2016

BMFA Heavy Lift Challenge 2016

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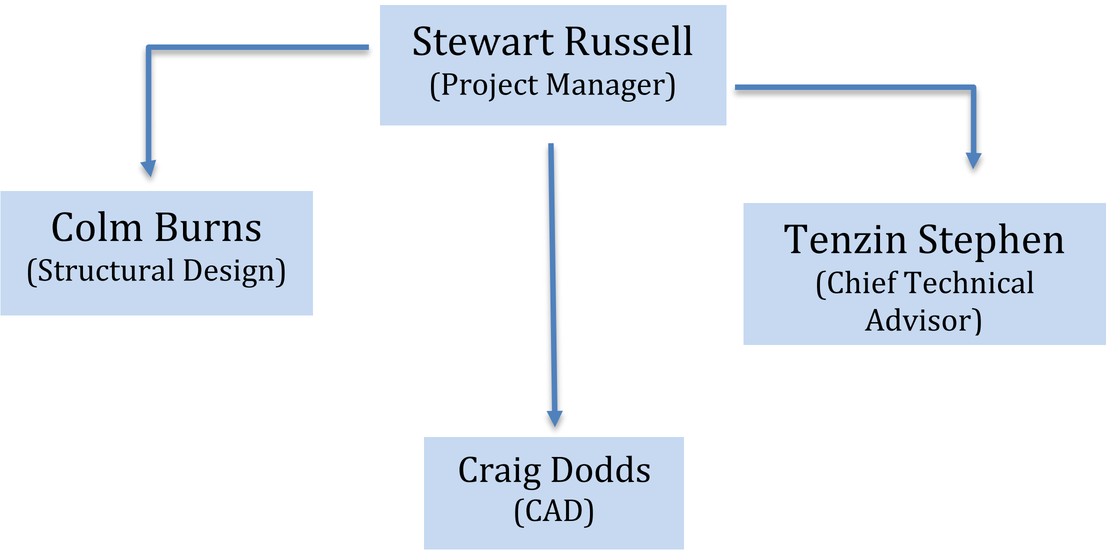
Executive Summary

This document summaries the design, manufacture and testing of Napier team B’s aircraft for entry into the 2016 Heavy Lift Challenge. The aircraft has been designed to complete three flight missions carrying different payloads.

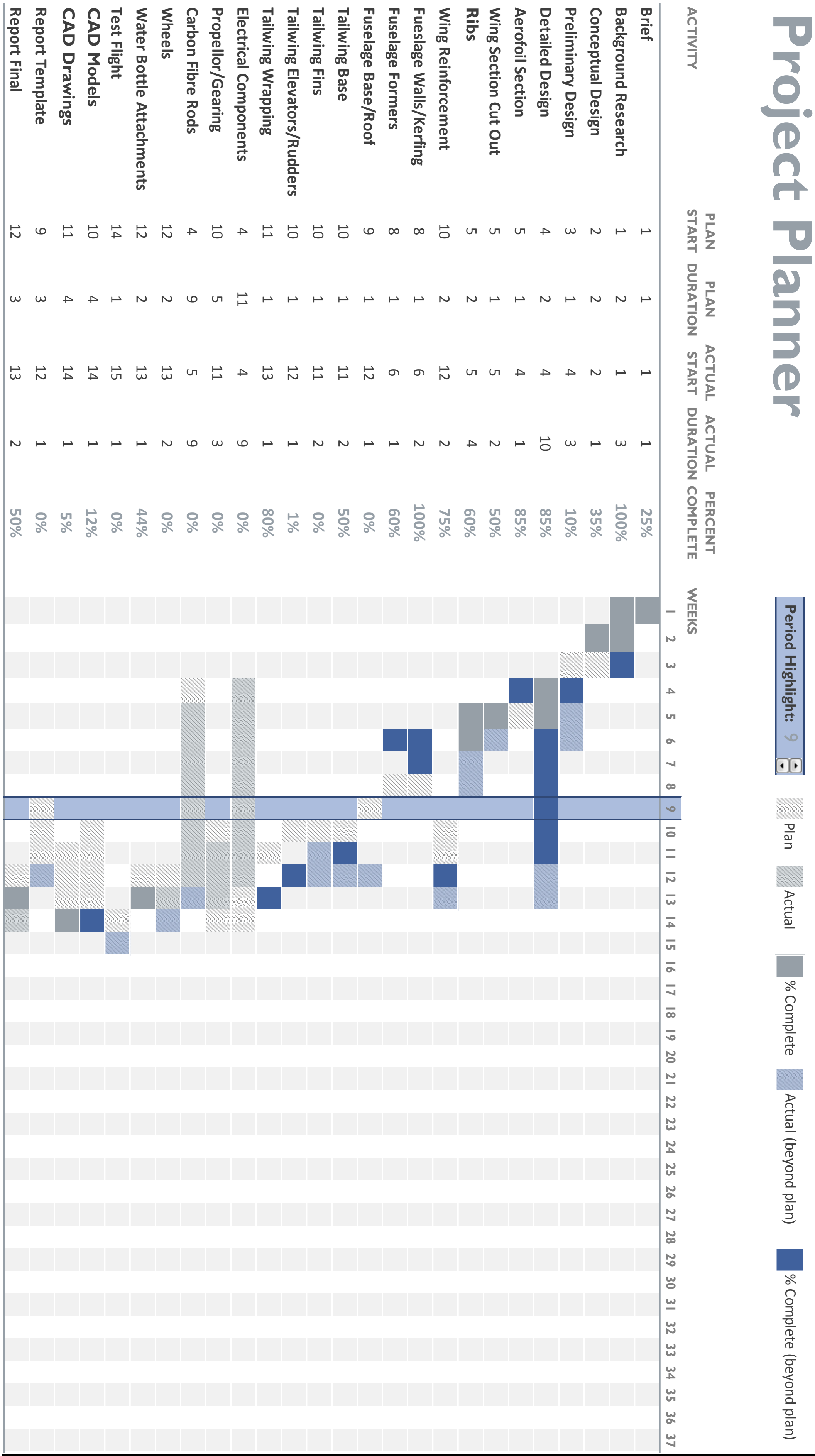
- Mission 1 – No payload
- Mission 2 – Maximum payload of 2kg
- Mission 3 – Maximum payload of 4kg

