AME40462 - Aerospace Senior Design - Spring 2016

Flappy Gilmore

Final Report

3 May 2016

Group 5

Matt Borowiak
Chris Brownschidle
Alexa Klaus
Nick Stasack

Table of Contents:

I. Conceptual Design

Design Proposal

The proposed aircraft is a small-scale prototype for a military use aircraft, designed to deliver troops to a specified drop zone and return to its point of departure. The proposed aircraft will carry an expendable payload of 24 golf balls, representing paratroopers. It will fly three laps around the airfield, deliver the paratroopers within an acceptable range of one another, and complete an additional three laps.

The designed aircraft will be a monoplane with a front mounted propeller and a conventional tail that drops the golf balls through a door in the bottom of the fuselage. The golf balls will be held closely in a styrofoam holding block to ensure that they do not shift during flight, and that they land safely and close together upon landing. While the range before the drop and after departure are important, it was determined that the optimum performance is weighted towards delivering the most paratroopers safely to the drop zone.

Estimated Weight

Using the spreadsheet from *Design of Aircraft* for estimated take-off weight, the plane design has an estimated takeoff weight of 8.56 lbs when fully loaded with golf balls. The estimate includes 2.4 pounds of expendable payload (24 golf ball paratroopers, weighing 1.62 ounces each) and approximately 2 pounds of non-expendable payload (battery, motor, servos and other electrical components not factored into the spreadsheet). The predicted loaded speed of this aircraft is Mach 0.04, which is approximately 45 ft/s at an altitude of 50 ft. This speed was estimated based on the performance of past RC aircraft with similar size and weight. This spreadsheet overestimates the weight because it does not take into consideration that the plane will be using wood, and there is no fuel weight required because our plane is battery powered. Therefore, for our preliminary calculations we will be using an estimated weight of 8.0 lbs. This is still probably an overestimation of the weight, but at this point in the design it is best to be conservative with the calculations. If this is later determined to be a large overestimation, provided there is enough power to overcome this weight, additional payload can be added to increase the aircraft score.

Wing Loading

This aircraft will require a moderate wing loading. The desired wing loading should be low enough so that the aircraft can achieve a slow stall speed for accuracy with the payload drop but also high enough to resist wind gusts. The wing loading spreadsheet was used to determine the optimal wing loading for these design drivers. From the spreadsheet, the wing loading was determined to be 1.28 lbs/ft^2. According to the *RC Model Aircraft Design* book, wing loading should be somewhere between 1 and 1.4 lbs/ft^2 for a moderate-speed sport aircraft with an aspect ratio of 6-8. The value for this design falls within that range, and still has some room to increase if necessary.

Main Wing Design

The airfoil selected for this design was the Clark Y airfoil. It was selected because it has a high success rate with remote control aircraft of this scale. It also has a nearly flat bottom which will provide ease of construction and mounting onto the fuselage. The Clark Y airfoil also provides a large coefficient of lift. The outline of the selected airfoil can be seen in Figure 1, below.

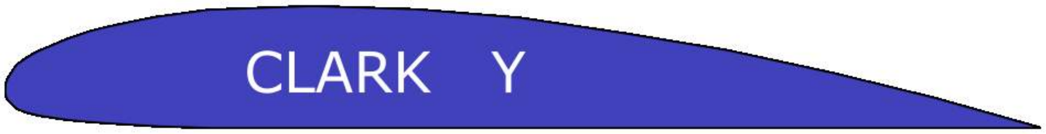


Figure 1. Clark Y Airfoil

The wing will have an aspect ratio of 7, and will be constructed with no taper because of the low Mach and Reynolds numbers. The wing will have a span of 6.6 ft, a chord of 0.9 ft, and a resulting wing area of 6.24 ft^2, as shown in Figure 2. Although making a 6.6 ft wing that is both strong and light enough to be successful will be challenging, it is certainly doable and should improve its ability to meet mission expectations. In order to improve performance, semi-circular foam wing tips will be to the ends of the wing. These wing tips will optimize the performance of the wing to be closer to that of an elliptical wing. The addition of the wing tips will reduce the induced drag.

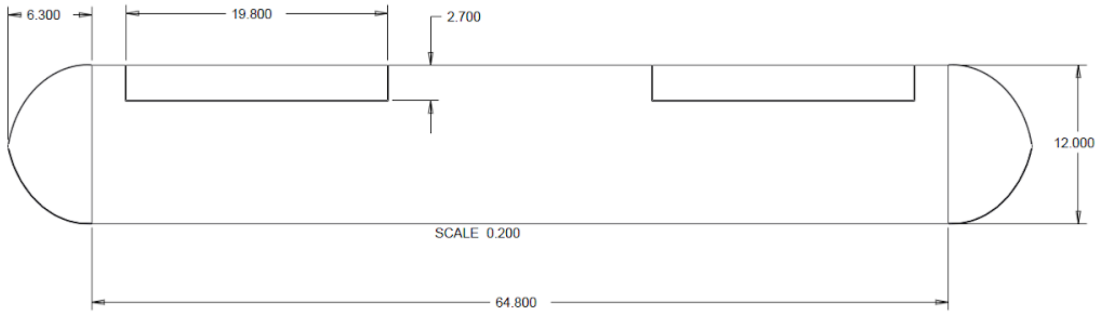


Figure 2: Wing design (dimensions in inches).

The aspect ratio was selected because it was within the range of suggested aspect ratios for a moderate-speed sport aircraft class according to *Basics of R/C Model Aircraft Design*. It was kept low enough to ensure that the aircraft can land, be maneuverable, and be structurally sound but large enough to obtain the suggested wing loading for that class of aircraft and to reduce induced drag. The thickness to chord ratio used was 14%, because of the very low Mach number, as shown in Figure 4.5 of *Design of Aircraft*. The total wing drag is 0.327 pounds, calculated using the design spreadsheets.

The wing will be a high wing, mounted to the fuselage through the use of rubber bands and dowels. This method will allow for ease of transportation, additional durability, and ease of repair should the wing get damaged. Additionally, building the wing separate from the fuselage also provide another access point into the body of the fuselage.

Fuselage

The primary design driver for the fuselage is the ability to hold the necessary number of golf balls, as well as have a mechanism for letting them go. The fuselage can be divided into sections. At the very front there is a nose cone that will taper back from the tractor propeller. The nose section will house all of the electrical components required for the propeller, and will also have a door on the side to allow access to these electrical components.

The main body of the fuselage is where the golf balls will be loaded. Due to the way the wing is mounted, there will be access to the main part of the fuselage from the top. However, for loading the plane will be flipped over and the golf balls will be loaded into the bottom. The balls will be loaded into a Styrofoam holding block so that they do not shift position during flight. The holding block will be 6x2 with 2 layers to achieve 24 golf balls. The dimensions of this part of the fuselage therefore need to be at least 4.5 in. x 4.5 in. x 14 in. in order to accommodate the payload.

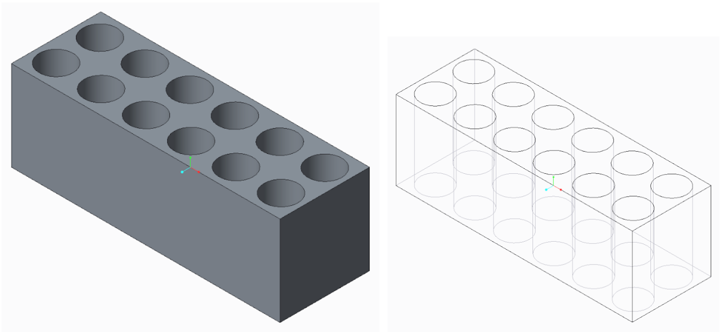


Figure 2. Holding Cell Design

The dropping mechanism for this design will consist of a stick-built hatch with two doors. The hatch doors will open down the center, using servos. Once opened, the balls will simply fall out of their foam bracing, and the hatch doors will then be closed.

Finally, the fuselage will taper back to the horizontal and vertical stabilizers. This portion of the fuselage needs to be long enough to provide significant moment arm and not require massive tail. The resulting total fuselage length is 51.5 inches. Using the spreadsheets, the drag contribution from the fuselage is very minimal, about 0.022 pounds. We estimate that the total drag of the plane including wing, fuselage, tails, and landing gear will be about 0.4 pounds.

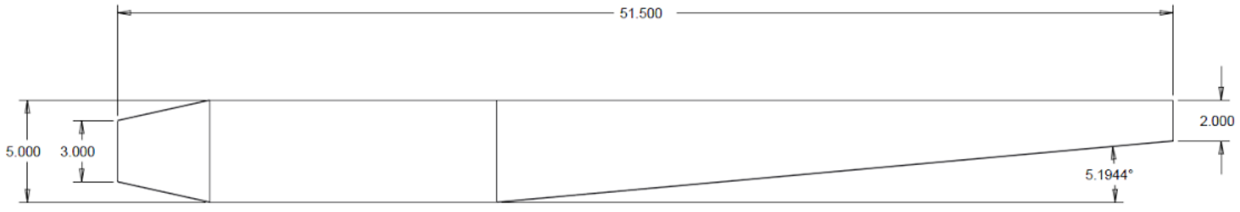


Figure 3: Fuselage Design (dimensions in inches)

Horizontal and Vertical Stabilizers

A conventional tail was selected for this design because it is the lightest tail to build and the plane design does not create a need for any other tail variation. Currently, the horizontal and vertical stabilizers are designed to be flat plates for ease of construction, but the potential of using a symmetric airfoil instead is being considered. The spreadsheet for tail design overestimated the size of the tail, particularly the height of the vertical tail. The horizontal tail was properly sized according to the pilot Scaling Advice available on the course website (15-20% of the wing area, the design uses 16%).

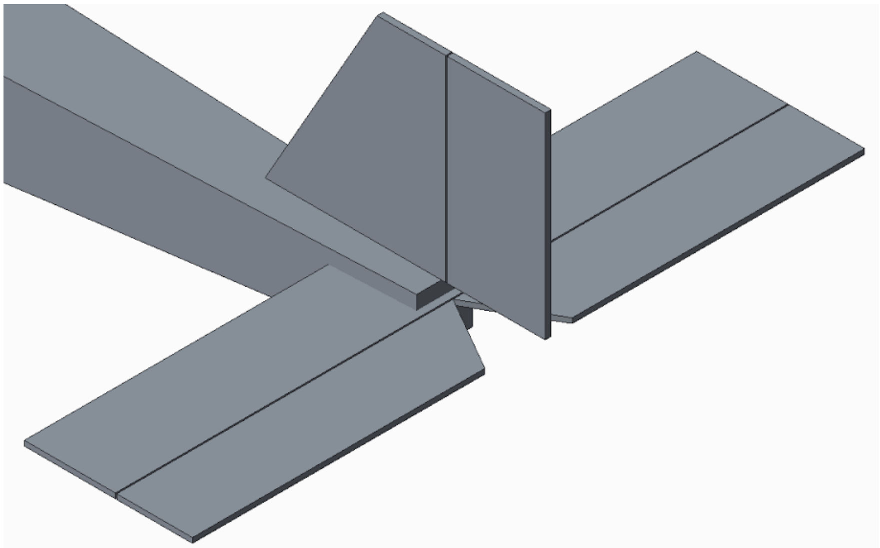


Figure 4: Vertical and Horizontal Tails

Control Surfaces

Stability and control are two key components for success for this aircraft, therefore, rather than using the spreadsheet values, the dimensions were calculated using the Scaling Advice from the pilots. The ailerons will have dimensions of a quarter of the chord by a quarter of the wing span, and will be located on the outer half of each wing. The dimensions of the ailerons are 1.65 feet in length by 0.225 feet (2.7 inches) in width. The elevators are scaled to be 20-30% of the horizontal stabilizer area. To ensure that the pilots are given ample control, the design used 30%. The dimensions of the elevator are 1.05 feet in span and 0.285 feet (3.4 inches) in width. Finally, the rudder size is 0.58 feet (7 inches) by 0.292 feet (3.5 inches). This yields an area of 0.17 ft^2, which is just under half the area of the vertical tail. The pilot's scaling advice suggested a rudder area of one third to one half of the vertical tail area. The designed dimensions fall within this range.

