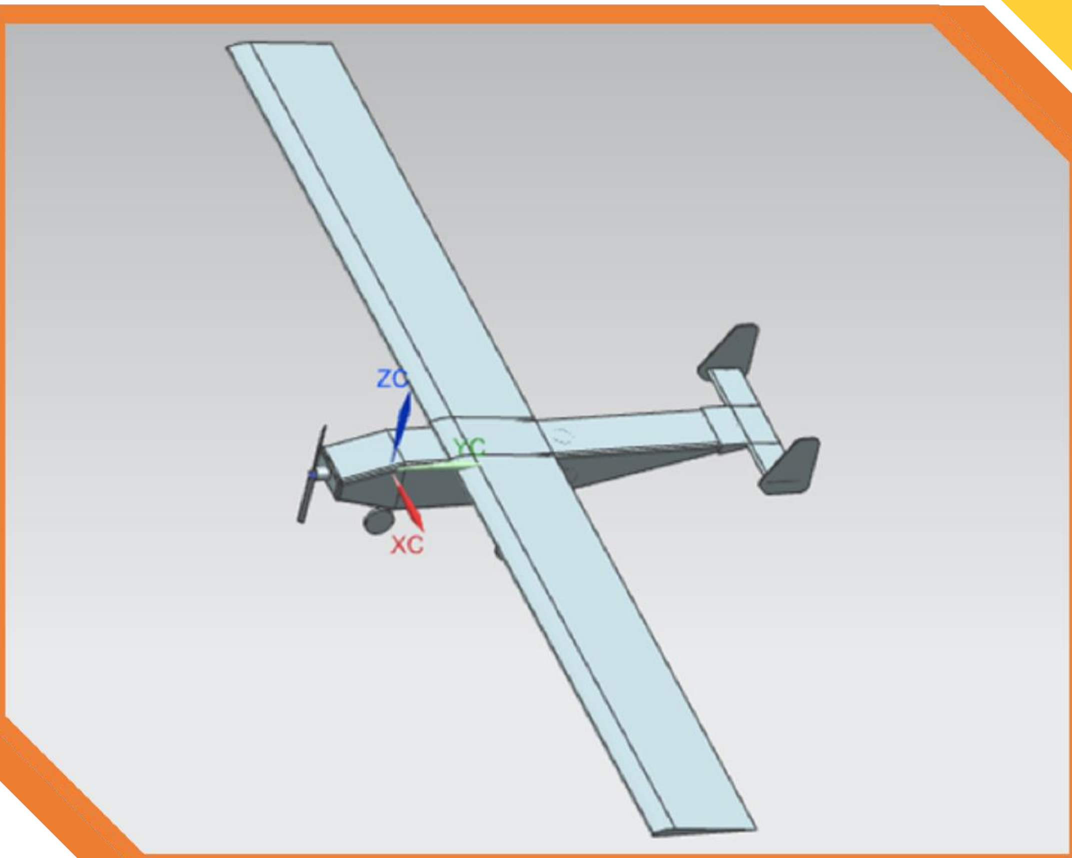
WINGIN' IT

presents.....

FIREFLY



Loughborough University team 2

Payload challenge 3: The Weighting Game

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1.WELCOME TO THE TEAM!

