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Redesign of an experimental Unmanned Aerial Vehicle (UAV) for its conversion into an operational laboratory platform

Philippe White[1,*], John Vaca[2], Jorge Villalba[3], Diego Martinez[4], Gerardo Pardo[5], Hernán Cerón-Muñoz[6]

[1]*MEng University of Sheffield, Aeronautical engineer at Corporación de la Industria Aeronáutica Colombiana (CIAC) and lecturer at the Fundación Universitaria Los Libertadores.*

[2]*MSc Universidad Nacional, Aeronautical engineer and lecturer at the Fundación Universitaria Los Libertadores*

[3]*MSc Universidad Nacional, Mechanical engineer and lecturer at the Fundación Universitaria Los Libertadores*

[4]*Aeronautical engineer at Corporación de la Industria Aeronáutica Colombiana (CIAC)*

[5]*MSc Universidad Autónoma de Bucaramanga, lecturer at the Fundación Universitaria Los Libertadores*

[6]*PhD Universidad de Sao Paulo - Escola de Engenharia de Sao Carlos, Engenharia Aeronautica and lecturer at Escola de Engenharia de Sao Carlos*

Abstract

Following its maiden flight in 2016, the VANT SOLvendus of the Fundacion Universitaria Los Libertadores underwent the first iteration of design improvements. Various shortcomings of the design had been observed, including lack of torsional rigidity of the twin booms, limited transportability and maintainability. Furthermore, the damage incurred from just one flight demonstrated that attrition to the primary and secondary structure would make it difficult (if not impossible) to continue operating the platform for more than a handful of flights before a major overhaul would be necessary. Plans were therefore made to improve its design in preparation for its conversion into an operational laboratory platform. A tubular cross section was proposed as the replacement for the I-beams currently used for the twin boom structure and conceptual designs were developed for the implementation of this tubular structure into the current overall design. This article presents the technical analysis performed with regards to the rigidity of the new structure and its suitability in the design whilst also detailing the conceptual designs of the supporting structural components.

Keywords: Unmanned Aerial Vehicle, UAV, torsional rigidity, redesign, tubular cross section.

INTRODUCTION

Following in the trend of university funded Unmanned Aerial Vehicle (UAV) projects around the world, the Fundación Universitaria Los Libertadores (FULL) began its own project back in 2013 with the aim of constructing its own UAV; the VANT SOLvendus (VS). Colombia has an important role to play in the future of the agro-industrial world and this UAV was originally designed as a support platform for this ever important sector. Mueller and DeLaurier describe some kinds of UAV developed by some commercial companies [1], [2]. The UAV was also to be a technology demonstrator for some of the emerging areas of aeronautical interest; implementation of all carbon fiber constructions and renewable energy sources.

The VS is a twin boomed UAV designed for operation at low Reynolds numbers in the role of surveillance in the agro-industrial sector (See Figure 1). Table 1 shows a brief summary of the first prototype’s geometry and estimated flight characteristics.

Following its maiden flight in 2016, observations were made regarding various shortcomings of the prototype; lack of torsional rigidity in the primary structure, transportability and maintainability. Furthermore, the damage incurred from just one flight demonstrated that attrition to the primary and secondary structure would make it difficult to continue operating the platform for more than a handful of flights before a major overhaul would be necessary.

It is common knowledge that tubes provide significantly improved resistance to torsion when compared to an equivalent

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[*] *Corresponding author: Philippe White,*
Fundación Universitaria Los Libertadores, Bogotá D.C. Colombia
Email: wphilippea@libertadores.edu.co

I-Beam (albeit at the cost of reduced flexural rigidity). Due to the limited time frame afforded to the project, the decision was made to replace the booms with carbon fiber tubes (components that can be easily purchased at relatively low cost) and a structural analysis was performed to assess the suitability of the new design for implementation into the VS.