Stability Analysis

Stability is a crucial design factor for this aircraft to be successful in its missions. It is imperative that the aircraft be stable with and without the 2.4 pound expendable payload. For a preliminary stability analysis the static stability spreadsheet from *Design of Aircraft* was used. After entering the appropriate weight and their respective locations into the spreadsheet, a positive static margin of 0.01757 was achieved. The resulting longitudinal stability coefficient was a stable value of -1.48, which is within the suggested range. The resulting directional and lateral stability coefficients were 0.0627 and -0.0627, respectively, both of which are stable. As previously discussed in the fuselage section, the method of loading the golf ball paratroopers was designed to keep the center of gravity in approximately the same place, forward of the center of lift. Since the foam holding cell will have six rows of golf balls, it will be placed so that the rows 3 and 4 are centered about the CG location, thus the CG location should not change between the unloaded and loaded configurations and the plane should be stable for both cases.

II. Detailed Design

This section of the report details the changes made to the preliminary design after a preliminary design review and a critical design review. These changes were made in order to improve the performance of the aircraft as well as implement proper construction techniques. These changes reflect the final design of the built aircraft.

Fuselage

The fuselage underwent a series of changes in order to ensure the best construction of the aircraft as well as improve the overall performance. All pieces of the fuselage were laser cut from either balsa or lite ply wood for construction. Each of these pieces were designed with lightening holes to reduce weight and notches to aid in construction and structural strength. These changes can be seen in Figure 5.

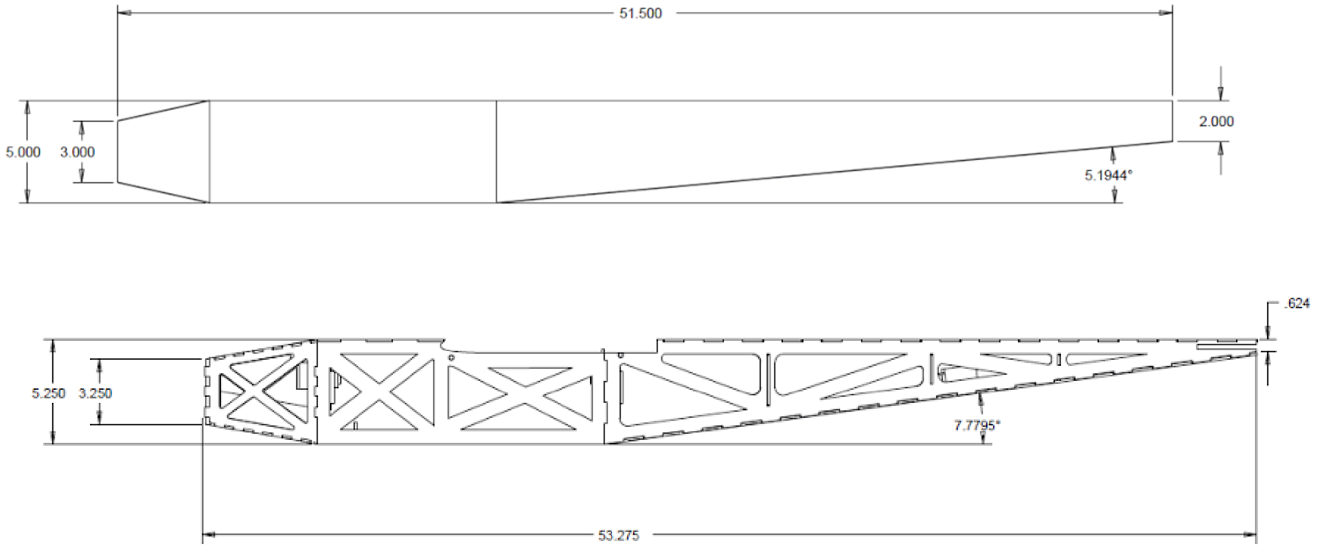


Figure 5. Fuselage Design Changes

The size of the aft-most portion of the fuselage was decreased from 2" x 2" to ¾" x ¾" to reduce bluff body separation effects. Ideally it would have tapered down even smaller, however, this size was maintained to allow for the notch where the horizontal tail would be installed.

In addition to the changes for the means of construction, the fuselage also underwent changes in order to incorporate the wing. The wing cutout at the top of the fuselage was made deeper in order to accommodate more of the wing and keep it attached with the use of dowels and rubber bands. The nose was made larger in order to better fit the electronics. The top of the nose was also made into a hinged hatch so that the electronics would be easily accessible, shown in Figure 6 on the following page.

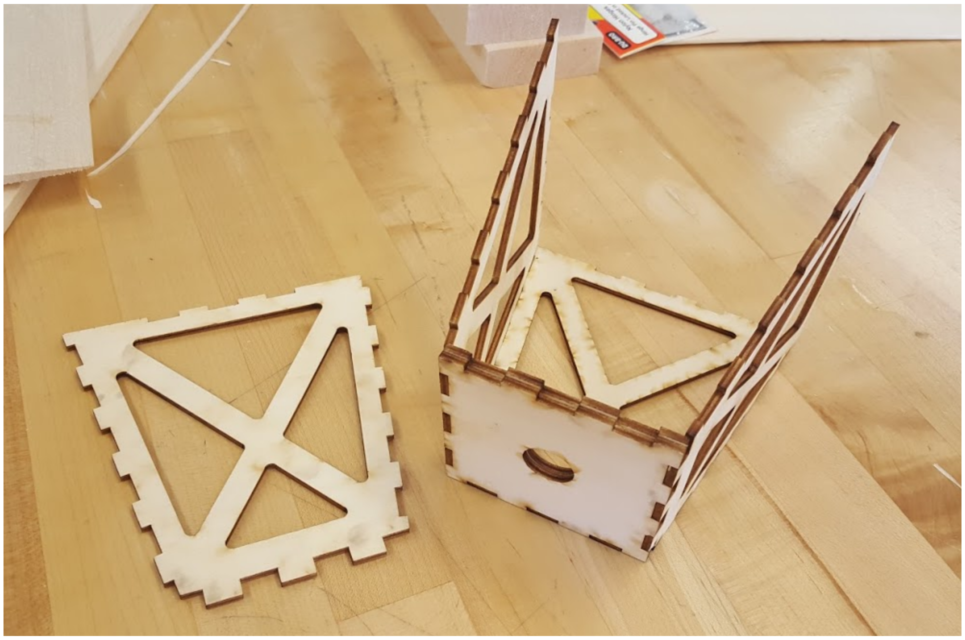


Figure 6: Updated Nose Design with Hatch for Electronics Access.

The holding cell for the golf ball paratroopers was also modified. Rather than having a foam holding cell, the material was changed to balsa wood to make construction easier, as well as take up less space. The spaces between the golf balls was also eliminated so that instead the holding cell is just small enough for them to be touching each other and keep each other in place. The main fuselage itself was not made any smaller, but this downsizing of the holding cell allowed there to be enough space on each side of the holding cell to run all of the necessary servo wires from the wing and tail to the nose. A figure of the updated holding cell is shown in Figure 7.

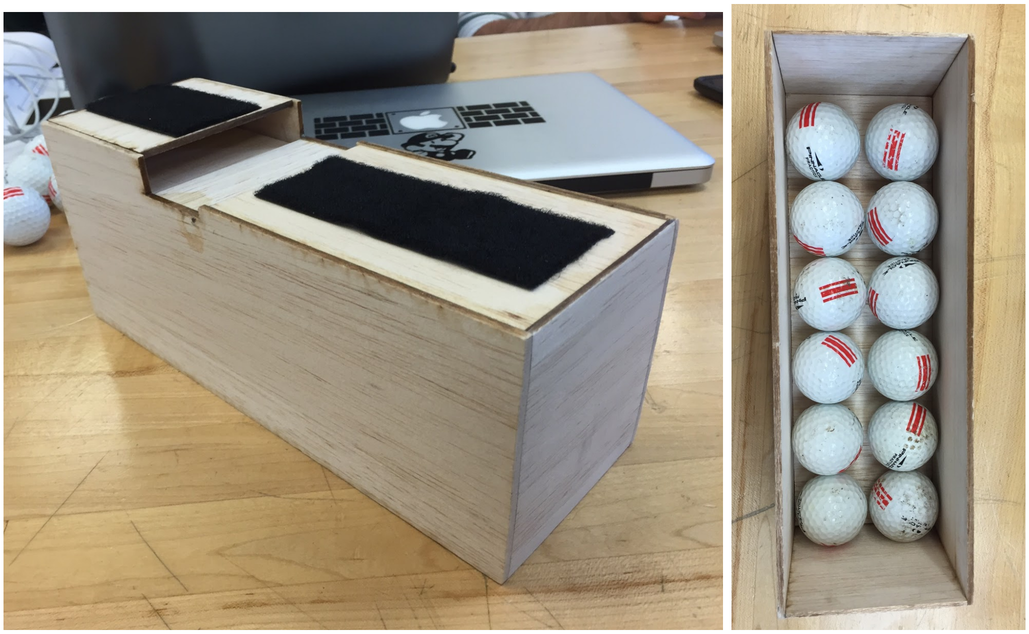


Figure 7: Golf ball holding cell.

The updated holding cell was designed to be removable in order to move the center of gravity if necessary for stability reasons. The top of the holding cell had two strips of velcro - one that attached to the top of the main fuselage and the other that attached to the bottom of the removable wing. Within the holding cell there was also an additional piece of balsa to keep the golf balls level when being loaded into the inverted aircraft prior to flight.

Tail

The design of the horizontal and vertical stabilizers were kept the same in terms of dimensions. However, a slot was designed into the tail portion of the aft fuselage so that the horizontal stabilizer could be inserted as a single piece for structural strength. In addition, the position of the cutout was changed to the rudder rather than out of the elevator to allow for proper control surface motion. By changing this cutout position, the elevator was able to be constructed as a single piece and controlled by a single servo rather than splitting it into two pieces as it was before. This can be seen in Figure 8.