1.1 Team Members

Ben Jenner

Wing design and manufacture

Nam Vu

Production of fuselage and tail

John Brown

CAD design/ computer technology

Lucy Wootton

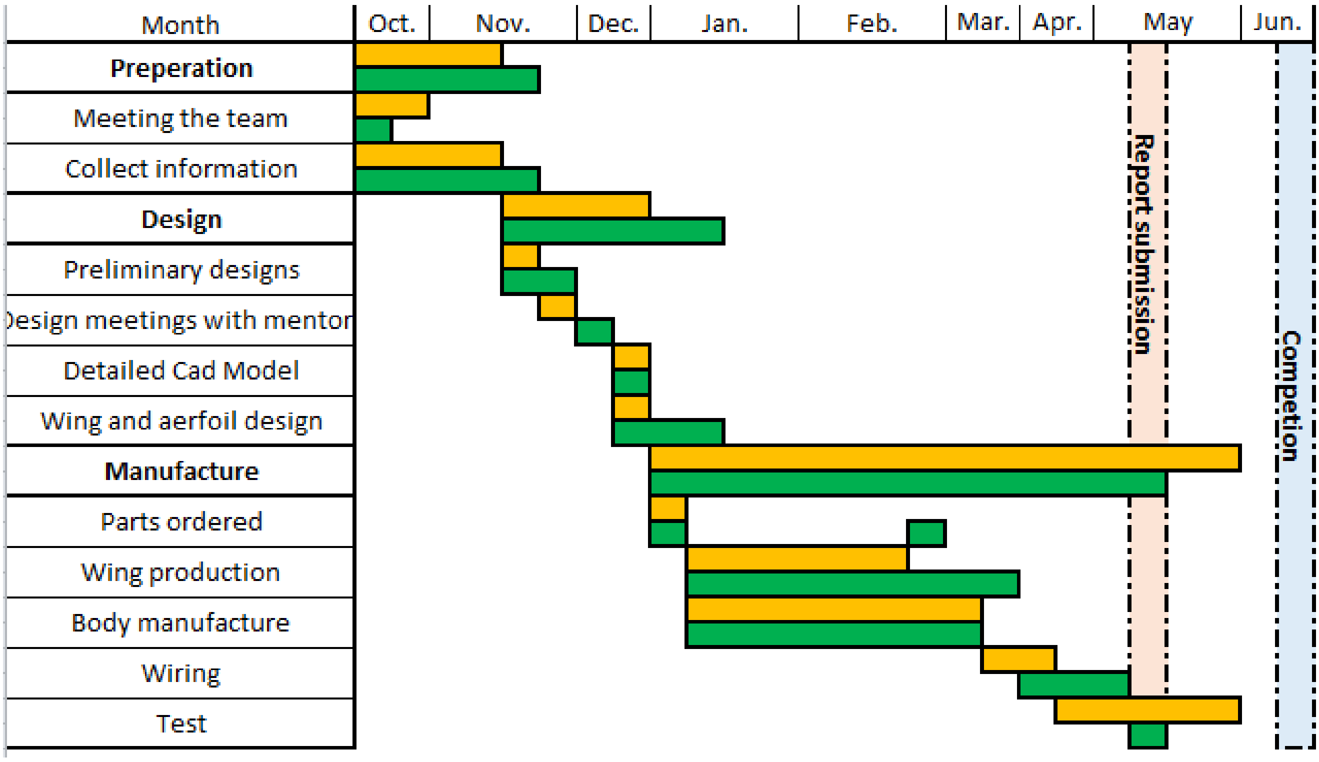
Water bag design and manufacture

Georgie Jones

Report creation/ design support

The main individual responsibilities of each team member are outlined above. Additionally, everyone will be actively involved in the overall manufacturing process of Firefly. All five members are first year aeronautical engineering students, and the delegation of tasks has been assigned based upon skill sets and personal preference.

1.2 Team Organisation and Schedule



On the previous page is the Gantt chart which was constructed shortly after committing to this project. This has aided us in organising and planning the dates of which specific tasks should be accomplished by. The orange represents our aimed span of completion, whereas the green is its actual.

2. Overall Design Philosophy

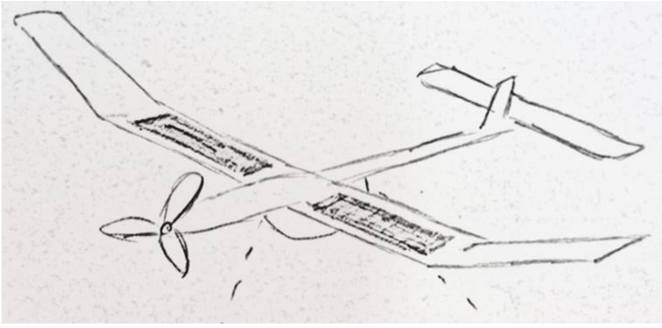
2.1 Mission Requirements

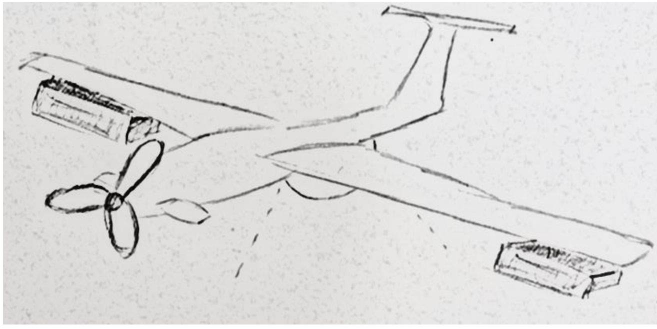
Our main objective, common for all participating teams, is to maximise the value of the ratio 'payload/ aircraft empty mass'. Furthermore, we aim to complete the drawings and report to the best of our abilities, carrying key data and information forward to our presentation. The most significant design requirements and constraints of our aircraft have been summarised below.

- Only fixed wing designs are allowed
- The propulsion unit is a fixed E-flight Power 10 motor, one E-flight 40A speed controller and a 3 cell LiPo battery of a capacity under 2200 MAh.
- A 150mm in diameter, unmodified, expanded polystyrene ball must be located in the fuselage, allowing for a clear 60˚ conical view vertically down.
- The aircraft must carry up to 4kg water in removable containers.
- Empty water containers should not weigh more than 10% of their filled mass.

2.2 Initial Ideas

Our initial designs were a brainstorm of many different features which we have learnt about and researched over the course of the year. Each demonstrates its advantages and drawbacks and our final development was chosen largely due to its lesser opportunity cost. Simple sketches of two of these are shown below.