Figure 1. VANT SOLvendus [3]

Table 1. Basic Aircraft Data for VANT SOLvendus
Source: Own work

Aircraft Geometrical Data	
Aircraft Boom Length	3 m
Twin Boom Separation	1,39 m
Wing Span	6 m
Wing chord (Root)	0,4 m
Wing chord (Tip)	0,15 m
Taper Position (Half-Span)	60%

Aircraft Performance Data	
All-up Weight	15 kg
Height of Operation	9500ft - 2895,6m
Operating Speed	52 km/h
Endurance (Battery)	30 minutes

Table 2. Standard profiles Source: Own work

Profile	Section	Dimension
I-Beam I		H = 1,08in W = 0,78 in B= 0,038 in T = 0,038 in
Tube I		O/D = 35 i/d = 25
Tube II		O/D = 20,7 mm i/d = 13,72 mm
Tube III		O/D = 40,32 mm i/d = 38,1 mm
Tube IV		O/D = 30 mm i/d = 26 mm

The change of such an important structural component also requires many other modifications to the aircraft and so other necessary supporting structures were designed in preparation for the dramatic change in boom design. These changes would also try to address the other problems previously mentioned in this article.

BEAM CROSS-SECTION SELECTION

A supplier of readily purchasable carbon fiber beams was found and the various available cross sections were evaluated considering criteria such as weight, stiffness, and cost. The studied profiles are shown in Table 2

The outcome of the analysis demonstrated that the best option would be Tube III due to the low deformation (25,5mm) with a minimum increase in weight. 3 meters of Tube III weighs 520g which is equivalent to an increase of 4% over the original design.

Table 3. Weight estimation
Source: Own work

Components	Mass (g)	Weight (N)
Main Wing	5915	58,0
Right Boom	500	4,9
Left Boom	500	4,9
Right Engine	111	1,1
Left Engine	111	1,1
Fuselage	288	2,8
Vertical Stabilizer (Left)	186	1,8
Vertical Stabilizer (Right)	186	1,8
Horizontal Stabilizer	536	5,3
Main Landing Gear (Right)	300	2,9
Tail Landing Gear (Right)	300	2,9
Main Landing Gear (Left)	300	2,9
Tail Landing Gear (Left)	300	2,9
Right Engine	111	1,1
Left Engine	111	1,1
Payload	2000	19,6
Total	15189	113,1

ASSESSMENT OF THE BOOM STRUCTURE

A plethora of studies already exist surrounding the subject of composite aircraft structural development. Lee and Kim, developed a semi-empirical analysis of the structure of a Smart UAV. They calculated the internal loads with ARGON and performed the stress analysis using NASTRAN.

Additionally, they also developed tests for major structural components [4]. Kumar developed a structural analysis of a skid type landing gear focused upon material selection. The skid was modeled in CATIA, and the optimization process performed using ANSYS [5]. Alsahlani et al. developed a code for estimating loads in composite wing structures (written in MATLAB) and the outcomes were validated using commercial software (ANSYS) [6].

Finite Element Analysis (FEA) is an effective tool in the aircraft design process, however, the accuracy of the model depends of the knowledge of the user and their understanding on the limitations of the models and their boundary conditions [7].

Weight estimation

The values of weight were measure directly or estimate bases on data-sheet. The values are shown in Table 3.

Loads estimation

Aerodynamic Loads Three Loads were derived for analysis of the boom.

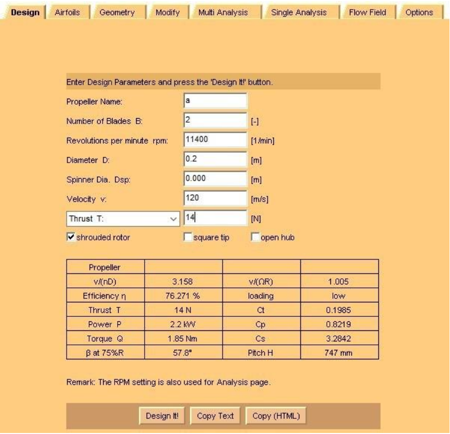
1. The mean load under straight and level flight conditions (n=1g)

2. Maximum pitching loads expected from maneuvering. The loads were estimated based on recommended load factors for an aircraft of this type as evaluated by Ortiz y Salcedo [8] [9] and verified by the values listed in the bibliography (Table 4) [10] (n=4,5g in this case).

3. Limit loads estimated using a safety factor of 1,5 which is the value recommended by FAR 23, 25 and 27 and is implemented by Lee y Kim [4].

Table 4. Recommended Load Factors [10]

Aircraft Type	*npositive*	*nnegative*
General Aviation normal	2,5 to 3,8	-1 a -1,5
General Aviation Utility	4,4	-1,8
General Aviation Acrobatic	6	-3
Home-build	5	-2
Transport	3 to 4	-1 to -2
Strategic Bomber	3	-1
Tactical Bomber	4	-2
Combat Aircraft	6,5 to 9	-3 to -6



Enter Design Parameters and press the 'Design It!' button.

