAV is the procurement of an appropriate set of inflatable wings. Two companies in the United States produce inflatable wings small enough for use in unmanned aircraft: ILC Dover [1] and Vertigo Inc. [2]. These wings are designed for UAVs larger than the ATDAV and cost approximately $5,000. Building and testing two inflatable wings using readily obtainable materials is our preferred approach at this point. This process offers an additional advantage, namely it will allow us to modify the wing if it does not meet the design specifications. Two inflatable wings will be made, the first similar to those produced by ILC Dover and Vertigo Inc., the second using a novel method to simplify construction.

The first method, used in most inflatable wing aircraft, relies on inflated tubes to provide shape and stiffness to the wing. The ILC Dover and Vertigo Inc. wings are similarly constructed of multiple tubular cells, which when inflated provide the wing with shape and rigidity. The wings constructed by ILC Dover have a number of bumps running longitudinally down the wing as a result of the internal construction (Figure 5). As shown in Figure 6, the bumpy profile improves aerodynamic performance by reducing flow separation in the low density, high altitude conditions for which these wings are designed [3].

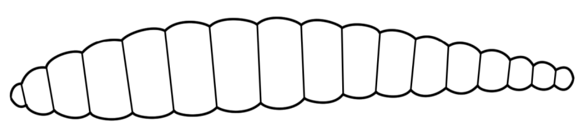

Figure 5 – Cross-section of an inflatable wing, such as those manufactured by ILC Dover. Shown is an inflatable version of the Eppler 398 airfoil selected for the ATDAV.

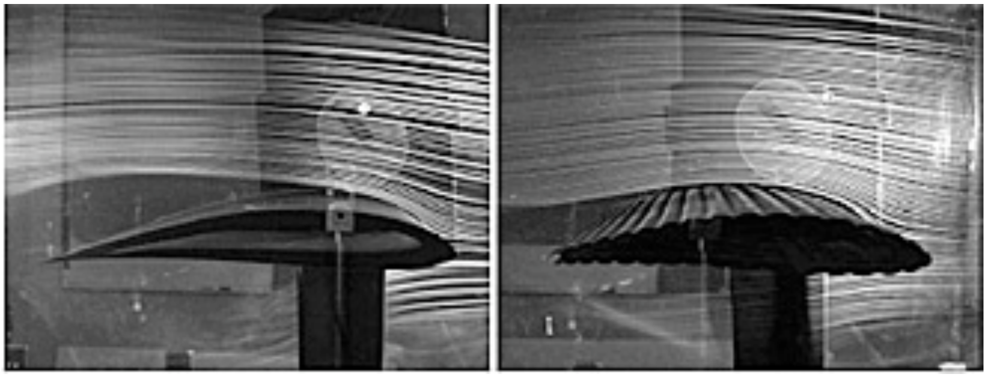

Figure 6 – Wind tunnel testing of an ideal (left) and inflatable (right) Eppler 398 airfoil. The bumpy inflatable airfoil is experiencing less flow separation than the ideal airfoil [3].

The inflatable wings manufactured by Vertigo Inc. are built with the same internal structure as the ILC Dover wings but lack the bumpy surface due to their more complex construction. The tubular spars are covered with collapsible open cell foam, which is then covered with a nylon fabric outer shell. This allows the wings to be collapsible but with a smooth surface at the cost of an additional layer of fabric and foam.

A novel design being considered for the ATDAV wing may allow a simpler manufacturing process that is more suited to the small size of the ATDAV wings (Figure 7). Open cell foam is cut to the shape of the airfoil using a hot wire device. This foam becomes the core of the wing and is adhered to PVC fabric, which is sealed with vinyl cement and heat. The purpose of the foam core is to provide the tensile force necessary to allow the wing to maintain its shape when pressurized. Because this design only requires the use of a single large chamber, it appears well suited for small wing designs where multi-chamber construction would require tiny diameters for the smaller tubes. Additionally, this design allows for a smooth airfoil without the increased complexity of the Vertigo Inc. approach. Disadvantages of this design are reduced rigidity, especially in torsion, due to the loss of internal structure. This may not pose as much of a problem with the small and slow ATDAV as it might with a larger, faster aircraft. A prototype of this wing type was built with partial success. The foam core was successfully cut from a sheet of open cell foam, and the PVC fabric adhered to it and sealed. Upon inflation, however, the foam partially delaminated from the membrane, causing the wing to lose its shape. The sections where the vinyl was sealed remained airtight. The problem encountered with adhering the foam to the membrane may be correctable through the use of a different adhesive or technique.

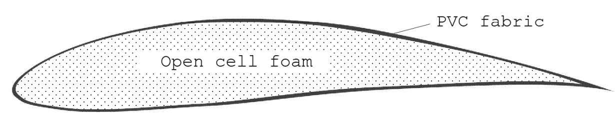

Figure 7 – A novel design idea that will be tested for use in the ATDAV inflatable wings.