Also the weight of the aircraft was minimised as much as possible to maximise the aircrafts final score.

Team Management



Project Planner



ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Brief	1	1	1	1	25%
Background Research	1	2	1	3	100%
Conceptual Design	2	2	2	1	35%
Preliminary Design	3	1	4	3	10%
Detailed Design	4	2	4	10	85%
Aerofoil Section	5	1	4	1	85%
Wing Section Cut Out	5	1	5	2	50%
Ribs	5	2	5	4	60%
Wing Reinforcement	10	2	12	2	75%
Fueslage Walls/Kerfing	8	1	6	2	100%
Fuselage Formers	8	1	6	1	60%
Fuselage Base/Roof	9	1	12	1	0%
Tailwing Base	10	1	11	2	50%
Tailwing Fins	10	1	11	2	0%
Tailwing Elevators/Rudders	10	1	12	1	1%
Tailwing Wrapping	11	1	13	1	80%
Electrical Components	4	11	4	9	0%
Propellor/Gearing	10	5	11	3	0%
Carbon Fibre Rods	4	9	5	9	0%
Wheels	12	2	13	2	0%
Water Bottle Attachments	12	2	13	1	44%
Test Flight	14	1	15	1	0%
CAD Models	10	4	14	1	12%
CAD Drawings	11	4	14	1	5%
Report Template	9	3	12	1	0%
Report Final	12	3	13	2	50%

Figure 1 - Project Planner Gantt Chart

Mission Requirements

- **Empty weight –** Aircraft must be as light as possible for a higher weight ratio
- **“Optical Sensor” 150mm polystyrene ball –** The ball has to be included in the design to simulate an “optical sensor.” Additionally it must be a minimum of 400mm away from the propeller/motor and have a 60° conical view vertically down.
- **Fixed wing –** Only fixed wings will be accepted.
- **Propulsion unit –** One E-flight power 10 motor and one E-flight 40A speed Controller.
- **Isolator –** Must be accessible and located a minimum of 100mm from the polystyrene ball.
- **Payload Containers –** Containers must be removable and weigh no more than 10% of their empty mass.

Table 1- Translation Mission Requirements to Design Requirements

Mission Requirement	Design Requirement
Weight Ratio	Aircraft must be as light as possible
Polystyrene Ball	Fuselage must be big enough to store & remove the ball
Fixed Wing	Wing will be as light as possible and generate a high lift
Electrical components	Isolator, motor etc. will be stored inside the fuselage
Payload Containers	Payload will be stored inside smart bottles and stored on the wheels
Propeller	Will act as a puller at front of the aircraft 400mm from the "optical sensor"