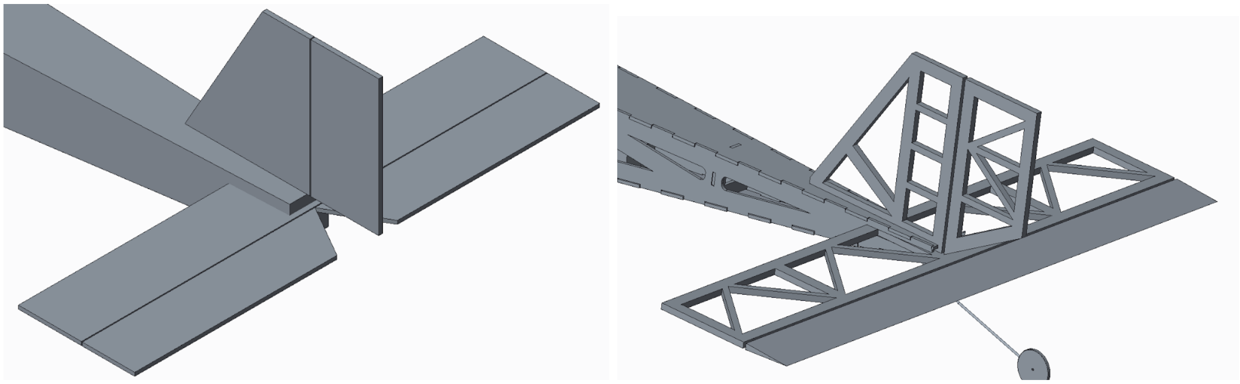


Figure 8. Changes made to horizontal and vertical tail control surfaces.

During the construction phases, the wood that would be laser cut for the aft fuselage arrived warped. Many methods were used to flatten the wood. However, once the aft fuselage was ultimately built, the wood returned to being warped and caused a twist in the aft fuselage, rotating the horizontal and vertical tail. This was due to the way that the wood was laser cut as two identical pieces. Had they been cut as mirrored pieces, the warping could have gone against each other and not caused this issue. After a discussion with the pilots, it was determined that this not-so-horizontal tail would not be an issue because of their ability to trim once flight testing began.

Wing

The design of the wing was primarily changed with regards to construction. The geometry, sizing, and airfoil selection remained the same as the preliminary design. The design for the built wing included three spars - one at the leading edge, one at the quarter chord, and one near the trailing edge. The design also incorporated 1/16” balsa skin as well as trailing edge stock in order to make sure that the design was structurally sound. The balsa skin was used from leading edge to quarter chord on both the top and bottom of the wing, as well as used for cap strips at the top and bottom of each of the ribs to aid in monokoting, shown in Figure 9. The design of the wing was also adapted to ensure access to each servo operating the ailerons and the tubing for the pitot tube.

Figure 9: Wing construction, with balsa sheets on the leading edge and the wing ribs.

The ailerons were constructed by sanding a balsa block into the proper shape and drilling out holes to reduce weight, shown in Figure 10. In the final design, they were placed as close to the outer edge as possible, right next to the foam wing tips.

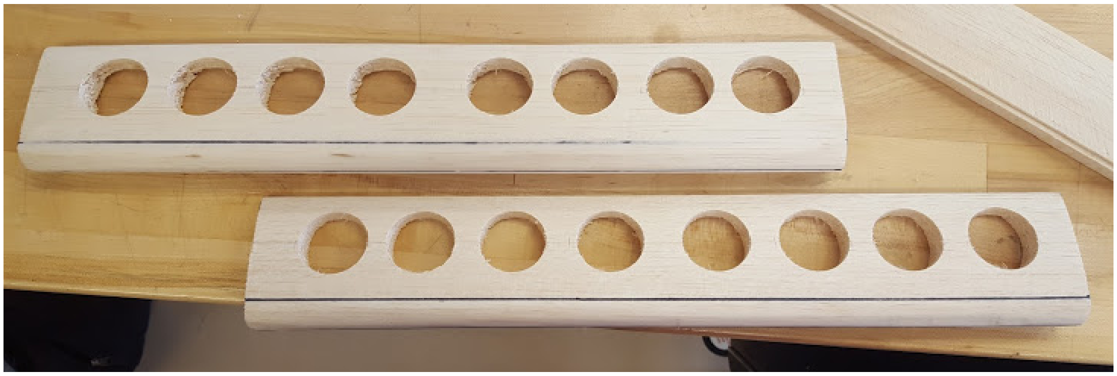


Figure 10. Ailerons Constructed from Balsa Blocks

The wing tips were constructed using a low density foam. Using the CNC router, the initial shape of the tapering airfoil was cut away, shown in Figure 11, below. After using the CNC router, the wing tips were sanded to create a smooth finish and coated with a few layers of white paint.

Figure 11. Wing tip milling and final model.

Drop Mechanism

The drop mechanism design remained the same in concept. The drop mechanism consisted of two stick built hatch doors covered with a balsa sheet to keep the balls inside. Each door was operated by its own large servo. The hatch door can be seen in Figure 12.

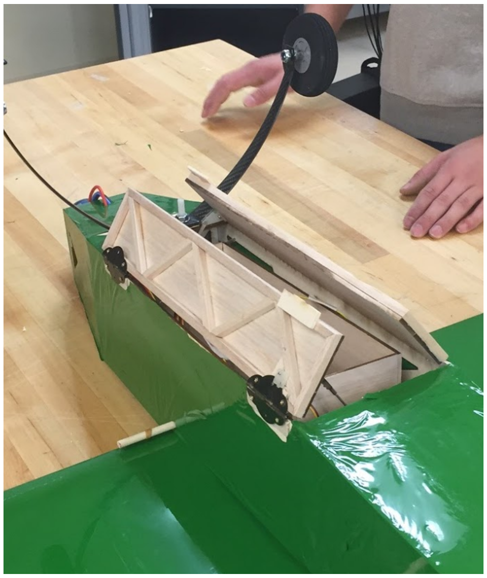


Figure 12: Hatch Door.

In order to make sure that battery concerns were addressed, the design allowed the rest position of the servo to be when the wire connected to the control horn on the hatch door was directly in line with the servo arm, as shown in Figure 13. This made it so that the physical design was holding the door shut rather than relying on the servo battery throughout the flight. In order to allow enough room for the payload to be freely loaded and unloaded, the servo arms were connected to control horns near the very end of each hatch door. This resulted in there being more support on one end of the hatch door than the other. In order to adjust for this, small wooden tabs were added to the bottom of the doors at the end supported by the servo arm. This allowed for the servo arm for one door to also help support the free end of the other door.

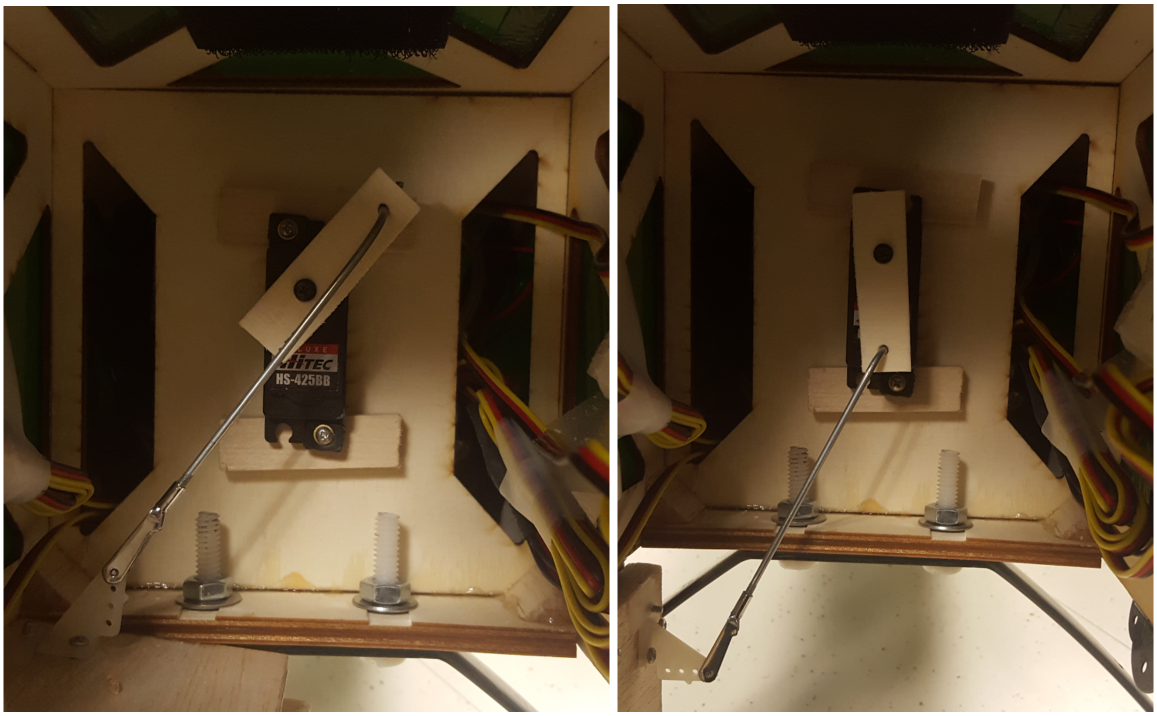


Figure 13. Drop Mechanism in Closed (left) and Open (right) Positions

Landing Gear

Once the final design of the fuselage was determined, the carbon fiber main landing gear and foam landing gear wheels were sized appropriately to allow for propeller clearance. The final rear landing gear design was not steerable. However, it was determined that the aircraft would have enough steering power due to the large size of the rudder.

Final Construction

A final comparison of the design and the as-built aircraft can be seen in Figure 14, on the following page. Detailed CAD drawings of the components for the final design can also be found in the Appendix at the end of this report.

Figure 14. Final Build vs. Final CAD Model

Performance Parameter Predictions

Table 1 below shows the predicted versus measured values for the final design of the plane.

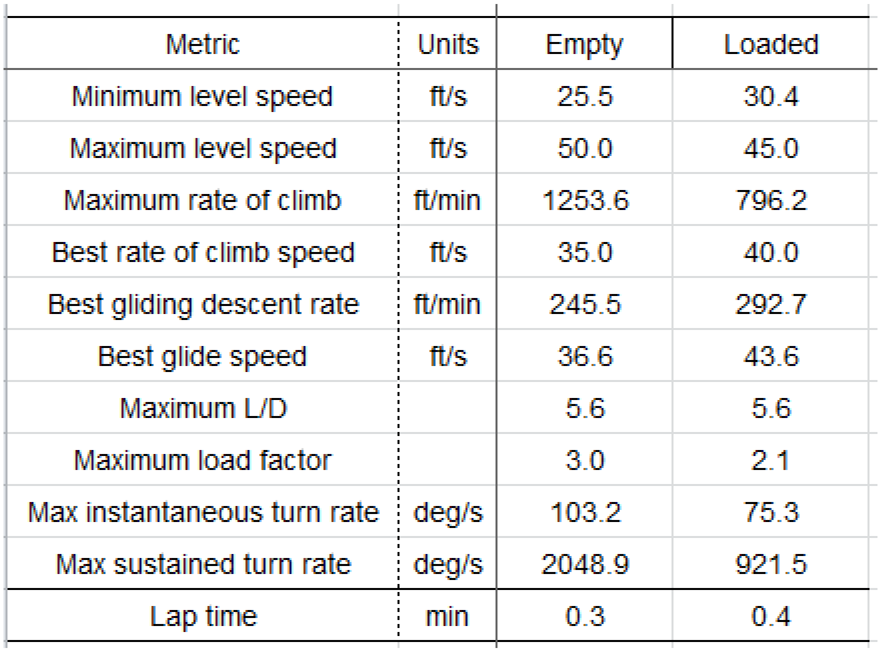
Table 1. Physical Design Metrics

Metric	Units	Empty		Loaded	
		Predicted	Measured	Predicted	Measured
Weight, fuselage	lbs	3.83	4.30		
Weight, wing	lbs	1.18	1.51		
Weight, empty	lbs	5.83	5.81		
Weight, payload	lbs			2.43	
Weight, loaded	lbs			8.27	8.24
Location, CG	x/L	-0.03	0.17	0.02	0.15
Location, center of lift	x/L	0.25	0.25	0.25	0.25
Static Margin	%	27.50	8.30	23.05	9.90
Wing area	ft^2	5.38			
Wing span	ft	6.58			
Aspect ratio		7.76			
Wing loading	lbs/ft^2	1.08	1.08	1.54	1.53

