CORNELL FORMULA SAE

Racecar Aerodynamics

Applications in Formula SAE

Amanda Costello & Masaki David Endo

5/22/2014

I. Keywords

Aerodynamic, aerodynamics, wing, wings, mounting, airfoil, airfoils, delta, deltas, attached, flow, flow visualization, coast down, coastdown, tuft, tufts, tufting, taco molds, foam shaping, hot wire, downforce, underbody, undertray, tunnels, aero.

II. Abstract

This project explores the possibilities and benefits of adding an aerodynamic system to Cornell's formula SAE vehicle by designing and implementing a prototype system. The constructed aerodynamic system significantly increased the drivability of the racecar without adding significant weight or being difficult to mount and dismount as needed. Cornell was one of the last consistently successful teams in FSAE to adopt aerodynamics, but faster cars and faster tracks at competition have greatly increased its applicability to this competition. The motivation behind this project was to maintain our competitiveness in this year's competition.

The design began with a vehicle stability analysis using a simple two wheel model. The analysis yielded the minimum aerodynamic forces necessary to stabilize the vehicle as well as a baseline for the desired aerodynamic balance. Next, the lap simulation program was developed and used to determine target values for lift and drag of the front and rear wings. This step considered the penalty in fuel economy due to drag as well as the performance increases and stability attained. The end result of these analyses was a good starting estimate for the desired performance of the aerodynamics system.

The design of the wing geometry aimed to attain the target lift and drag values determined in the previous analyses. Documented airfoil data and SAE papers were used for choosing such parameters as the aspect ratio, cross-sectional shape, number of elements, etc. The design also considered flow disruptions caused by other parts of the vehicle such as the tires and driver helmet.

Once the geometry of the wings was decided upon, the structure of the wings was designed to withstand the expected loads acting on the system. Expected aerodynamic loads were determined from the designed lift and drag values and the top speed attained on the track. Other loads such as impacts from cones were also taken into consideration. In order to create the most lightweight structure that would meet the strength requirements, composite materials were used. The structural aspects of the design also involved constructing a lightweight method for attaching the wings to the car.

The proposed system was manufactured and implemented on this year's car. Straight line tests were performed to measure the actual lift and drag of the system and to verify that the performance targets were met accordingly. Flow visualization tests involving tufts were performed to inspect the motion of the air around the wings and to see whether the flow was attached.

III. Background

Aerodynamic devices have been used to increase the performance of racecars for several decades. Devices such as wings and underbody tunnels manipulate the air flow around the vehicle to produce lift and drag forces. They are most commonly used to generate downforce, or downwards thrust to push the vehicle towards the ground and increase grip. Since these aerodynamic forces are proportional to the square of the air velocity, the greatest benefits of the devices are seen when the vehicle is moving at high speeds. The downsides of aerodynamic devices include the added weight and complexity of the system as well as increased drag. However, the benefits of a well-designed aerodynamics package commonly outweigh the downsides for high speed applications.

Many of the top FSAE teams have moved toward incorporating aerodynamics packages into their cars due to the recent rule changes for wings and increased track speeds at competition. These trends in the top cars have spurred the need for research and development of aerodynamic devices in order for Cornell to stay competitive. Therefore, this project aimed to design, manufacture, and test an aerodynamics package for Cornell's 2014 entry.

There are numerous reports on aerodynamics for the Cornell FSAE car, but few were related to actually producing an aero package for the car. The most recent previous to this year is Obinna Ehirim's report in 2010. Though we used '05's wings for our baseline testing, there was no report from that year, possible due to the fact that they did not run wings at competition. Joseph Katz has many valuable works that were used to prepare for this project. All works referenced are listed in the Bibliography.

The following is a short summary of the undertray testing done in 2011.
In this technical report, two undertray/diffuser sections (curved and 8º diffuser sections) prototypes were built and tested on the track with Cornell University (FSAE) ARG10 race car. The test results indicated that the undertray with a curved diffuser section produced a slightly lower down force than its 8º counterpart. Computational fluid Dynamics was done on an undertray with a 14º diffuser section but this has not been completed.

The following is a short summary of wing testing done in 2001.
In the Cornell FSAE completion year of 2000/2001, a central wing design was built and tested. The test prototype was designed with the idea of mounting the wing to the A-arm attachment points of the race car. The wing prototype had a span of 48 inches and 60 inches in length. The wing was designed to produce maximum down force with minimum drag. The flap of the wing had an angle of attack that can be varied from 5° - 20° and the wing weighed about 23 lbs. The test results conducted at speeds of 40-55mph indicated that the central wing distributed a down force of 11% front and 89% rear with a lift coefficient of 1.5 and subsequent variation in the angle of attack produced a down force distribution of 23% front and 77% with a lift coefficient of 2.3.

IV. Body

Fall Testing

’05 Wings

To understand the magnitude of forces that could be expected from adding an aerodynamics package to ARG ’14, the wings made in ’05 were retrofitted to be mounted on ARG ’13. We performed coastdown testing at an airstrip near Ovid, with and without wings in both directions due to the fact the airstrip was lower in the middle than on the edges. We collected load data using load cells mounted to the suspension. We also used a GoPro camera to film tufts we had attached to the underside of the wings. This allowed us to see whether or not the flow was attached. The results showed approximately 175 lbs of downforce at 60mph. Due to the fact that the wings were not optimized for that car, the results were promising and we decided to move forward with an aero package that would be ready for MIS in May 2014. See Figure 21: Coastdown Testing w '05 Front and Rear Wing (white: no wings, color: ’05 wings).

Figure 1: '05 Wing Baseline Testing at Palm Rd.

Drag Estimates

We used the same data collected at the airstrip to estimate the drag produced by the wings. It was found to be 22 lbs at ~60 mph. See Figure 22: Drag Estimates (white: no wings, color: ’05 wings).

Delta Wing

The second round of testing performed during the fall semester was a front delta wing, imitating the design of the Nissan Le Mans Car. Unfortunately, due to rules limitations and the geometry of the car itself, very little downforce was produced. The same load cells and flow visualization was used as in the previous testing. It was decided not to pursue this concept further. See Figure 23: Coastdown Testing w/ Front Delta Wing (green: no wing, white: delta, blue: ’05 wing).

Figure 2: Nissan Delta Wing Le Mans Car

Figure 3: Delta Wing Mock-Up Testing at Palm Rd.

Stability Analysis

In order to determine the minimum aerodynamic loads required to stabilize the car, a two wheel car model was considered. During steady-state cornering for an oversteer vehicle (which is the case for ARG13), there exists a critical speed above which the vehicle will be unstable. Gillespie defines this critical speed as:

$$V_{crit} = \sqrt{-L * g/K}$$

Where V_{crit} is the critical speed in ft/s, L is the wheelbase in feet, g is the acceleration due to gravity in ft/s^2, and K is the understeer gradient which is defined as:

$$K = \frac{w_f}{C_{\alpha f}} - \frac{w_r}{C_{\alpha r}}$$

Where w_f and w_r are the load on the front and rear axles respectively and $C_{\alpha f}$ and $C_{\alpha r}$ are the cornering stiffness of the front and rear tires respectively. The units of load are pounds and the units of cornering stiffness are lb/rad.

From the tire data of the Hoosier R25B tires, the front and rear cornering stiffnesses were found to be 5730 lb/rad and 6303 lb/rad. See figure 9 in the appendix for the tire curves. Using the above two expressions and the tire data, the critical speed of the current car without wings is found to be 120 ft/s or 81.8 mph. These expressions can also be used to determine the amount of aerodynamic load required to make the car neutral steer, or stable. The calculation shows that about 50 pounds of downforce on the rear axle is required to stabilize the car.

The desired balance of the car is to have slight oversteer in low-speed corners and slight understeer or neutral steer in high-speed corners. Take the threshold between low and high speed to be 40 mph. This means that the minimum aerodynamic load required to balance the car is a device that generates 50 lb of normal load on the rear axle at 40 mph. This can be achieved with a moderately sized rear wing with a modest lift coefficient (15 inch chord and 53 inch span with a C_L of 2).

Lift & Drag Targets

From the stability analysis, the lower bound for the aerodynamics system was found. To find the upper bound, there are several factors that come into play including, maximum speed limitations due to drag, fuel efficiency penalties due to drag, increase in vehicle weight and CG height, and size constraints due to the rules. Although the effects of drag forces are not negligible, they are not the limiting factor in determining the maximum size of the aero-package based on results from the lap simulation program. The engine provides enough torque to prevent the top speed of the car to be severely limited by aerodynamic drag, assuming that the drag coefficient is roughly that of a typical high lift wing. Also, the points gained from the increase in performance outweigh the points lost due to decreased fuel efficiency. See the lapsim technical report for more details.

It is somewhat more difficult to consider the penalty due to the increase in vehicle weight since the weight plays a significant role in the design event as well as the dynamic events. If the assumption is made that the design score will not be negatively affected if the increase in weight is well justified by significant increases in performance, then the limiting factor becomes the size constraints imposed by the rules, specifically of the front wing. According to the rules, no aerodynamic devices can be placed more than 30 inches forward of the front of the tires. With the nose of the car taking up a sizeable portion of the front wing space, the maximum area of the front wing is rather limited.

Using these spatial constraints, the upper bound of the system was found to be a front wing with the maximum planform area allowed by the rules. Doing the force balance on the car and assuming that the front and rear wings will have the same lift and drag coefficients, it was found that the area of the rear wing must be about 1.25 times that of the front wing to meet the stability requirements.

Airfoil Design

A very basic approach was taken to determine the wing geometry that would meet the lift and drag targets. The cross sectional shape of the wing was taken from SAE paper 951976 by Joseph Katz. The paper presents several wing designs for race car applications. The chosen shape was designed for low speed and high lift applications, which is suitable for the FSAE car. The airfoil coordinates were digitized and modeled in 3D CAD software. The figures below show the cross sectional shapes of the main element and flaps.

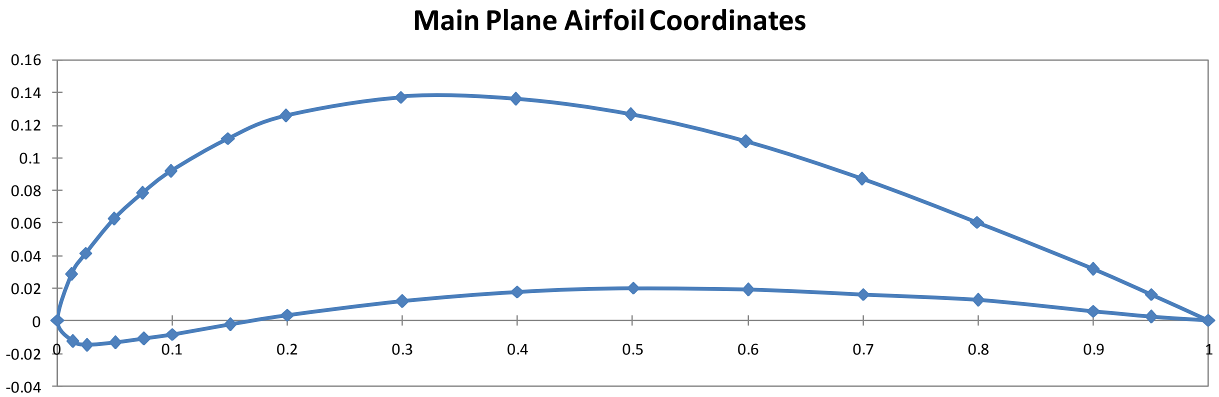


Figure 4a: Airfoil Coordinates of the Main Element

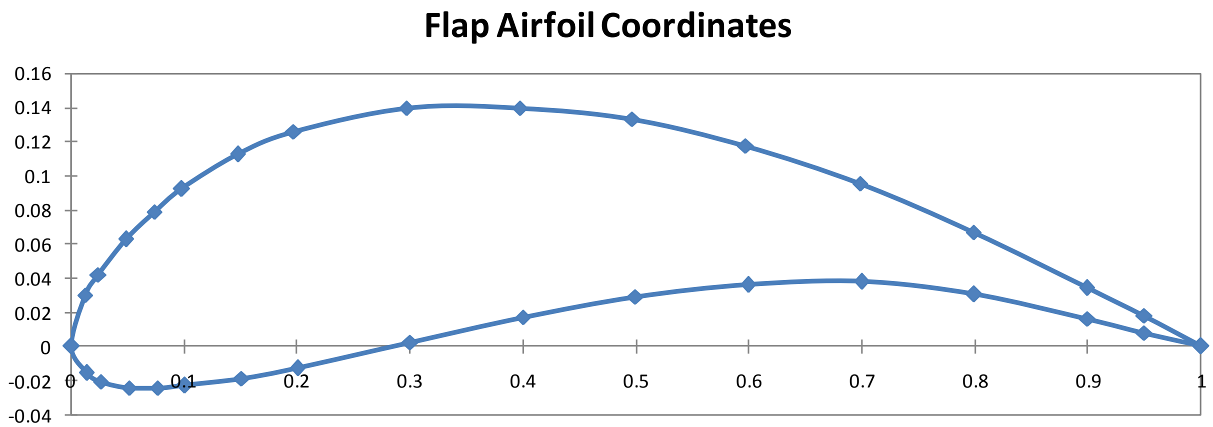


Figure 4b: Airfoil Coordinates of the Flaps

The gap sizes and the relative angles between the elements were also taken from the SAE paper. These parameters are adjustable on the prototype via separate mounting holes in the endplates. The endplates were simply flat plates that attach the flaps to the main element. The figures below show the final wing geometry.