Overall Design Philosophy

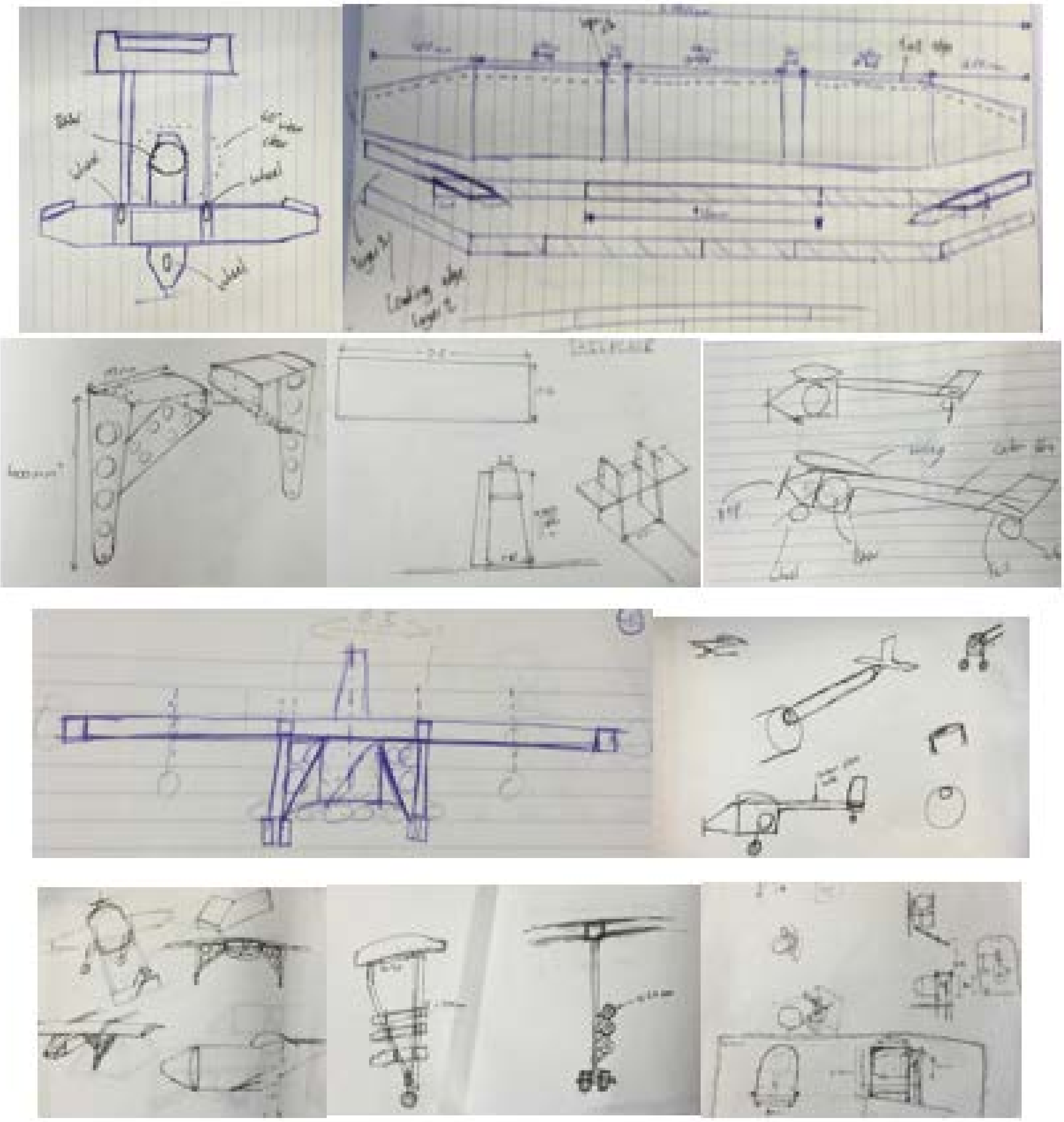
Morphological Table

In order to derive the chosen configuration of the design of the aircraft, the formal concept generation technique of a morphological table was utilised.

Table 2 - Morphological table

Function	Means				
Wing	Rectangular	Tapered	Elliptical	Delta	Semi-Elliptical
Fuselage	Rectangular	Cylindrical			
Tailplane	No. Of Tails	Elevator	Rudder		
Payload Containers	500ml Water Bottles	Water tight Container	x 4) One Litre Bottles	CamelBak reservoir	
Wheels	Double Front/Single Back	Double Front/Back	Single Front/ Double Back		
“Optical Sensor” & Propeller Position	Ball Front/ Propeller Back	Ball Back /Propeller Front			

Concept Drawings



Aerodynamic Design

Wing

Planform

As the wing is the most important aspect of the design in order for it to fly, research was carried out in order to decide which wing shape was right was the mission requirements.

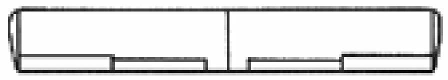


Figure 2- Rectangular Planform

- Simple manufacture.
- Generally light (referring to Piper PA 38)
- Easy Control.
- Fair Speed.

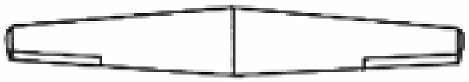


Figure 3 - Tapered Planform

- Modification of the rectangular wing, varied chord across wing span approximates elliptical wing lift distribution.
- North America P-51 Mustang.
- Fairly easy manufacture
- Reduced aspect ratio.

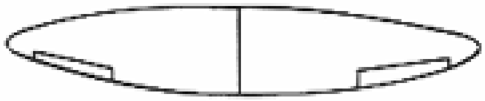


Figure 4 - Elliptical Planform

- Ideal for flight as slow speeds.
- Minimum drag for given aspect ratio
- Difficult manufacture.
- High lift without need for a lot of momentum/speed.
- Long wing span caps wind currents.
- Spitfire

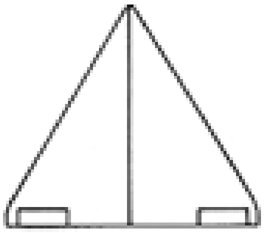


Figure 5 - Delta Planform

- Fast speeds.
- Very low aspect ratio (which is why it is used in supersonic aircraft.) however this creates a lot of drag.
- Very high efficiency.
- Large wing area allows for reduced wing loading and improves manoeuvrability.
- Structurally strong.
- Difficult manufacture.