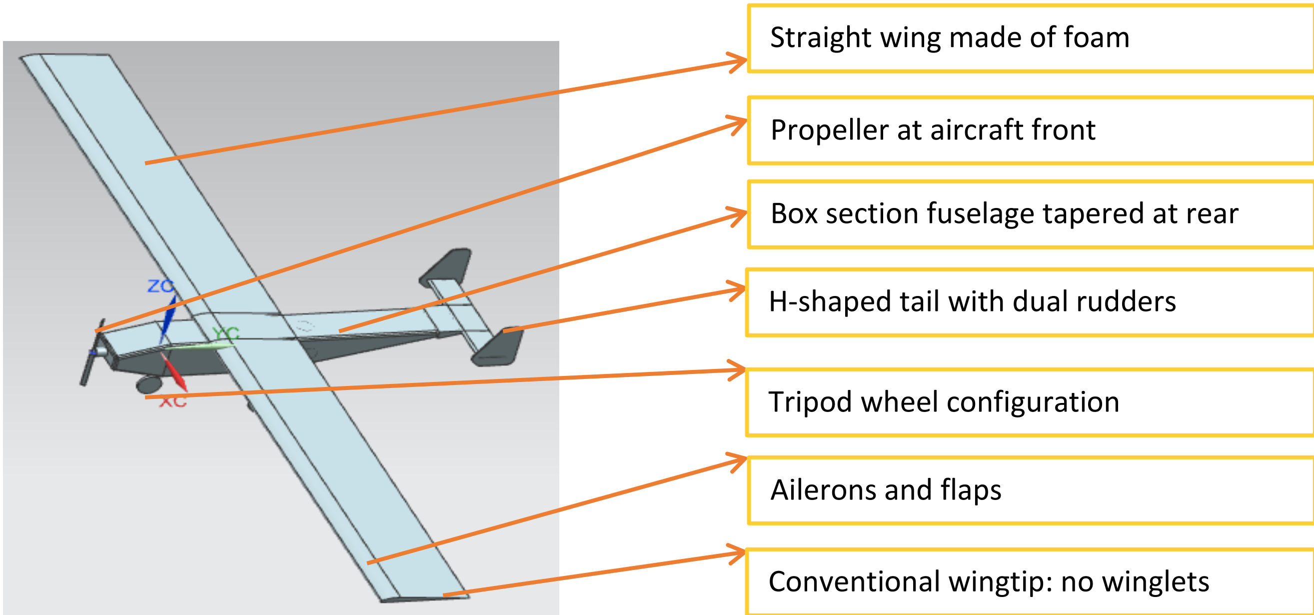


Main features:
Fuselage mounted tail plane
Long, shallow sloped winglets
Water inside wing structure (black rectangles)
Thin fuselage

Main features:
T-tail tail plane
Complex fuselage shape
Water externally mounted beneath wings
Straight wing

We began an iterative process to take forward the best parts of each concept forward and combining them to generate Firefly. The logic used to derive this configuration is as follows.

2.3 The Configuration of Firefly



2.4 Wing Section and Planform

We decided on using a straight wing with a conventional wingtip for design simplicity and ease of manufacture. The sweep wing alternative would have little or no effect on the aircraft performance as we are not concerning with supersonic airflow. A high wing was also chosen as this is inherently stable in its roll and there is no requirement for a joint to pass through the fuselage, removing obstructions and increasing water storage capabilities. With a high dihedral, the aircraft would be too stable and not respond to pilot commands in a short enough time frame.

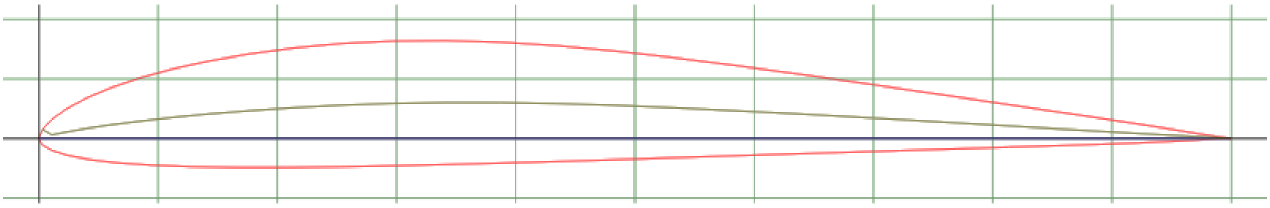


Figure 1 [1]

The specific aerofoil chosen, as above, was the E205 (10.48%), which corresponds with a low Reynolds number (assumed to be greater than 30,000 for the sake of calculations). It has a maximum thickness of 10.5% at 29.7% chord, and a maximum camber of 2.5% at 38.7% chord. Internet reviews assures us that this type could penetrate well in windy conditions with very little height loss [2]. We decided on a 2.5m wingspan and a 0.2856m chord length and from this calculated our aspect ratio. A high aspect ratio tends to generate more lift. The thrust provided by our engine is limited, thus this is advantageous.

$$\boldsymbol{Aspect\ ratio\ (AR) = \frac{(wing\ span^2)}{wing\ area} = \frac{2.5^2}{0.75} = 8.3}$$