Propeller Name: a
Number of Blades B: 2 [-]
Revolutions per minute rpm: 11400 [1/min]
Diameter D: 0.2 [m]
Spinner Dia. Dsp: 0.000 [m]
Velocity v: 120 [m/s]
Thrust T: 14 [N]
☑ shrouded rotor ☐ square tip ☐ open hub

Propeller			
v/(nD)	3.158	v/(ΩR)	1.005
Efficiency η	76.271 %	loading	low
Thrust T	14 N	Ct	0.1985
Power P	2.2 kW	Cp	0.8219
Torque Q	1.85 Nm	Cs	3.2842
β at 75%R	57.8°	Pitch H	747 mm

Remark: The RPM setting is also used for Analysis page.

Figure 2. Load estimation due to Engine Thrust
Source: Own work

Loads from Aircraft Engines The values of torque were determinate using de Software JavaProp R . The interface to the software is show in Figure 2.

Finite Element Analysis of boom

Having determined the geometry and loads for the new booms, a finite element analysis was performed to determine their suitability.

The values of the shear force and bending moment were determined based on linear elasticity theory [11].

$$dV = \int_a^b W(x) \quad (1)$$

$$dM = \int_a^b V(x) \quad (2)$$

The integrals were evaluated using the online application Mathematica and graphs of the shear force and bending moment are shown Figure 3.

The meshing was performed with tetrahedral elements with a element size of 3 mm. The total number of nodes is 566395 and the elements number 283085. The mean element quality is 0,6 with a maximum of 0,9 and a minimum of 0,2. The main outcomes are summarized in Table 5 and the graphics of simulation are shown in Figure 4.

CONCEPTUAL DESIGN MODIFICATIONS

In parallel to the analytical evaluation of the primary structure, conceptual designs were generated for attachment of existing structures or components to a tubular boom. Each new or modified component was also designed to improve the maintainability and logistical characteristics of the aircraft. Design limitations were placed on the aerodynamics of the overall structure and center of gravity. As the aircraft was being reinforced in some areas, a small deviation in total mass would be permitted [12].

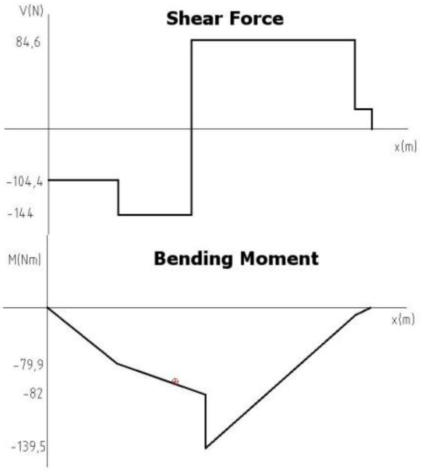
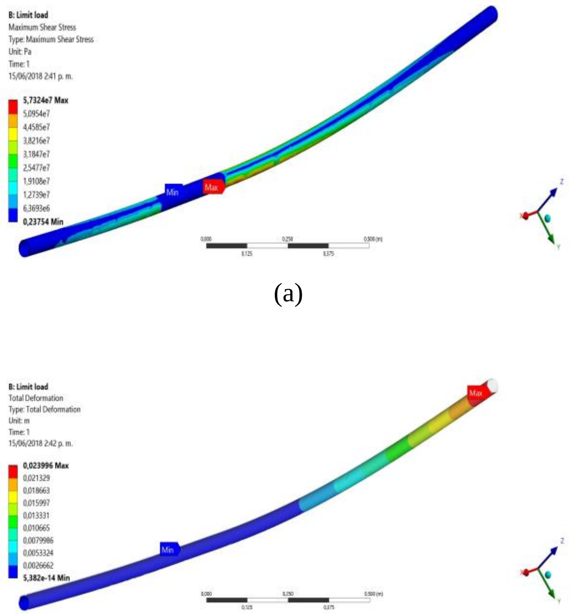


Figure 3. Shear force and bending moments in booms
Source: Own work

Table 5. Boom Results
Source: Own work

Material	Max Stress	Max deformation
Commercial Carbon Fiber (Limit Load)	109,5 MPa	0,023m
Commercial Carbon Fiber (Max Load)	69MPa	0,0159m
Commercial Carbon Fiber (Mean Load)	7,5MPa	0,0012m



(a)

(b)

Figure 4. Boom Equivalent Stress *Source: Own work*

Originally, only the Main wing, Tail and Engine attachments were to be modified however, the decision was eventually taken to completely modify the entire structure of the Main wing itself (due to concerns over the attrition rateof the main wing upon each landing).