Development

Upon researching the various types of wing planform and learning about their performance properties, an elliptical planform initially seemed the most suitable. The fact that it has very low drag in relation to aspect ratio, supplies higher lift at lower speeds than other planforms and is ideal for flight at low speeds seemed perfect for our purposes.

However, upon considering the manufacturing implications of an elliptical wing and the difficulties associated with it, it was decided this was not a viable option. Instead, a planform that could 'mimic' some of the performance aspects of an elliptical wing whilst maintaining a reasonably simple construction was decided upon.

The design was to be predominantly rectangular in shape, but with tapered sections throughout the last 400mm of each wing tip, this theoretically reducing wing-tip vortices in much the same way an elliptical wing would, and maintaining straightforward construction.

Aerofoil Section

Due to the nature of the challenge at hand, it was necessary for a high-lift aerofoil section to be used.

To determine the amount of lift that would need to be generated by the wing, the final weight of the completed aircraft (including payload), and the velocity it would be travelling at had to be estimated, and the surface area of the planform of the wing determined and stated. The following equation could then be used to determine the coefficient of lift:

$$L = \frac{1}{2}\rho v^2 \times S \times Cl$$

Where '*L*'=the amount of force (in Newtons) needed to overcome the weight, $'\rho'$= air density, '*S*' = area of wing planform, and *'Cl'*=coefficient of lift.

By implementing this equation it was found that:

$$Cl = 1.283$$

Using this number for the coefficient of lift, and the assumed airspeed of 10m/s, it was then possible to select a standard aerofoil section that would suit our needs. By consulting standard graphs representing the relationship between angle of attack and coefficient of lift, it was found that a S1223 aerofoil section was the most suitable. The Velocity-Coefficient of lift graph for this design is shown in Figure 6.

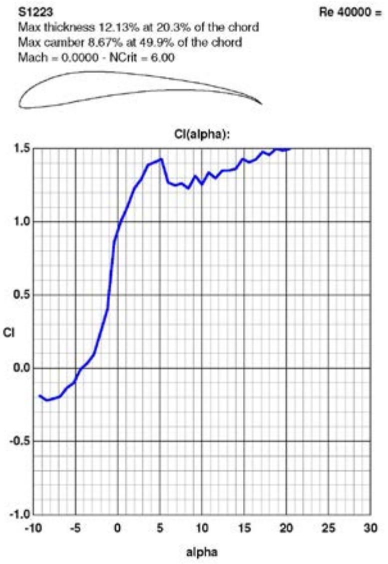


Figure 6 - Coefficient of Lift Against Angle of Attack

Propeller

Diameter

In order to determine the necessary diameter of the propeller, the following equation was used:

$$D = \sqrt[4]{\frac{Kw}{RPM^2 \times Km/h \times 24.8}} \times 24500$$

Where D= propeller diameter, Kw=motor power, RPM=motor revs per minute, and Km/h=velocity of the aircraft.

Working through this equation with the known values related to the motor and an assumed velocity, a value for 'D' of approximately 32cm was found.

However, in order to improve the static thrust produced by the propeller, it was deemed necessary to gear it up in relation to the power produced by the motor. A gear ratio of 2:1 would be sufficient.

This meant that the diameter of the propeller had to be scaled to align with this change, the new diameter calculated using the equation:

$$D2 = D1 \times \sqrt{G}$$

Where D2=the scaled diameter, D1=the initial diameter, and G=gear ratio (where 2:1 is equivalent to 2).

Using this equation, the scaled propeller diameter was found to be 45cm.

Pitch

Finding the necessary pitch for the propeller was quite a simple task – by referring to a table which relates velocity and RPM to pitch, it could easily be found that the pitch should be approximately 18cm.

It is perhaps worth noting that the RPM used was not the same as that which was used to find the initial propeller diameter, but rather half that (6000 RPM). This was due to the gear ratio of 2:1 that was used. Figure 7 shows the graph that was referred to.