The predicted values come from the final CAD model of the plane and the measured values are from the fully constructed model. Note that the predicted weight of the fuselage does not include the weight of the horizontal tail, vertical tail, or landing gear, which is why the predicted fuselage weight plus the predicted wing weight do not add up to the predicted empty weight. Ultimately the measured weight for the constructed plane was almost exactly the same as the predicted weight. The measured location of the center of gravity of the plane ended up being much better than what the CAD model had predicted, this is because the actual weight of the carbon fiber landing gear was much less than originally anticipated. The CG locations were measured relative to the leading edge of the wing over the chord of the wing. The CAD model predicted that the unloaded CG would be 3% in front of the leading edge and that the loaded CG would be at 2% of the wing. These values would have resulted in an aircraft that was too stable. The switch to a lighter landing gear resulted in an unloaded CG at 17% of the wing and a loaded CG at 15% of the wing, both of which were within the range of appropriate values for the stability of this type of aircraft. Additionally, the unloaded and loaded CG locations were close enough to each other that there would not be a significant change in the flight characteristics of the plane at the time of the payload drop. The wing was designed exactly to the specifications of the CAD model so the predicted and measured wing parameters were the same. The suggested wing loading for a moderate-speed sport aircraft according to *Basic of R/C Model Aircraft Design* was 1.0 lbs/ft^2 - 1.4 lbs/ft^2. The unloaded wing loading for this plane fell within that range, and the loaded value was slightly higher than the suggested range but still within the acceptable range for R/C planes in general.

The predicted flight performance metrics for the aircraft can be seen in the table below.

Table 2. Predicted Flight Performance Metrics



Metric	Units	Empty	Loaded
Minimum level speed	ft/s	25.5	30.4
Maximum level speed	ft/s	50.0	45.0
Maximum rate of climb	ft/min	1253.6	796.2
Best rate of climb speed	ft/s	35.0	40.0
Best gliding descent rate	ft/min	245.5	292.7
Best glide speed	ft/s	36.6	43.6
Maximum L/D		5.6	5.6
Maximum load factor		3.0	2.1
Max instantaneous turn rate	deg/s	103.2	75.3
Max sustained turn rate	deg/s	2048.9	921.5
Lap time	min	0.3	0.4

The majority of the flight metrics were calculated based on the aircraft's wing loading. The minimum level speed was calculated using the equation for stall speed, shown in the equation, below.

$$V_{stall} = \left(32.2\,\frac{W}{S}\,\frac{2}{\rho C_{L,max}}\right)^{1/2}$$

Where $\frac{W}{S}$ refers to wing loading, ρ is air density, and $C_{L,max}$ is the maximum 3D lift coefficient. Maximum level speed was determined using Corke's spreadsheets as well as comparison RC aircraft. The maximum rate of climb is determined by the excess power of the aircraft. Assuming the aircraft climbs at a constant speed, the rate of climb is given by the equation below.

$$\frac{dH}{dt} = V\left(\frac{T-D}{W}\right)$$

The minimum glide descent rate is given by the following equation:

$$\frac{dH}{dt}_{glide} = 4\sqrt{\frac{2W}{\rho S}}\left(\frac{k}{3}\right)^{0.75} C_{Do}^{0.25}$$

The best glide speed is the speed that minimizes drag. This speed is given by the following equation:

$$V_{glide} = \sqrt{\left(\frac{2W}{\rho S}\right)\left(\frac{k}{C_{Do}}\right)^{0.25}}$$

The following equation govern the instantaneous and sustained turn rates, respectively:

$$\psi_{inst} = \frac{g}{V}\sqrt{\left(\frac{qCl_{max}}{W/S}\right)^{2} - 1}, \qquad \psi_{sust} = \frac{g}{V}\sqrt{\frac{q\pi Ae}{W/S}\left(\left(\frac{T}{W}\right)_{max} - \frac{qC_{Do}}{W/S}\right) - 1}$$

The calculate values for the sustained turn rate were much higher than expected. This may be attributed to incorrect assumptions about the aircraft's maximum thrust or minimum drag coefficient. The load factor is given by $n = \frac{qCl}{W/S}$. The maximum load factor was found to occur at takeoff, when lift coefficient was maximized. The maximum lift to drag possible is the maximum lift coefficient divided by C_{Do}, which was found to be 5.6. The lap time was found by multiplying the speed of the aircraft by the distance traveled. The cruise speed of 40 ft/s was used during the straight portions of the track, while the instantaneous turn rate was used for the curved portions of the track.

III. Flight Tests

Flight Test Day 1:

Unloaded

The first flight test of Flappy Gilmore was an unloaded flight test to ensure that the plane would be able to withstand the loads of flight prior to loading any golfballs. Upon arrival to the field there were a few issues regarding the servos for the ailerons. Once the servos and arms were properly aligned and the radios were programmed, the plane was ready to begin flying.

After a successful takeoff, the plane was in the air. The pilot tested Flappy's control as well as ability to stall. Thanks to the nearly elliptical wing, the plane did not stall easily. In fact it simply gained altitude during the first attempts to stall. A photo of the plane in the air can be seen in Figure 15 below.

Figure 15. Flappy Flying

Due to the wind conditions, the pilot needed to land the plane in the grass, perpendicular to the runway. Upon landing, the nylock bolts did not shear off as intended but rather the landing gear as well as the plywood plate that the main landing gear was attached to broke away from the plane after its bouncy landing in the grass. The propeller was also broken in half upon impact, as shown in Figure 16 below. Though the damage rendered Flappy unflyable for the remainder of the day, the repairs were easily done prior to the next flight test day.

Figure 16. Propeller Damage after First Flight

It appears as though the GPS may have shifted during this initial flight, as only a small portion of the data was collected. However, the team felt that this flight proved the flight worthiness of the aircraft and the data from the remaining flight tests would provide plenty of information about the plane's performance.

Flight Test Day 2:

The second day of flight testing included three flights: two carrying half the design load (12 golf balls) and one flight carrying the full load (24 golf balls). After arriving at the field and setting up all of the electronics within the nose, a ground test was performed for the dropping mechanism. In this test, the airplane was loaded to full capacity in order to verify that the doors could hold the entire weight of 24 golf balls. The servo motors were able to hold the doors shut and open them properly, but one screw for the door's hinge came loose during the test. The door was quickly repaired on site by inserting a longer screw through the hinge and fastening it with a plastic backing. With the longer screws, the doors were able to hold the full load and the plane was ready for flight.

Half Loaded Flight 1

The team decided that for the first loaded flight, it would be safest to attempt flying at only half load and for a conservative number of laps (3). With the wind in the direction of the runway, Flappy quickly took off and completed 3 laps before dropping its payload, finishing with another 3 laps and a successful landing. After the flight was completed, the spread of the golf balls was investigated. It was found that 4 balls landed within a 3 feet diameter circle, giving Flappy a score of 9 on the first scoring flight. The path for this flight is shown on the following page in Figure 17.

Figure 17: Half Loaded Attempt 1 Flight Path and Airspeed

Half Loaded Flight 2

With a very successful first flight that day, Flappy was quickly ready for another flight. Seeing how quickly the plane was able to complete 3 laps, the team decided that attempting 5 laps for the second flight would be a realistic goal. Like the first flight that day, Flappy completed 5 laps before and after dropping the half load, with a successful drop in between. The pilot again landed the plane smoothly and easily within the 5 minute time limit for the mission. The path of this flight is shown below in Figure 18.

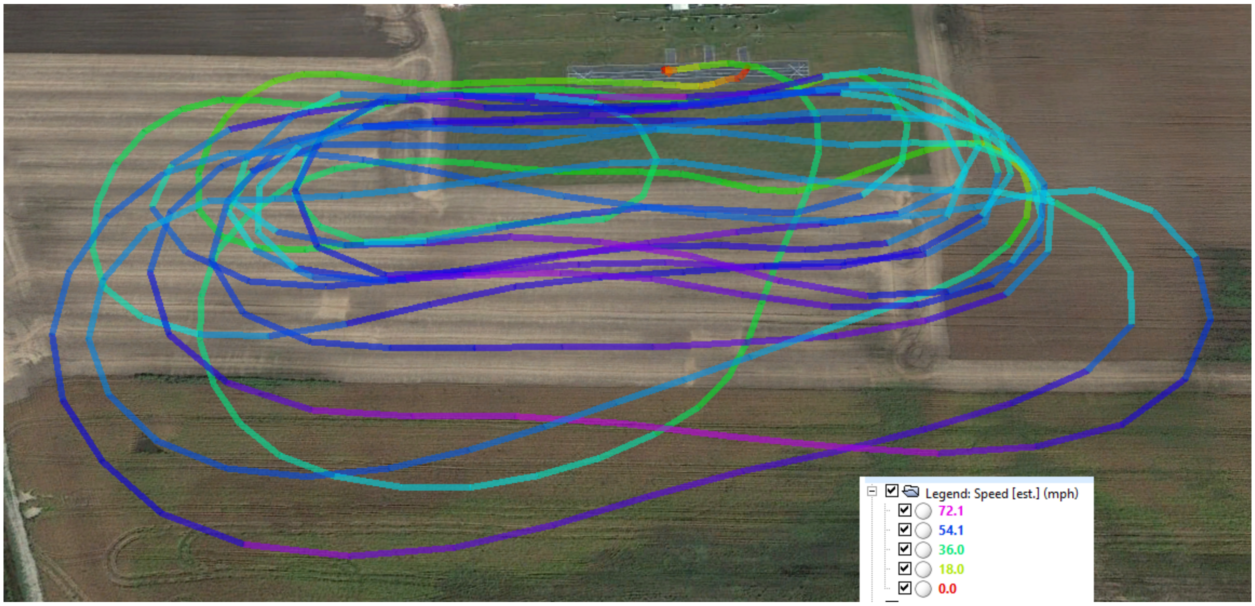


Figure 18: Half Loaded Attempt 2 Flight Path and Airspeed

When retrieving the dropped golf balls, it was found that only 3 landed within a 3 feet diameter circle, giving Flappy a score of 10 for the second flight.

Fully Loaded

In the final flight of the second test day, an attempt was made at flying fully loaded (24 golf balls) and completing 5 laps before and 5 laps after dropping the payload. This flight was extremely successful and its performance can be seen in Figure 19 on the following page.

Figure 19: Fully Loaded Flight Path and Airspeed

From the above figure, it can be seen where Flappy slowed down prior to dropping the payload after completing 5 laps. The payload was found after the flight, and with the full 24 golf balls dropped, Flappy achieved its best score of 20 due to 5 golf balls landing within the 3 feet scoring circle, shown in Figure 20 at the top of the next page. The 10 total laps were completed in 4:36, with its fastest fully loaded lap being 26 seconds and its fastest empty lap being 22 seconds.

Figure 20: Golf Balls Scored from the Fully Loaded Flight

Flappy set the bar high for all competitor aircraft during the first day of scoring flights, as seen in Figure 21, below.