Table 6. Volume estimations for transportable sub-assemblies
Source: Own work

	Length (m)	Width (m)	Depth (m)	Unitary Volume (m^3)	Quantity	Volume (m^3)
Booms	3	0,05	0,05	0,0075	2	0,015
Main wing spar(s)	4	0,05	0,05	0,01	4	0,04
Main wing sections	0,4	0,25	0,1	0,01	16	0,16
Tapered Wingtips	1,2	0,4	0,1	0,048	2	0,096
Landing Gear	1	0,4	0,1	0,04	2	0,08
Engine mounts	0,4	0,1	0,1	0,004	2	0,008
Tail Section	1,5	0,5	0,5	0,375	1	0,375
Total	-	-	-	-	-	0,774

General design philosophy

Maintenance Aspect Each component of the VS prototype was originally produced by hand by the university students which resulted in a very lengthy manufacturing process (2 years). Whilst this process was considered acceptable at the time (the objectives of the original project were also to learn how to manufacture carbon fiber components), the aircraft costs would be too high and the maintenance down-time too long were it ever to be operated at the projected attrition rates suffered by a flying laboratory.

It was therefore decided new components would need to be easily purchased or easily manufactured using low tech or fully automated solutions (such as the university 3D printer and CNC machine). Material selection would no longer be limited to carbon fiber and use of cheaper material solutions would be permitted. Ideally, to avoid regulary replacing entire sections of aircraft, all new assembly processes should also be completely reversible.

Logistical Aspect The university does not possess a landing strip next to the workshop and so the aircraft would need to be easily assembled and disassembled into distinct sections for transport and use in the field.

The new aircraft would be designed to be broken down into transportable sections as follows:

- Main wing spars
- Main wing sections
- Tapered Wingtips
- Booms
- Landing Gear
- Tail Section
- Engine and Battery mounts

Estimations for logistical volumes required for this transportation configuration can be seen in Table 6.

The benefits when compared to the volume of the fully assembled configuration (18m^3) are clear to see.

Main Wing

The main wing forms the very backbone of the overall aircraft design. It uses the Eppler 212 airfoil along its whole length and features a constant chord (40cm) up until 60% of the half span whereupon it tapers down to a wingtip chord of 15cm. The prototype featured a single C-beam cross section at 27% of the chord with rib spacing of 15cm [Figure 5].

The entire 6m structure was originally enclosed in a carbon fiber skin, glued to the ribs and spar. Any damage incurred to the primary structure would result in the loss of the whole wing. Additionally, the solar cells were also glued to the wing surface. A damaged or malfunctioning cell would have to remain attached to the structure (as removal would damage the skin of the structure).

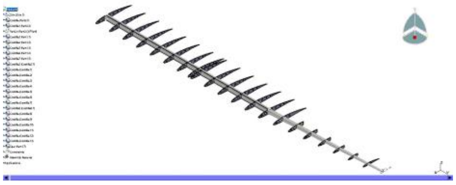


Figure 5. Prototype wing structure
Source: Own work

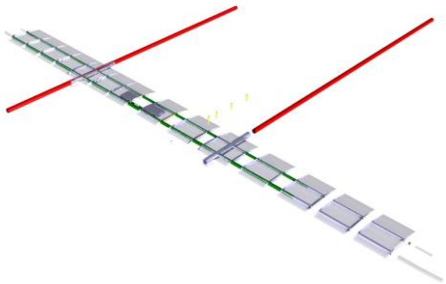


Figure 6. Main wing constant-chord sections
Source: Own work

The new wing will therefore incorporate a modular design philosophy. The wing will be divided into sections that can be interchanged at will. Should a solar cell fail or a wing section be damaged, the whole section can be interchanged with another.

The original C-Beam Main Spar design was a very resource intensive manufacturing process and so, given that the new boom sections would be purchased components, it would not be considered unreasonable to purchase tubes of carbon fiber for use as the main spar as well.