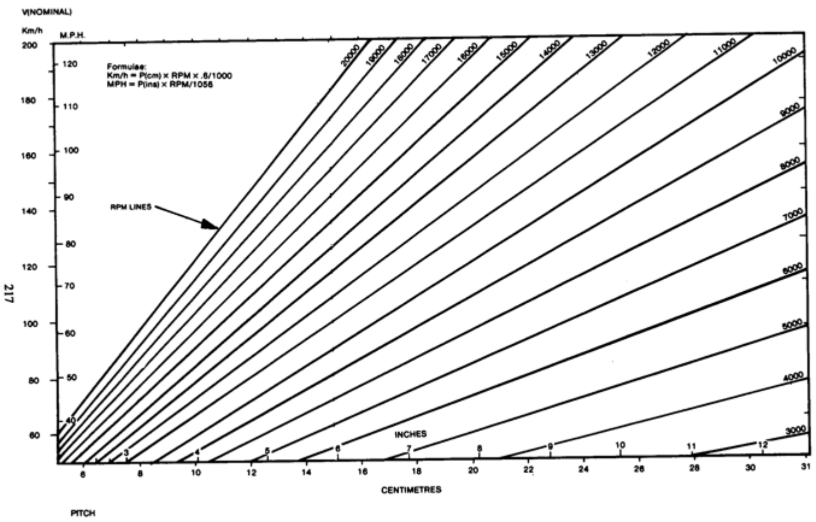


Figure 7- Propeller Pitch Graph

Tailplane

Designing the tailplane was dependent on a number of equations which would be used to determine the dimensions necessary, in relation to the dimensions of the wing and the fuselage. First of all, the dimensions for the tailplane itself (aka the horizontal flat section) would be found.

It is known that the area of a tailplane should be approximately 18% of the wing. In this case its area was $0.57m^2$, so to find the approximate area of the tailplane:

$$0.57 \times 0.18 = 0.1$$

So, the area of the tailplane was found to be approximately $0.1m^2$.

This did not give the actual dimensions, however these could be easily found by exploiting the knowledge that the approximate ratio of length to breadth should be 5:1. The final dimensions decided on were 800mm×160mm.

Having calculated this, the next step was to consider the length of the whole tailplane section. This could be calculated using the equation:

$$Vs = \frac{Ss \times Lc}{Sw \times C}$$

Where 'Ss' = Tail Area, 'Lc' = (1/4 Chord of the tailplane – aerodynamic centre of the wing), Sw = wing area, and 'C' = Wing area/Span.

In order to determine the length of the tail section, 'Lc' had to be calculated. By substituting each variable with the numbers previously calculated and the equation rearranged, 'Lc' could be found to be about 1.2m.

Finally, the side area of the fins had to be calculated. This could be found by relating the area of the side of the fuselage and the distance between the area centre and aerodynamic centre of the fuselage, to the length of the tailplane and an assumed area of the side of the fin. The relationship should be:

$$L2A2 > L1A1$$

Where L2=length of tailplane, A2=Area of fin, L1= distance between the area centre and aerodynamic centre of the fuselage, and A1= area of the side of the fuselage.

L1 was estimated to be 0.2m, and A1 was found to be $0.144m^2$, meaning:

$$L1A1 = 0.0288$$

It was known L2 was approximately 1m, and A2 was assumed to be $0.07m^2$, meaning:

$$L2A2 = 0.07$$

Controls

The way the aircraft was to be controlled in the air would be through the traditional method of ailerons on each tapered section of wing tip which control the banking of the aircraft, rudders attached to the fins which control the yaw of the aircraft, and an elevator integrated into the tailplane which control the pitch of the aircraft.

Due to the thin trailing edge inherent in the design of the S1223 Type 1 aerofoil, it was decided that instead of integrating the ailerons into the wings in the 'traditional' manner that they would be externally hung from the bottom section of the trailing edge. This would allow for a much more robust and simple construction.

Calculating the necessary surface area of each control surface was a simple task – it is known that the chord of a control surface (ailerons, rudders, elevator), should be 20-30% of the chord of the wing (ailerons), fins (rudders) and tailplane (elevator).

Using this fact it was extremely easy to calculate suitable dimensions, design and build each control surface.

Performance

When deciding upon what type of aerofoil section would be used, standard graphs were consulted, relating each aerofoils' coefficient of lift to the angle of attack it would be operating at, coefficient of drag to the angle of attack it would be operating at, as well as coefficient of lift to coefficient of drag. This gave somewhat of an indication of how the wing and aircraft as a whole should perform, however no other performance predictions were made.