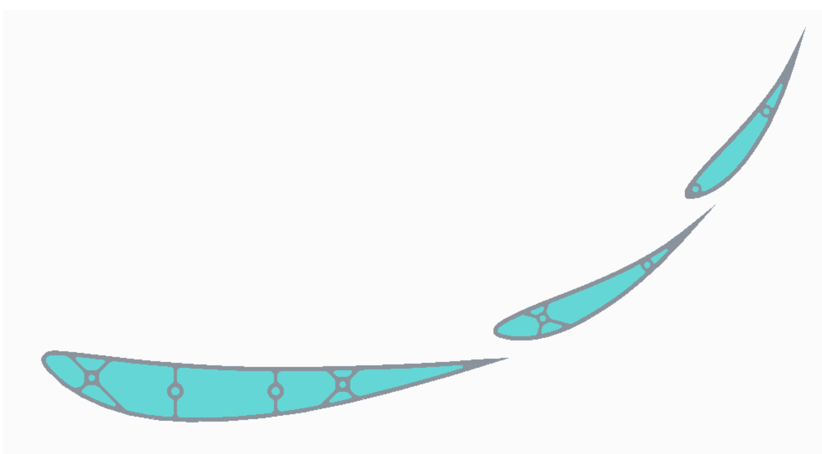


Figure 5a: Final Airfoil Cross Section

Figure 5b: Final Rear Wing with Mounts

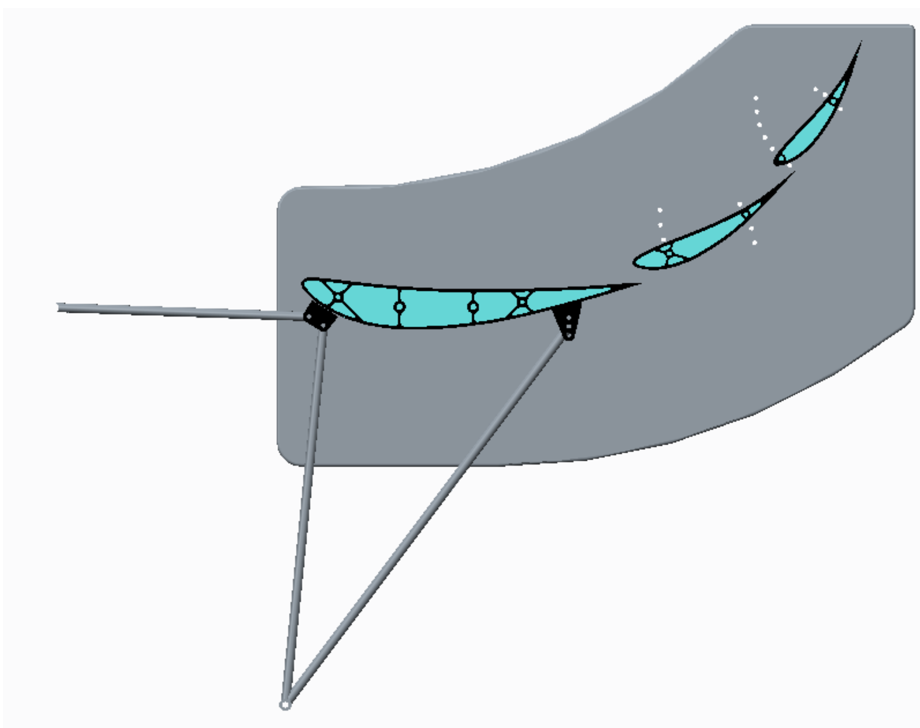


Figure 5c: Rear Wing Cross Section

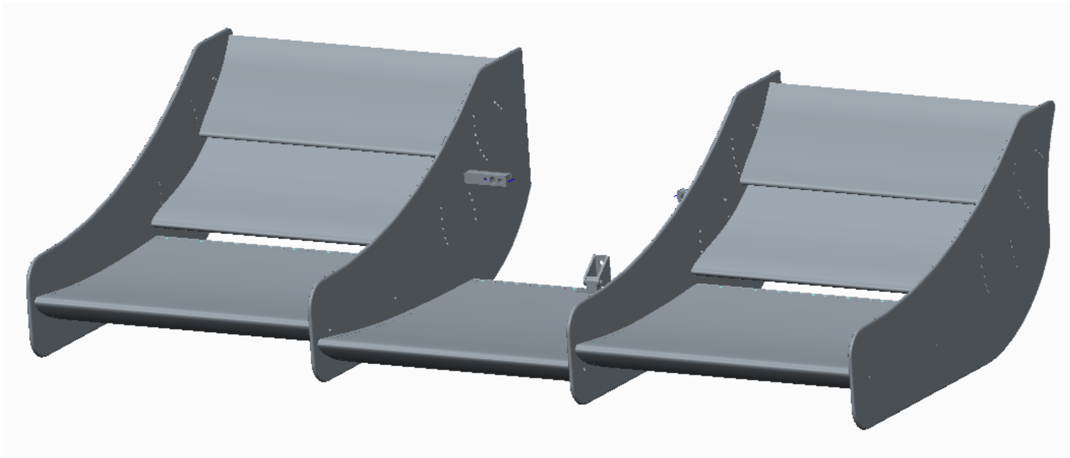


Figure 5d: Final Front Wing with Mounts

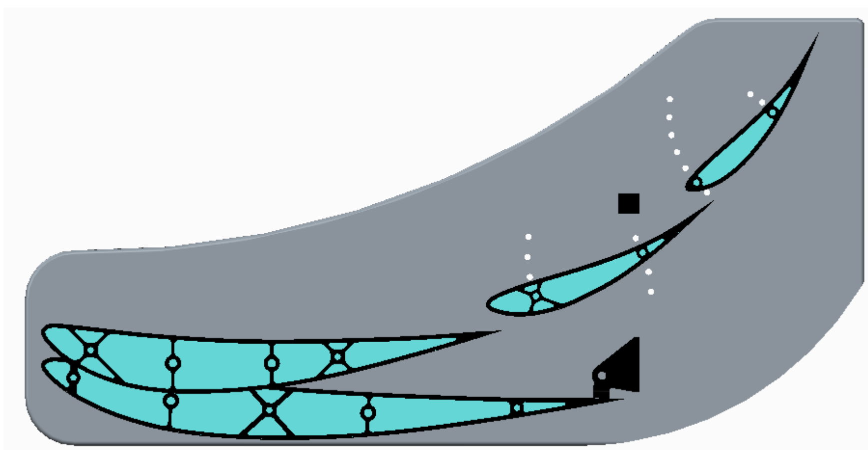


Figure 5e: Front Wing Cross Section

Manufacturing

Another crucial decision for the aero package is the manufacturing process for the wings. Weight is of high concern due to the fact that every pound added takes away from the overall benefit of adding wings to the car. In addition the wings, especially the front wing, must be able to structurally withstand hitting cones on the track. We began the decision by considering the many ways wings are manufactured both for racing and for lightweight kit planes. See Figure 24: Wing Manufacturing Options.

It was decided that the most feasible manufacturing methods were carbon over foam and carbon fiber laid up in a mold. The molds pose a considerably larger man hour demand, but the surface finish would be better than the carbon laid up over foam. In the end it was decided that since this was the first year and there was a high chance we will need to make multiple different air foils, foam was the most sensible option.

Figure 6: Foam Wing before Composite Wrapping

In order to ensure durability of the front wing against repetitive impact, we reinforced the front section with Kevlar. We also layed up the wings such that there is more material in the center so that the wing is stiffer at the mount point. Aluminum inserts were placed between the foam sections of the wings to serve as mounting points.

Step-By-Step Manufacturing Process

1. **Foam Cutting**

   To cut the blue insulation foam in the shape of the airfoils, the hot-wire technique outlined below was used.

   a. **Wire Guides**

      The wire must be guided while it is cutting the foam to obtain the desired shape. The guides were cut from particle board on the CNC router in the Emerson machine shop. This material was probably not the best choice since it had a tendency of cracking off at the thin trailing edge. For the future, it is recommended to use a more homogenous material such as hard plastic and use a waterjet to cut the guides. Two guides are required for each airfoil, one on each side of the foam.

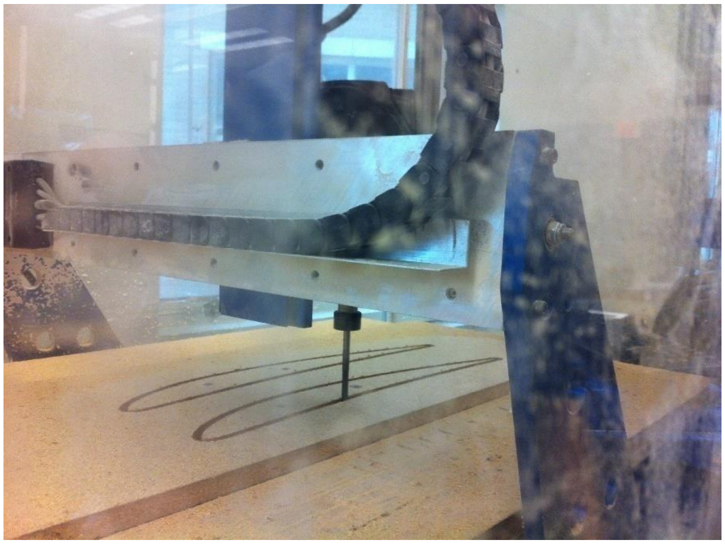


Figure 7: CNC Routing Wing Templates

b. Hot Wire

The hot wire cutter was constructed following the instructions found at http://www.instructables.com/id/Hot-wire-foam-cutter/. A copy of these instructions can be found in the appendix. A few modifications were made to improve the provided design:

i. The guitar string was replaced with 30 gauge nichrome wire purchased from amazon.com. (http://www.amazon.com/gp/product/B00AWS4D8A/ref=oh_details_o02_s00_i00?ie=UTF8&psc=1)
ii. A PVC tube was added to stiffen the main beam of the cutter so the wire could be pulled tighter.
iii. A project box from radio shack was purchased to house the electronics.

Figure 8: Hot Wire Cutting Wing Sections from Insulation Foam

c. Cutting the foam

Before the foam can be cut to the airfoil shape, it must be cut into a block of the correct length and width. Then the guides are attached to the sides with wood screws. The guides must be properly aligned to produce a straight airfoil. The alignment was done by spacing the guide from the bottom of the block using a piece of flat metal and by marking a line spaced from the front.

The airfoil can now be cut. This step is a bit difficult and will most likely require some tuning of the hot wire and a few practice runs. The block of foam is taped to a flat surface that provides enough clearance so that the ends of the hot wire do not hit the table. The tape will keep the foam from moving around while cutting and will keep the loose pieces from coming up after the cut is made. From this year’s experience, the best surface finish was obtained by cutting with a hotter wire (more current) and by moving the wire relatively quickly. It is recommended to make as few cuts as possible and to avoid holding the wire stationary as it will leave gouges in the foam.

Only two cuts were required to make the airfoils, one on the top surface and one on the bottom. It is conceivable that it can be done in one cut but it would be very difficult. The cuts are made by first plunging the wire from the top of the foam to the wooden guide then pulling it across the guide. Once the wire reaches the other end, it is pulled up and out of the foam. The chunk of foam that was removed is put back into place and the whole piece is flipped over to make the second cut which is done in the same way as the first cut. After the airfoil is cut out, the guides are removed and the foam will require some sanding to remove ridges or gouges.

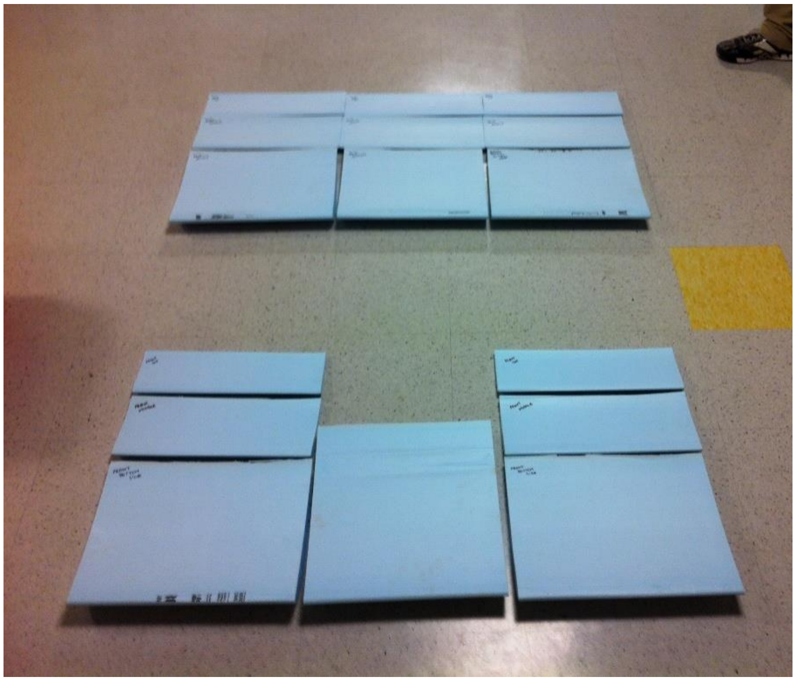


Figure 9: Foam Wing Sections Cut to Size

2. **Inserts**

Aluminum inserts for the ends and mounting points of the wings were cut on a waterjet out-of-house at Dennie's Manufacturing. The holes in the inserts were drilled and tapped after waterjetting. Then the outer surfaces were sanded smooth, cleaned, and soaked in acetone to be prepared for bonding to the foam and carbon fiber.

Figure 10: Aluminum inserts after water-jetting, before post-machining.

3. **Layup**

The following layup technique was developed through trial and error to provide a smooth surface finish and to prevent crushing of the foam.

a. **Pre-layup**

Before the layup, the inserts must be bonded to the ends of the foam airfoil pieces. The inserts are placed by aligning the leading and trailing edges then held in place by bolts with ends sharpened to a point. The inserts are bonded to the foam with 5 minute epoxy. Be sure that no acetone is put on the foam as it will dissolve very quickly. Once the epoxy has cured, some sanding may be required to smooth the interface between the inserts and foam.

Figure 41: Acetone Soaking Inserts in Preparation for Lay-up

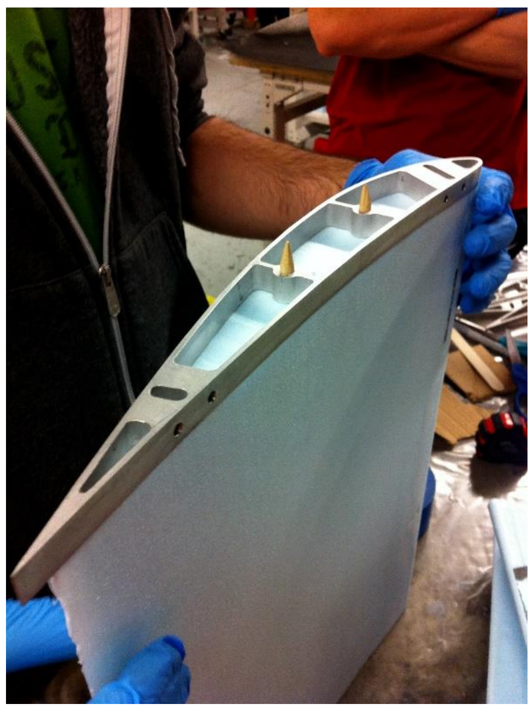


Figure 12: Aligning Wing Section with Inserts in Preparation for Lay-up

b. Layup

The layup was done with US Composites 3K carbon fiber weave and West Systems epoxy system. Each piece of carbon fiber is wet out with mixed epoxy and hardener before it is put on the foam and inserts. Once the carbon is "wet," it must be handled carefully so the weave does not skew or stretch. The best layup method was found to be to start at the leading edge and work toward the trailing edge. With the carbon wetted out on a flat surface, place the leading edge of the foam at the center of the carbon sheet. Carefully lift up one side of the ply and begin to apply it to the foam from the leading edge. Be sure to avoid wrinkling or folding the carbon fiber. Do the same thing on the other side then repeat with the second layer of carbon. An extra layer of Kelvar is laid up on the leading edge of the main elements in the front wing. This step will most likely require one or two practice pieces to get the technique right.

c. **Bagging**

The bagging procedure must be done carefully to prevent ridges in the part and to provide a smooth surface. The release film must be applied to the carbon fiber with no wrinkles or folds. The smoothness of the release film will reflect the smoothness of the part. The breather must also be applied in a similar fashion, without excessive overlap or folds. The part is put into the bag with the leading edge at the very edge of the bag. The bag is smoothed over the part as the vacuum is being pulled. Again, prevent wrinkles or folds. The leading edge should be propped up on a round bar or tube to maintain the airfoil curvature (camber) and the trailing edge should be weighed down with some rectangular bars to make sure that it is flat and straight. See photos below.