To make the replacement of parts (rather than their repair) a low cost affair, foam was chosen as the main building material, cutting the blocks to the length of the solar cells being used. This would ensure that even if future modifications are made to the type of solar cell used, the same production process can be used.

As the straight wing section contains only cables (which can be run down the length of the tubular spar or run along a groove cut into the foam), each section is 100% interchangeable with the other. The foam can be cut with a hot wire using wooden templates on either side of the blocks to get the correct shape.

Foam is light, cheap and rigid but does have some important limitations:

- Fragile and brittle (especially when considering its rigidity).
- Low resistance to high temperatures

It is hoped that by using high strength carbon fiber for the main spars that bending deformations can be reduced on the foam sections. It is also hoped that by having many shorter sections of wing that we can reduce large amounts of bending forces on the material. To avoid thermal damage to the foam, soldering of the solar cells will have to be performed before gluing them to the wing sections.

An aircraft wing (especially one with a large aspect ratio), must resist large bending and twisting forces. As the use of segmented wing sections would drastically reduce the torsional resistance of the wing, a two spar system was adopted. The chordal positioning of the spars was chosen to be 17% and 60% as suggested in [13].

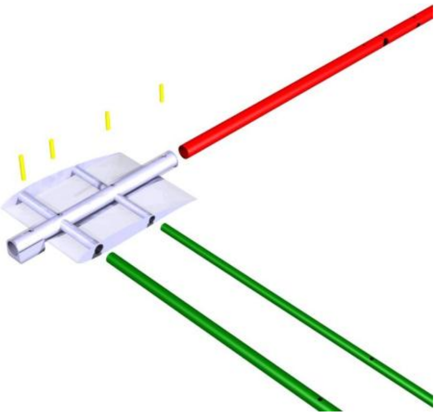


Figure 7. Center Wing Box Design
Source: Own work

Originally, a special wing fitting was planned to attach the wing to the booms but having studied other designs like the Penguin

C, a more streamlined (and potentially stronger) solution was chosen; to run the spars directly through the booms and at the same time, run the booms through the main wing section.

To prevent the bending moment of a strong pitching maneuver from breaking the reduced working cross section of the booms, a specially adapted wing section would be required. For all intents and purposes, this section will be called the center wing box (CWB). The CWBs will have a modified thickness (their original thickness must be increased by 10%) in order to house the boom with enough material to comfortably provide enough structural support. Due to material selection and manufacturing process (CNC machined from blocks of aluminum), these CWBs will most likely be the most expensive sections of the new design, however, considering their location (with the exception of a catastrophic event), they will be the component least likely to require replacement or maintenance.

The whole ensemble would be held in place by a series of 4 pins. The outermost pins would be to alleviate the longitudinal forces and the innermost pins to prevent the wing spars from sliding freely within the booms. The structure can be seen in Figure 7.

At the end of the aircraft wing constant-chord section, special aluminum adapters (that can be seen in the lower right hand corner of Figure 6) will slot into the most complicated section of the main wing; the tapered wingtip.

The whole wingtip has been designed to be fully detachable for transport and consists of 4 sections and an aileron. The three inboard sections and the aileron are made of the same foam material used in the main wing, whilst the very outboard section (in grey) will be made of rubber. Rubber should be rigid enough to resist aerodynamic deformation whilst highly resistant to damage during landings where the wing might touch the ground. [see Figure 8]

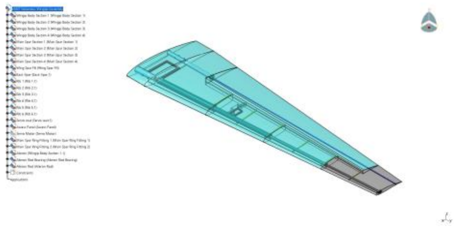


Figure 8. Wingtip section
Source: Own work

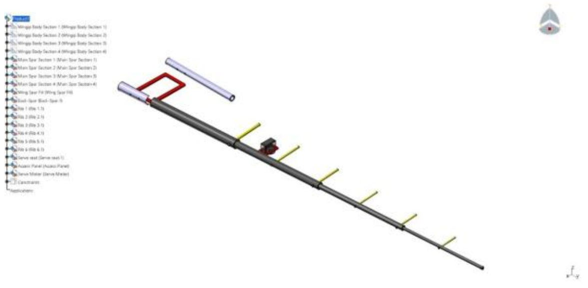


Figure 9. Wingtip Internal Structure *Source: Own work*

The wingtip sections due to their complex form will be cut using CNC machining. Special care must be taken on the trailing edge of the inboard section as foam is brittle and the CNC process will damage the very thin trailing edge. It is recommended that the trailing edge of this section be finished by hand.