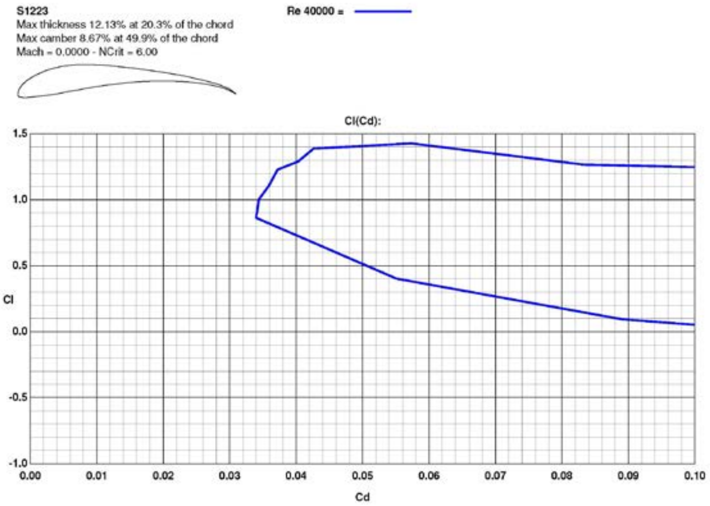


Figure 8 - Coefficient of Lift Vs. Coefficient of Drag

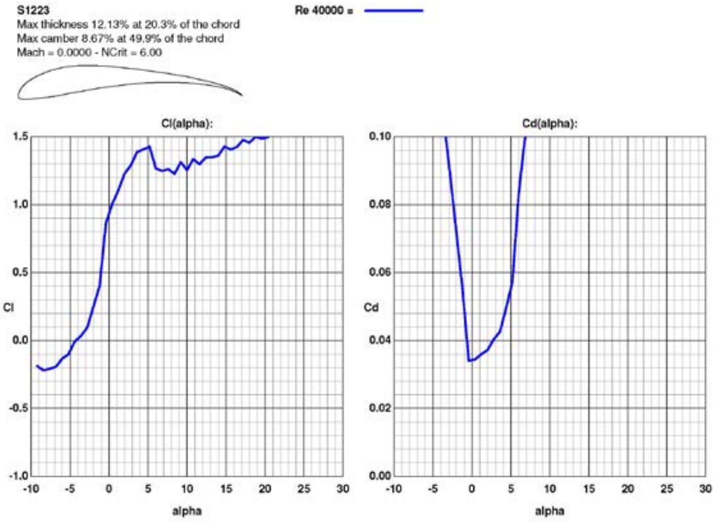


Figure 9 - Graphs of Coefficent of lift vs Angle of attack, and Coefficient of drag against Angle of Attack

Structural Integrity

Wing Construction

The construction of the wing was considered one of the most important stages of construction. This because it is the most important component in the design of the aircraft – without it, no lift would be generated, and flight would not be possible. So it was very important that the wing was constructed in a robust, yet accurate manner – ensuring that the aerofoil section produced the lift that it theoretically should, and that the component should not fail during use.

For ease of construction, (and in order to achieve the correct aerofoil section accurately) it was decided that the body of the wing (forming the middle and majority of the front section) should be first carved out of foam, in five separate sections, then glued together.

The rest of the aerofoil section would be formed by the use of a number of 'ribs' (39 in total plus two 'super' ribs), which were to be slotted into the back of the foam section.

This construction on its own had little to no constructional merit, so needed to be considerably reinforced.

First of all, two long but thin, square section spruce spars were glued all along either side of the foam body. Then a 12mm wide balsa wood leading edge was layered on and glued, further adding to the strength of the wing. The next stage was to cover the foam in a material that would both protect the foam and stiffen the wing. It was decided that 0.4mm thick plywood was a suitable for this application, and sections of it were glued over the foam.

The layers of plywood separated by the foam essentially form an ‘I’ beam, helping to stiffen the wing to a great deal. However, it was initially not known that such an ’I’ beam type of construction using plywood would be sufficiently strong to withstand the tensile stresses that the wing would be subjected to during use. In order to determine the amount of strength necessary, the amount of stress that the I-beam section would be put under needed to be calculated. First, the second moment of area for the section needed to be found, using the equation:

$$I = \frac{(bh)^3}{12}$$

Where ‘I’= second moment of area, ‘b’=estimated breath of the horizontal pieces of plywood, and ‘h’=the average separation between the pieces of plywood. Inputting these values, it was found that ‘I’=1.667×10^{-7}.

The stress could then be found using the equation:

$$\sigma = \frac{My}{I}$$

Where σ=tensile stress, ‘y’=$\frac{1}{2}$ × h, and ‘I’= second moment of area.

Using this equation, the maximum tensile stress was found to be approximately 6.1MN/m^2. The tensile strength of the ply would have to exceed this number in order for the wing to remain structurally sound, and a tensile strength test of the plywood had to be undertaken to ensure this. The results of this test can be found in the ‘testing’ section.

The same 0.4mm ply was also used to reinforce and form the trailing edge – further strengthening the wing and ensuring a straight, accurate edge.

Fuselage Construction

The first factors considered when design of the fuselage began were of course the main functions that it would serve.

These were primarily; containing much of the power delivery and storage systems (aka the battery, motor and gearbox) along with some of the radio gear, and allowing the propeller to be mounted to it. It must of course also be able to be attached to the wing and the rest of the aircraft.

If these were the only design constraints, it would have been relatively straightforward to design and build a relatively small, light and aerodynamic fuselage. However, there was one more significant design constraint that had to be considered – the fact that the fuselage must also contain a polystyrene ball with a diameter of 150mm, held at least 400mm from the propeller, and with a 60 degree field of regard beneath it.

In order to meet this requirement, the design for the fuselage had to be scaled up considerably, this resulting in it being much heavier and less aerodynamic.

When it came to deciding how to manufacture the fuselage, it was decided that building it predominantly from balsa wood was a viable and effective option. This material is very light and easy to manufacture with due to its low density, meaning it could be bent and glued in place to create curved sides and therefore a more aerodynamic design.

In order to achieve curved sides as well as a structurally sound construction, formers made from thin ply wood were manufactured at different widths to slot in between the two walls all along the length of the fuselage. Lightening holes were drilled through the middle of these, reducing weight as well allowing more space for the necessary electronic equipment to be housed.