Figure 13a: Vacuum Bag with Controlled Leak to Prevent Foam Crushing

Figure 13b: Controlled Leak Set-Up

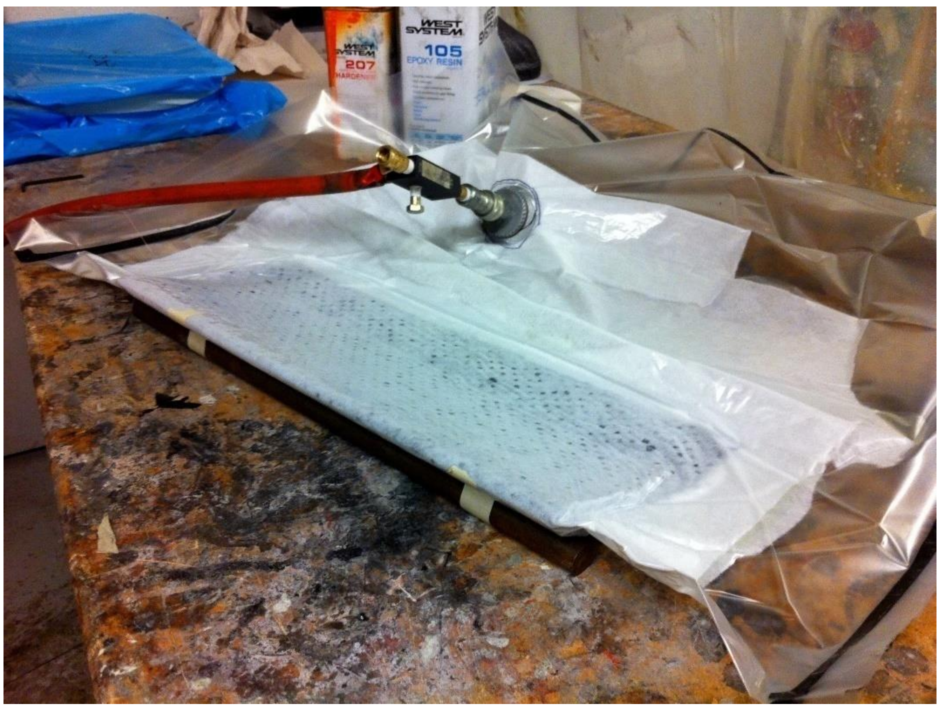


Figure 13c: Wing Curing

Figure 13d: Weighing Down the Trailing Edge to Maintain Flatness

d. **Cure**

The cure for the wing elements is a bit unlike other cures for other carbon fiber parts. The epoxy cures at room temperature so it does not require the oven. The amount of vacuum being pulled on the bag must be limited because the foam will crush if too much pressure is applied to it. Through trial and error, an adequate pressure was found to be about 10 in Hg (~5psi) of vacuum inside the bag. The pressure inside the bag was varied using a valve at the end of the hose. The hose should be attached to the bag sufficiently far away from the part as to apply the pressure fairly evenly about the entire surface.

4. **Trimming / Finish Work**

After the epoxy has cured, there will be excess carbon fiber on the sides and at the trailing edges of the wing elements which needs to be trimmed with a dremel or cut off tool. Any epoxy ridges or bumps should be sanded off of the remaining surfaces. The threaded holes in the inserts may need to have a tap run through them if any epoxy has gotten into them. The rear main element will need 8 holes drilled through the carbon to access the mounting holes in the middle two inserts. Finally, the wing elements should be clear coated and let to dry. We used Rust-Oleum glossy clear spray paint, which is available at Lowes or similar stores.

Figure 14: Wing Elements after Trimming

5. **Endplates**

The endplates were cut out of sandwich panels of carbon fiber (same as the wing elements) and 3/16" thick aluminum honeycomb core. The sandwich panels were made by laying up the carbon fiber and core on a flat sheet of plexi-glass, vacuuming it in a bag, and letting it cure at room temperature. The cured panels were cut to the endplate profile on the waterjet on campus and the holes were drilled out on a drill press. A stainless steel sleeve was bonded into each of the holes using 5 minute epoxy to prevent corrosion and wear. Grommet material was put on the edges of the endplates also to prevent wear.

Figure 15: Water-Jet End Plates

6. **Mounts**

The front wing mounts were machined out of aluminum on manual mills. They were four fairly small and easy to machine parts. These parts bolt directly to three points on the anti-intrusion plate to support the inner endplates and center element. The mounts that attach to the endplates have steel threaded inserts to prevent stripping the aluminum threads.

The rear wing mounts consist of 4 machined steel tabs that were welded to the main roll hoop and roll hoop supports, a set of steel tube linkages, and 4 machined aluminum clevises that were bolted to the main element. Due to the relative inaccuracy of the location of the roll hoop, the linkages were made with threaded rods and turnbuckles such that they would be adjustable. All of the welding was done with the car on the ground to ensure that the wing would be installed level to the ground. For competition, a new set of linkages without turnbuckles will be made to reduce unnecessary weight. See appendix for CAD drawings.

7. **Assembly**

The assembly of the aero package is relatively simple. The endplates are attached to the wing elements with 10-32 pan head bolts that thread into the aluminum inserts. The front wing attaches to the car with a ¼-20 bolt at each of the mounts (which are bolted to the anti-intrusion plate). The rear wing has four aluminum clevises that are held on by two 10-32 bolts each. These clevises attach to the linkages with more 10-32 bolts. The other ends of the linkages attach to the tabs welded on the roll hoop with special quick release pins from Carr Lane. The pins have a clamping feature that allows the length to be varied. These were chosen to allow for quick installation and removal of the rear wing which must be taken on and off quite frequently.

Figure 16: Assembly of the Rear Wing

Spring Testing

Due to the delays in the monocoque manufacturing and several engine issues in the spring, not much testing was done for the aero system. The only testing we were able to do was an afternoon of straight line testing at Palm Road. The test consisted of 40 and 60 mph constant speed runs measuring downforce via load cells at the four pushrods. We measured and observed the effects of varying the angle of attack of the rear wing and changing the flap angles of both wings. We also tufted the undersides of the wings to visualize the flow on those surfaces.

For the downforce measurement, the pushrod load must be converted to the normal load at the tire. This is done by scaling the measured load by a factor of 0.85 for the front and 0.75 for the rear. These values are based on the push rod angle relative to the ground and were verified using the suspension scales. The figure below shows the downforce generated during a 60 mph run. By averaging the data from several runs, the average downforce was found to be about 330 pounds.

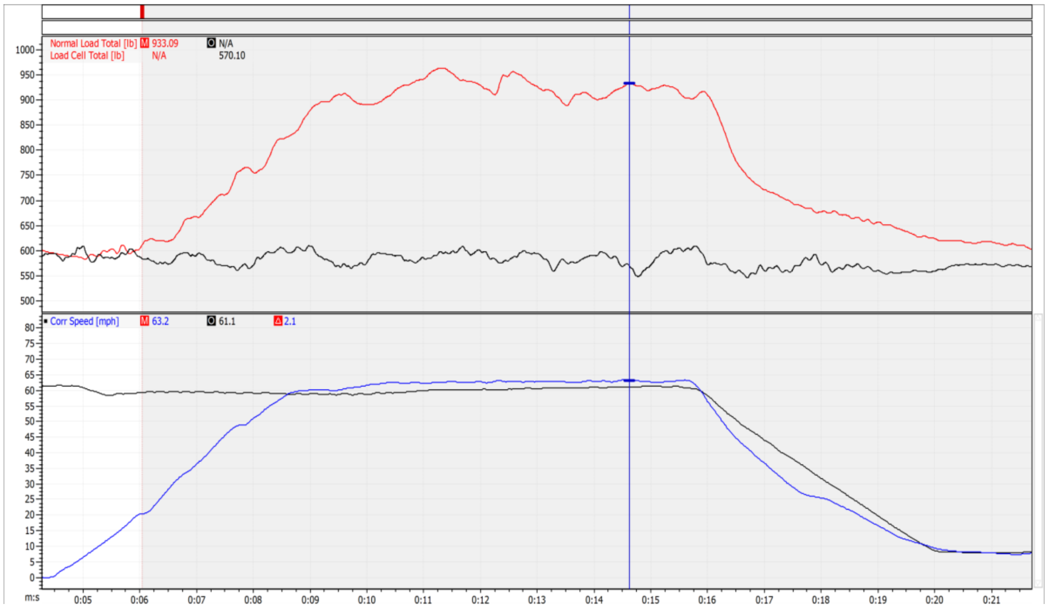


Figure 17: Normal Load Data for 60 mph Run (black: no wings, color: w/ wings)

By looking at the difference between the normal load in the rear and the front axles, the aerodynamic balance can be observed. The figure below shows that the aero balance is rearward, with the center of pressure at about 6 inches behind the center of gravity. This shift in weight distribution is desirable for high speed stability.

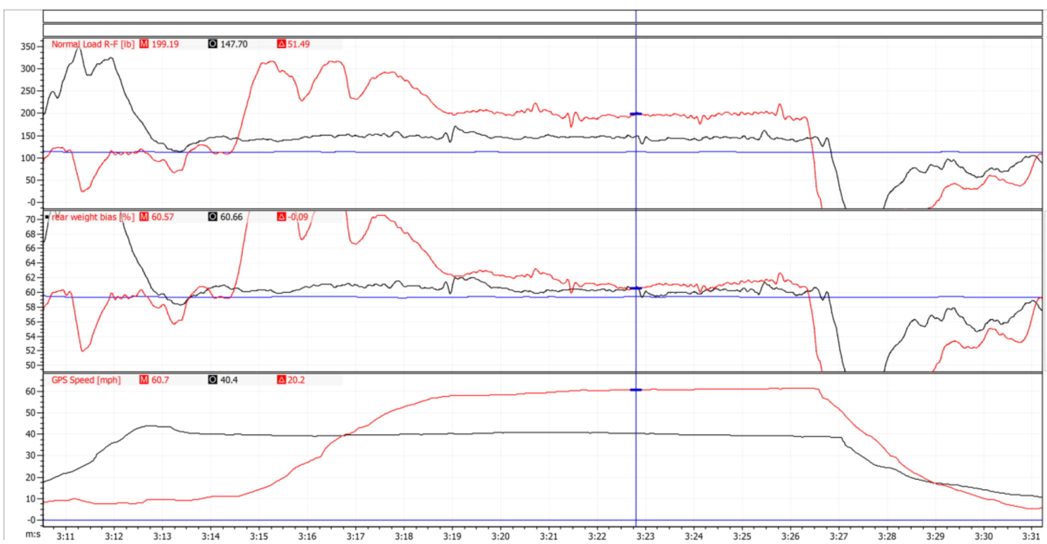


Figure 18: Weight Distribution at Different Speeds (blue: 0 mph, black: 40 mph, red: 60 mph)

The variation in downforce with three different flap settings is shown below. For both the front and the rear wing, the adjustability in the flaps allows for a large change in the generated downforce. The green curves on the plots show that there is essentially no downforce generated with the flaps wide open. By closing the flaps, the downforce can be incrementally increased.

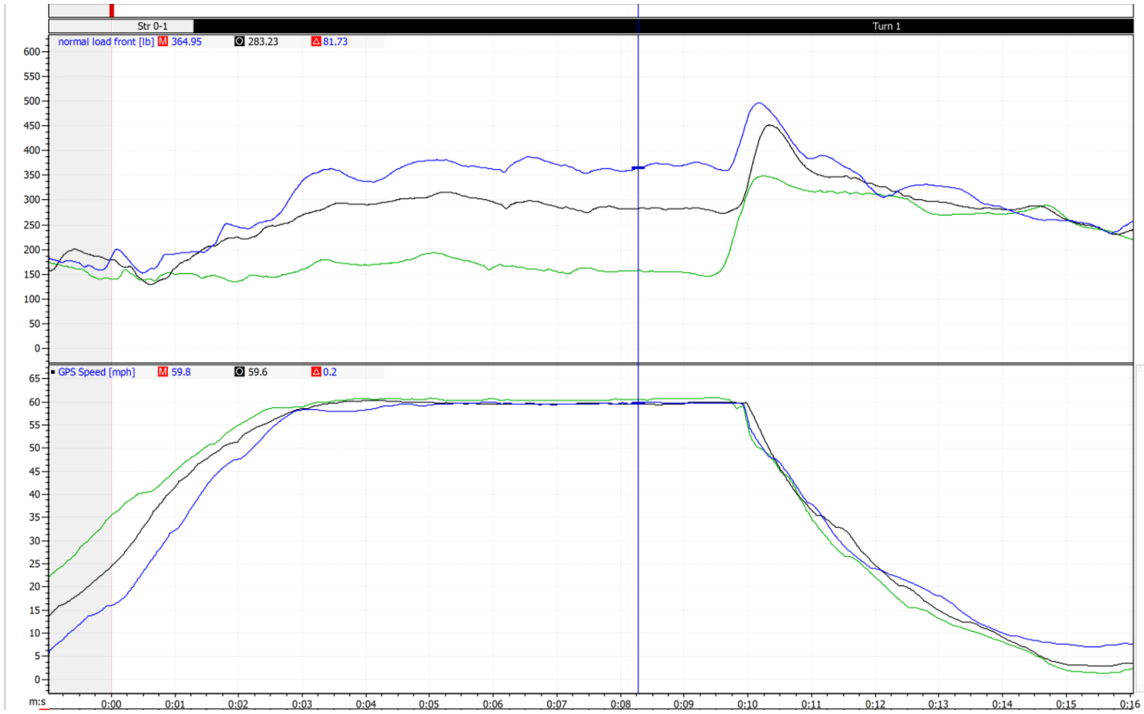


Figure 19a: Front Downforce Variation with Flap Opening (green: fully open, black: half open, blue: barely open)

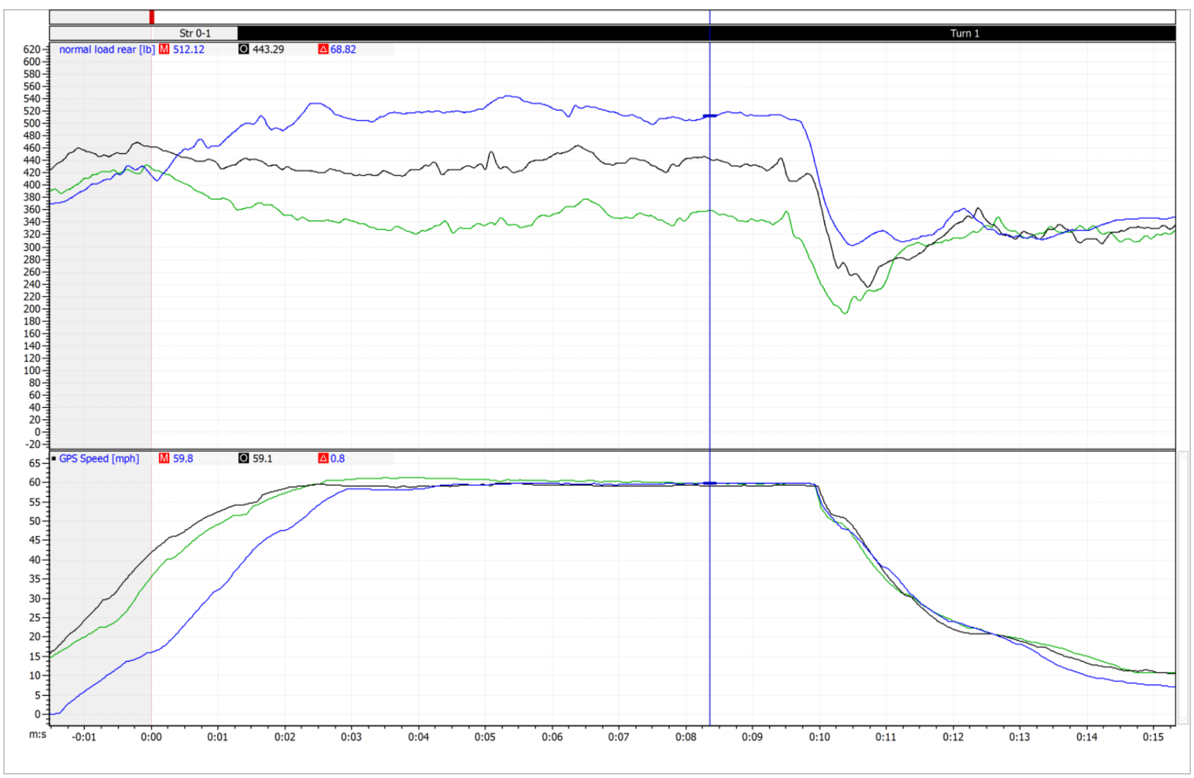


Figure 19b: Front Downforce Variation with Flap Opening (green: fully open, black: half open, blue: barely open)

The tuft testing showed that the airflow on the underside of the wings was mostly attached. The photo below shows the tufts on the rear wing. The tufts on the flaps and on the ends of the main plane are pointed straight indicating attached flow. It is not very evident in the photo but the video shows that the center of the main plane is disrupted by the wake of the helmet and head rest. To see the videos go to Cars>ARG14>Multimedia>Aero Testing 5-5-14.