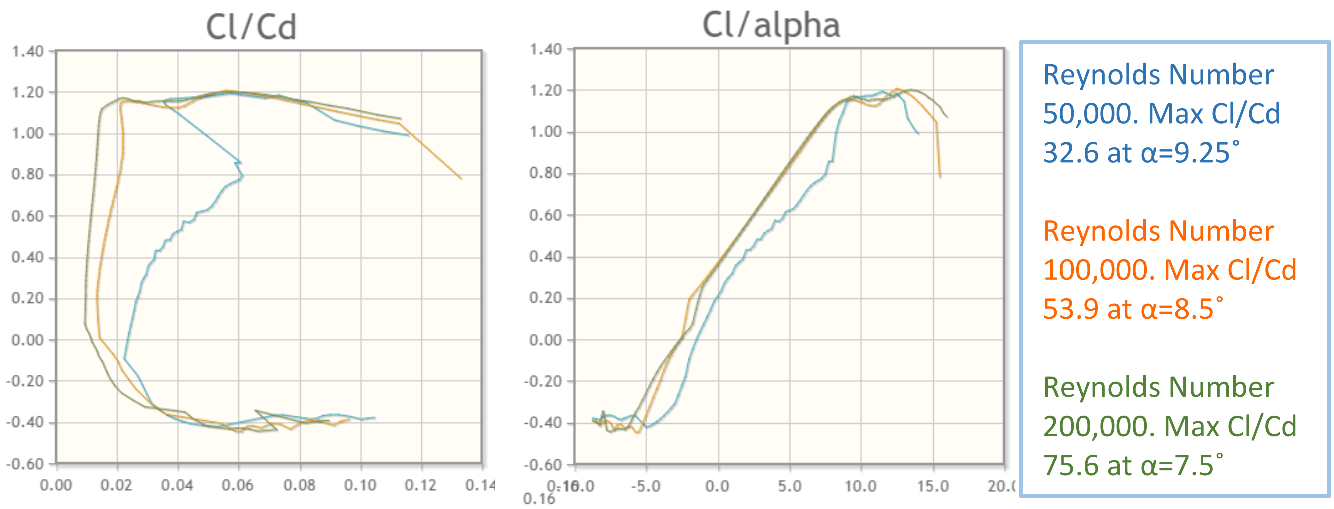


Figure 2 [1]

Our aerofoil was selected due to its strong performance characteristics as shown in the graphs at different Reynolds Numbers. It can be seen that our aerofoil has acceptable stall characteristics.

2.5 Propeller Diameter, Pitch and Rotational Speed

Our propeller diameter, i.e. the distance across the circle swept by the extreme tips of the propeller blades, is 304.8mm. Our pitch value is 152.4mm, which is the theoretical distance travelled for one revolution of a single propeller[3]. These dimensions have been maximised given the power output of our engine, as the higher the pitch value, the faster our plane will travel. Our propulsion system is a key factor in determining the maximum loaded weight of the aircraft.

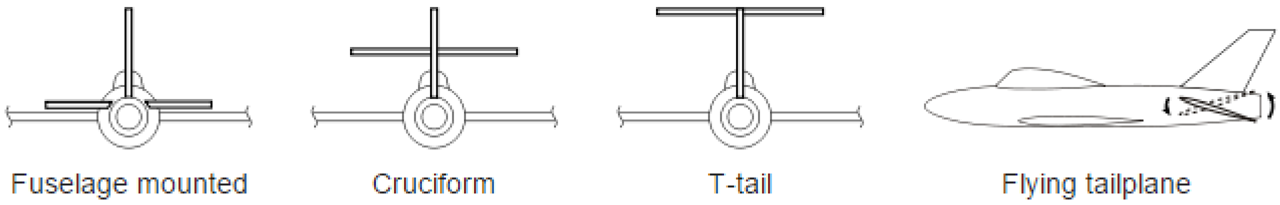
The standardised competition motor is rated for a maximum current of 42A at burst lasting no longer than 15 seconds to the prevent overheating of the motor. However this is rated for a continuous current of 32A which is typically used at cruise for a maximum cargo load[4]. In researching, we found that a diameter larger than 12" would display an issue with ground clearance. Our aforementioned APC 12x6E has a very highest static thrust value relative to other realistic alternatives such as the 10x6 or 12x5. This should be able to sustain a constant temperature in air at a value safe for operation. The E-Flite Electronic Speed Controller (ESC) is designed for a maximum of 40A continuous current, but like many ESC's it is capable of providing higher current in bursts. This permits use of the APC12x6E propeller for the motor which can reach a maximum of current draw of 42A at full throttle.

The propeller is to be placed at the head of the aircraft so as the airflow is not disturbed by the wing and fuselage. It is to be placed centrally to provide symmetry about the centre point of the fuselage to maximise efficiency.

2.6 Tail Plane Configuration and Landing Gear

In determining the configuration of the tail plane (comprising the fixed horizontal stabiliser and movable elevator), we needed to determine the number of control surfaces, their location(s), and whether the stabiliser would be fixed or movable. The main options are on the next page.

Figure 2 [5]



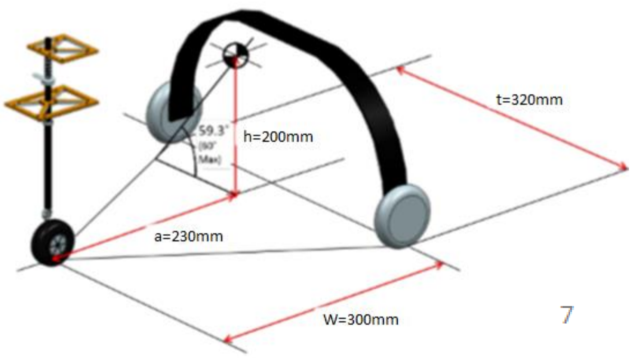
The flying tail plane would provide little advantage to a scaled down model such as our own, and would only complicate the manufacturing process. The T-tail sits in clean air which can be advantageous over the conventional layout in which the tail plane is working in the wash from the wings hence would be less effective[6]. However this idea was rejected at an early stage due to issues with stall recovery and that our elevator would sit largely out of the propeller wash. This would largely impair slow speed control[7]. A cruciform layout interferes with our objective to make a model easy to construct, and if applied loads prove too great, the tail plane is most likely to dislodge from its position, bend or snap. Additionally, our fuselage mounted tail plane is conveniently attached directly to the fuselage. The H-shaped tail with two rudders is for added control and stability in yaw.

