DESIGN, BUILD AND TEST FLY A RADIO-CONTROLLED MINI AIR BLIMP

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1. Abstract

Global warming has become a greater cause for concern. To reduce carbon emissions, green technology should be explored. Though several disadvantages to air blimps include their slow speed and size, they have high endurance, are environmentally-friendly and energy efficient as they rely on lighter than air gases for lift, making them suitable for long term surveillance. The goal of this project was to design a radio-controlled air blimp with an endurance of 3 hours, 1 hour of live surveillance and a 500 metres range. The air blimp was designed to be aerodynamic and able to carry a payload of 250g with an NPL envelope profile and fineness ratio of 4. To fabricate the envelope, 4 Mylar gores were heat sealed together using Microlite and E-lite. The propulsion system utilizes biomimicry, imitating that of a fish's tail to control the blimp's yaw and a ballast to control its pitch. During the test flight, the air blimp was stable and easily manoeuvrable. Though a flight time of 3 hours was not met due to helium leakage, the other objectives were met. While outdoors flight is unfeasible as the air blimp is susceptible to weather conditions, it remained very stable in indoor conditions.

2.Background and Purpose of Research

An airship is a steerable lighter-than-air aircraft that derives its lift using buoyant gas. There are three types of airships — rigid, semi-rigid and blimps. Rigid airships maintain their structure using an internal frame, and semi-rigid airships have a partial frame but mainly rely on internal air pressure to keep their shape. Blimps are non-rigid and rely fully on internal air pressure to maintain their shape.[1]

Uses of blimps range from advertising, hauling cargo to tourism.[2] Despite their large size and slow speed, they have other advantages such as their long endurance, fuel efficiency and eco-friendliness. This paper explores the possibilities of blimps being used for surveillance purposes.

3. Engineering Goals

Our aim is to design and fabricate an airship with a considerably long time of flight (3 hours) due to the long endurance of airships, and a large range of control (500 meters) as the airship was designed for surveillance purposes. However, after considerations (see 4.4.5), the 1kg payload was revised into a 250g payload due to lack of materials and difficulty of manufacturing.

4. Design of airship

Even though a frame would maintain the shape and decrease the tension of the envelope, a blimp was eventually chosen due to the weight, difficulty and cost of creating a frame for rigid and semi-rigid airships.The airship consists of four main components — the propulsion system, surveillance system, the gondola and envelope. The addition of stabilisers was considered but eventually ruled out. (See 4.5)

4.1. Propulsion system

Two propulsion systems were considered as shown below. The first system utilises 4 propellers which can be attached at the sides of the gondola or on the rudders and elevators. With the propellers attached at the sides of gondola, they will face forward so that they can produce forward thrust and can be vectored to control pitch and yaw. (Figure 1) As for the propellers attached onto the rudders and elevators, the rudders and elevators would have to be mobile to control the yaw and pitch of the blimp. (Figure 2) The second system utilises a tail which will move from side to side to propel the blimp forward. (Figure 3) To control the yaw of the blimp, the tail will be deflected towards one side to act as a rudder. A moveable ballast will also be attached at the bottom to adjust the pitch of the blimp.

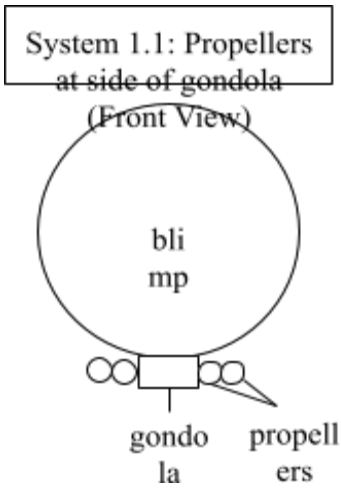


Figure 1 — System 1.1

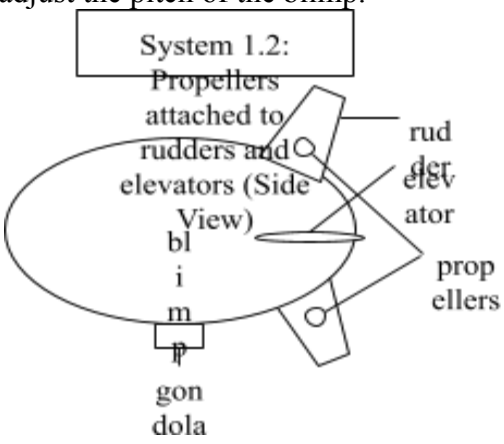


Figure 2 — System 1.2

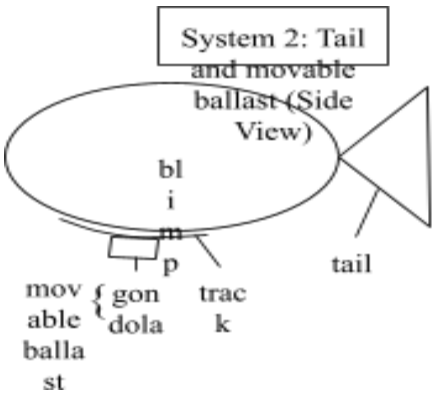


Figure 3 — System 2

	Propeller Design	Tail and Ballast Design
Weight	68g	35g
Power Consumed	More	Less
Noise Produced	More	Less

Table 1 — Comparison of Propeller Design and Tail/Ballast Design

After considerations, the tail design was chosen as it was much lighter than the propeller design and would consume less power, lengthening the battery life. As the blimp would be used for surveillance, noise production was also an important consideration. In addition, the movable

ballast allows us to control the pitch statically, allowing for increased manoeuvrability in confined spaces. The conventional elevator systems may not be effective due to the slow speed of the blimp, as they are only effective in pitch control when there is sufficient speed to generate enough lift on the elevators.

4.1.1 Movable Ballast

The ballast moves along a track, changing the position of the centre of gravity. This changes the pitch of the airship, allowing the airship to move vertically up or down. All components besides the caudal fin and FPV camera are attached to the ballast to maximise pitch control authority.

To create such a system, a servo was modified to drive the ballast along the track. The gears were modified to allow the servo to rotate 360 degrees. Firstly, the physical stop on the gear was removed and extra teeth were cut to enable full rotation. Secondly, the feedback potentiometer was removed and calibrated to a neutral value. The potentiometer was fixed at a setting such that the servo stops moving when given a neutral signal. This will allow the servo to move continuously in either direction when given a Pulse Width Modulated (PWM) signal above or below the neutral pulse width of 1500µs.