6.5 Inflation System Design

A cylinder of compressed CO_2 inside the fuselage connected to a common manifold will inflate both wings upon deployment. A reliable method to trigger inflation is required. To this end, the RouseTech CD3 device [4] has been selected, that uses a small pyrotechnic charge to puncture a gasket in a CO_2 canister. This device is typically used to deploy parachutes for rockets at altitude. Minimal modification will allow the gas to be directed into the manifold for the inflatable wings.

6.6 Lateral Control System

Lateral control surfaces (ailerons) are used to bank the airplane by creating a rolling moment about the fuselage. For many small model gliders this is deemed unnecessary due to the coupling between the yaw created by an appropriately sized rudder and the roll created by the wing dihedral. One additional reason in favor of this design is the fact that inflatable wings are extremely hard to manufacture with control surfaces. Successful designs involve methods to warp the wings but this adds undesirable complexity for a small design such as the ATDAV. Our design forgoes direct roll control and uses instead control surfaces on the empennage to provide directional control.

7. Empennage Design

7.1 Sizing

The tail volume coefficient method was used to size the empennage [5]:

$$S_h = \frac{V_h S c}{X_h} \qquad S_v = \frac{V_v S b}{X_v} \tag{1}$$

where S, S_h, and S_v are the wing, horizontal, and vertical areas; X_h and X_v are the distances of the horizontal and vertical aerodynamic centers from the wing leading edge; b is the wingspan and c is the wing chord; V_h and V_v are the volume coefficients for the horizontal and vertical stabilizers.

A parametric study of the aircraft shown in Table 1 led to our choice of V_v = 0.20 and V_h = 0.26, while Figure 8 shows that X_v = X_h = 13 in. From our wing design presented earlier, S = 180 in^2, b = 36 in, and c = 5 in. Using these values in Equations (1), S_h and S_v are calculated to be 18 in^2 and 9.72 in^2 respectively. To fit inside the deployment tube, the span of the horizontal stabilizer must be 9 in, leading to a chord of 2 in. Setting the chord length of the vertical stabilizer to 2 in, the span of the vertical stabilizer is calculated at 4.86 in.

7.2 Longitudinal and Directional Controls

To maintain simplicity and maximize longitudinal control, especially with a short tailboom, a free-flying stabilator design was selected. The vertical stabilizer has a conventional rudder, hinged at 50% of the chord.

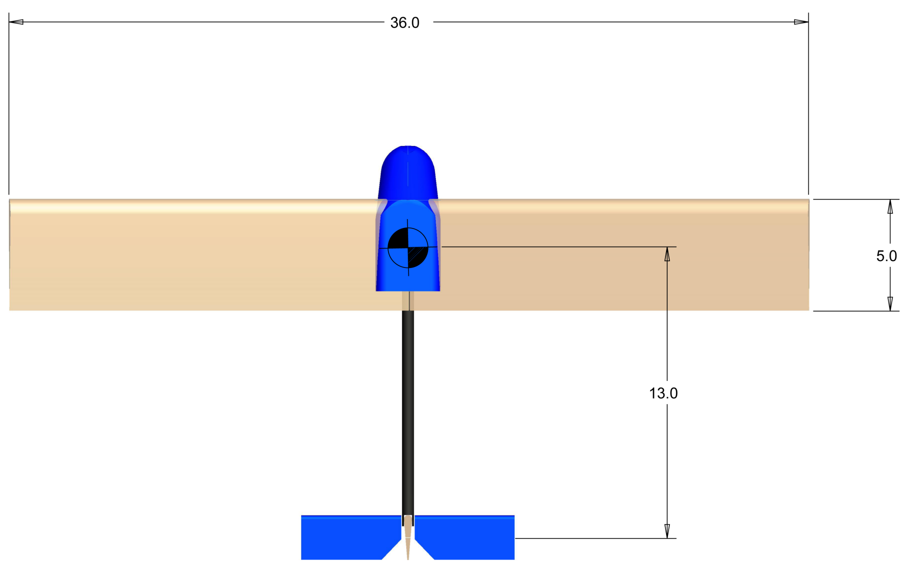

Figure 8 – Aircraft dimensions used in the sizing of the empennage.

8. Weight and Balance Analysis

A ballast is necessary to improve performance in high wind conditions and to properly balance the aircraft. A heavy ballast is usually indicative of a poor design. However, for our aircraft balance is a secondary concern compared to the requirement for stowability. The calculation in this section determines the minimum amount of ballast for a 10% static margin, a requirement we set for acceptable longitudinal static stability [5].

The reference line is placed at a distance of 10% (0.5 inches), in front of the wing aerodynamic center (quarter chord point). The ballast is calculated such that the moment about this point is zero. Table 2 shows the various components of the aircraft along with their weights and moment arms from the reference line. The minimum ballast required is calculated at 0.75 lbs, which results in a minimum aircraft weight of 2.54 lbs. The location of the aircraft center of gravity as a function of ballast weight is plotted in Figure 9.