Figure 21: Competitors Jealous of Flappy's Success

Flying conditions for this day were very favorable. There was a slight East to West wind which allowed for easy takeoff and smooth landings. The pilot was able to climb in altitude while flying very fast along the back stretch thanks to the tailwind, and then was able to dive into the headwind in order to maintain relatively high speeds when flying West to East. This trend can be seen in Figure 22 below which plots the ground speed data against time. The East to West paths tend to average over 60 mph, while the West to East paths average around 55 mph.

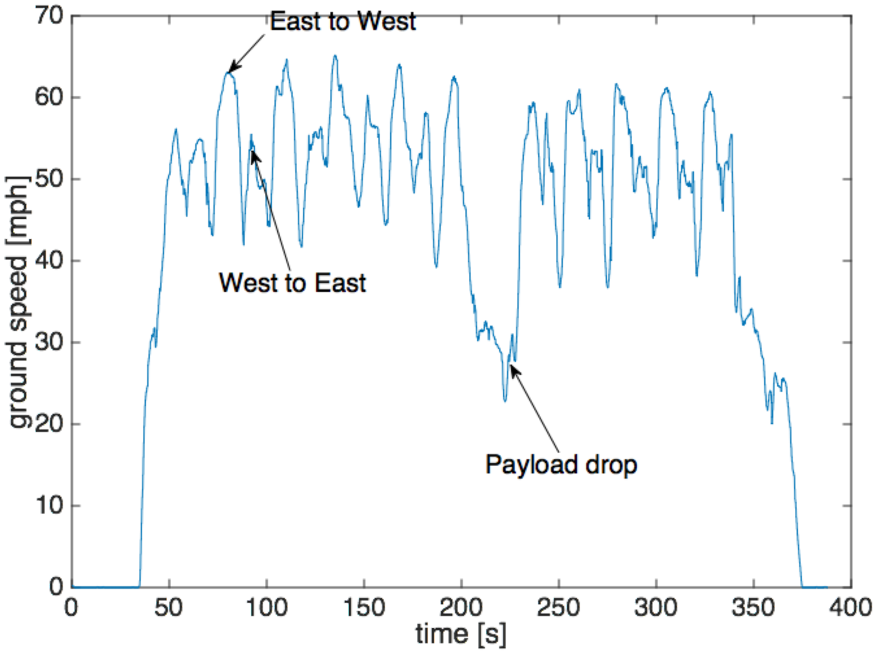


Figure 22. Ground Speed vs. Time

Flight Test Day 3:

Fully Loaded - No Data Collected

The team returned to the field for a third day of flight testing in order to allow members who had been absent for the previous flight tests to see Flappy in action. Because data had already been collected in each of the previous flights data was not collected, but the team still sought to improve the overall score. The plane was fully loaded with 24 golf balls. The conditions were windy, but Flappy still got up in the air and performed well for the first lap. Upon banking for a turn in the beginning of the second lap, one of the sides of the hatch door broke due to the force of the turn, and Flappy was quickly brought in for a landing and inspection. The damage to the hatch doors, landing gear and propeller can be seen in Figure 23, below.

Figure 23. Damage to Hatch Door

During this turn, the paratroopers were quickly ejected and landed in the dirt surrounding the field. The first attempts at retrieval were unsuccessful. However, they were later found having dug themselves foxholes, as shown in Figure 24.

Figure 24. Rescued Paratrooper

The sustained damage will not be enough to keep Flappy out of commission for the commencement flight.

Final Results

Ultimately, Flappy's best results came on the third flight of the second flight test day when it flew with a full payload of 24 golf balls, completed 5 laps before and after the payload drop, and dropped 5 balls inside of the hoop for a final score of 20. The 5 laps were 2 laps better than originally anticipated during the design phase. Figures 25 through 28 show the data from this flight.

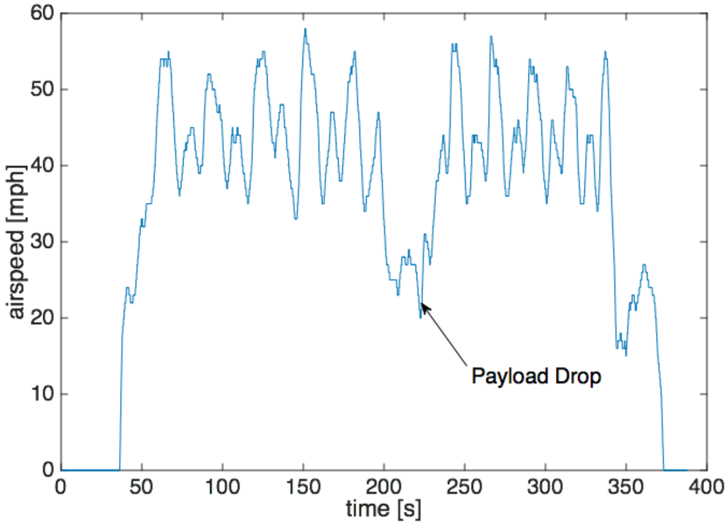


Figure 25. Air Speed versus Time

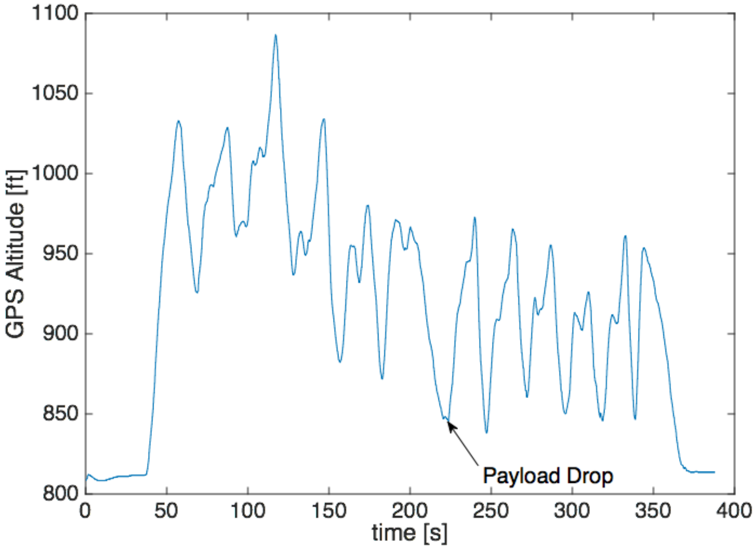


Figure 26. Altitude versus Time

Figures 25 and 26 above show that the payload was dropped at approximately 221 seconds. At this point the air speed of the aircraft was 24 mph and it was at a height of 847 ft above sea level. The altitude of the airfield was found to be 808 ft above sea level, so in this flight the payload was dropped from 39 ft above the ground.

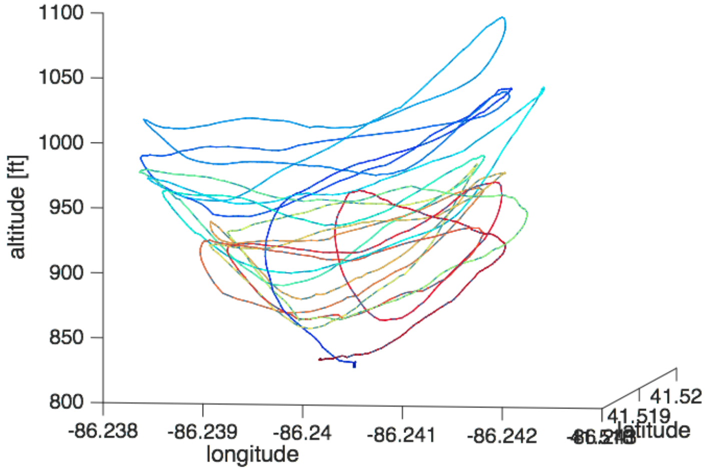


Figure 27. Plot of the flight path versus altitude

Figure 27 above shows a graph of the plane's altitude with its longitude and latitude. The graph is color coded for time such that blue is takeoff and red is landing. Figure 28 below more clearly shows the aircraft's flight path.

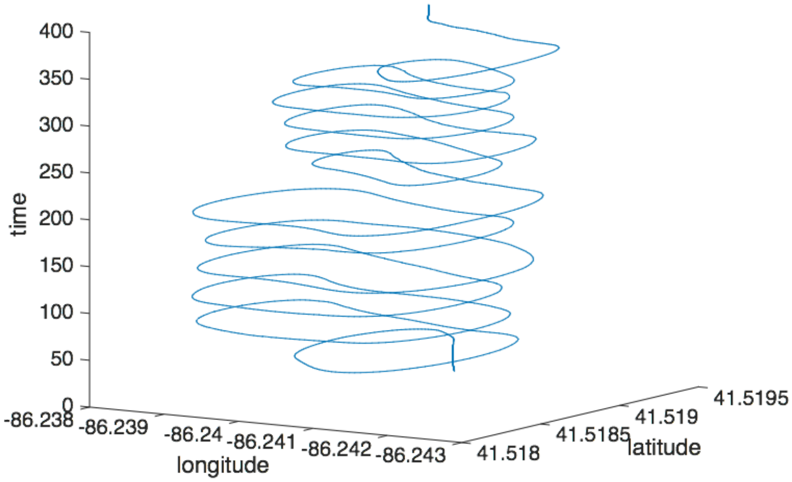
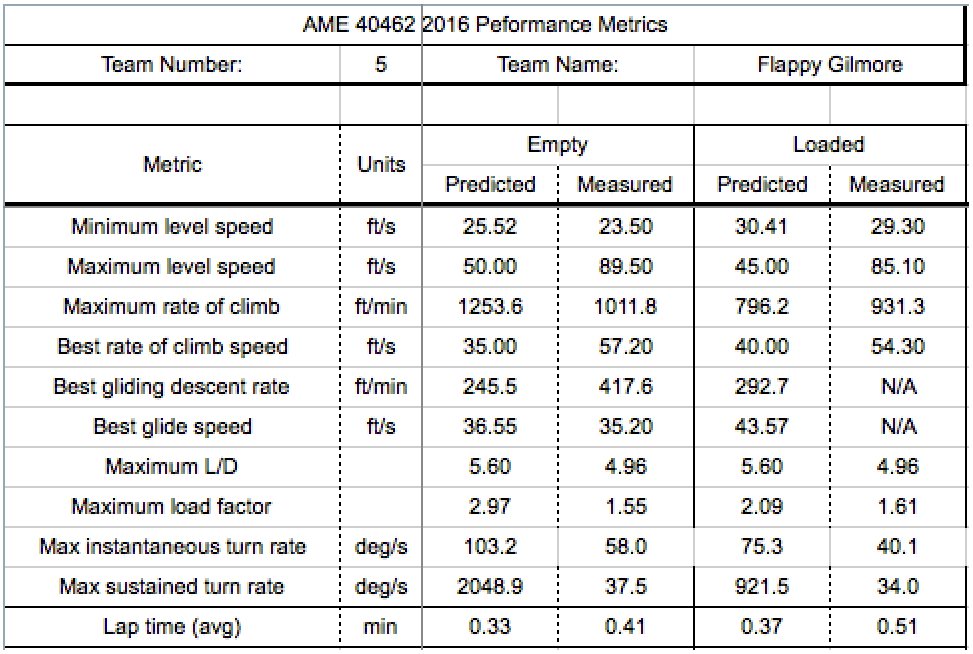