4.1.2 Caudal Fin

To produce thrust, a caudal fin will be attached at the back of the airship. Through varying its sidewards motion, it can yaw to either side as well. In order to create such a system, a servo was modified by adjusting the potentiometer to 1500µs using a servo tester. The potentiometer was then fixed at a setting such that the servo stops moving when given a neutral signal. If adjusted to more than 1500µs, the servo would spin clockwise and move the tail to the right, and vice versa. As there would be a bit of offset, the transmitter was used to subtrim the signal back to 1500µs.

Various shapes were considered for the fin by researching the different caudal fin shapes of fishes. There are several types of caudal fin shapes, namely rounded, truncated, forked and lunate, in decreasing order of surface area. The larger the surface area of the fin, the greater the manoeuvrability, despite the increase in drag.[3] Hence, a forked caudal fin shape was chosen to minimise drag but simultaneously ensure good manoeuvrability. Mylar was attached to carbon fibre rods to make the fin.

4.2. Surveillance system

Two types of surveillance systems were considered, the GoPro Hero 3 (with DJI Lightbridge) and the Eachine TX02 FPV Camera system.

Characteristics	GoPro Hero 3 (with DJI Lightbridge)	FPV Camera System
Weight	153g[4]	5g[5]
Resolution	Ranges from 848x480 to 1920x1080[4]	720x480[5]

Frames per Second (FPS)	Ranges from 12 to 240, depending on resolution[4]	30[5]
Range	3.5km[4]	600m[5]

Table 2 —Comparison of GoPro Hero 3 and FPV Camera System

A decision matrix was formed to decide which surveillance system was used. (See Appendix B) Weight was deemed the most important factor, with the FPV system being much lighter than the GoPro Hero 3. The next most important factor was range. Both fulfilled the aim of a 500m control range, though the GoPro's range was much larger. Resolution and FPS were less important factors, in which the GoPro was superior. Hence, the FPV Camera System was chosen as the surveillance system.

Given an airship of larger scale, the GoPro hero 3 with DJI Lightbridge should be used due to its much better resolution and FPS. However, for a smaller scale airship, such as in this project, the FPV Camera System is sufficient.

4.3 Gondola

Both Balsa Wood and Polylactic Acid (PLA) were considered as materials for the gondola. (See Appendix C) Eventually, PLA was chosen as it could be more easily fabricated into a streamlined shape reducing form drag. Its larger tensile strength also ensured it could fulfil the main function of the gondola, which is to protect the electronics it contains.[6]

Based on existing literature, three shapes were considered for the design[7][8]. (See Appendix D) The final shape and design of the gondola is shown below.

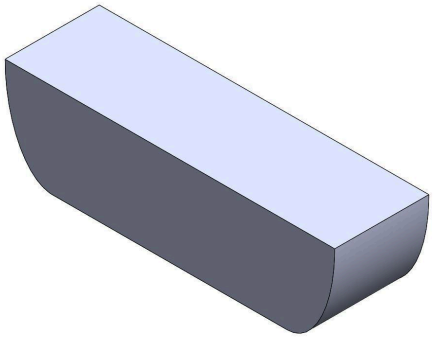


Figure 4 — Shape of Gondola

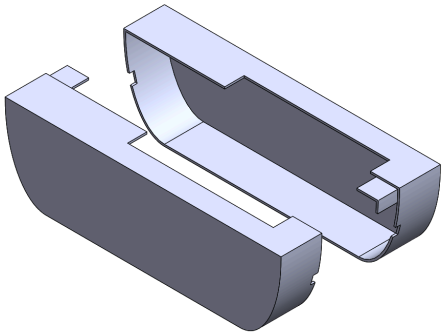


Figure 5 — Design of Gondola

The gondola was designed in Solidworks and 3D printed. It housed the ballast, battery and receiver. There is a 2cm by 7.5cm hole at the top for the component of the ballast that is attached to the track. The rest of the top surface rests on the top of the ballast. On each end of the gondola, there is a 0.5cm by 0.5cm hole for the wires from the caudal fin and the FPV camera to connect to the receiver.

One consideration is that the ballast needs to be easily removable to allow the battery and other components to be accessed and even removed. As such, two separate halves was designed to be

attached over the ballast. The halves were to be taped at the bottom to form a hinge. Locating structures were attached on each half to ensure they are attached together securely.

4.4 Envelope

The function of the envelope is to contain the helium used for lift. There are several considerations in designing the envelope, namely the material and sealing, the shape, the size and the fabrication method.

4.4.1 Material

Mylar, Microlite and E-lite were considered for the fabrication of the airship envelope. Mylar was chosen as it is often used in small-scale airships[9], while Microlite and E-lite are used as lightweight glider coatings.

Materials	Mass per unit area/ g m^{-2}	Sealing temperature/ °C
Mylar	16.6	200[9]
Microlite	20.3[10]	90[10]
E-lite	27.8[11]	200[11]

Table 3 — Comparison of envelope materials

Heat sealing with the following materials was attempted. It was found that heat sealing two pieces of Mylar together was ineffective as they could easily be peeled apart. Microlite sealing was relatively strong, and its one-sided adhesive made the process simpler. E-lite sealing was the strongest. Microlite and E-lite were able to seal effectively to Mylar as well, with E-lite being stronger.

As such, Mylar was chosen as the main material to fabricate the envelope due to its low mass and price. Microlite and E-lite were used to seal pieces of Mylar together.

4.4.2 Sealing

Heat sealing was chosen as the preferential method due to the fact that heat sealing does not add much weight to the envelope, unlike other adhesives like epoxy and UHU glue. The materials decided on, such as Microlite and E-lite, were heat activated adhesives.

After the fabrication of Prototype 2, it was observed that Microlite, with a sealing temperature of 90ºC, would shrink too much and create creases at the sealed area if the temperature of the heating iron was any higher than 110ºC. The adhesive on E-lite could also be activated at 110ºC even though it had a sealing temperature of 200ºC. Therefore, a sealing temperature of 110ºC was chosen for the final prototype.

4.4.3 Shape

Three envelope shapes were considered for the design of the blimp, namely GNVR, NPL and an ellipsoidal shape. An ellipsoid was considered as it is the simplest shape for fabrication and calculations. Existing literature shows that the GNVR shape[12] and NPL shape [7] are commonly

used for mini-blimps. However, the calculations and fabrication process associated with the GNVR shape is likely to be more complicated than that of the NPL shape.