We have implemented a tricycle configuration which allows all wheels to stay in contact with the ground until take-off is achieved. This is advantageous as a tail dragger would need to pitch forwards. Also, Firefly may land easier as when it flares, the main wheel can lead and then the aircraft can pitch down. A summation of its stability is as follows. The equations on the left are those which must be satisfied.

$$\tan^{-1}\left(\frac{2hw}{at}\right) < 60^\circ \qquad \tan^{-1}\left(\frac{2*200*300}{230*320}\right) = 58.5^\circ$$

$$\tan^{-1}\left(\frac{a}{h}\right) > 40^\circ \qquad \tan^{-1}\left(\frac{230}{200}\right) = 49.0^\circ$$

$$6^\circ < \tan^{-1}\left(\frac{w-a}{h}\right) < 20^\circ \qquad \tan^{-1}\left(\frac{300-230}{200}\right) = 19.3^\circ$$



2.7 ControlSurfaces and Moment Arms

The moment arm of each control surface in this case is defined as the distance between centre of lift and the centre of mass of the aircraft in the origin in the three axes of rotation. We will incorporate two ailerons, two rudders and one elevator in Firefly.

The ailerons will affect roll, elevator the pitch and rudder the yaw as is standard. The size of the ailerons aims to be enlarged to compensate for the lack of roll performance allowed with our stable high wing approach. The ailerons at the wingtips are each 75mm long with an approximate chord length of 70mm. Dual rudders are used to increase the operative area meeting the oncoming airflow at low speeds, where flight control effectiveness is reduced.

3. AERODYNAMIC DESIGN, STABILITY AND CONTROL

3.1 Longitudinal Stability

The stability of an aircraft is its ability to return to its original position once a deformation or distortion has been applied, and the forces deforming or distorting it have been removed, all without the aid of pilot intervention[8]. To assess the longitudinal stability of Firefly we must calculate where the centre of gravity (CG) lies relative to the neutral point (NP). The NP is the position through which all the net lift increments act for a change in angle of attack[9]. If the plane is loaded with a CG too far aft, it will amend to a nose up rather than a nose down attitude. In this case the inherent stability will be lacking and control of the aircraft in this plane will be difficult even with the elevator located in the downwards position[10].

To calculate the centre of mass, the individual masses of all significant components must be assumed alongside their relative distances to the aircraft nose.

Component Name	Mass/ kg	Distance from Component Centre of Mass to Nose/ m	Moment/ kg m

Motor and Speed Controller	0.122	0.085	0.01037
Battery	0.167	0.169	0.02822
Transmitter	0.030	0.180	0.00540
Undercarriage	0.072	0.369	0.02656
Wing	~0.700	0.432	0.30240
Tail	~0.036	1.209	0.04352
Fuselage and sphere	~0.340	0.448	0.16456

To find the centre of gravity, we divide the total moment by the total mass[11].

$$\boldsymbol{CG} = \frac{\mathbf{0.01037 + 0.02822 + 0.00540 + 0.02656 + 0.30240 + 0.04352 + 0.16456}}{\mathbf{0.122 + 0.167 + 0.030 + 0.072 + 0.700 + 0.036 + 0.340}}$$

$$= \mathbf{0.388}\ \boldsymbol{m\ clear\ of\ the\ nose}$$

Weight and balance are often expressed as a percentage of Mean Aerodynamic Chord (MAC), which in the case of using our straight wing is simply 0.2856m. If the aerodynamic force is applied at a location 1/4 from the leading edge of a rectangular wing at subsonic speed, the magnitude of the aerodynamic moment remains nearly constant even when the angle of attack changes. This location is called the wing's Aerodynamic Centre (AC) [12]. In order to obtain a good Longitudinal Stability, the should be close to the main wings' AC. Hence, we should find that our centre of gravity should lie close to 0.359m. In comparison to our value calculated above of 0.388m, we can assume to achieve longitudinal stability in empty aircraft flight. Once the water is being carried, its mass must lie equally about the CG in order to remain stable. With a forward CG position, although the stability of the aircraft increases, the elevator control authority is reduced in the capability of raising the nose of the aircraft. This can cause a serious condition during the landing flare when the nose cannot be raised sufficiently to slow the aircraft. And hence, due to the configuration of the undercarriage it is imperative that the CG position is not severely alters relative to the above calculations.

The Neutral Point (NP) is most simply calculated by using the areas of the two horizontal lifting surfaces, the main wing and stab, and is located proportionally along the distance between the main wing's AC point and stab wing's AC point.

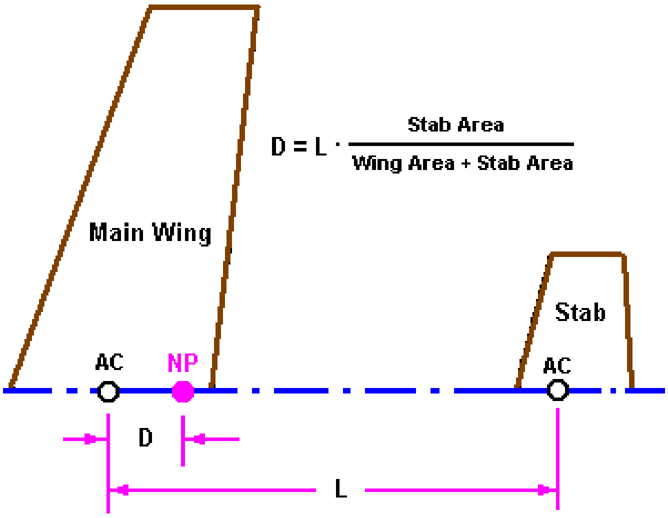


Figure 3 [12]

Where:
L = 0.722
Stab area = 0.035
Wing area = 0.357

$$D = 0.722 * \left(\frac{0.035}{0.357 + 0.035}\right) = 0.065m$$

The NP is 0.4249m from Firefly's nose.