Table 2 – Aircraft component weights and their respective moment arms

Component	Weight (lbs)	Distance (in)
Ballast	?	-3.25
Futaba R114F Receiver	0.025	-1.25
Futaba S3108 Servos	0.04	11.5
Battery	0.1	-1.25
Fuselage	0.23	-0.75
Tail Boom	0.09	0.63
Horizontal Stabilizer	0.06	13.5
Wings + Inflation System	1.2	0.75
Vertical Stabilizer	0.04	13.5

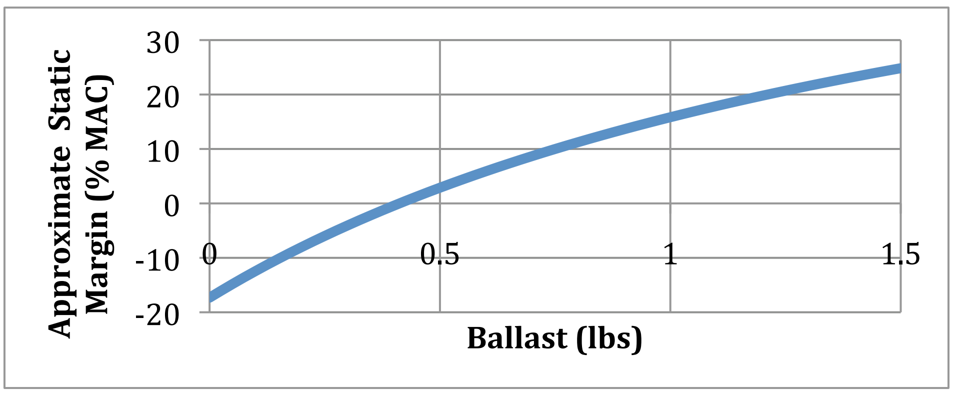

Figure 9 – Center of gravity travel as ballast is increased from 0 to 1.5 lbs.

9. Drag Analysis

The drag coefficient of the glider is broken down as follows:

$$C_D = C_{D\,wing} + C_{D\,fus} + C_{D\,emp} \quad (2)$$

The wing, fuselage, and empennage drag coefficients were calculated to be 0.0277, 0.0828, and 0.0117, respectively giving a total drag coefficient of $C_D = 0.122$. This is a relatively high value, however, as mentioned earlier, it is appropriate for the mission of the ATDAV.

10. Longitudinal Stability Analysis

To determine the change in static margin as a function of the horizontal stabilizer size, the center of gravity and the aerodynamic center locations for the glider are plotted as functions of the horizontal stabilizer area in Figure 10. The static margin can be determined from the difference between the two lines. To meet our requirement of a 10% static margin (measured as a percentage of the wing chord) the area of the horizontal stabilizer must be approximately 14 in^2.

11. Conclusion

This paper has demonstrated the plausibility of constructing a deployable unmanned aerial vehicle. While the avionics necessary to complete the mission are not discussed in this paper, a variety of off-the-shelf autopilots designed for lightweight aircraft is available in the market. Some of the more advanced models have an automatic landing phase functionality, which would be essential for meeting our mission requirements. The aircraft weight is substantially higher than similarly sized designs, however most similarly sized aircraft are not designed to operate in the wide range of wind conditions the ATDAV is likely to encounter. The large amount of weight in the front of the aircraft, currently ballast, could be replaced with additional equipment, such as a larger autopilot or a camera system.

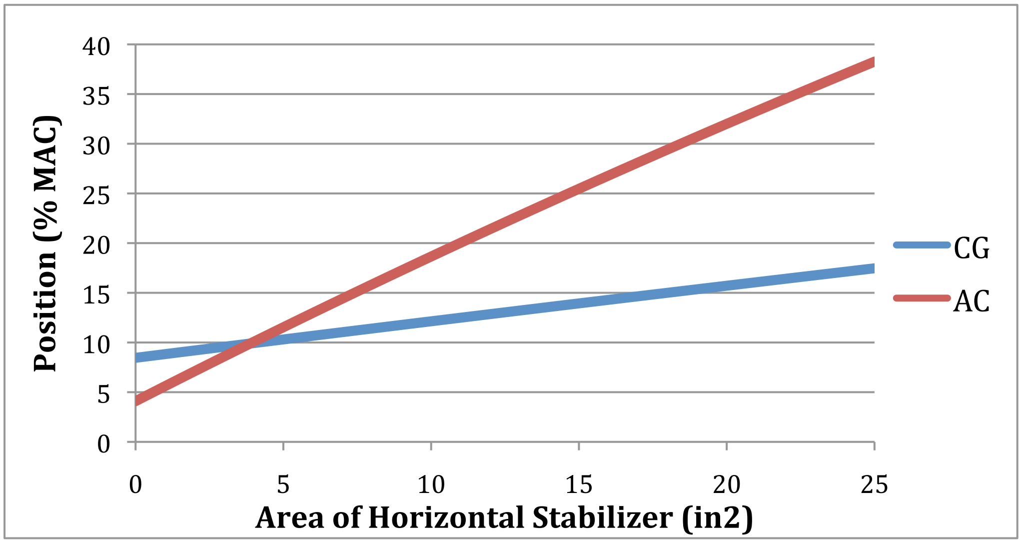

Figure 10 – Longitudinal X-plot, showing the locations of the center of gravity and the aerodynamic center as functions of the horizontal stabilizer area.

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