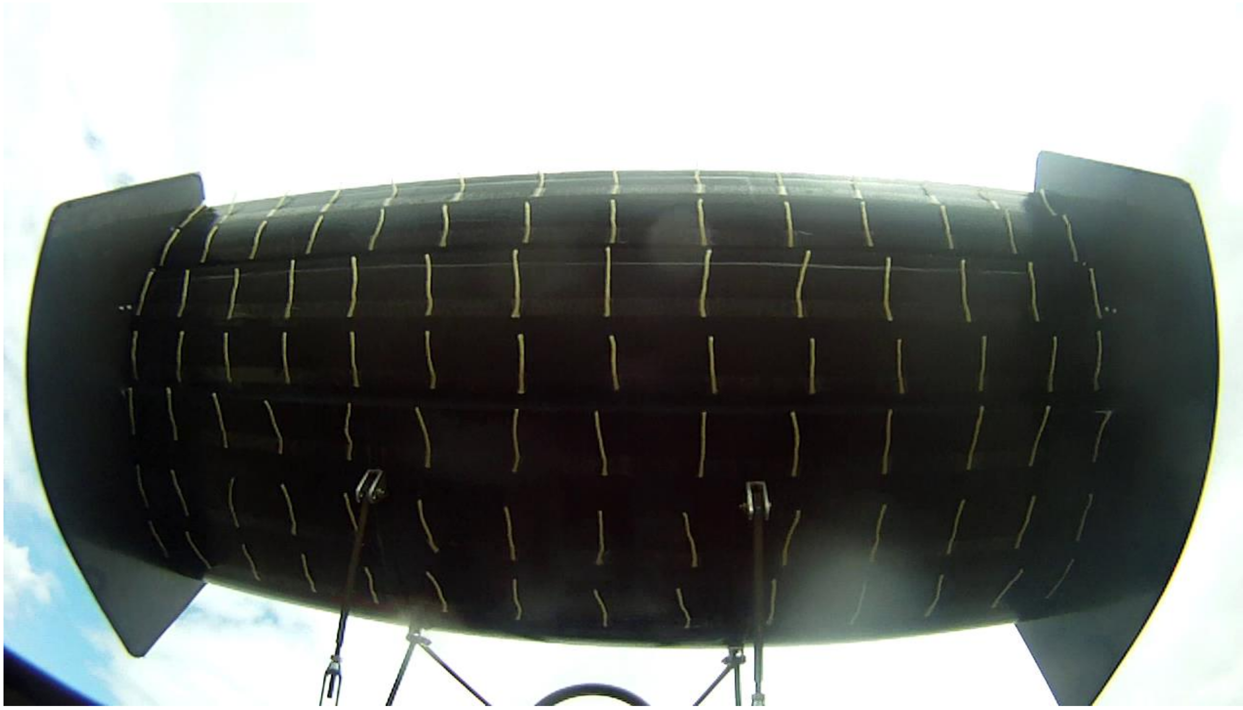


Figure 20: Tufts on Rear Wing

V. Conclusions

For a first year aero package, the system performed fairly well. The system slightly exceeded the downforce target that was set in the design. We predicted a total amount of downforce to be 300 pounds and the system generated 330 pounds. This significantly improved the performance of the car in terms of lateral and longitudinal acceleration and decreased lap times. Cornering and braking increased by 0.2 g's and autocross times were decreased by 2.5 seconds on average. The drivers also reported large improvements in the balance of the vehicle's handling. The measured aerodynamic balance of the system was more forward than what it was designed to be. This meant that the car was still somewhat oversteery at high speeds, though much better than without the aero package. Overall, the project was successful in implementing on the car a set of wings that met the goals proposed in the fall. This year was a good stepping stone for future teams in improving and refining the aerodynamics package for the race car.

VI. Recommendations for the Future

As always… Plans are nothing, planning is everything!

This is the first year we ran wings at competition for many years and the first year they were justified due to the speed of the track and cars. The design process moved slowly due to time taken to consider all the options. Once the design was established, manufacturing techniques were explored, settled upon, and executed. Testing in the spring showed that the system worked well and increased the performance of the car significantly. From our design this year, more testing will be able to be done in the fall in order to fine tune the system and to figure out how to make improvements. The one obvious improvement is the aerodynamic balance, which was too far forward this year. There should be effort put into finding the optimal balance for the next aero package.

Eventually adding an undertray to the aero package should be considered. This must be considered very early in the design of the car in order to leave proper spacing under the car for the tunnels. Without this consideration, the tunnel placement is limited to mostly behind the car in order to avoid interference with the suspension and other engine component low points. See Obinna Ehirim's undertray report from fall '10 and Amanda Costello's undertray technical from spring '10 as a baseline for what has been researched thus far.

VII. Annotated Bibliography

The following is your primary reference and I would recommend buying a copy if you're planning on designing the aero package. (Make sure to get the 2nd Ed.)

Katz, Joseph. *Race Car Aerodynamics: Designing for Speed*. Cambridge, MA, USA: Bentley, 2006. Print.

Anything not gone into in depth enough in this book can probably be found hashed out in a paper Katz has written or collaborated on. From there look at the people he's collaborated on papers with and you will find endless papers covering the vast subject area of vehicle aerodynamics.

If you're feeling extra ambitious there is a list of references at the end of each of his chapters that you could also explore, just don't forget ARG's rule about sorting through to what's actually useful and relevant otherwise you will never stop reading.

Some specific papers that of interest are:

Breslouer, Oren J. & George, Albert R. *Exploratory Experimental Studies of Forces and Flow Structure on a Bluff Body with Variable Diffuser and Wheel Configurations.*

Desai, Sachin S., Lo, Chi-Man Betty, & George, Albert R.*A Computational Study of Idealized Bluff Bodies, Wheels and Vortex Structures in Ground Effect.*

George, A. R. *Aerodynamic Effects of Shape, Camber, Pitch and Ground Proximityon Idealized Ground Vehicle Bodies.*

George, A. R. &Donis J. E. *Flow Patterns, Pressures, and Forces on the Underside of Idealized Ground Effect Vehicles.*

Earnshaw P. B. &Lawford, J. A. *Low-Speed Wind-Tunnel Experiments on a Series of Sharp-Edged Delta Wings.*

VIII. Contacts

Ehirin, Obinna
Masters in Mechanical and Aerospace Engineering at Cornell University
Undertray and Aerodynamic Research
Email: ohe4@cornell.edu

Eakin, Zach
Cornell FSAE Alumni
Worked on the DeltaWing Car
Email: zje2@cornell.edu

George, Albert R.
Professor of Mechanical and Aerospace Engineering at Cornell University
FSAE Faculty Advisor, Primary Reference
Email: arg2@cornell.edu
Phone (Office): (607) 255-6254

Warhaft, Zellman
Professor of Mechanical and Aerospace Engineering at Cornell University
Wind Tunnel
Email: zw16@cornell.edu
Phone (Office): (607) 255-3898

IX. **Appendices**

2014 Design Questions
Suspension Preliminary:

1. What were the goals of the suspension system?
2. How did you meet these goals?
3. Describe the testing you performed on the car.
4. How did you decide on the weight distribution?
5. How did you select your tires?
6. What is your roll stiffness distribution front and rear? With and without the antiroll bars.

Aero Preliminary:

1. Why did you decide to run an aero package?
2. What is your aero balance?
3. How did you choose this balance?
4. What kinds of analysis/testing/validation did you do for the aero package? Describe your methods.
5. Is the flow attached on the underside of the wing? How do you know?

Preliminary design is more relaxed in the sense that the judges will let you steer the conversation in whichever direction you want to. The key is to steer the conversation in the direction that you are most confident in and that you have analysis and data to back up what you are saying. Being confident while presenting is almost as important as the presentation material itself. This requires some practice and a genuine understanding of the systems. Good preparation of the posters and notebooks will help to inspire confidence and make the presentation more professional. This year, we did a fairly good job practicing and preparing for preliminary design.

Suspension Final:

1. Where is the roll axis?
2. Have you considered the effects of changing this location?
3. Where is the pitch axis?
4. Where is the yaw axis?
5. How do tire pressures affect the handling of the car?
6. What is the effect of pressure on vertical, lateral, and cornering stiffnesses of the tire?
7. Did you model these effects using the TTC data? If so how?
8. What is your brake rotor made of? Why?
9. How did you analyze the thermal effects of the brakes?
10. Did you do any testing for brake temperatures? Describe.
11. What is your camber compliance?
12. What is your toe compliance?
13. Are these values theoretical or measured?
14. How do these compliances affect the dynamics of the car?
15. Did you set targets for these compliances during the design? If so, how did you decide on the target values?
16. Describe how you modeled the stresses in the uprights.
17. How did you constrain the model?
18. What were the loading conditions in the model?

19. How did you come up with these loads?
20. What were the outputs of the model? Present the results.
21. Did you do any vehicle dynamics or lap time simulations? Describe.
22. How were these simulations used to design the car?
23. What are the purposes of the dampers?
24. How did you select your dampers?
25. What are your damping coefficients in compression and rebound, high speed and low speed?
26. How did you design these values?
27. What is “high speed” and what is “low speed” damping?
28. What kind of testing did you do for the dampers? Describe the process in detail.
29. Did you use sensor data or driver feedback to tune the dampers?
30. What adjustments can you make on the suspension?
31. Do you have different setups for different events? If so, what do you change and why?
32. How much adjustability do you have in your anti roll bars?
33. Why are your antiroll blades made of titanium?
34. Why do you run toe out for skidpad?
35. How did you design your steering geometry?
36. What is your bump steer? Theoretical or measured?
37. How does this affect the car’s handling?
38. How did you choose your spring stiffnesses?

Aero Final:

1. The rear wing does not seem to be well supported laterally. Why is that?
2. Why are there turnbuckles on the rear wing mounts?
3. Why didn’t you use rod ends at the ends of the tubes?
4. Where is the center of pressure on the car?
5. What are the downforce and drag values?
6. How does the aero balance affect the handling of the car?
7. Describe the testing procedure in detail. What kind of instrumentation did you use?
8. Why did you only test at two different speeds?
9. Did you do any flow visualization?
10. Do you think a gurney flap could have improved performance?
11. Did you do any CFD or wind tunnel experiments? Why not?
12. How do ground clearance, pitch, and roll variation affect the front wing?
13. How did you design the airfoil shapes?

Final design was much more pointed and detail oriented than preliminary design. Instead of having a set queue of judges, all of the judges go around and spend a little time talking to each team. Unlike preliminary design, you do not get to steer the conversation, rather the judges pick a certain topic and ask you very detailed questions about it. One of the biggest complaints from the judges was that we only had one person presenting both suspension and aero. For the future, they suggested that we have multiple present these sections so that we maximize the time we have with each judge. They also suggested that we bring as much data printed out and in our notebooks as possible. This includes very detailed analysis and testing for each part.

‘05 Testing Data:

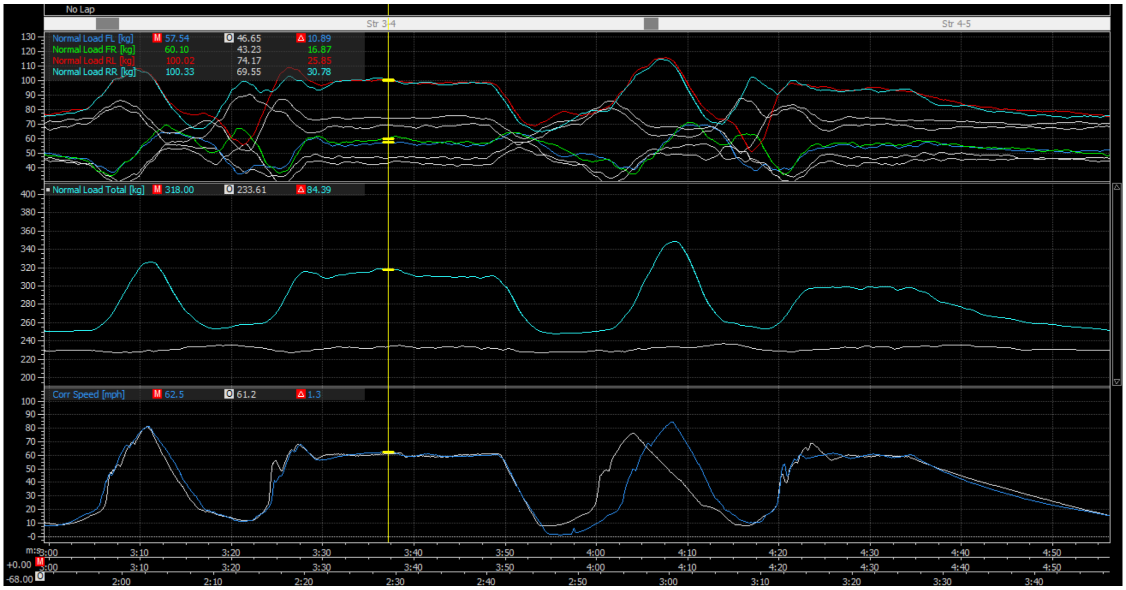


Figure 21: Coastdown Testing w '05 Front and Rear Wing (white: no wings, color: ’05 wings)