This formula predicts a good distance between the main wing AC and the calculated NP, however in practice this distance should be shorter as the tail plane operates in disturbed air.

The static margin is defined as the distance between the centre of gravity and the neutral point of the aircraft, expressed as a percentage of the mean aerodynamic chord of the wing [13].

$$\boldsymbol{static\ margin} = \frac{\boldsymbol{NP-CG}}{\mathbf{0.2856}} * \mathbf{100} = \frac{\mathbf{0.4249-0.3880}}{\mathbf{0.2856}} * \mathbf{100} = \mathbf{12.9\%\ MAC}$$

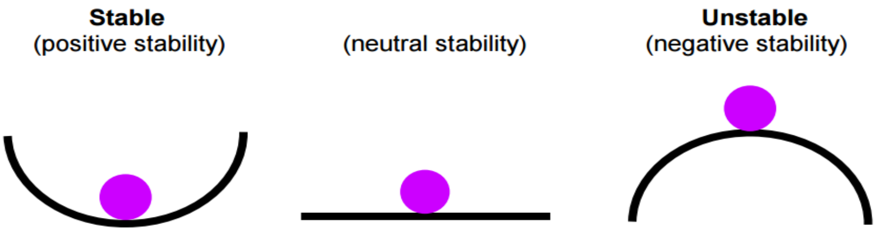
The static margin often corresponds to good stability when a value between 5-15% MAC has been achieved. One obstacle we may face is in the theory that although a higher Static Margin may result in greater static stability, it can reduce elevator authority. Additionally too much Static Margin makes the aircraft nose-heavy, which may result in elevator stall at take-off and/or landing.

3.2 Lateral Stability

Lateral stability is achieved through dihedral, sweepback, the keel effect and a proper distribution of weight. It may be evaluated that our straight wing design is not optimising the aircraft potential for directional stability. When a disturbance causes an aircraft with a sweepback to slip or drop a wing, the low wing presents its leading edge at an angle that is perpendicular to the relative airflow. As a result, the low wing acquires more lift, rises, and the aircraft is restored to its original flight attitude. This is a benefit which Firefly cannot see without the extensive use of rudder control. Conversely, we have two rudders to replicate these effects.

Although dihedral allows the aircraft to easily roll back to its original position after a disturbance, it is more usually a feature of low wing planes. In our case our wing, because it is attached in a high position, the weight is acting at a lower point than the lift. When one wing dips, i.e. after a sudden gust, the weight acts as a pendulum as shown in the diagram, returning Firefly to its original attitude [14].

Figure



4. PERFORMANCE

4.1 Thrust and Level Flight

At a Reynolds number of 50,000, the maximum 2D lift coeffcient is approximately 1.2 from Figure 2 on page 5 of this report.

$$C_{L\,MAX} = 0.9 * C_{l\,max} * cos\Delta_{\frac{1}{4}}$$

$$C_{L\,MAX} = 0.9 * 1.2 * \cos(0) = 1.08$$

Where $\cos\Delta_{\frac{1}{4}}$ is equal to 1, as we have no sweep wing

$C_{L\,MAX}$ = maximum 3D lift coefficient

From the maximum 3D lift coefficient we are able to calculate parameters to evaluate the predicted performance of Firefly. From static testing we achieved a value of 14.4N as our thrust. The optimistaion of the thrust (T) to weight (W) ratio and the wing loading form a major part of analysing the design. In this section we will be working towards a prediction of take off distance at maximum payload, and for this to be shortened we will require a low T/W and W/S, where S is wing planform. From page 9, the aircraft empty mass is 1.467kg. Hence;

$$\boldsymbol{W_{empty} = 1.467 * 9.81 = 14.4N}$$

For calculations we shall assume maximum weight, i.e. that of the aircraft and 4kg of water being carried. Thus;

$$\boldsymbol{W = (1.467 + 4) * 9.81 = 53.6N}$$

This produces a thrust to weight ratio of 0.27 and wing loading of 74.9N/m^2.

At straight and level flight, all forces are in equilibream. Lift (L)=weight and thrust=drag (D). We can find the stall speed (V_{stall}) and cruise speed (V_{cruise}).

$$\boldsymbol{V_{stall} = \sqrt{\frac{2W}{\rho C_{L\,MAX} S}} = \sqrt{\frac{2 * 53.6}{1.225 * 1.08 * 0.714}} = 10.7m/s}$$

As taken from Figure 2, there is a maximum lift to drag ratio at α=9.25˚, however cruise is taken to be at zero incidence where α=2˚. Here $C_{L\,CRUISE}$ =0.5.

$$\boldsymbol{V_{cruise} = \sqrt{\frac{2W}{\rho C_{L\,CRUISE} S}} = \sqrt{\frac{2 * 53.6}{1.225 * 0.5 * 0.714}} = 15.7m/s}$$