Solidworks was used to calculate the volume to surface area ratio of the various airship shapes based on a fixed volume of 0.24071m^3, the volume of the final airship constructed. The higher the ratio, the less significant the skin drag and the lower the weight of the envelope, while maximising the lift force.[13]

Shape	Volume to Surface Area Ratio
GNVR	0.10923
NPL	0.10095
Ellipsoidal	0.10113

Table 4 —Comparison of Volume to Surface Area Ratio of various envelope shapes

A decision matrix was drawn up to decide which shape to fabricate. (See Appendix E) The NPL shape was chosen due to its relative ease of fabrication and decent volume-surface area ratio.A fineness ratio (ratio of the length of a body to its maximum width) of 4 was chosen for the envelope, as existing literature suggested that it minimised form drag.[14][15]

4.4.5 Size

The size of the envelope was chosen based on the volume needed to generate enough buoyant force to lift the payload. To lift a payload of 1 kg, a volume of 0.96283 m^3 was needed. (Calculations in Appendix F) Using this figure, the dimensions of the airship envelope required was calculated. However, the sheets of material needed for an airship of that size was extremely large, and fabrication would involve the grafting of two sheets together increasing the incidence of leaks. Hence, the weight of the airship components was estimated and the payload was lowered to 250 grams. Given the new payload of 250 grams, the dimensions for the airship are as shown below.

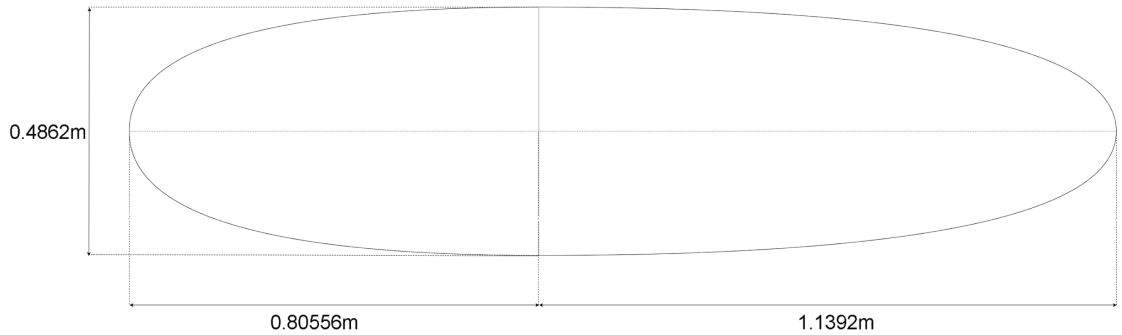


Figure 6 — Dimensions of Airship

4.4.6 Method of Fabrication

To fabricate the shape required, gores were cut and sealed together at the sides and ends. (See Appendix G) The greater the number of gores, the closer the envelope would be to the intended

shape and the fewer wrinkles at the seams[16]. However, using too many gores would increase the sealing area, increasing incidence of leaks. Hence, a compromise of 4 gores was decided upon.

4.5 Stabilisers

The addition of stabilisers was considered as stabilisers are a common feature of many airships, but it was ultimately decided against. Due to the slow speed of the airship, the restoring force exerted on the stabilisers would not be significant, so the stabilisers would not be very effective.

5. Fabrication of Airship

There were several phases to the fabrication of the airship, namely fabrication of the envelope, connecting the electronics (propulsion and surveillance system), and attaching of the components.

5.1 Envelope

2 prototypes of the envelope were created before the final one was made.

5.1.1 Prototypes 1 and 2

Two prototypes (See Appendix A, A8-A11) were created to test out the planned fabrication method and troubleshoot if necessary. One recurring problem was the holes on both ends of the envelope, resulting in severe leakage. Fabrication of cardboard domes to seal the ends against allowed us to create a 3-dimensional shape, alleviating the problem in Prototype 2.

A soap and water leak test was conducted on Prototype 2. However, the mixture resulted in the Microlite used for sealing peeling off. Hence, this leak test was deemed unsuitable.

5.1.2 Final Envelope

A similar method of fabrication was used for the final envelope. For the ends, a larger dome was fabricated using cardboard and newspaper to seal against. (See Appendix I)

However, leaking was rather severe, with the envelope deflating quickly. As a soap and water leak test could not be conducted, the leaks were detected manually by squeezing the envelope filled with air, while we felt for any leaks or escaping air. The leaks were patched up by sealing E-lite over the areas.

5.2 Connecting electronics

The electronics system consisted of the FPV camera, caudal fin, and ballast, which also contained the receiver and battery. They were connected according to the set-up below.

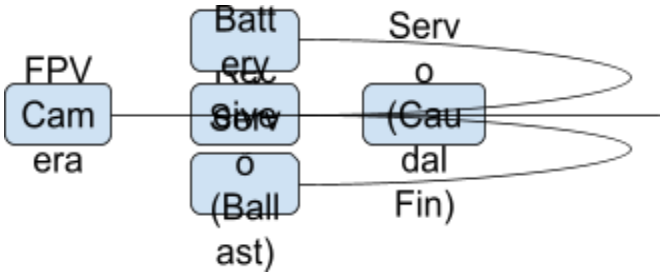


Figure 7 — Electronic System Set-up

5.3 Attachment of components

The components were placed on the underside of the airship such that the centre of gravity was directly below the centre of buoyancy. (Calculations in Appendix J) The centre of gravity must be below the centre of buoyancy so as to ensure longitudinal and lateral stability[17]. This is so that the centre of gravity will act as a restoring moment, allowing the airship to return to equilibrium position. Otherwise, the weight acting at the centre of gravity will further destabilise the airship.