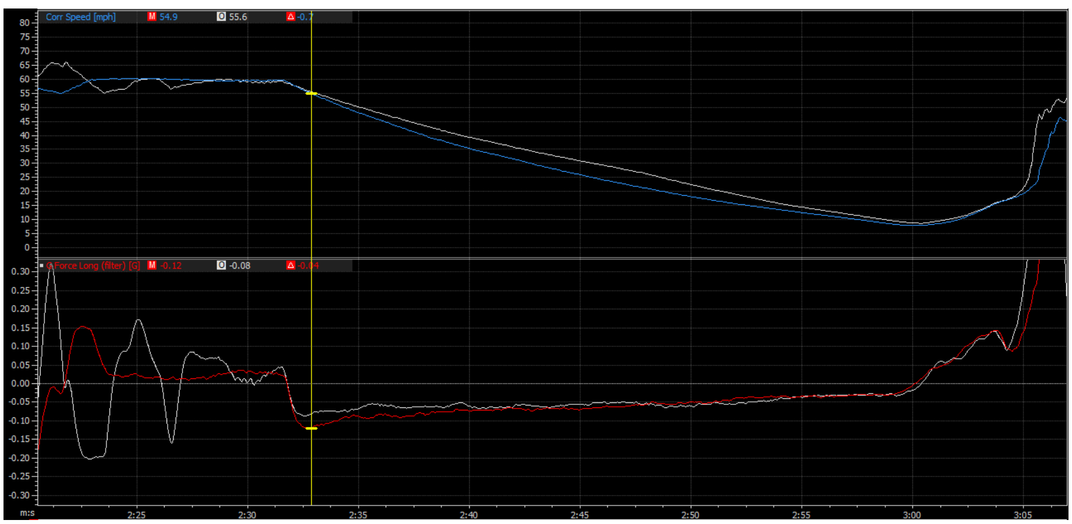


Figure 22: Drag Estimates (white: no wings, color: ’05 wings)

Nissan Delta Wing Car and Undertray

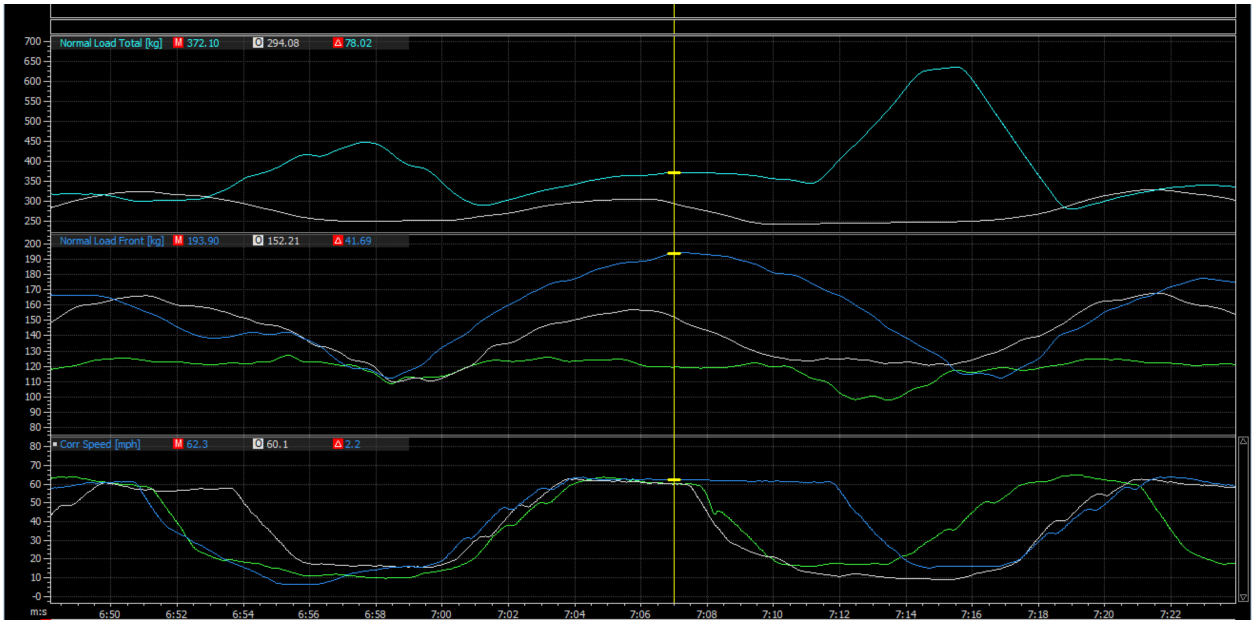


Figure 23: Coastdown Testing w/ Front Delta Wing (green: no wing, white: delta, blue: '05 wing)

Options	Estimated Cost to Team ($)	Estimated Weight (lbs)	Durability (1-5,1 – low, 5 – high)	Estimated Production Time (man hrs) (1-5)
Carbon Fiber	$400	15lbs	5	5
Glass	$400	20lbs	5	5
Carbon over foam	$500	15lbs	4	3
Glass over foam	$500	20lbs	4	3
Sheet metal	$750	25lbs	5	4
Wood frame w fabric	$400	12lbs	2	3
Metal frame w fabric	$500	15lbs	2	3
Wood frame w mylar	$300	10lbs	3?	3

Figure 24: Wing Manufacturing Options

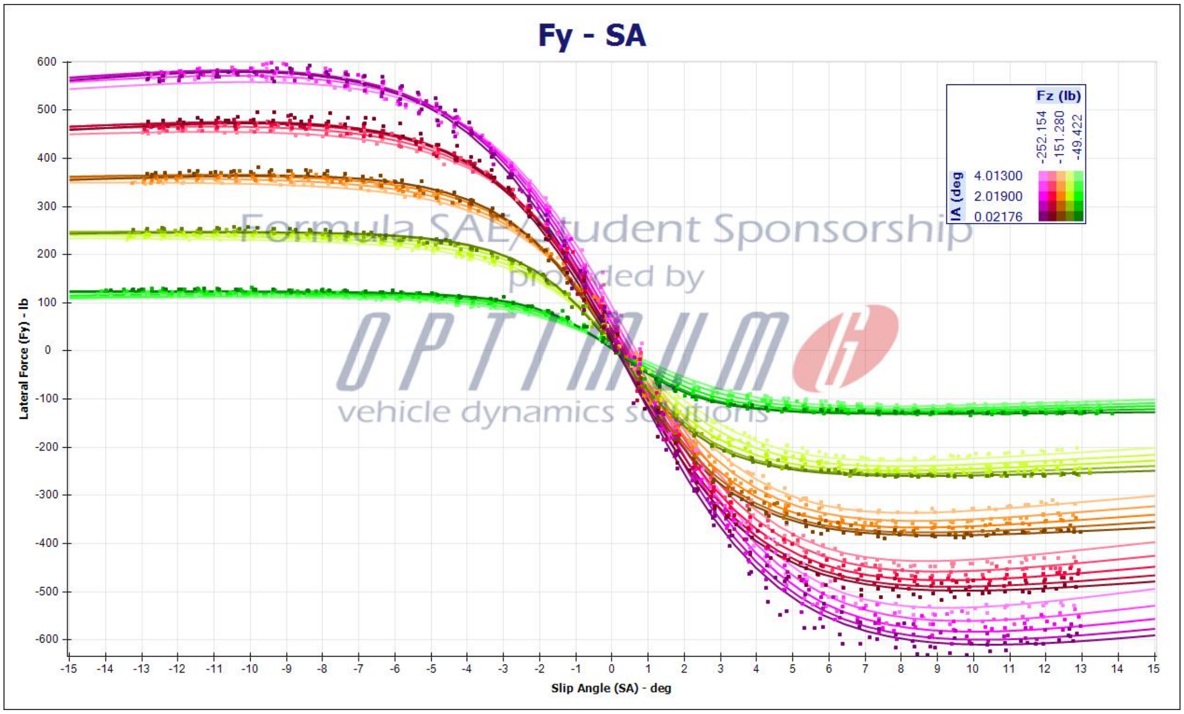


Figure 25: Lateral Force vs. Slip Angle for 10” Hoosier R25B Tire

Relevant 2014 Formula SAE Rules

ARTICLE 9: AERODYNAMIC DEVICES

T9.1 Aero Dynamics and Ground Effects - General

All aerodynamic devices must satisfy the following requirements:

T9.2 Location

T9.2.1 In plain view, no part of any aerodynamic device, wing, under tray or splitter can be:

a. Further forward than 762 mm (30 inches) forward of the fronts of the front tires

b. No further rearward than 305 mm (12 inches) rearward of the rear of the rear tires.

c. No wider than the outside of the front tires or rear tires measured at the height of the hubs, whichever is wider.

T9.3 Minimum Radii of Edges of Aerodynamic Devices

T9.3.1 All wing edges including wings, end plates, Gurney flaps, wicker bills and undertrays that could contact a pedestrian must have a minimum radius of 1.5 mm (0.060 inch).

T9.4 Ground Effect Devices

No power device may be used to move or remove air from under the vehicle except fans designed exclusively for cooling. Power ground effects are prohibited.

T9.5 Driver Egress Requirements

T9.5.1 Egress from the vehicle within the time set in Rule T4.8 “Driver Egress,” must not require any movement of the wing or wings or their mountings.

T9.5.2 The wing or wings must be mounted in such positions, and sturdily enough, that any accident is unlikely to deform the wings or their mountings in such a way to block the driver’s egress.

Estimated Budget

Testing (Fall)	Item	QTY	Cost

	Yarn	1 roll	$7
	Scotch tape	1 roll	$2
	Powder paint	1 jar	$8
	Kerosene	1 can	$11
	Anemometer	1	$60
Manufacturing (Spring)			
	Fiber glass	1 lg. roll	In house
	Resin	2 cans	$50
	Gel Coat	1 can	$30
	Carbon fiber	<1 roll	Donated
	Core	1 sheet	Donated
	Foam	20ft3	In house/Donated
	Mounting hardware		~$200
	Lay-up consumables		$25
		Total	$400

Hot wire cutter instructions from http://www.instructables.com/id/Hot-wire-foam-cutter/

Step 1: Parts

The parts should be pretty easy to find.

1. 12 foot, 16 guage extension cord, about $2 at Home Depot

2. 2 wooden yard sticks from the Home Depot paint department, $.97 each

3. 4 #10-24 x 1.25" machine screws with nuts, $1 at Home Depot

4. 10 #10 washers, $1 at Home Depot

5. About 12 feet of strong, low-stretch string. I used 200 lbdacron kite line.

6. A single-pole dimmer switch. About $10 at Home Depot.

7. A 25 volt, 2 amp transformer, $10.49 from Radio Shack.

8. An electric guitar string, about .10 - .16 size. I think around $1? You can get these individually at a music store or you can use either of the 2 smallest strings from a packaged set. You should keep a spare handy because they can burn out or break from too much tension.

9. A length of two conductor electrical wire with a regular plug on the end. I salvaged mine, but you could use another extention cord if you like.

10. A piece of wooden dowel or stiff plastic rod about one foot long (not shown). I used a bamboo skewer.

11. Optional: 4 regular-thickness CD cases. These are for the box that holds the transformer and dimmer switch, but you would be much better off with something like a "project box" from Radio Shack.

Step 2: Tools and supplies

You might be able to do the whole project with just a knife, a drill and some tape, but it would be better to have the following:

1. Utility knife

2. Small wood saw

3. Drill with a bit slightly bigger than the #10 screws

4. Screwdriver

5. A couple of cable ties or twist ties

6. Electrical tape

7. Wide packaging tape

8. Nibbler

9. Multitester (you don't NEED one but it's a good safety check)

10. Wrench to match the nuts (I didn't have my SAE wrenches handy so I used a 9mm)

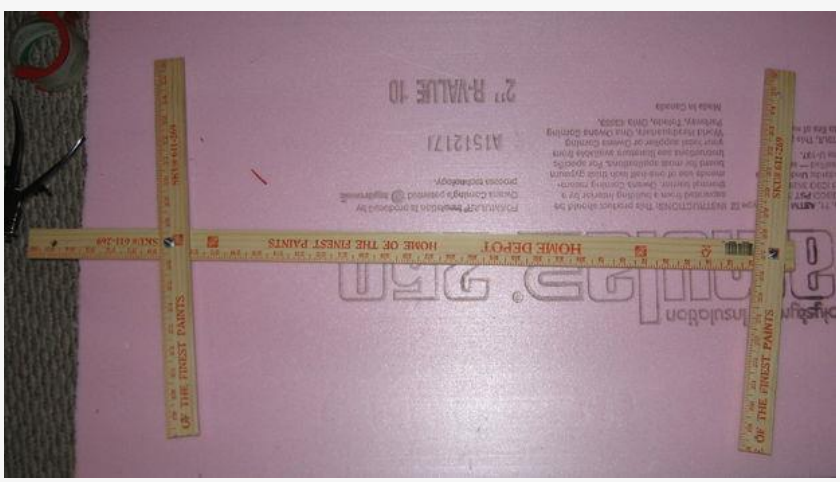
11. Solder and soldering iron, if you like

Step 3: Making the frame pieces

Cut one of the yardsticks in half. In each half, drill a hole in the middle and one about 1/2 inch from each end. One end of one half will already have a big hole in it, so you won't have to drill that end.

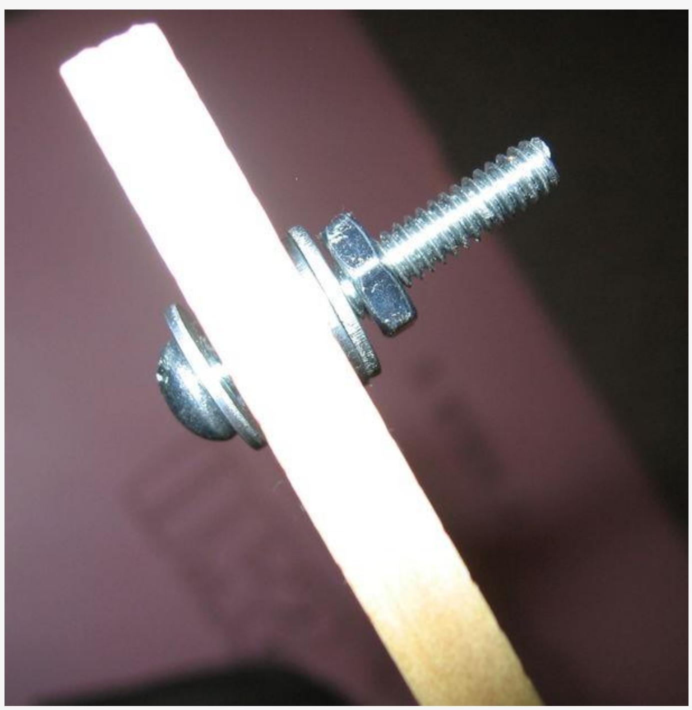
One the remaining, uncut yardstick, drill a hole about 6 inches from the pre-existing hole (see photo), and another about 1 inch from the other end (not shown in this photo, but visible in later steps).

Step 4: Bolting the frame together



Make a sort of a big H shape out of your pieces by bolting them loosely together with the machine screws. Don't tighten the nuts down yet, just get 'em on therekinda loose.

Step 5: Attaching the lead wires to the frame



Now we're going to attach the wires that carry the 25V current to the cutting wire. We'll use two machine screws as terminal posts.

First, cut off each end of your 12 foot extension cord. Save the plug and outlets for future projects, if you like. Strip the insulation off the last inch of one end of one wire of the cord.