4.2 Drag

Component	Reynolds Number	Coefficient of Friction	Coefficient of Drag
Wing	306×10^{3}	2.40×10^{-3}	4.80×10^{-3}
Horizontal stabiliser	161×10^{3}	3.31×10^{-3}	6.26×10^{-3}
Fuselage	1122×10^{3}	1.25×10^{-3}	5.00×10^{-3}
Vertical stabliiser	215×10^{3}	2.86×10^{-3}	2.86×10^{-3}

$$C_{D\,TOTAL} = C_{DO} + \frac{1}{\pi Ae} * C_{L\,CRUISE}^{2} = (2.40 + 3.31 + 1.25 + 2.86)x10^{-3} + \frac{1}{\pi * 8.3 * 1.11} * 0.5^{2}$$

=0.028

Where C_{DO} is the summation of the individual coefficients of drag, and $C_{D\,TOTAL}$ is the calculated value of the coefficient of drag. This is an appropriate value, but the payload has not been taken into account, hence the real result may differ. Our total drag is expected to 0.36N.

4.3 Climb

$$V_{MD} = \left(\frac{W}{0.5\rho S}\right)^{0.5} * \left(\frac{b}{3a}\right)^{0.25} = 6.29m/s$$

$$D = 0.5\rho V^{2} S C_{D} = 0.5 * 1.225 * 6.29^{2} * 0.7125 * 0.028 * 4 = 0.36N$$

$$climb\ angle = \frac{T - D}{W} = \frac{14.4 - 0.36}{53.6} = 0.26\ radians$$

$$climb\ speed = v * sin\emptyset = 1.62m/s$$

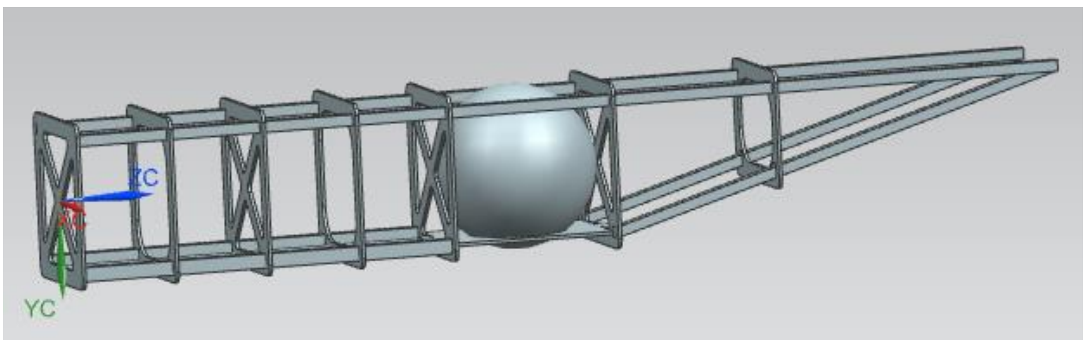
The calculations above should in theory coincide with the performance of Firefly.

5 STRUCTURAL INTEGRITY

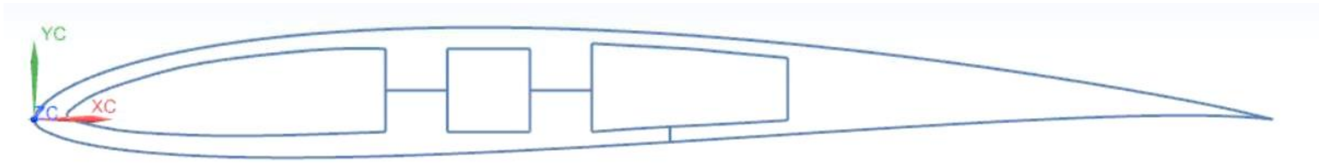
5.1 Fuselage Design

Structural integrity is the ability of a structure or a component to withstand a designed service load, resisting structural failure due to fracture, deformation, or fatigue[16].

Our fuselage consists of a box section tapered at the rear for aerodynamic efficiency and reduced weight. As observed in the CAD model, there is plenty of room avaliable within the structure for water storage and for the passing of electrical components such as the motor battery. The spherical polystyrene object, representative of the UAV design requirement, has a clear 60˚ conical view as required, and is removed by dislodging a detachable balsa plate underneath. Our internal structure contains seven ribs of balsa wood which has an ideal strength to weight ratio for our requirements, and four carbon spars. These are equally spaced as to ensure that there is no concentration of load piled upon a weak spot, and are vital in maintaining the structural integrity of the fuselage. To reduce Firefly's weight as much as possible whist still allowing it to retain adequate strength, every other rib has a cross section cut into it via a laser cutter. Each cross section was initially designed to be 5mm thick, however through testing of a prototype this value was increased to 6.5mm. The fuselage is trusted to induce the forces of the wing and landing gear into its four main carbon spars without deformation or degredation over the course of its test flights.