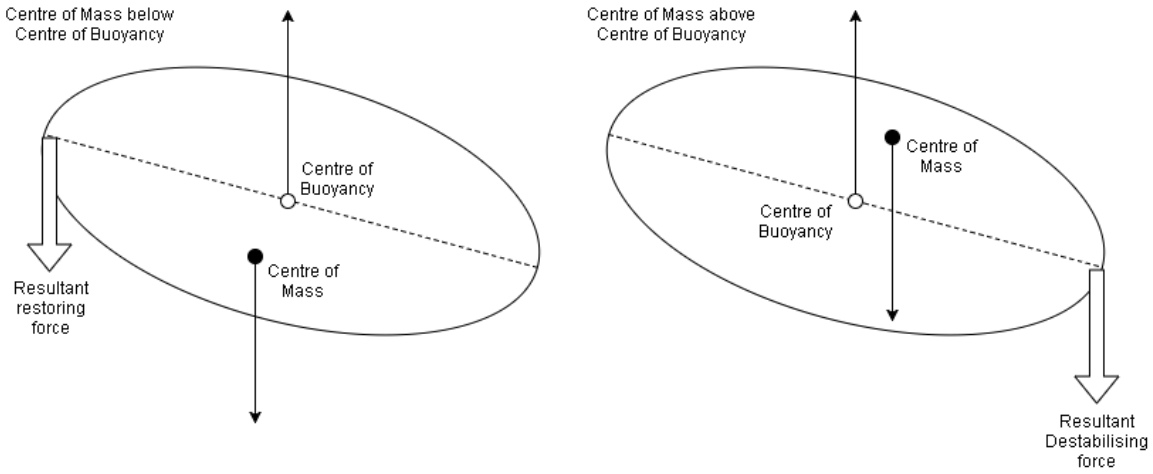


Figure 8 —Longitudinal Stability of Airship

The caudal fin was attached using hooks placed on the top, left, right and bottom of the middle portion of the airship. Elastic string was used to tie the fin to the hooks to ensure that when the caudal fin paddles, it exerts a force onto the entire body. Otherwise, the sidewards motion may result in a force only exerted on the back portion of the body causing the hind portion to bend as a result.

The FPV camera was attached using a foam cutout of its outline. This is to ensure the FPV camera could be easily removed or replaced, and to secure it without damaging the electronics if tape were used instead.

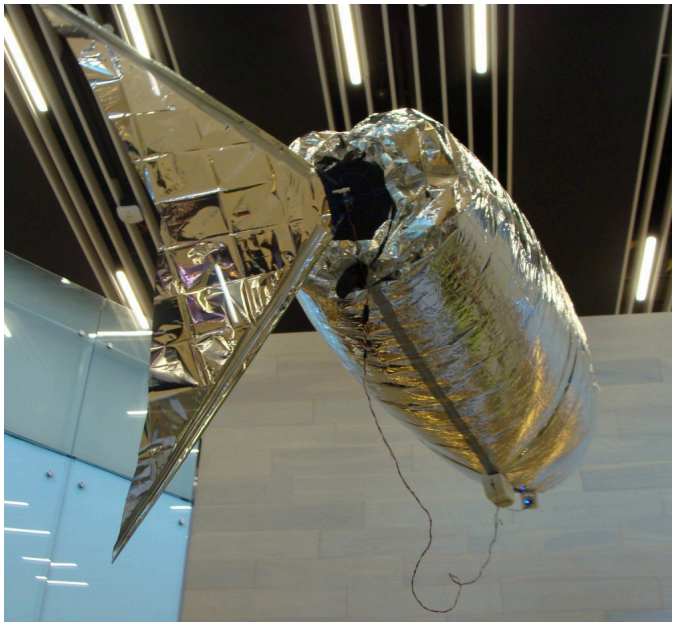


Figure 9 —Final Airship

6. Test flight of airship

The test flight involved 4 tests — the cruise test, the maximum pitch test, the climb test and the yaw test.

6.1 Cruise Test

The procedure involved measuring the time taken for it to travel a fixed distance of 15.00m (see Appendix K). The average speed was found to be 0.386m s^{-1}. (See Appendix L) This is lesser than the calculated critical speed (the speed where the upsetting moment just equals the righting moment) of the blimp of 1.20m s^{-1}, and thus, the blimp will be stable. (See Appendix M)

6.2 Maximum Pitch Test

The maximum pitch test involved moving the ballast to the furthest point forward and backward and measuring the angle produced while the airship was static. (See Appendix K) The downwards pitch angle and upwards pitch angle were 22° and 15° respectively. (See Appendix L) The pitch angles were not of the same value, possibly because the ballast placement was not centered, especially after the addition of weights. Other components such as wires along the bottom were also not factored in when calculating the placement of the components, possibly exacerbating the issue.

6.3 Climb Test

The climb test involved measuring the time taken for the airship to travel a fixed distance of 2.5m. (See Appendix K) The rate of climb was found to be 0.102m s^{-1}. Using the cruise test and pitch angle results of 0.39m s^{-1} and 15º respectively, the estimated rate of climb was calculated to be 0.0999m s^{-1}. (See Appendix L)

$$\text{Rate of climb (estimated)} = 0.386 sin(15º)$$
$$= 0.0999 \text{ m s}^{-1}$$

The climb test results were similar to the estimated rate of climb. The small difference in the calculated rate is most likely due to inconsistencies in piloting or different weight of the airship due to leakage.

6.4 Yaw Test

The yaw test involved measuring the time taken for the airship to travel 360º. The turn radius was also recorded. (See Appendix K) The clockwise and anticlockwise rate of yaw are 11.0° s^{-1} and 9.6° s^{-1} respectively, while the clockwise and anticlockwise turn radii are 1.01m and 1.39m respectively. (See Appendix L) The turn radius is noted to be significantly less than that of a conventional aircraft, making it highly manoeuvrable.

6.5 Discussion

There were some general observations for this mini air blimp. Firstly, the blimp remained stable indoors, so stabilisers were not needed, allowing the blimp to carry more weight. However, it was sensitive to weather conditions and would become unstable and difficult to manoeuvre if going against the wind direction. Thus, it was concluded that it cannot be used in the outdoors. Another observation was that the weight of the ballast needed to be adjusted regularly due to helium leakage, most likely due to inconsistencies in the sealing, resulting in a decrease in buoyant force. Due to the large size of the envelope, there is increased chance for error. This is most likely exacerbated by two factors — that flat sheets of material were used to create rounded surfaces, and that small pieces of Microlite were used for sealing, increasing chance of leakage.

The blimp will technically be able to lift its payload of 207g if weights were slowly removed over the flight time goal of 3 hours. However, the blimp was unable to remain neutrally buoyant for the full 3 hours without adjustments. Hence, the 3 hour flight time goal was not achieved. However, the surveillance and propulsion system lasted for the full 3 hours.

However, as the pilot's inputs and adjustments are based on the behaviour of the airship, inconsistencies are inevitable.