Insert a machine screw in the top of the right leg of your "big H" as shown in the photo. This is the leg that is on the other side of the H from the handle. Use one washer on the screw head side and two on the nut side, as shown in the second picture below. Put the nut on, but don't tighten it down at all. You need room between the washers so you can put your wire in there.

Bend the bare wire of the extension cord (the part you just strippeed) into a U shape, and hook it around the screw between the two washers. Now you can tighten down the nut. You can see what the final hook-up looks like close-up in the photos for step 7.

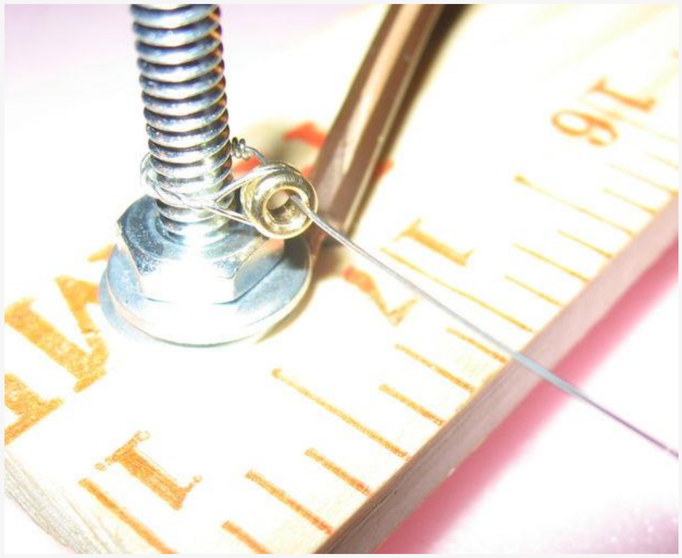
Starting the the end you just hooked up, pull the two conductors of the cord apart so that it's split for about 3 1/2 feet. Cut the unmounted side of the split to about one foot. Strip the end of the one foot section and mount it to the other leg of the H the same way you hooked up the first wire. You'll see what I'm talking about here if you look at the photo.

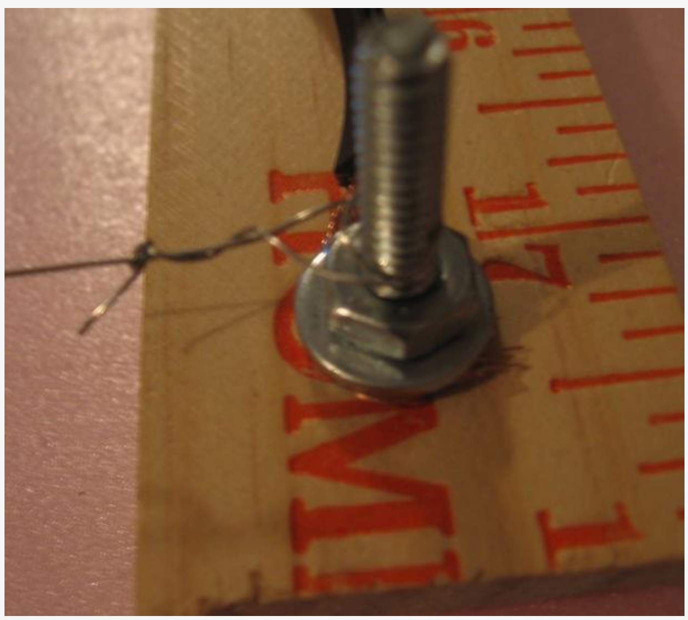
Use cable ties, twist ties or string to keep the wire close to the frame so it won't get in the way when you're using the tool.

Step 6: Making the tensioning loop

Take a piece of string about 6 feet long and thread it through each hole on the other ends of the legs, as shown. Tie it into a loop so that when you pull the legs apart the string keeps the legs fairly parallel. So, the length of the loop when taut should be about the same as the distance between the bolts.

Step 7: Attaching the hot wire





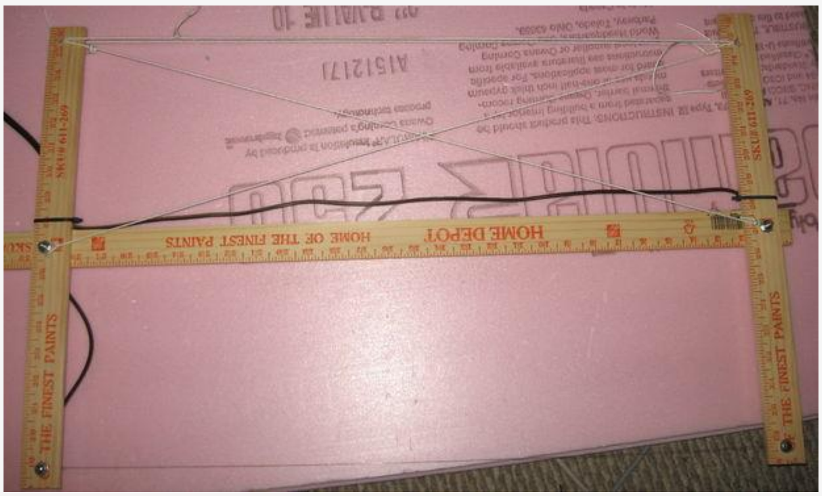
While you are hooking up your wire, try to avoid making any kinks it.

Your guitar string should have a sort of a bead (for lack of the proper name) on one end. Make a loop by feeding the other end through this bead. Hook the loop over one terminal and sinch it up. Keep the loop pretty close to the nut or there will be too much twisting force on the leg when the wire is tensioned. But also make sure it's not touching the wood.

To hook up the other end of the wire, pull the frame legs towards each other so your string tensioning loop on the other end is taut. Wrap the end of the wire around the other terminal screw and twist it off. See the second photo. It might help to use pliers to keep good tension, but be careful not to pull too hard and break the wire.

If the wire is not super tight at this point, don't worry. It can be kind of floppy when plucked but should be pretty much straight when at rest. We'll add more tension later.

Step 8: Cross strings



Now we need to install the mechanism that keeps the the legs square to the wire. Without this step your contraption will easily wobble into a parallelogram.

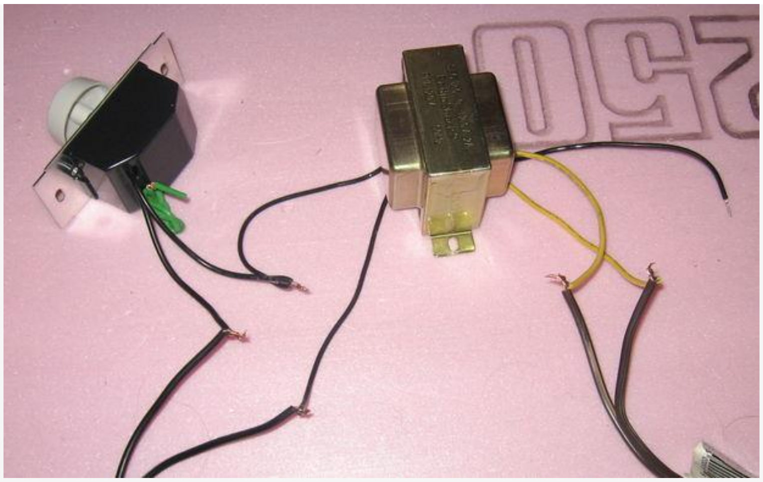
Tie a loop in one end of a 3 foot piece of string and hook it under the washer of one of the middle screws. See the photos. Thread the other end of the string though the opposite leg's hole. Square up the frame and tie off the string. Repeat with another string for the other side, but when you tie off the string at the top of the leg this time, make sure you have some tension. Now both of the criss-crosstrings should be pretty tight, and there should be some slight tension on the wire too. It's ok if the tensioning loop is a little floppy at this point. Now you can tighten down both of the middle screws with the wrench. No need to chrush anything, just make 'em tight enough to hold everything together.

Step 9: Applying tension

Insert a ruler or dowel in the tesioning loop and twist it until it seems to be getting a little tight. Careful not to twist too much or you'll break the wire or the frame. Pluck the wire and listen for a musical tone. If it sounds like "fwubababa" it needs more tension. If it sort of hums it should be enough to start. You can always add more if it seems too floppy when you try to make your cuts. Once you are happy with the tension, slide the ruler or dowel down so that the yardstick keeps it from unwinding (see the photo).

You'll have to readjust the tension later, after the wire gets hot for the first time. Or maybe every time.

Step 10: Wiring up the transformer and dimmer switch



This photo is your wiring diagram. The black two conductor wire on the left goes to the wall plug, and the brown one on the right goes to the hot wire.

This photo is just to show what connects where. You should of course use the wire nuts that came with the dimmer switch (esp on the 120V connections) and/or tape to ensure that no bare wires touch each other, or you, or your pet. Be careful not to electrocute yourself or start a fire.

Step 11: My crappy project box

I really want to make a different box for this project, or buy a project box at Radio Shack. This box was made from 4 cd cases and some packaging tape. Two CD cases are openned to right angles, then pushed together to make 4 walls. The corners join up nicely. Run a strip of packaging tape down each corner. Now take the lid off another case and tape it to the bottom of the 4 walls. The bottom will touch two opposite walls and there will be gaps under the other walls. Don't tape over the gaps, they provide ventillation. Take the lid and plastic tray off a 4th cd case and throw them out. Nibble or cut a hole for the dimmer switch and tape it in. Then connect up all the wiring according to the diagram in the previous step, tape in the transformer, and tape the top on. In the photo, the box has been turned on it's side.

If you drop the box, the transformer will shatter it. Have I mentioned that you should use a different design for your enclosure?

I think this kind of box might have some other uses. Maybe you could make a version without a top and bottom, put some nice photos in it, and set a small plant pot inside with the plant sticking out?

Step 12: Turning it on

Set the rig up somewhere where it won't catch the house on fire or melt the carpet if something is wired wrong, or if the wire overheats and breaks. Take a moment to look over your creation and make sure all the wiring seems to make sense.

Turn the dimmer all the way down (counterclockwise).

With your fire extinguisher handy and your body away from the device, plug it in.

Are the lights still on? Is the hotwire still whole? Sweet.

You can use your multimeter to see if there's any current between the terminals. There shouldn't be yet. SLOWLY (like 5 degrees per second) turn the dimmer up (clockwise) til the wire starts to quietly hum. With the wire I used that's about 1/4 or 1/3 of the full rotation. If the wire doesn't hum or heat up by the time the dimmer is halfway up, turn the dimmer all the way down, push in til it clicks, and start again.

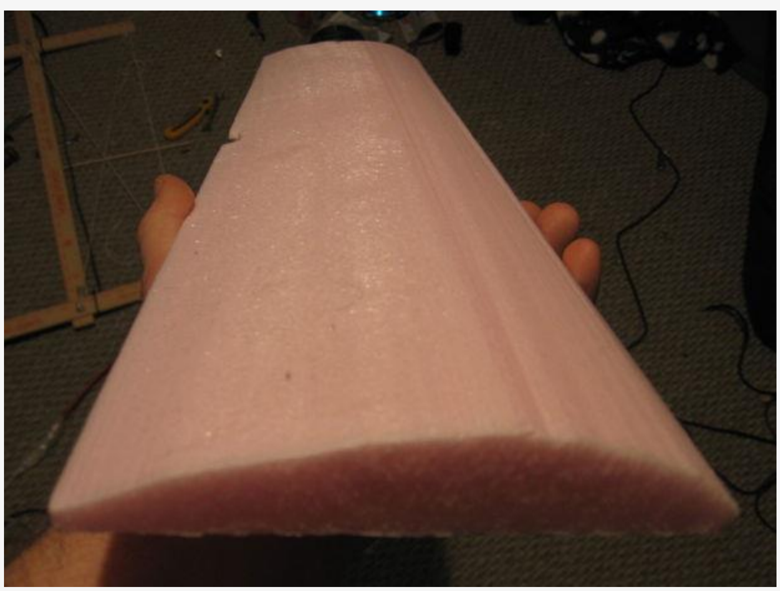
If you turn up the dimmer too fast, your wire may burn out before you realize that it's even hot.

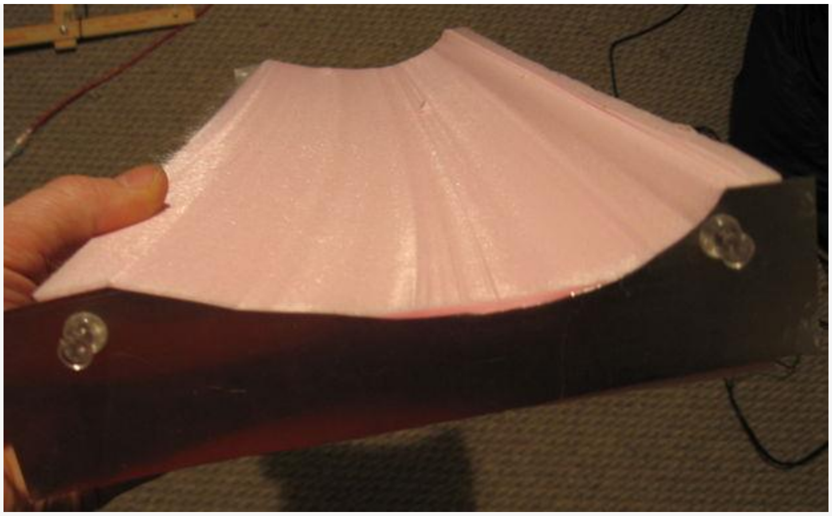
Once you are sure everything's all set, grab the frame and try laying the wire on some scrap styrofoam. It should slice smoothly into the foam. You shouldn't have to push very hard. Try playing with the dimmer switch setting to get the best cut. I've read that cutting slower and cooler makes a smoother cut.

The wire heats up and cools down within a second or two.

Next time you use the foam cutter, make sure nothing meltable or flammable is touching the wire when you plug it in, just in case the dimmer isn't off.

Step 13: Quick and dirty sample cuts





Here are some freehand and template-cut shapes to give you an idea of what the tool does. These are really basic one-cut shapes. You can of course bevel edges, etc, with a second pass.