Due to the taper, the forward spar must be offset, be positioned parallel to the leading edge and must also reduce cross-sectional diameter as it approaches the wing tips extremity. A telescopic spar design solves this problem whilst permitting the use of purchased carbon fiber tubes. Any gaps between the different sized tubes can be filled with plastic tubing.

The rear spar is made of aluminum to provide the rigidity required to resist the aileron hinge moments during maneuvering. A bearing will be placed into the aluminum rear spar and a guide rod inserted. The other end will be supported by the rubber outer section.

To prevent the outermost 3 sections of the wing from freely rotating around the forward spar (as we transition from double spar to single spar), plastic clip pins (in yellow in the drawing below) will be inserted into the back of the aileron housing and will clip into holes drilled into the carbon fiber tubing. These pins will also hold the telescopic sections of the forward spar in place.

A special junction must be made to take into account the angular offset of the leading edge spar. This junction will be supported by an aluminum plate that not only adjusts for the angular offset but will also include threaded holes to allow the main wing spar section to be bolted onto the wingtip (as it is not possible to bolt into foam directly). The aluminum rear spar also includes these threaded holes. The very root of the innermost wingtip section has been hollowed out and an access panel hole (the leftmost red square in Figure 9) has been made to provide enough space for a hand to enter the wing. Two screws have been planned for both forward and aft spars.

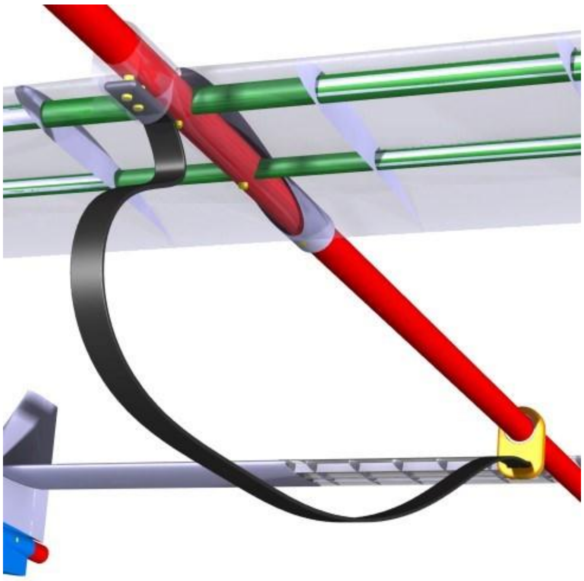


Figure 10. Landing Gear Design

Source: Own work

The access panel hole is protected by a thin epoxy seat into which small screws can be drilled to hold thin cover plates in place. The aileron servo will be housed directly in the foam body of the wing and will also be seated upon an epoxy rim into which the servo motor can be screwed into place. Cables for control of the aileron servos can be run along the telescopic spar and exit through a hole made in one of the tubes.

Landing Gear

Following on from the work produced by the university students [14] on the laminar carbon fiber landing gear, a carbon fiber skid will be made. The CWBs (previously mentioned) will be extended a little further forward and a section added onto the lower edge within which this carbon fiber skid can be inserted. The skid will be held in place with a bolt that can be screwed into the CWB, as shown in Figure 10. The aft part of the skid will be housed in a special free rolling bearing that will allow for the better absorption of landing impacts. The bearing will permit the aft end of the skid to slide along the boom. This should also reduce the axial forces that could be introduced into the boom.