7. Conclusion

7.1 Summary

An airship with an NPL envelope profile, fin and ballast propulsion system and FPV camera system was designed, with a gondola to protect the ballast and its components. The envelope was fabricated using Mylar gores sealed together with Microlite and E-lite.

During the test flight, the air blimp was stable and easily manoeuvrable. The surveillance and propulsion system was able to last for the full duration and a control range of 500m was met. However, a flight time of 3 hours was not met due to helium leakage. . Though outdoors flight

would not be feasible as the air blimp is susceptible to weather conditions, it remained very stable in indoor conditions.

7.2 Future Development

In future prototypes, a camera gimbal should be looked into as camera gimbals are often used for surveillance purposes. They enable a greater range of view which will enable the pilot to base the movements of the blimp from the camera itself instead of visually adjusting the blimp. Also, given an airship of larger scale, the GoPro Hero 3 with DJI Lightbridge should be used due to its much better resolution and FPS as compared to the FPV.

If adapted for outdoor use, stabilisers could be added to confer more stability to the airship.

An area for improvement is the helium retention of the envelope. To solve this, alternative methods of fabricating an envelope could be considered, such as radio frequency welding of thermoplastic materials such as polyurethane.[12]

8. Acknowledgements

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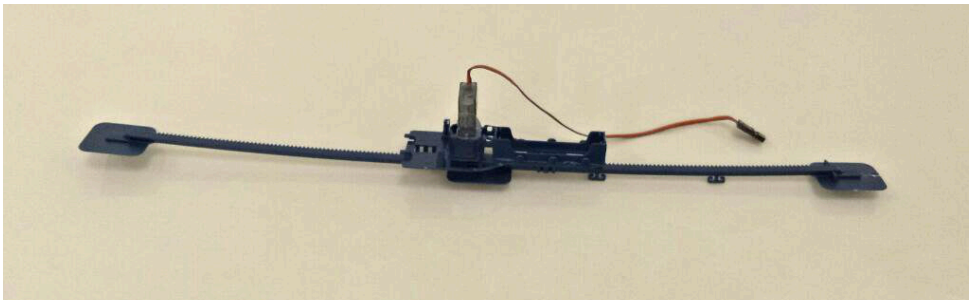
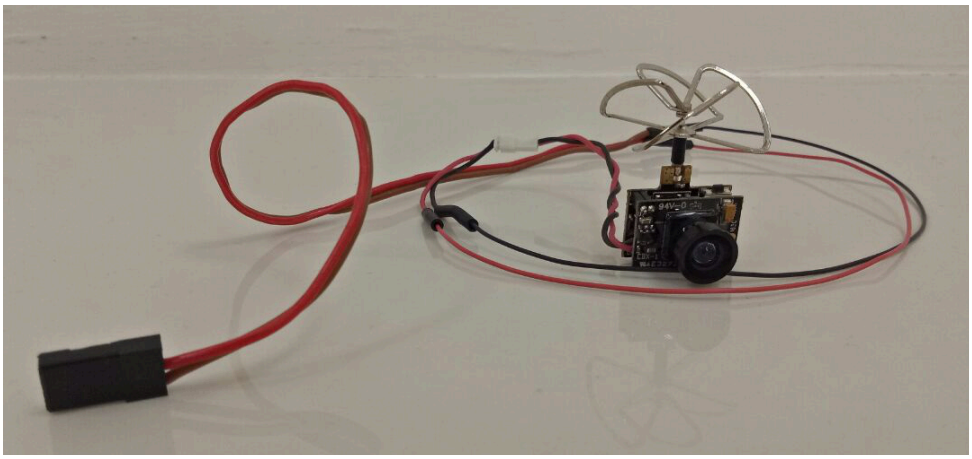
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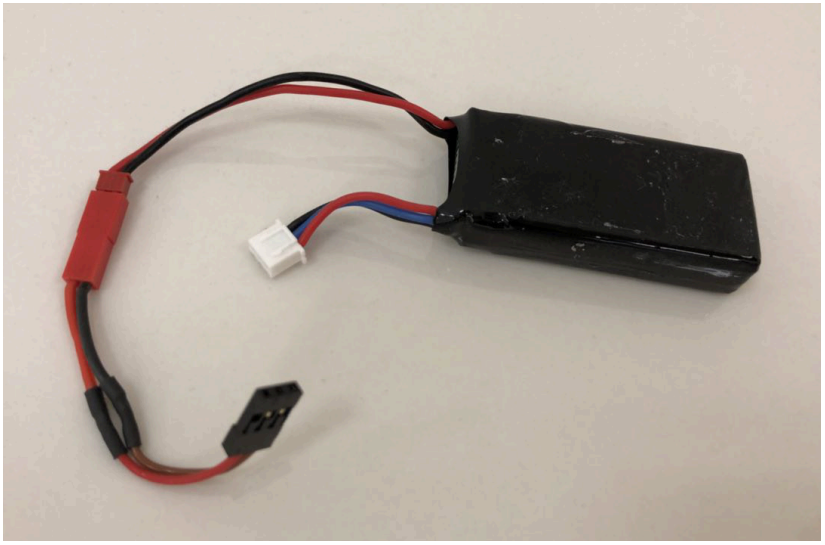
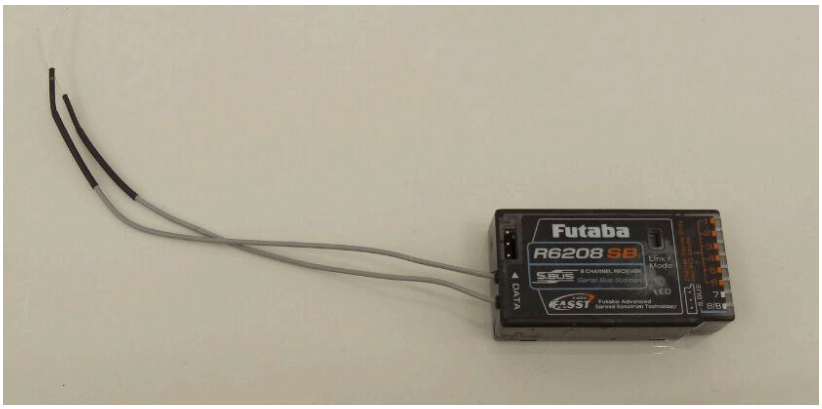
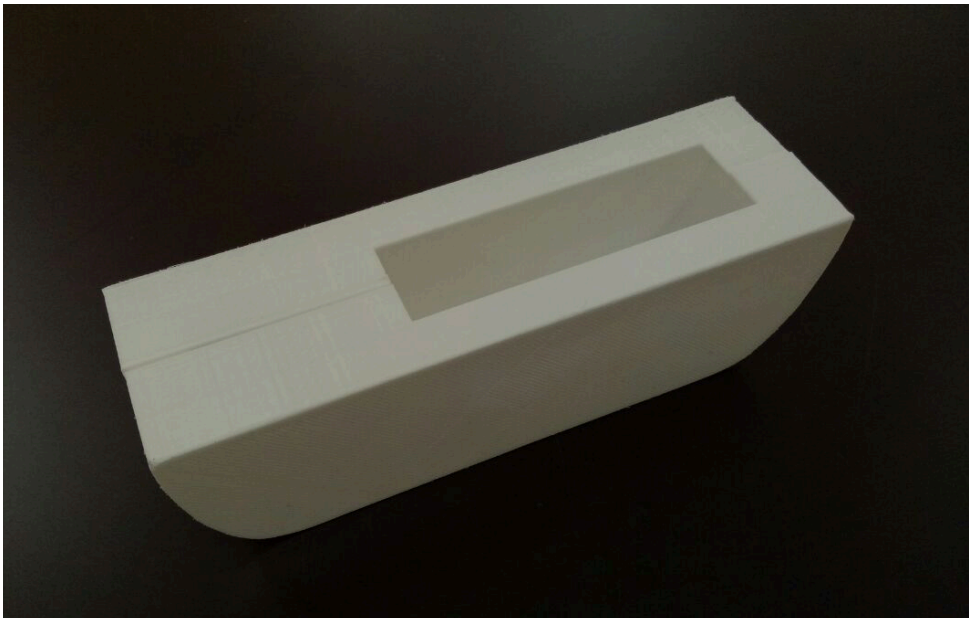
[20] Gases - Density. (n.d.). Retrieved December 28, 2017, from https://www.engineeringtoolbox.com/gas-density-d_158.html