5.2 Wing Structure

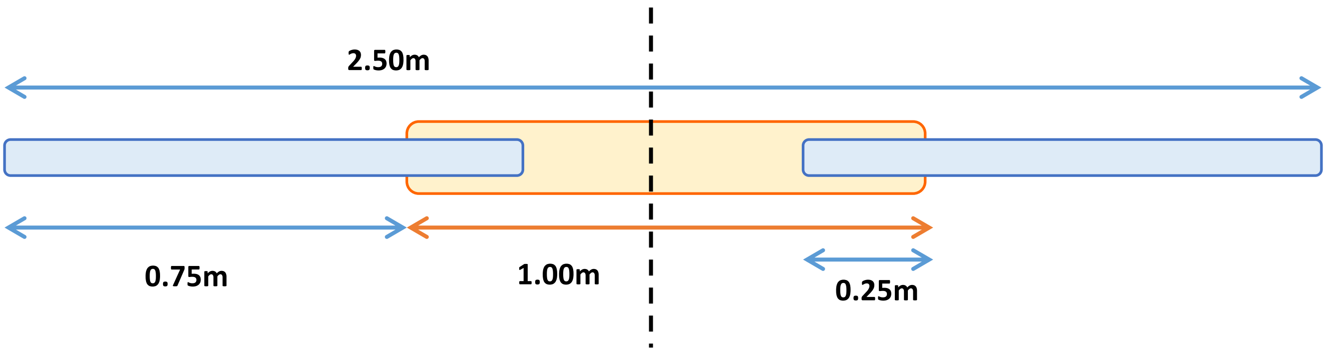


Our E205 aerofoil as above is common to gliders and models of this type. It is to be cut using a foam cutter, and with foam glue we are to rejoin the foam with depron.

Because the leading edge and trailing edge would be damaged easily in transfer of upon landing we are to solidify the wing with a fibreglass composite. The servos used for our control surfaces are xl-09HMD. We chose metal gears on the design because, despite their cost increase, they are guaranteed to last longer and can be used in designs in the years to come.

The carbon fibre spars in the wing will bear loads and resist bending. This is enhanced via them having a square cross sectionto withstand torsion.

The internal carbon spars are split into three.Their overlaps are drawn below as a top view of Firefly and the dimensions are labelled. The wing is symmetrical about the centroid as shown.

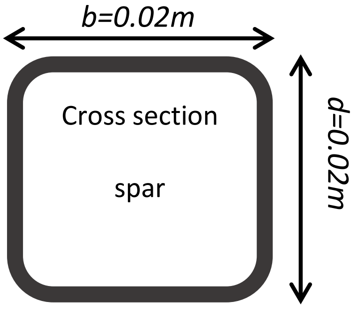


The orange block is a hollow rectuangular carbon spar 20mm x 20mm in size. Its length is 1.00m and spans outwards in poth the positive and negative X axes. There is a 0.25m overlap on each end of the spar where two individual 10mm x 10mm carbon spars will sit. Each of these are 1.00m in length but only support 0.75m of the wing load independednt of the orange spar.

In addition there are two lightning holes shown in the aerofoil section; one at the back, the other at the front. These are also advantageous in providing the space to carry our water payload.

5.3 Wing Bending

The deflection of the wing under extreme conditions is an indication of its structural welfare.



The external breadth and diameter of a cross section of the largest spar is shown.

$$I_{xx} = \frac{b * d^3}{12}$$

$$I_{xx\,OUTER} = \frac{0.02 * 0.02^3}{12}$$

$$I_{xx\,INNER} = \frac{0.017 * 0.017^3}{12}$$

I_{xx} is the second moment of inertia, and is $I_{xx\,OUTER} - I_{xx\,INNER}$ **= 6.373x10^{-9}m^4**

Deflection δ, under a force of 3G- the maximum at sharp turn-is shown. A weight of 7kg has been used for the worst case scenario option, as the maximum aircraft empty mass is 3kg and the water 4kg.

$$\delta = \frac{3WL}{48EI_{xx}} = \frac{7 * 3 * 9.81 * 2.5}{48 * 150 * 10^9 * 6.373 * 10^{-9}} = 0.0112m = 11.2mm$$

This is not a significant deflection given the wingspan of Firefly, hence shall not affect the performance greatly or be responsible for control or stability issues due to this.

5.4 Wing Stress

In evaluating the strength of our carbon spar, a comparison may be made relative to the corresponding UTS value. The material is brittle, hence presents no yield.

$$Z = \frac{I_{xx}}{z} = \frac{(6.3732 * 10^{-9})}{10 * 10^{-3}} = 6.3732 * 10^{-7}$$

$$s = \frac{Wx}{2Z} = \frac{7 * 3 * 9.81 * 2.5}{2 * 6.332 * 10^{-7}} = 404MPa$$

W = maximum weight at 3G
x = half span
Z = section modulus of the spar cross section
z = distance from neutral axis to edge
I_{xx} = second moment of inertia
s = stress at cross section

The UTS of carbon fibre is 1600MPa. Our maximum value of 404MPa, by comparison is extremely favourable. This gives us a safety factor of four.

5.5 Prediction of takeoff distance

At maximum payload, i.e at a total of 7kg, Firefly will require the following distance to takeoff.

$$takeoff\ distance = \frac{Maximum\ Weight \div Wing\ area}{1 * (T \div W) * C_{L\ MAX}}$$

$$takeoff\ distance = \frac{7 * 9.81 \div 0.714}{1 * (14.4 \div 7 * 9.81) * 1.08} = 425m$$

However, using our predicted empty payload mass instead of the maximum, this new value will be produced, and is henceforth the estimated takeoff distance.

$$takeoff\ distance = \frac{5.467 * 9.81 \div 0.714}{1 * (14.4 \div 53.6) * 1.08} = 259m$$

Although these values are high, we hope to reduce them in practice flights, and will reduce the water carried if necesarry.

6 REFERENCES

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[8]TTA 106: Aircraft systems and Performance 1, Lecture notes page 82, James Knowles

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