Engine Attachments

The new boom cross-section has also made it necessary to come up with three new types of component for the front of the aircraft:

- A new way to fix the battery to the fuselage/boom
- A new way to fix the motors to the fuselage/boom
- A battery fairing

Originally the fuselage was large enough to house the batteries within the I-Beam structure; however, the new tubular structure is too small for this purpose. A tubular structure also provides no surface into which a motor can be bolted. The newly proposed battery fairing has been designed as a means to attach the batteries and motors securely to the airframe with the following considerations:

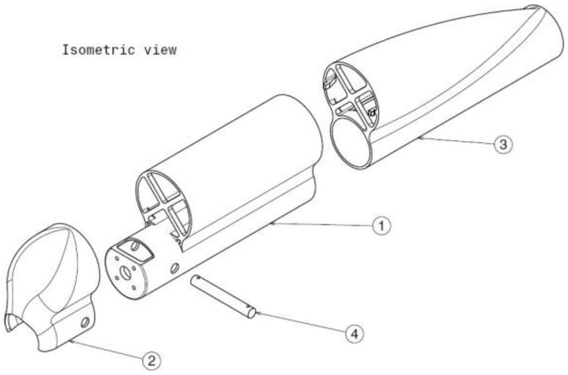


Figure 11. Engine mount and Battery fairing assembly

Source: Own work

- Minimum distance from the motors
- Reduce drag as much as possible
- Ocupy as little space as possible within the propeller disk area
- Not form too large a surface upon which lateral gusts could adversely affect the flight characteristics
- Minimum weight (to not modify the center of gravity)
- Rapid interchangeability of the battery whilst in service
- Easy mounting and un-mounting of the motor
- Easily produced and replaced in case of damage
- Require minimal modification to the existing structure (so as not to weaken it)

With these objectives in mind the following design has been developed.

It is comprised of 3 main parts and a mounting pin. The aerodynamic shape envelopes not only the battery but also the cables protruding from the front.

Aerodynamic shapes are complicated to produce especially when repeatability is concerned. The location of this assembly and the abuse that it might receive (and the fact that we are trying to produce a light weight design) result in a high probability that this part will require relatively regular replacement. Equally important, the assembly must be produced in identical pairs (so as to avoid unwanted yawing effects).

To ensure that the design can consistently be produced to high standards of precision the following design has been envisaged with 3D printing as the production solution. To that end all fillets and dimensions have been limited to 1mm. The design was also split into parts that can be managed by the university printer (limited to 25cmx25cmx20cm). The diameter of the parts means that the three components should all fit onto one printing plate (reducing production time and costs). The engine attachment is show in Figure 11 to 14.

There are still some concerns with the surface finish from this technique and the rigidity of the final product but these can only reasonably be qualified with physical testing.

The battery will be slid into the rear compartment of the upper tube structure with the battery cables protruding through the X shaped stop position. The battery body itself will rest upon body of the lower tube structure.

The front disk on the lower tube has a central hole (for the main axis of the electric motors) and 4 radial holes so that the motor can be screwed directly onto this part. There should be enough space between the walls of the lower tuve and the screw holes to allow for a normal screwdriver to fix the motor to the part.

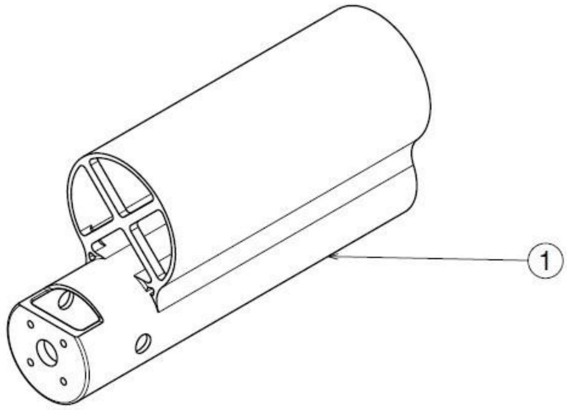


Figure 12. Main Battery Fairing *Source: Own work*

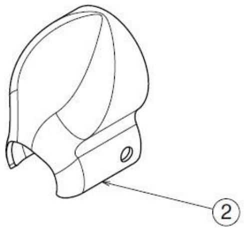


Figure 13. Front Battery Fairing *Source: Own work*

A rectangular hole has been cut away from one side of the tube (And will also need to be cut into the fuselage boom) to allow cables running up the tube to exit the tube and connect with the battery cables and motor cables.

The fuselage will be inserted into the back of the lower tube and will come directly into contact with the front disk. This should help share the stress of a frontal impact with the supporting pin located slightly further back (the pair of lateral holes that can be observed).

Fillets have been included on the battery stops to reinforce the structure against the inertia of the battery on landing and around the cable access point to avoid the cables fretting. Weight-saving grooves have been included along the connection between the two tubes.