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10. Appendices

Appendix A: Pictures of Components

Item	Picture
A1: Movable Ballast (with servo and track)	
A2: Tail	
A3: FPV Camera	

A4: Battery	
A5: Receiver	
A6: Gondola	

A7: Heating Iron	
A8: Prototype 1 (deflated)	
A9: Prototype 1 (inflated)	

A10: Prototype 2 (deflated)	
A11: Prototype 2 (inflated)	
A12: Final Envelope (deflated)	
A13:Final Envelope (inflated)	

Table 5 — Pictures of Components

Appendix B: Choice of Surveillance System

	Weightage	GoPro Hero 3 (with DJI)	FPV Camera System
Weight	50	10	45
Range	20	20	15
Resolution	15	15	5
Frames per Second	15	15	5
Total	100	60	70

Table 6 —Decision Matrix (GoPro Hero 3 and FPV Camera System)

Appendix C: Choice of gondola material

	Balsa Wood	Polylactic Acid (PLA)
Density/ g cm^{-3}	0.13[18]	1.3[19]
Tensile strength / MPa	14[18]	50[19]

Table 7 —Comparison between Balsa Wood and Polylactic Acid (PLA)

In addition, PLA can be more easily fabricated into a streamlined shape than balsa wood.

Keeping in mind that the function of the gondola is to protect the electronics it contains[6], tensile strength was an important factor in our consideration. Besides, it should also reduce form drag, so the material must be able to be fabricated into a streamlined shape. While weight was also one of our considerations, there was excess capacity, allowing for a heavier gondola. Hence, PLA was chosen as the material to fabricate the gondola.

Appendix D: Choice of Gondola Shape

Three designs were considered for the Gondola shape. Two factors were considered, namely the mass and surface area of the various designs. The table below shows the calculated values needed to fit our ballast, which we estimated to be a 4cm x 4cm x 10cm cuboid.

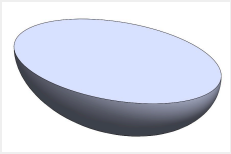
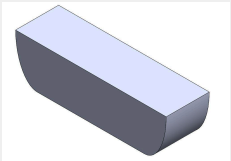
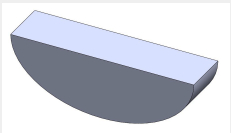
	Remarks	Surface Area/cm^2	Weight/g
Design A 	Half ellipsoid	233.35	28.4
Design B 	Rounded front and back walls, with a flat bottom and sides	185.13	28.5
Design C 	Rounded front and back walls with a rounded bottom , but with flat sides	248.17	26.1

Table 8 —Comparison between gondola designs

Although Design C was the lightest, it had the largest surface area, which would result in more skin drag. Besides, a difference of 2 grams between Design C and Designs A and B was considered almost negligible. Both design A and B had similar weights, but as Design B had the smallest surface area, it was chosen.

Appendix E: Choice of Envelope Shape

Criteria	Weightage	GNVR	NPL	Ellipsoidal
Ease of fabrication	50	20	45	50
Volume-surface area ratio (Skin drag)	20	20	15	15
Form drag	30	25	30	20
Total	100	65	90	85

Table 9 —Decision Matrix (Envelope Shape)

Appendix F: Calculations for dimensions of airship (1kg and 250g payload)

$$Buoyant\ Force\ (U) = Weight\ (W)$$
$$(\rho_{air} - \rho_{helium})gV = mg$$
$$(\rho_{air} - \rho_{helium})V = m$$
$$V = \frac{m}{\rho_{air} - \rho_{helium}}$$