Figure 28. Plot of the flight path versus time

Table 3. Final Flight Performance Metrics



AME 40462 2016 Peformance Metrics					
Team Number:	5	Team Name:		Flappy Gilmore	
Metric	Units	Empty		Loaded	
		Predicted	Measured	Predicted	Measured
Minimum level speed	ft/s	25.52	23.50	30.41	29.30
Maximum level speed	ft/s	50.00	89.50	45.00	85.10
Maximum rate of climb	ft/min	1253.6	1011.8	796.2	931.3
Best rate of climb speed	ft/s	35.00	57.20	40.00	54.30
Best gliding descent rate	ft/min	245.5	417.6	292.7	N/A
Best glide speed	ft/s	36.55	35.20	43.57	N/A
Maximum L/D		5.60	4.96	5.60	4.96
Maximum load factor		2.97	1.55	2.09	1.61
Max instantaneous turn rate	deg/s	103.2	58.0	75.3	40.1
Max sustained turn rate	deg/s	2048.9	37.5	921.5	34.0
Lap time (avg)	min	0.33	0.41	0.37	0.51

The final performance parameters for the aircraft can be seen in the Table 3 above. These metrics represent the best achieved performance of Flappy Gilmore across its three successful flights. For minimum and maximum speeds, the actual performance was better than predicted. These speeds were taken from the pitot tube data, which measures air speed. The actual minimum level speed values were very close to the predicted values. The maximum level speed values were much faster than predicted. Part of this discrepancy can be explained by the very favorable flying conditions on that day which allowed the pilot to feel comfortable flying the plane as fast as possible. The rest of the discrepancy can be explained by the motor performing better than originally estimated and by the plane’s sleek, low drag, design. The maximum empty speed was about 5 ft/s faster than the maximum loaded speed, as predicted.

The aircraft was never specifically tested for maximum rate of climb, so the loaded value for this metric was calculated during takeoff and the unloaded value was found at the highest climb rate achieved by the empty plane during flight. The maximum climb rate for the loaded plane was found to be higher than originally predicted. The maximum climb rate for the empty plane was found to be lower than originally predicted; however, since there was not a time during empty flight when high climb rate was necessary, this value is probably lower than what the plane is actually capable of. The best rate of climb speeds were determined by finding the highest speed achieved during those maximum rate of climb periods. Like the other speed values for the plane, these values ended up being faster than predicted. Since the plane was never actually tested for gliding descent rate, the best gliding descent rate was found by calculating the descent rate for landing and the best glide speed was the average speed during landing. Since the plane never landed fully loaded, there are only values for it while empty. The maximum lift/drag ratio was then calculated from the glide rate and glide speed by taking the reciprocal of the tangent of the glide angle as described by the NASA Glenn Research Center's website. This resulted in a maximum lift/drag ratio slightly smaller than predicted, but still on an appropriate scale for this type of aircraft. The maximum load factors were found by plotting the G-force data in the Y direction against time and can be seen in the figure below. These values were lower than predicted but that makes sense because the plane was never performing any maneuvers that would push it to its maximum load factor. However, the assumption that the maximum load factor would occur at takeoff was proven to be correct, as shown in figure 29.

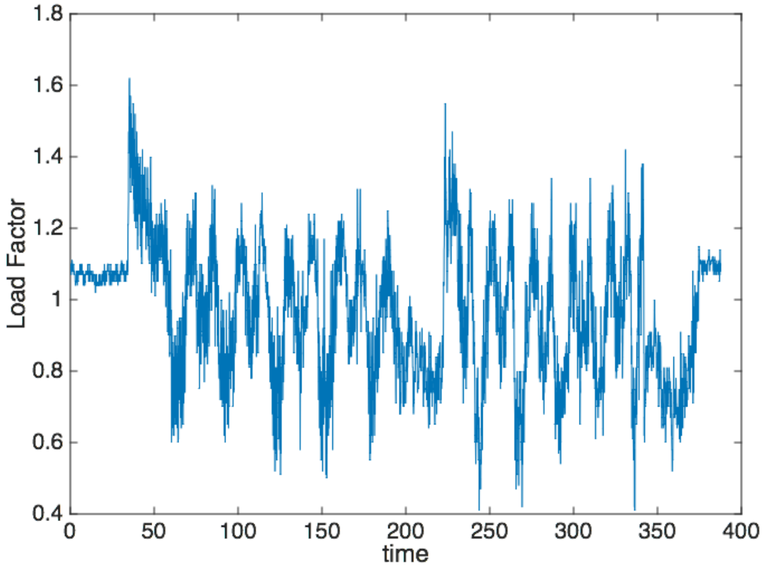


Figure 29. Load Factor

The maximum instantaneous turn rate for the loaded and empty configurations were found by adjusting the original instantaneous turn rate equation for the new wing loading value and the new measured maximum level speed. The measured values were lower than the predicted values since the maximum speed was higher than predicted. The maximum sustained turn rate was found by measuring the time it took the plane to complete a full 180 degree turn at the end of the flight course and from there calculating the turn rate. The measured sustained turn rates were slower than predicted; however, the predicted turn rates were very large and the measured values seem more appropriate. The measured sustained turn rate values were also slightly smaller than the measured instantaneous turn rate values which makes sense. Despite the plane demonstrating a much higher speed than predicted, the laps times were actually longer than predicted, most likely due to the much slower turn rates. The values in the table represent the best average lap times for loaded and empty flight, which were 30.4 seconds and 24.8 seconds, respectively. The fastest loaded lap and fastest empty lap were 26 seconds and 22 seconds, respectively.

Discussion of Results

Ultimately the plane flew very well. It performed better than expected in many ways, most notably was its speed. The plane's final score of 20 was good but not great relative to the other scores. However, a couple lucky bounces of the golf balls one way or the other could have resulted in a significant score increase.

In hindsight, all the planes regardless of their size were able to fly at similar speeds, with only one plane being able to fly a sixth lap. Thus, in order to achieve a higher score in the future, the plane should be designed to carry a larger payload so that there is a better chance that more balls will land close together.

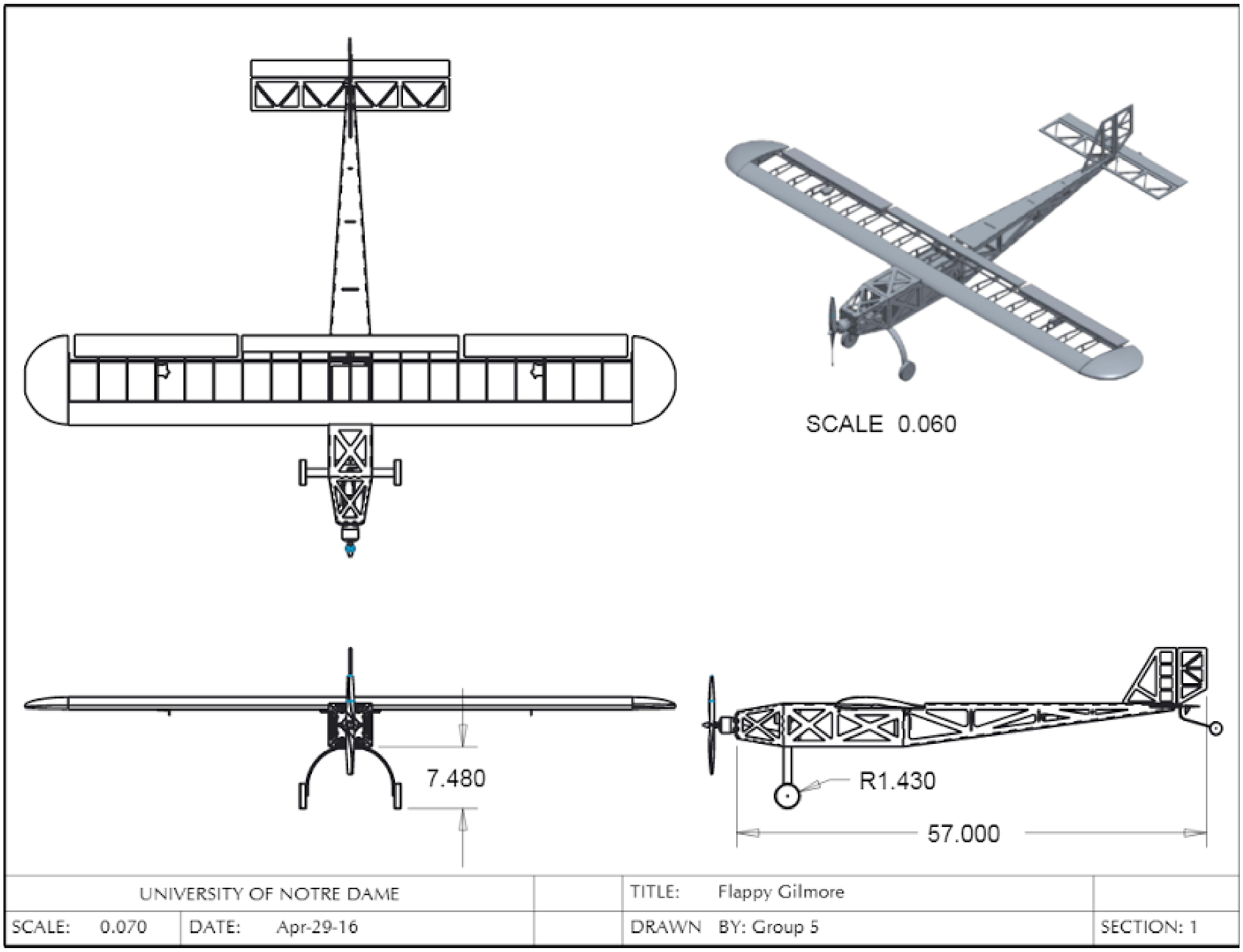
As far as modifications specific to Flappy Gilmore go, the only aspects that proved problematic were the dropping mechanism and a couple landings. The dropping mechanism initially worked exactly as planned, but its construction was a bit fragile so unfortunately the wear and tear of multiple uses combined with the rough flying conditions on day 3 resulted in a failure. The source of the builds fragility stemmed from its being secured by very small screws into balsa wood. The screws eventually pulled out of the balsa wood because they were not long enough to be secured with a backing. Using longer screws with a backing would have significantly improve the durability of the hatch door. Additionally, the balsa wood had been used in order to save weight; however, the strength to weight increase by using lite ply in at least some parts of the build would have certainly proved beneficial.