However, thin balsa wood is quite a delicate material, so some more reinforcement would be necessary in order to keep the design sufficiently strong. But, by strengthening the sheet balsa parts, much of their ability to bend would be lost.

In order to overcome this problem, inspiration was taken from a technique known as 'Kerfing' which is mostly used in the construction of wooden musical instruments. This involved cutting slits in the long square pieces of reinforcing balsa, at regular intervals, all along their length, and would allow these reinforcing beams to bend along with the sheet balsa parts they were reinforcing. Figure 10 shows an example of this technique in action.

Figure 10 - Example of 'kerfing'

Payload Carrier - Wheel Design

Originally the payload was going to be contained inside the fuselage, however due to design constraints such as the "optical sensor" and gear box, space was limited inside the fuselage therefore the payload had to be stored elsewhere. It was later decided that the payload maybe suited to being attached to the wing, this was taking inspiration from a commercial airplane such as the airbus, as its turbine engines are located on the wing. The four-kilogram payload would be putting far to much stress on the wing therefore “super ribs” had to be integrated into the wing design. It was concluded that the wheels of the aircraft would attach to these “super ribs” and the payload would then be strapped to the metal legs of the wheels using jubilee clips and tie straps. The payload will be carried inside 500ml bottles meaning that eight bottle will be required to carry the 4kg payload.

Manufacture

Hot Wire Cutter

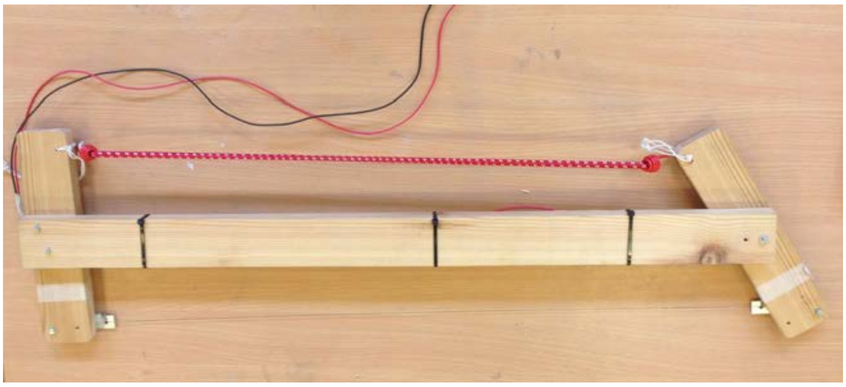


Figure 11 - Hot wire cutter

This hot wire cutter was made in order to cut aerofoil foam sections for the wing. We did this three times for the central 1.5m of the wing and twice for the 0.4 metre tapers.

Laser Cutter

The laser cutter was used for a fast and more precise manufacture (mainly for the thin trailing edge) of the ribs. The laser cutter cut all twenty-seven regular ribs and the twelve tapered ribs.

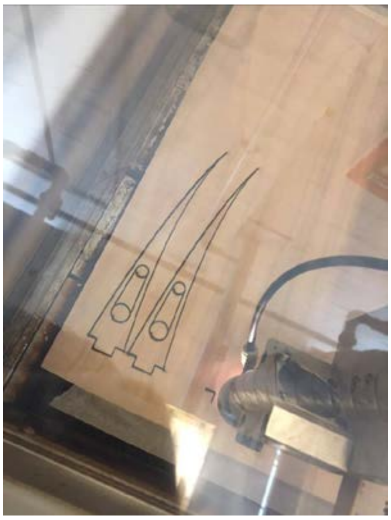


Figure 12 - Wing ribs being laser cut

Jigs

For a more successful accurate manufacture, jigs were manufactured, this allowed for a more precise construction.

Hot Wire Jig

This jig (as shown in Figure 13) was used during the very early stages of manufacture. It allowed for a clean precise cut when shaping the foam to the correct aerofoil section. This was done three times to create the centre 1.5 metre section of the wing, the same was done further on for the 0.4 metre tapered sections. Later on the jig was amended to allow a clean straight cut for attaching the balsa leading edge.

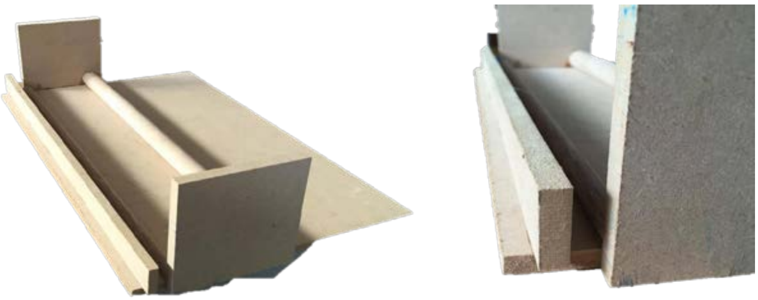


Figure 13 - Hot wire jig

Slit Jig

The purpose of the slit jig (which can be seen in Figure 14) was to supply a straight edge with a reference line for cutting vertical slits in the foam for the ribs. This ensured that the hacksaw blade used to cut the slits remained parallel with the foam and ensured it was cut to the correct depth. It was important for these slits to be cut at right angles so that the ribs sat straight when being slotted into the foam.