The front battery housing is a combination of a large dome mixed with the original Beluga shape. The open front area has been designed to fit comfortably over the existing motors (therefore directing the flow around the structure and not through it). This fairing will also cover the wires and prevent them coming into contact with the propellers.

The holes located on the side are of the same diameter as that of the main fairing and once the main fairing is in place and the wires connected, the front fairing can be placed over the motors and then the whole assembly can be held in place by an aluminum pin.

The final part of the assembly has been designed to be slotted onto the fuselage before the other two sections. It serves two purposes:

- Provide a smooth aerodynamic transition behind the body of the battery
- Close the battery compartment and hold the battery firmly in place.

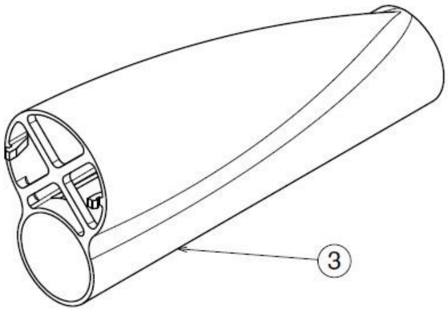


Figure 14. Rear Battery Fairing
Source:Own work

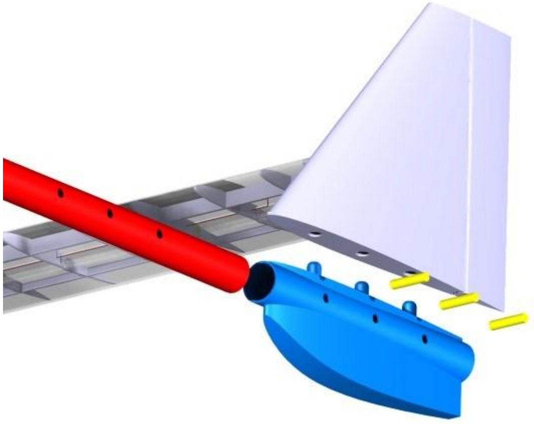


Figure 15. Tail Section attachment
Source:Own work

The aerodynamic shape blends smoothly into the lower tube which has also had a long triangular section removed (barely visible behind the battery back stop X) as a weight saving process.

As this part should not require (or need to provide) a lot of structural support a tentative proposal for a method to fix the rear fairing to the main fairing has been made; flexible clips.

These flexible clips should mean that no further holes need to be made in the fuselage and that even if the main fairing has some movement, that the rear fairing will always remain firmly attached to the main fairing.

To release the rear fairing, the operator would only have to squeeze the sides of the aerodynamic section (thereby releasing the clips).

Tail Section Attachments

The tail section of the aircraft is one of the few sections that was not considered for major modification. Attachment to the boom will be achieved with a series of pins through a 3D printed adapter as shown below. The 3D printing of this part was permissible in that dimensions of the empennage adapter did not surpass the limiting dimensions of the available 3D printer. A small skid has been added to the lower section of the attachment that will distance the trailing edge of the boom from the ground sufficiently enought to reduce damage to this important component,(see Figure 15).

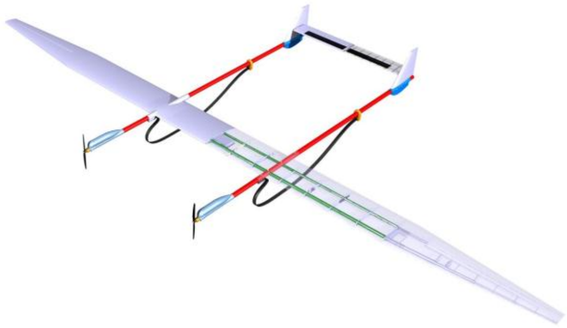


Figure 16. Final Assembly
Source:Own work

Assembly

It is estimated that in this configuration, the aircraft can go from logistical to flying mode in under 5 minutes (excluding correct preflight check procedures). The final assembly is presented in Figure 16.

CONCLUTION

The newly proposed aircraft booms have been analytically evaluated and found to be a suitable match for the aircraft and feasible designs for the implementation of the new booms have been developed. The new designs will undoubtedly improve the logistical abilities of this UAV and generate a superior platform for the university with which to conduct experiments in the field (albeit with a slight flight performance reduction).

The initial designs will require testing (both analytically and experimentally) before the revised UAV can be put back into operation and it is highly likely that weight saving modifications can be made to the existing designs (the CWB for example should be hollowed out).

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