Using estimates for the density of air and helium at room temperature and pressure[20],

$$V = \frac{m}{1.205 - 0.1664}$$
$$= \frac{m}{1.0386}$$

For an airship with a 1kg payload,

$$V = \frac{1}{1.0386}$$
$$= 0.962823m^3$$

Using the NPL shape (shown below),

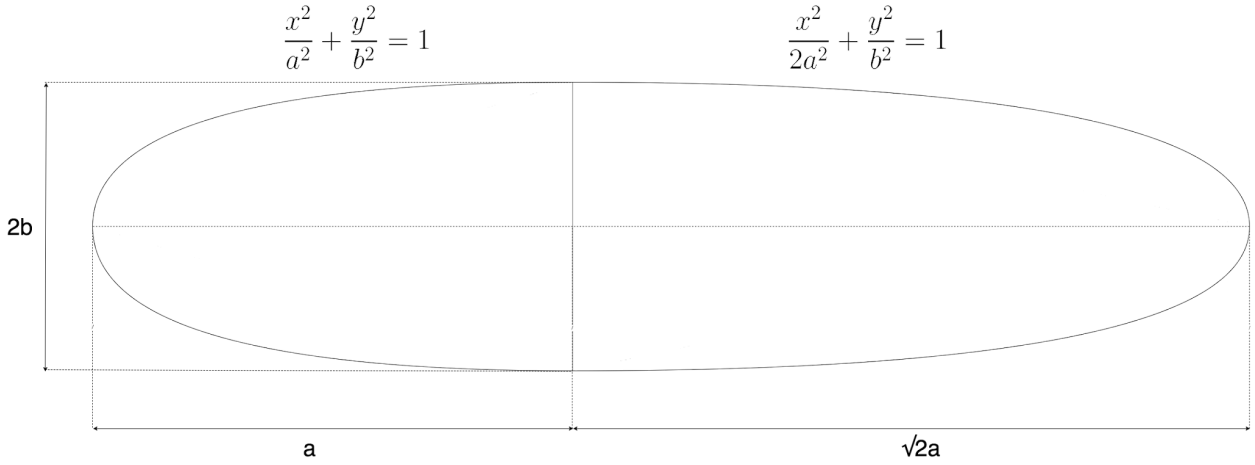


Figure 10 — NPL Shape

Given a fineness ratio of 4,

$$(1+\sqrt{2})a = 8b$$

$$V = \frac{4}{3}\pi(1+\sqrt{2})ab$$

$$= \frac{32}{3}\pi b^2$$

Since $V = 0.96284m^3$

$$b = 0.39628m$$
$$a = 1.0149m$$

Hence, the total length of the airship would be 2.45m, and the width and breadth would both be 0.79256m.

However, the largest sheet of mylar we had was 1.32m by 2.13m, so to fabricate an airship of this scale, two sheets needed to be grafted together. This would increase incidence of leaks, reducing the time of flight.

Given the above consideration and the estimated weight of our components (Appendix H), a smaller payload of 250g was selected.

Given a payload of 250g,

$$V = \frac{0.250}{1.0386}$$

$$= 0.24071m^3$$

Hence, using this new volume,

$$b = 0.24310m$$
$$a = 0.80556m$$

Appendix G: Gore fabrication process

In order to fabricate the envelope, 4 gores were cut out and sealed at the seams. The gores were cut to the shape shown below.

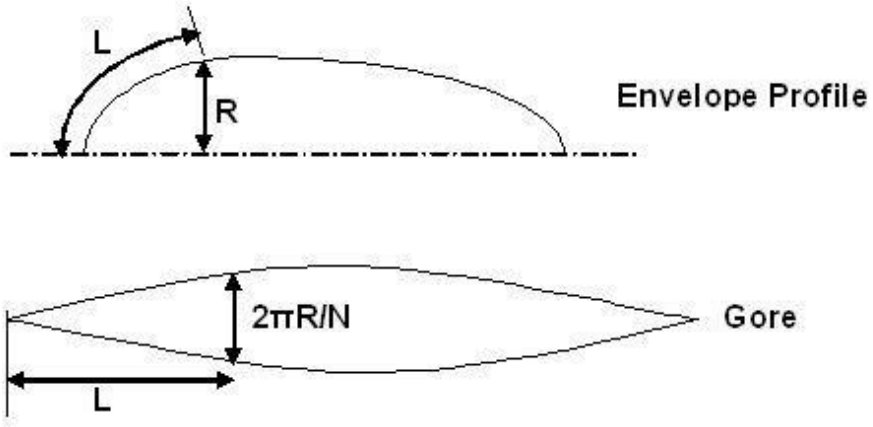


Figure 11 — Gore Dimensions [16]

The envelope profile was plotted out. At various intervals, the arc length from the nose and the radius (distance to the centre line) were recorded as quantities L and R respectively. Using these values, points were plotted out and connected to form the shape of the gore.

A cardboard cutout of the gore outline was then created to ensure all gores were cut to the exact same size, as shown below. This is especially important as any mistakes in the measuring and cutting of the gores will result in uneven edges, possibly leading to more leaks in the sealing process.

Appendix H: Weight of Components

Components	Weight/g
Envelope	53
Caudal Fin	15
Wire from Caudal Fin to ballast	14
Ballast	20
Receiver	14
Batteries	58
Camera	5
Gondola	27
Total	206

Table 10 — Weight of Components

An excess of 44 grams was left to allow for addition of extra weight to shift the centre of mass of the whole airship to the centre of the ballast track, as as for other components such as wires that were not factored in.

Appendix I: End supports

The end supports were created so that there would be a surface to seal the ends around. This is because sealing on a 2 dimensional surface would not create the 3 dimensional shape required, resulting in leaks.

To construct them, the radius of the cross sectional circle at 10cm intervals were calculated. Cardboard circles were cut using the calculated radii. Plastic cups were stacked and glued between each cardboard circle. This provided a skeleton for the end support, as shown below.



Figure 12 —Skeleton of Nose Support

Following this, mylar and newspaper were used to wrap around the structure in order to get the shape, and masking tape was used to reinforce the shape. The resultant two end supports are shown below. The one on the left was the front end support, and the one on the right was the back end support.



Figure 13 —Nose and End Supports

Appendix J: Calculations for placement of components

Using Solidworks, the centre of buoyancy (COB) and centroid of the envelope (COM) were both calculated to be 0.125 and 0.178m respectively from point O, as shown below.