Figure 14 - Slit jig

Rib Jig

The rib jig supplied the correct height for the ribs to sit from the ground when the super ribs were rested on it. Wooden blocks were glued 60mm apart (same as the ribs) so that they sat flush to the sides of the ribs allowing them to be inserted at a right angle to the wing, ensuring they remained straight.

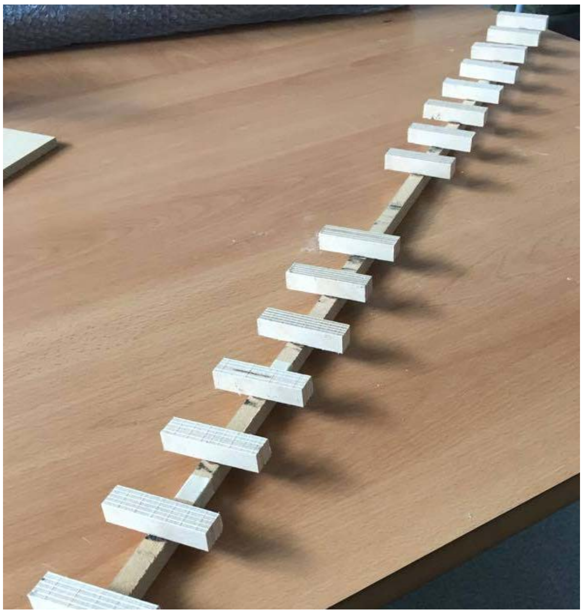


Figure 15 - Rib jig

Fuselage Jig

The fuselage jig (figure 16) was used to manipulate the balsa wood once it had been wiped down with water (this helping it to bend.) Once the bending started to occur, formers were placed between the two sections of 3mm balsa, and finally clamped with the jig. This ensured the desired shape was manufactured as a result of the jig.

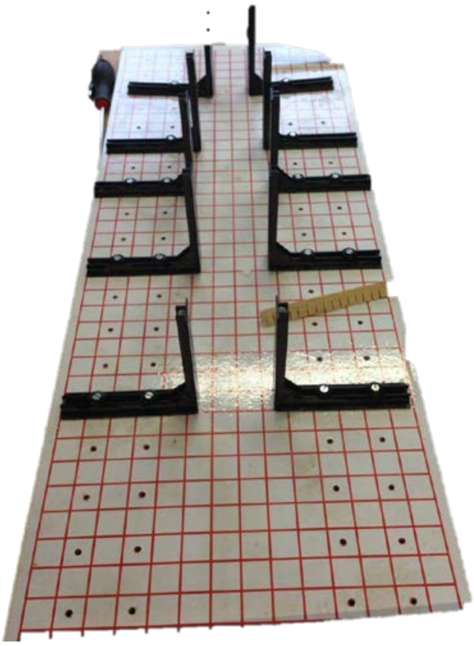


Figure 16 - Fuselage jig

Testing

Plywood Tensile Test

When designing the wing it was quickly decided that the leading edge would need some kind of reinforcement to stiffen and strengthen the wing. As we had a budget of £350, a debate arguing whether to order carbon fibre sheets to coat the wing or test another cheaper material to coat it was taking place. From this it was suggested that we consider using a very thin section of plywood to wrap the wing, first however it had to be tested to determine if its tensile strength was adequate enough.

Equipment

Zwick/Roell 2050 (50kN) Tensile Tester with computer control.

Test Specimens

Four test specimens of 0.4mm thickness plywood were tested as shown below:-

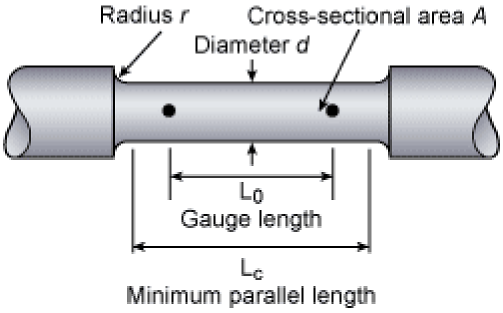


Figure 17 - Test sample geometry

Equipment

Zwick/Roell 2030 Tensile Tester with Computer Control.

Settings

Speed – 10mm/min **Pre-load** = 5N **Thickness** = 0.4mm

Test Pieces

All test pieces consisted of 0.4mm plywood
Gauge Length (Lo) = 60mm
Diameter (d) = 22mm

Four test runs were to be carried out for an average measure of the tensile strength of the particular plywood.

Table 3- Tensile Test Results

Test Run	Tensile Strength (MPa)
1	101
2	109
3	130
4	150
Average	**123**

Results

It was derived that plywood would be a suitable selection for the wing reinforcement due to the results gathered from the tensile test, as its tensile strength greatly exceeded what was required and had previously been determined (6.1MN$/m^2$).