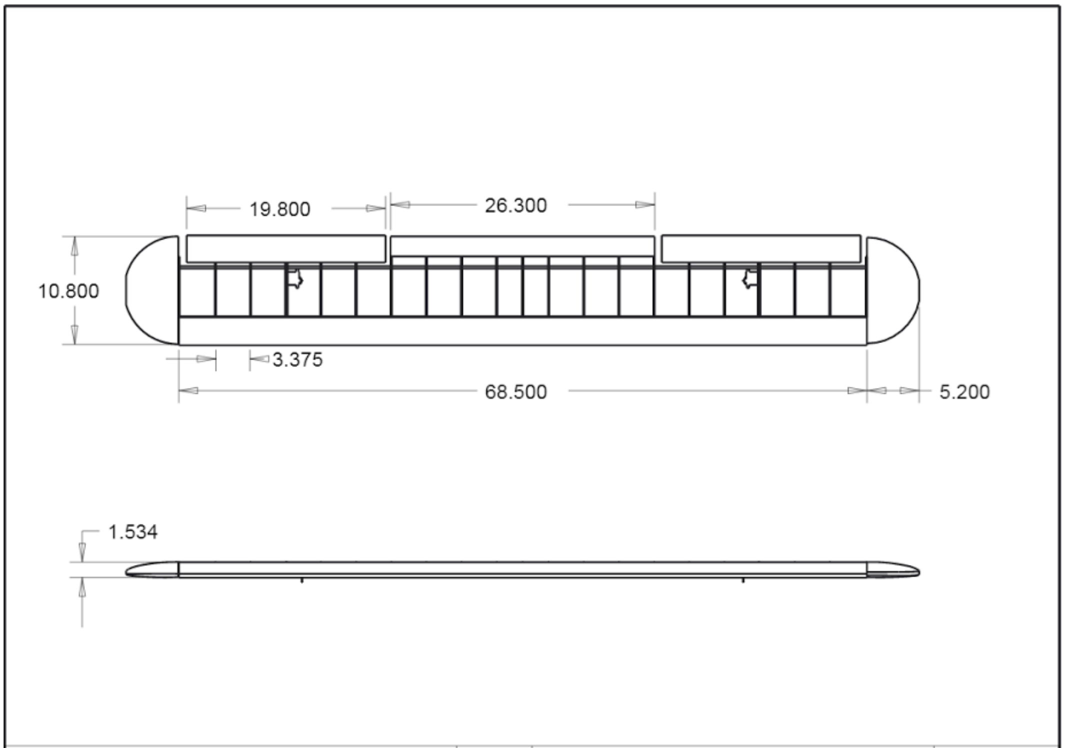
With regard to the two failed landings that Flappy suffered, both were the result of trying to land in fairly heavy winds and not coming in completely straight upon touch down. The three landings in which the plane was coming in for a straight landing on the runway were successful. Thus, the best way to prevent landing failure from happening moving forward would be to build up the landing gear mount even more than the double thick ply that it was or to only fly in conditions where the odds of a smooth and soft landing are relatively high. Fortunately, the design of the landing gear mount allowed for very easy repairs.

When taking off and in the air, the plane performed exceptionally well. It was able to take off very quickly and the non-steerable rear landing wheel did not pose any problems. The pilots seemed very happy with the plane's control and its stability. Finally, Flappy Gilmore's golf-course-green monokote combined with its golf-ball-white wing tips combined for a visually stunning appearance.

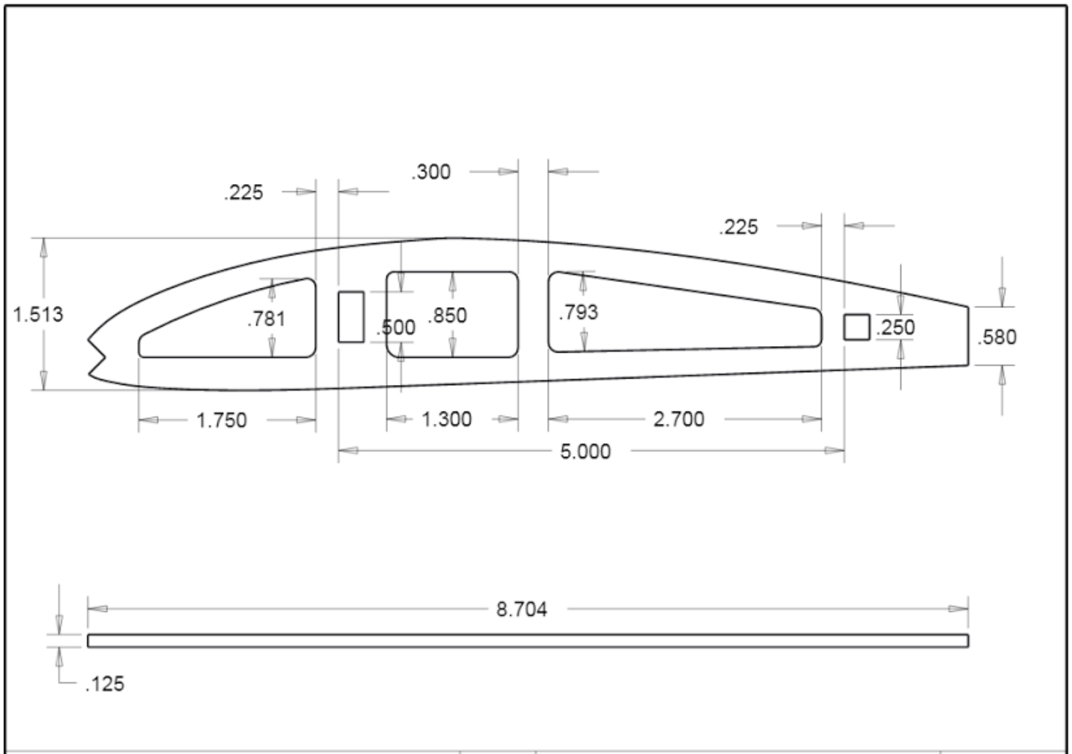
Appendix - Detailed Design CAD

*All dimensions are shown in inches

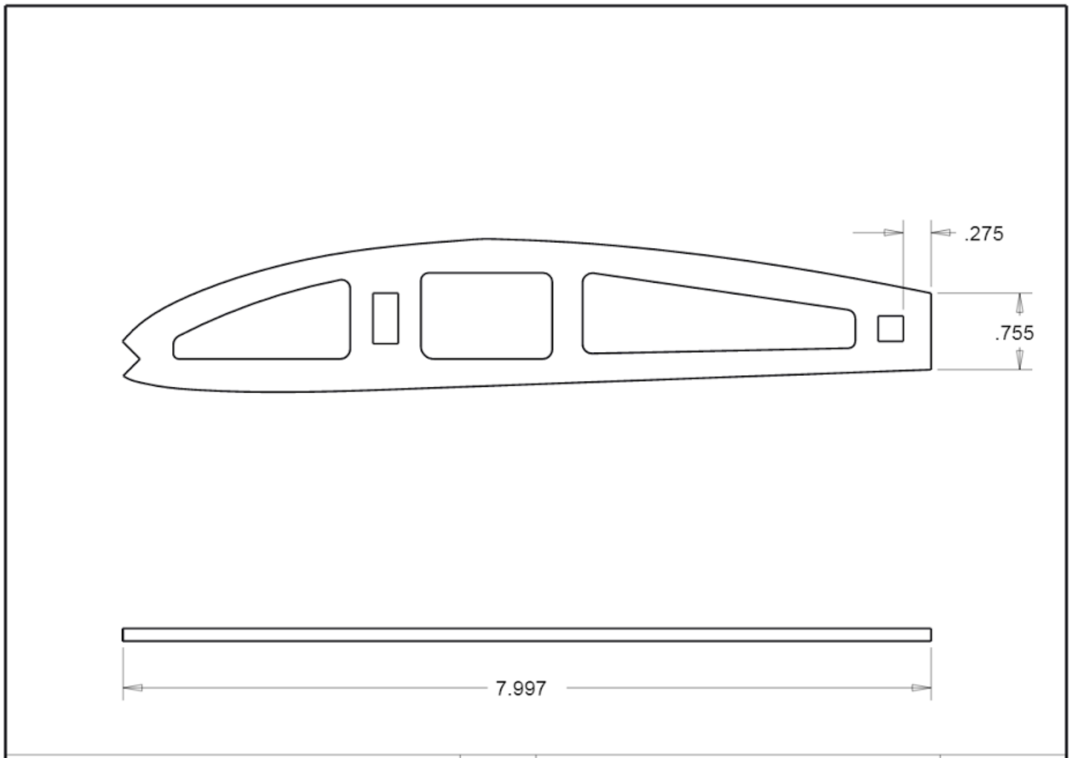




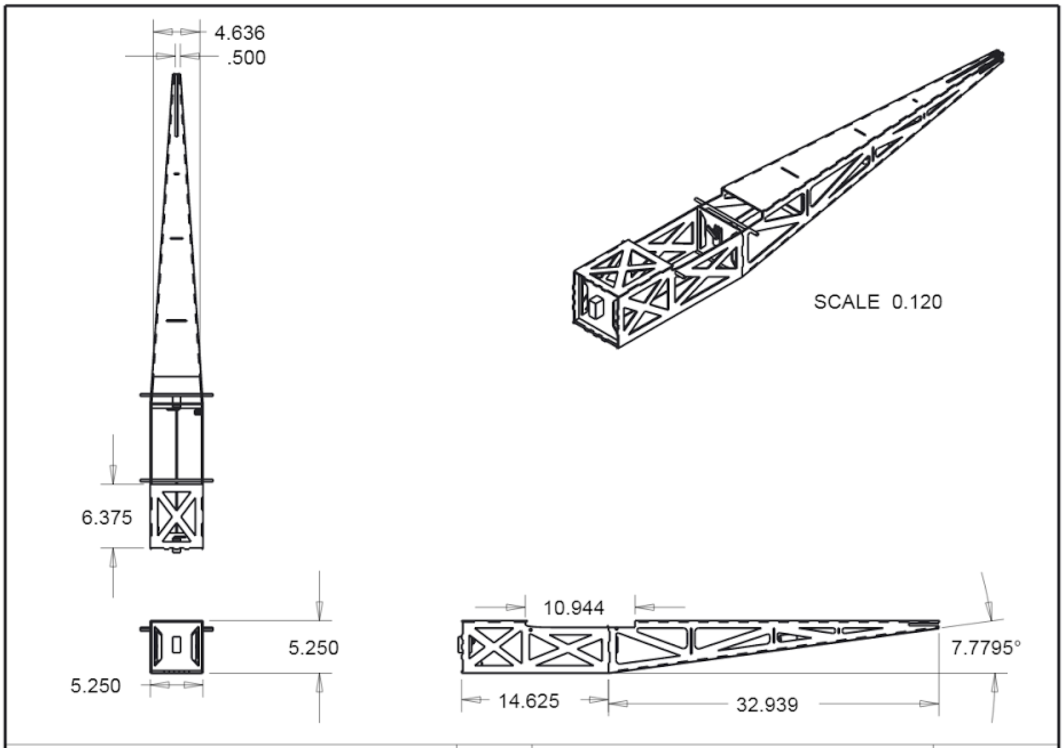
UNIVERSITY OF NOTRE DAME
TITLE: WING_RIBS_DRAW
SCALE: 0.100 DATE: Apr-28-16
DRAWN BY: Group 5
SECTION: 1



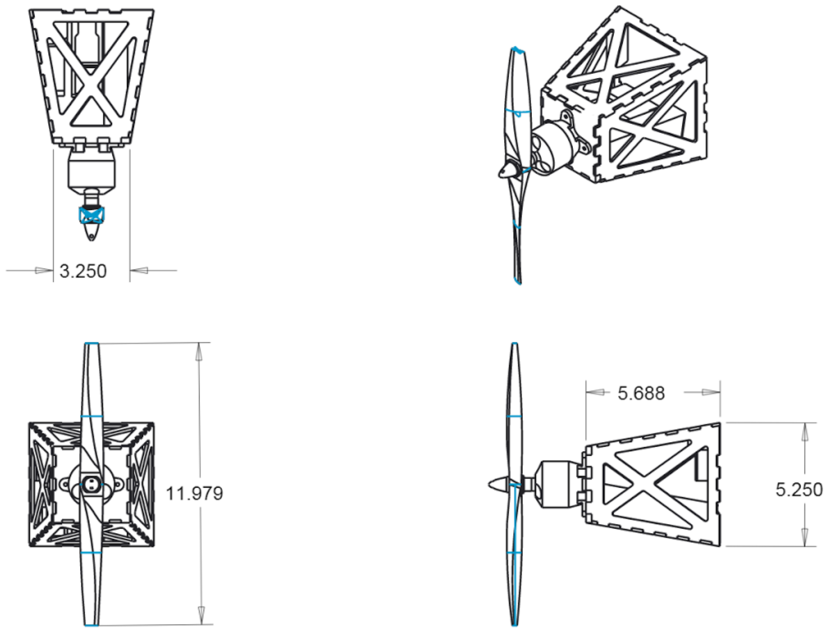
UNIVERSITY OF NOTRE DAME
TITLE: Wing Rib
SCALE: 0.333 DATE: Apr-29-16
DRAWN BY: Group 5
SECTION: 1