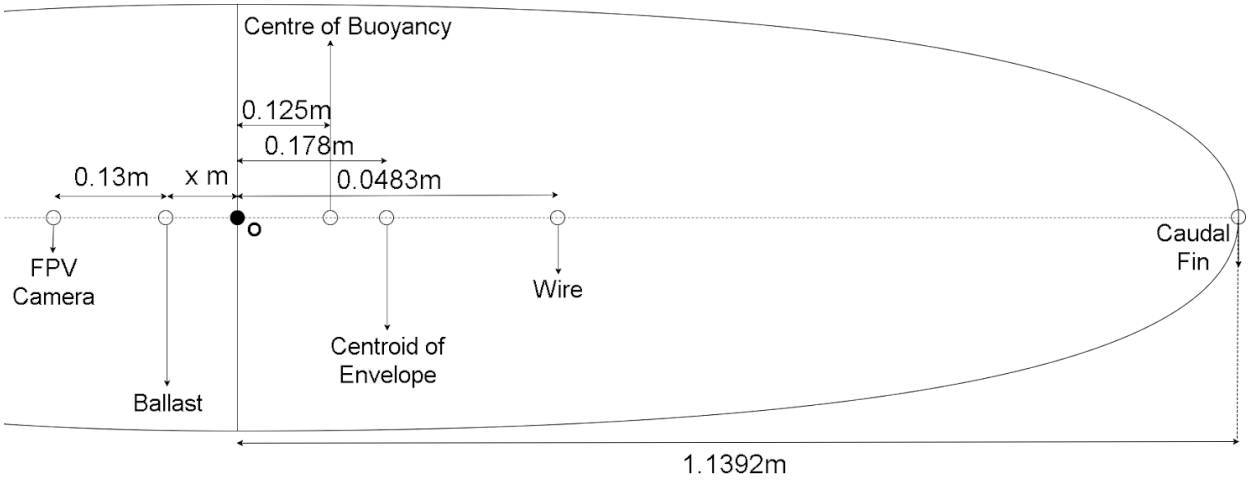


Figure 14 — Placement of Components

The centroid of the wire was calculated by assuming that it would be aligned along the bottom right quadrant of the ellipse. The position of the centroid was then calculated as shown below.

$$\text{Distance between centroid of wire and O} = \frac{4}{3\pi}(1.1392)$$
$$= 0.48349m$$

As some of the wire would be beyond point O, it was estimated to be slightly more to the left than calculated. Hence, a value of 0.480m was used.

The moments were calculated and balanced about the centre of buoyancy.

$\sum$ Anticlockwise moments
$$= 0.092(x + 0.125) + 0.05(x + 0.125 + 0.130)$$
$$= 0.092x + 0.0115 + 0.005x + 0.001275$$
$$= 0.097x + 0.012775$$

$\sum$ Clockwise moments
$$= 0.015(1.1392 - 0.125) + 0.014(0.480 - 0.125) + 0.053(0.178 - 0.125)$$
$$= 0.015213 + 0.00497 + 0.002809$$
$$= 0.02292$$

Equating clockwise moments with anticlockwise moments
$$x = 0.10533m$$

Using Solidworks, the distance between the head of the envelope and the ballast was then calculated to be approximately 76.9cm. Hence, the centre of the track was attached at that spot.

Appendix K: Procedures for Flight Tests

Cruise Test

1. Measure out a distance of 15 meters, and mark either end with tape
2. Allow the blimp to hover with its nose at the starting point, with a pitch angle of 0 degrees
3. Start the time when the blimp begins to move
4. Stop the time when the nose of the blimp is at the end point, and record the time taken

Maximum Pitch Test

1. Draw a vertical line perpendicular to the ground on the envelope.
2. Move the ballast to the back end of the track to obtain maximum upwards pitch.
3. Using a plumb line and a protractor, obtain the angle from the vertical line to the plumb line.
4. By subtracting the angle from 90^{o}, the maximum pitch angle is obtained.
5. Record all readings in a table.
6. Move the ballast to the front end of the track to obtain maximum downwards pitch.
7. Repeat steps 3-5.

Climb Test

1. A vertical distance of 2.5m was measured.
2. Mark the starting point and a point 2.5m above using tape.
3. Pitch the blimp upwards with the nose at the starting point.
4. Start the timer when the blimp starts moving.
5. Stop the timer when the nose of the blimp reaches the point 2.5m above the starting point.
6. Record all readings in a table.
7. Repeat steps 3-6 another time.

Yaw Test

1. Mark the starting point using tape.
2. Align the blimp such that the time keeper is in line with the nose of the blimp to ensure that it turns a full 360^{o}.
3. Start the timer when the blimp starts turning clockwise.
4. Stop the timer when the blimp has turned a full 360^{o}.
5. Mark the furthest point the blimp travels using tape and divide the value by 2 to obtain the turn radius.
6. Record all readings in a table.
7. Repeat steps 2-6 another time.
8. Repeat steps 2-7 two more times, but turning the blimp anticlockwise instead.

Appendix L: Results of Flight Tests

Time taken to travel 15.00m/s			Speed/ m s^{-1}
t_1	t_2	<t>	
38.6	39.1	38.9	0.386

Table 11 — Cruise Test Results

	Measured angle/º	Pitch Angle/º
Downwards Pitch	68.0	22.0
Upwards Pitch	75.0	15.0

Table 12 — Maximum Pitch Test Results

	Time/s			Rate of climb /m s^{-1}
	t_1	t_2	<t>	
Climb	25.2	23.9	24.6	0.102

Table 13 — Climb Test Results

Direction	Time taken for 360 degree rotation /s			Rate of Yaw/ º s^{-1}
	t_1	t_2	<t>	
Clockwise	31.2	34.5	32.9	11.0
Anticlockwise	35.2	39.8	37.5	9.6

Table 14 — Yaw Test Results (Rate of Yaw)

Direction	Turn radius /m		
	r_1	r_2	<r>
Clockwise	1.00	1.02	1.01
Anticlockwise	1.38	1.39	1.39

Table 15 — Yaw Test Results (Turn Radius)

Appendix M: Calculations for Critical Speed

The critical speed was calculated using the following formulae[17][21].

$$Volume\ (V) = 0.24071m^3$$
$$Density\ of\ air\ (\rho_{air}) = 1.205\ kg\ m^{-3}$$
$$Weight\ (W) = (0.206)(9.81)$$
$$= 2.0209kg$$
$$Height\ (h) = 0.1598m$$

$$M_c = V\left(\frac{\rho}{2}\right)(k_2 - k_1)$$

$$v_c = \sqrt{\frac{Wh\sin(\propto +\theta)}{M_c\sin(2\theta)}}$$

$$= \sqrt{\frac{Wh}{V\left(\frac{\rho}{2}\right)(k_2 - k_1)(2\cos\theta)}}$$

$$= \sqrt{\frac{(2.0209)(0.1598)}{(0.24071)\left(\frac{1.205}{2}\right)(0.778)(2)}}$$

$$= 1.20m\ s^{-1}$$