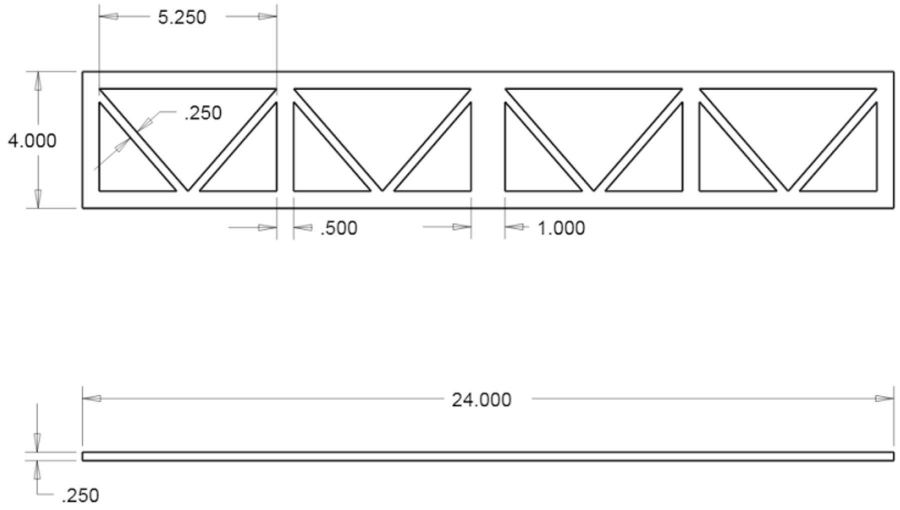
UNIVERSITY OF NOTRE DAME			TITLE: Wing Rib (Aileron)		
SCALE: 0.333	DATE: Apr-29-16		DRAWN BY: Group 5		SECTION: 1



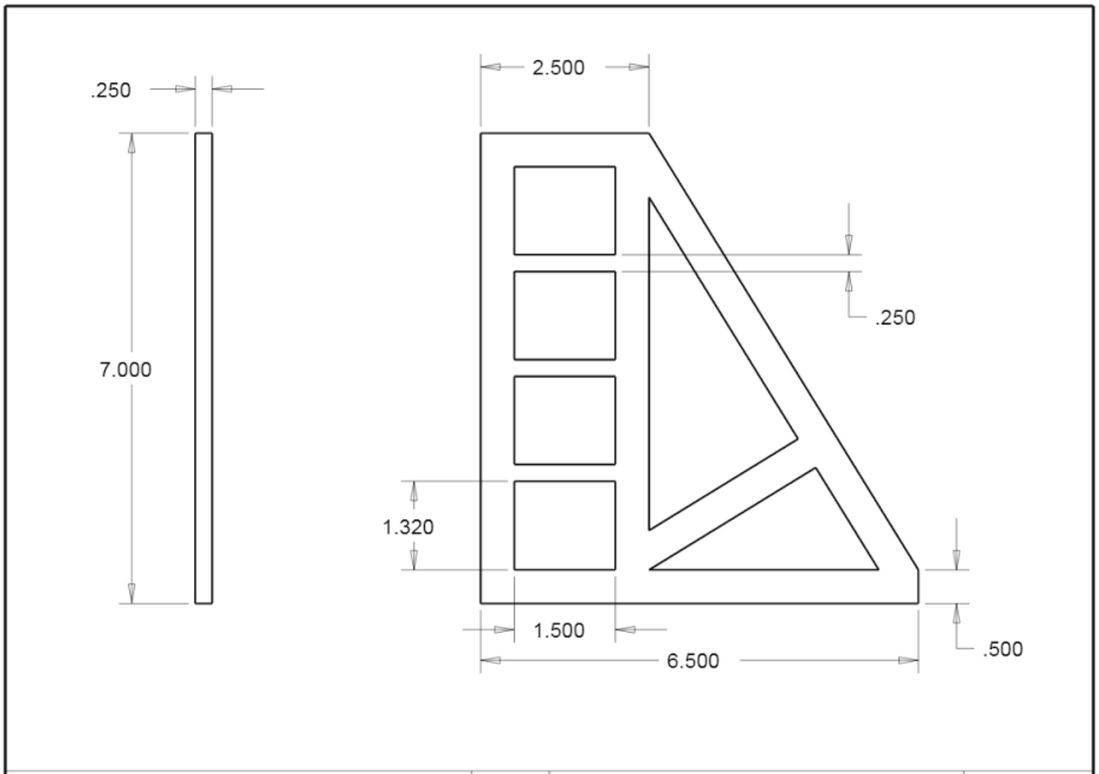
UNIVERSITY OF NOTRE DAME			TITLE: FUSELAGE_ASSEM_DRAWING		
SCALE: 0.100	DATE: Apr-28-16		DRAWN BY: Group 5		SECTION: 1



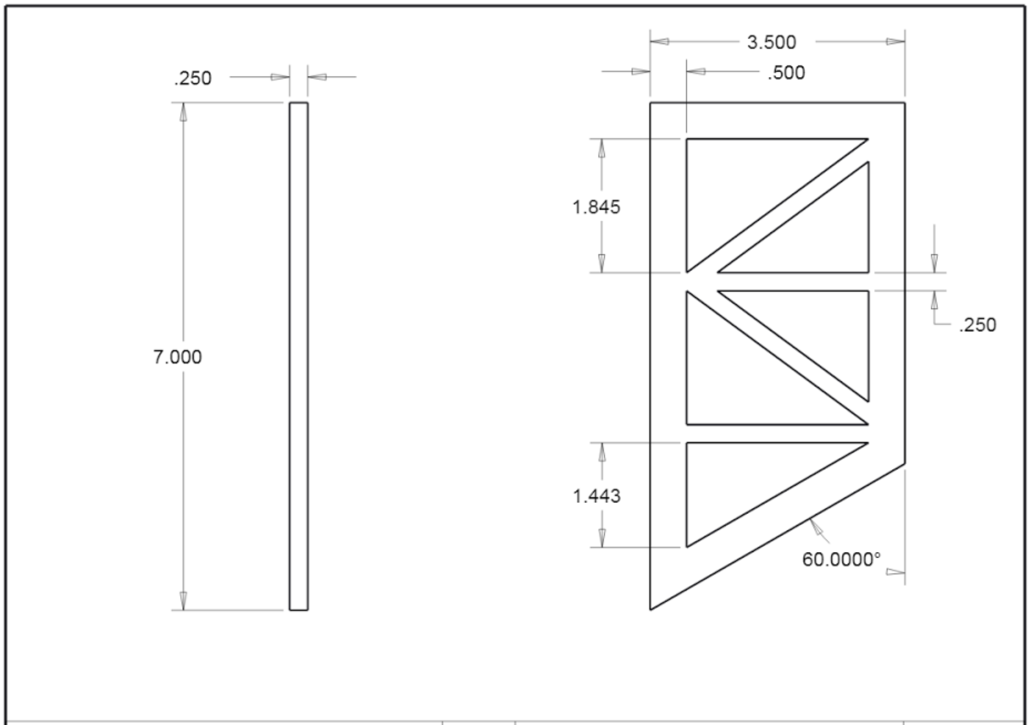
UNIVERSITY OF NOTRE DAME			TITLE: NOSE_ASSEMB_DRAW	
SCALE: 0.250	DATE: Apr-28-16		DRAWN BY: Group 5	SECTION: 1



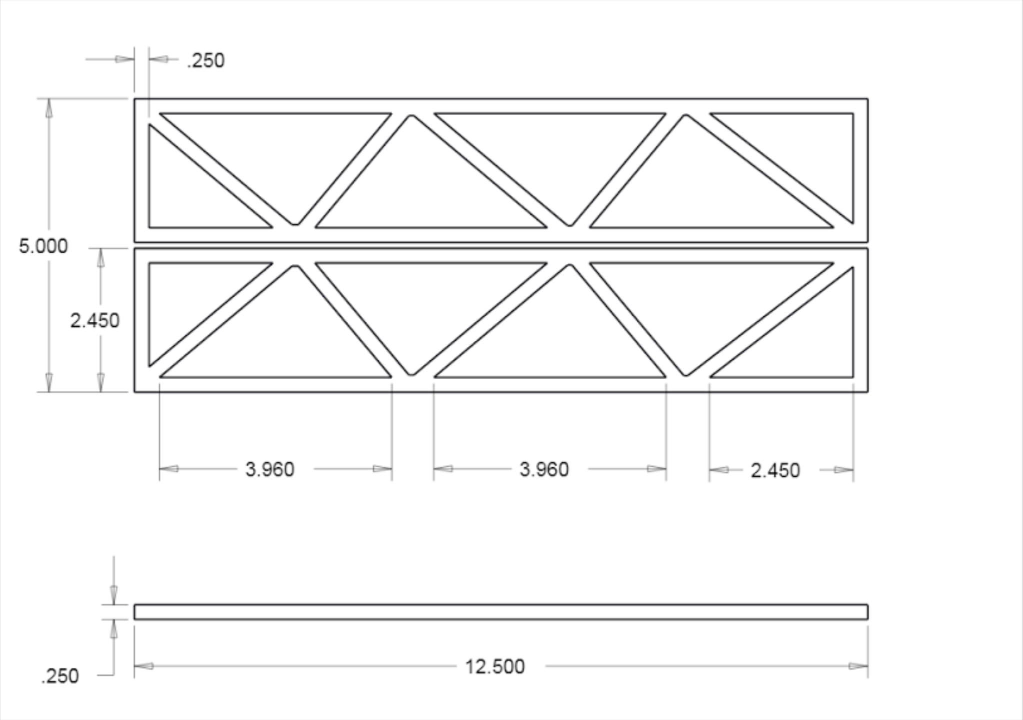
UNIVERSITY OF NOTRE DAME			TITLE: HTAIL_DRAW	
SCALE: 0.350	DATE: Apr-29-16		DRAWN BY: CHRIS BROWNSCHIDLE	SECTION: 1



UNIVERSITY OF NOTRE DAME		TITLE: Vertical tail	
SCALE: 0.65	DATE: Apr-29-16	DRAWN BY: Group 5	SECTION: 1



UNIVERSITY OF NOTRE DAME		TITLE: Rudder	
SCALE: 0.75	DATE: Apr-29-16	DRAWN BY: Group 5	SECTION: 1



UNIVERSITY OF NOTRE DAME		TITLE: Hatch Door	
SCALE: 0.600	DATE: Apr-29-16	DRAWN BY: Group 5	SECTION: 1