Step 14: Alternatives and expansion ideas

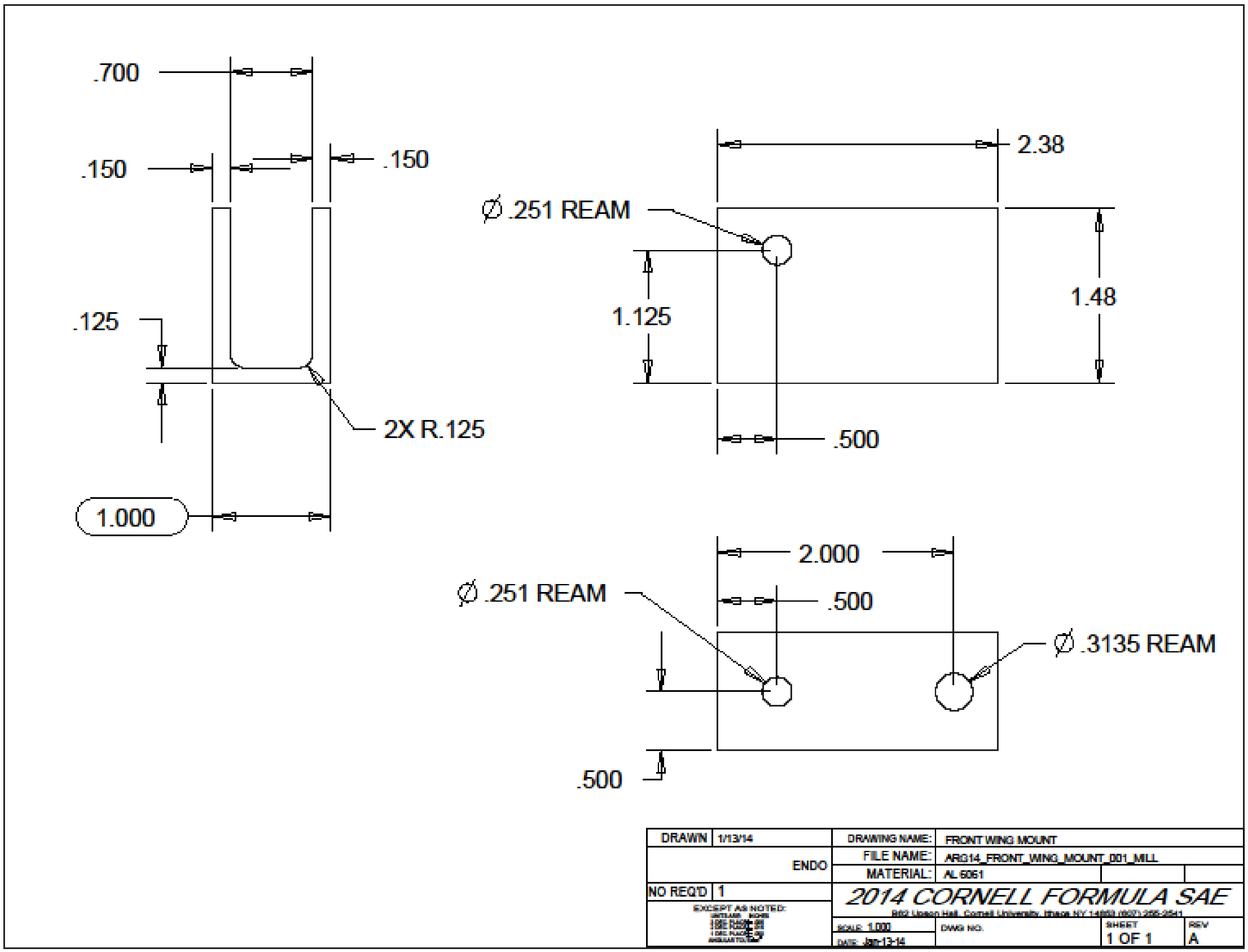
Some people set up their cutters in sort of a bandsaw configuration, so that small pieces can be manipulated against a table for precise cutting. Those are generally not useful for cutting wings or slicing chunks off larger pieces. See this page for an example:

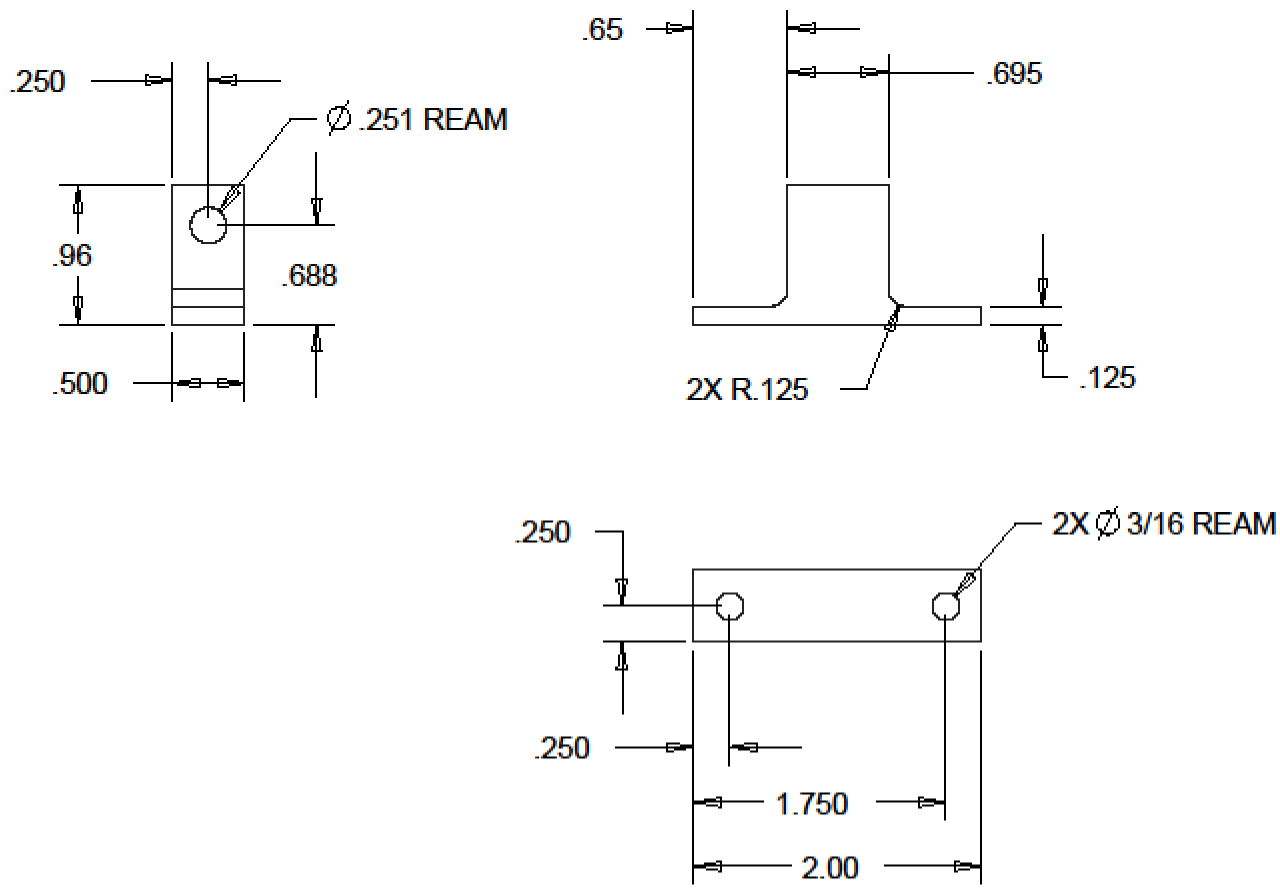
http://www.hhhh.org/~joeboy/resources/hotwire_foam_cutter/hotwire_foam_cutter.html

The enclosure for the transformer and dimmer needs to be more rugged, and it should incorporate a fuse, maybe a power indicator, and maybe a modular connector to facilitate attachment of larger or smaller cutters.

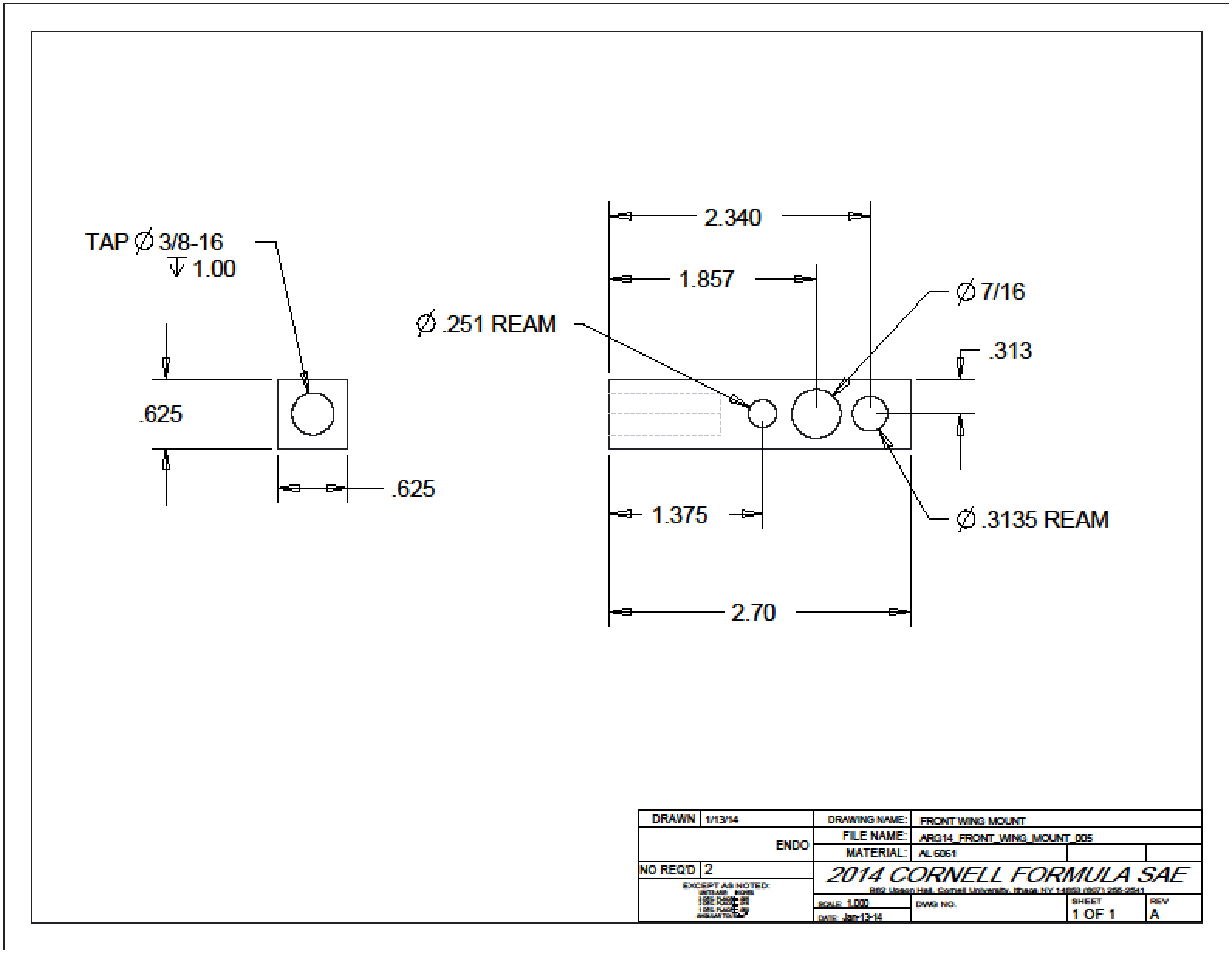
Instructables user Moofie suggested rigidifying the connection to one of the legs, perhaps simply by using a second bolt where the yardsticks overlap, to eliminate the need for the criss-cross strings.

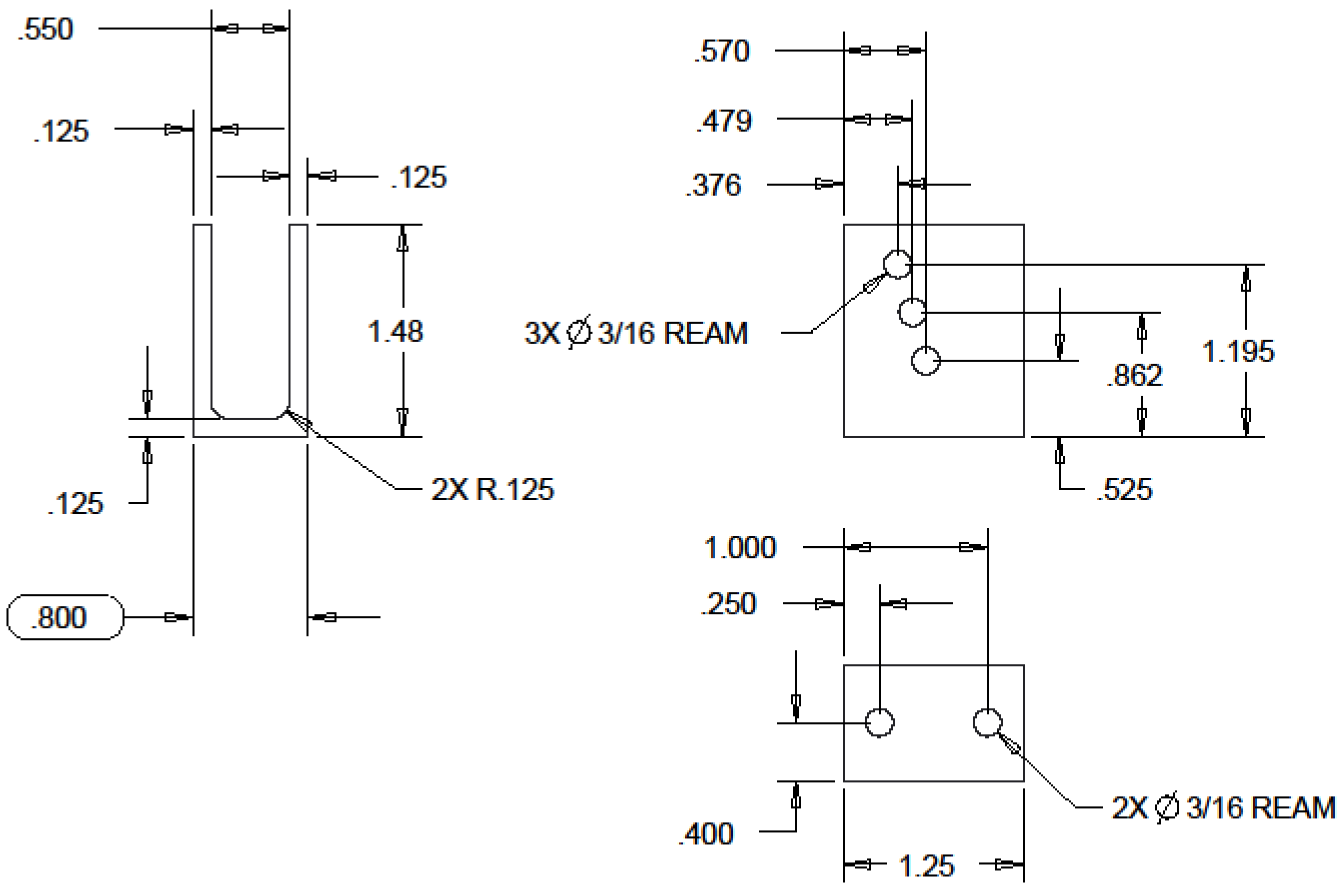
Wing Mount Drawings:



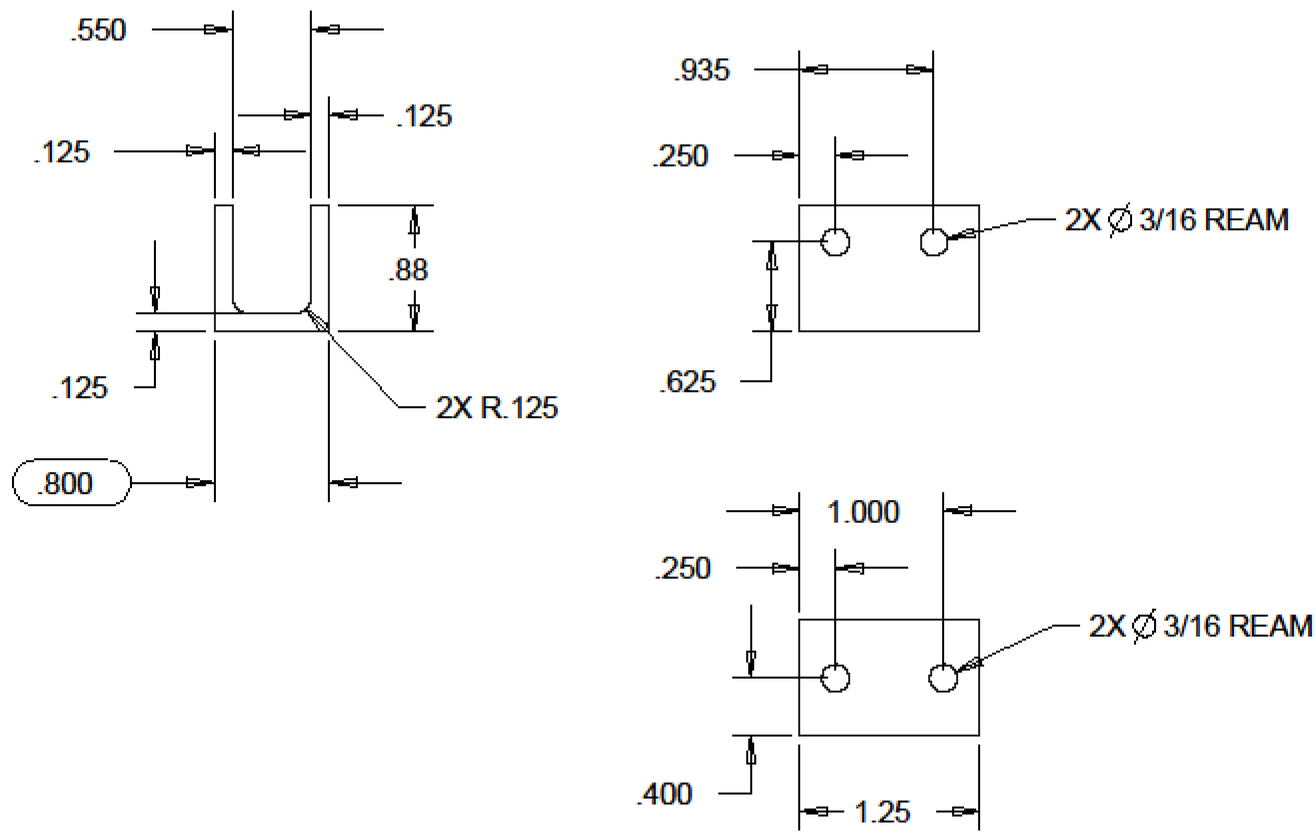


DRAWN	1/13/14	DRAWING NAME:	FRONT WING MOUNT		
	ENDO	FILE NAME:	ARG14_FRONT_WING_MOUNT_003_MILL		
		MATERIAL:	AL 6061		
NO REQ'D	1	2014 CORNELL FORMULA SAE B62 Upson Hall, Cornell University, Ithaca NY 14853			
EXCEPT AS NOTED:		SCALE: 1.000 DATE: Jan-13-14	DWG NO.	SHEET 1 OF 1	REV A

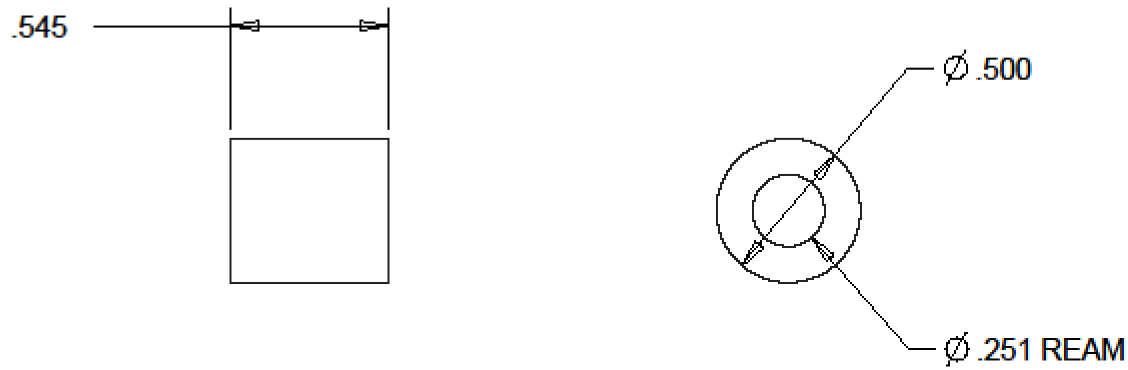

TAP ∅ 3/8-16
↧ 1.00
.625
.625
∅ .251 REAM
2.340
1.857
∅ 7/16
.313
1.375
∅ .3135 REAM
2.70
DRAWN
1/13/14
ENDO
NO REQ'D
2
EXCEPT AS NOTED:
DRAWING NAME:
FRONT WING MOUNT
FILE NAME:
ARG14_FRONT_WING_MOUNT_005
MATERIAL:
AL 6061
2014 CORNELL FORMULA SAE
SCALE 1.000
DATE Jan-13-14
DWG NO.
SHEET
1 OF 1
REV
A



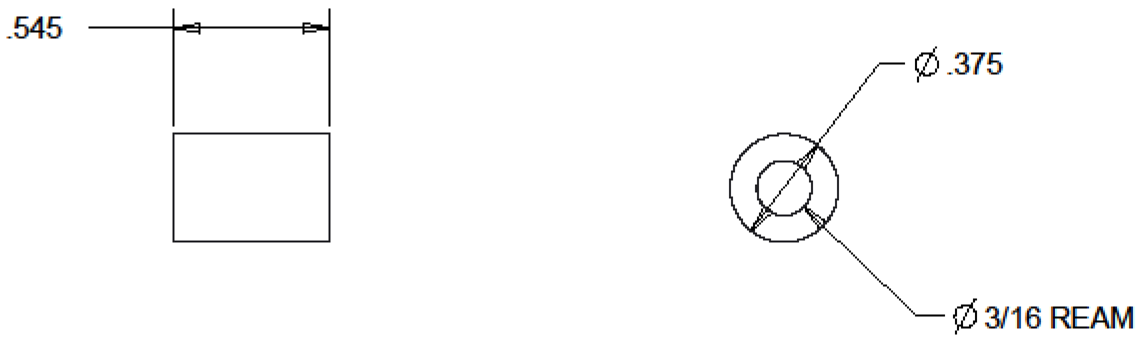
DRAWN	1/14/14	DRAWING NAME:	REAR WING MOUNT		
	ENDO	FILE NAME:	ARG14_REAR_WING_MOUNT_001_MILL		
		MATERIAL:	AL 6061		
NO REQ'D	2	*2014 CORNELL FORMULA SAE*			
EXCEPT AS NOTED:		SCALE: 1.000	DWG NO.	SHEET 1 OF 1	REV A
		DATE: Jan-14-14			



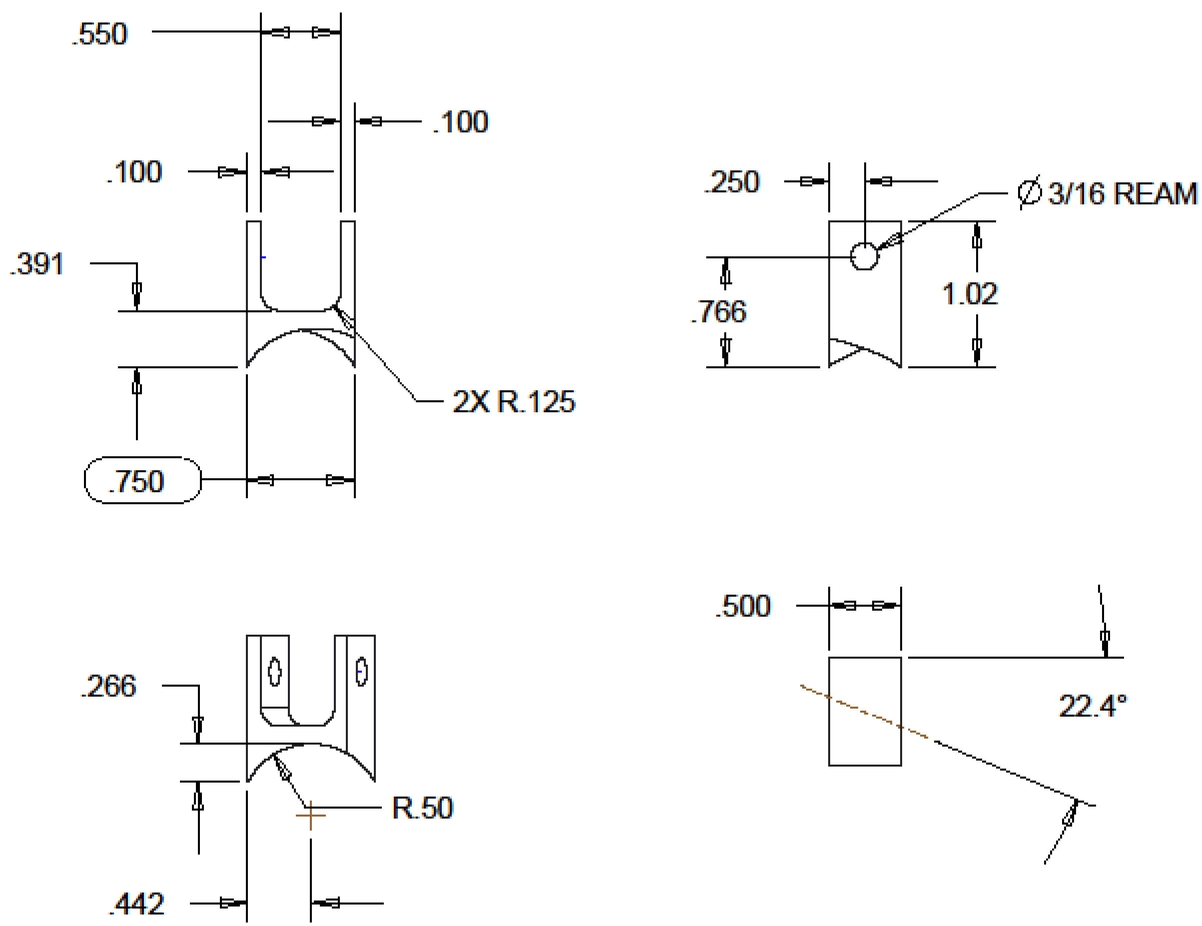
DRAWN	1/14/14	DRAWING NAME:	REAR WING MOUNT
	ENDO	FILE NAME:	ARG14_REAR_WING_MOUNT_003_MILL
		MATERIAL:	AL 6061
NO REQ'D	2	2014 CORNELL FORMULA SAE	
EXCEPT AS NOTED:		SCALE: 1.000	DWG NO.
		DATE: Jan-14-14	SHEET 1 OF 1 / REV A



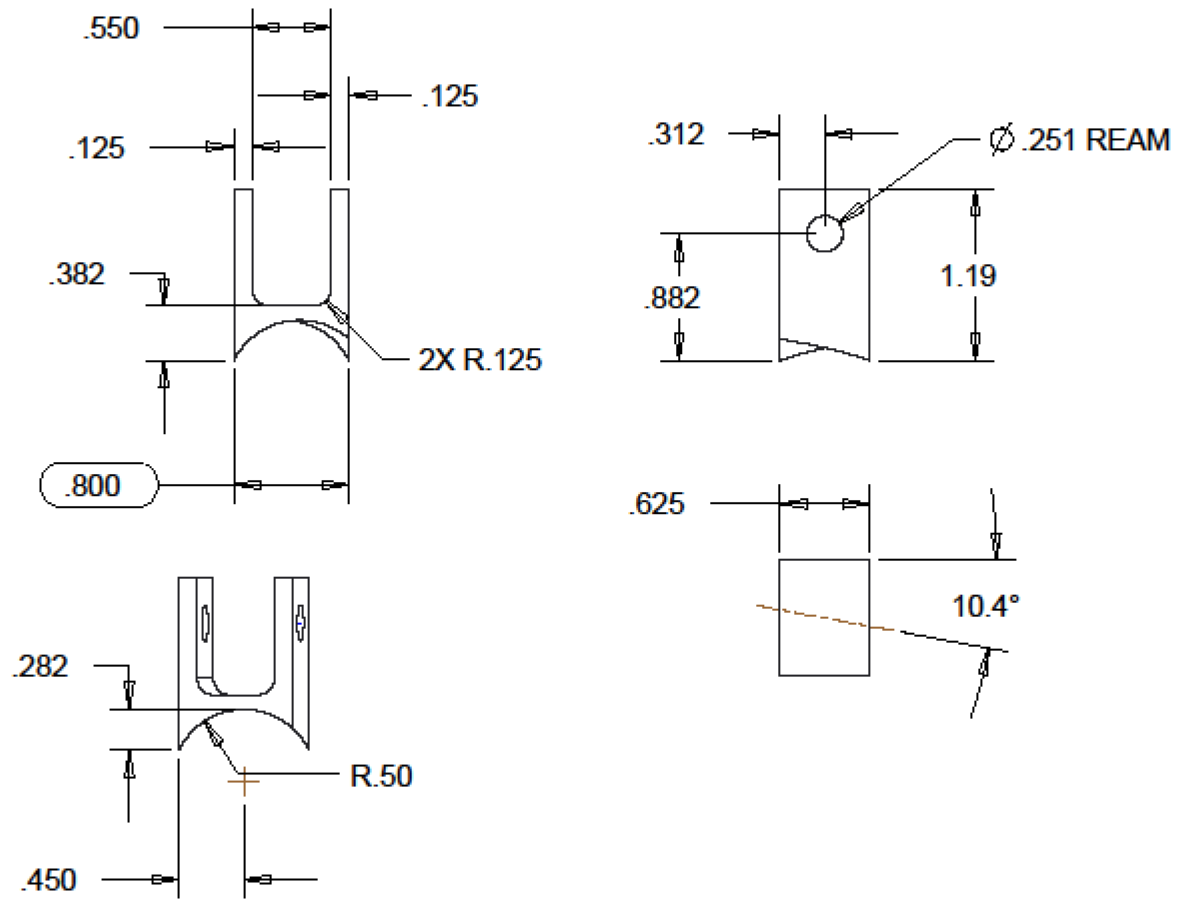
DRAWN	1/14/14	DRAWING NAME:	REAR WING MOUNT		
ENDO		FILE NAME:	ARG14_REAR_WING_MOUNT_005		
		MATERIAL:	4130 STEEL		
NO REQ'D	2	2014 CORNELL FORMULA SAE B62 Upson Hall, Cornell University, Ithaca NY 14853 (607) 255-2541			
EXCEPT AS NOTED:		SCALE: 2.000 DATE: Jan-14-14	DWG NO.	SHEET 1 OF 1	REV A



DRAWN	1/14/14	DRAWING NAME:	REAR WING MOUNT		
	ENDO	FILE NAME:	ARG14_REAR_WING_MOUNT_007		
		MATERIAL:	4130 STEEL		
NO REQ'D	8	2014 CORNELL FORMULA SAE			
EXCEPT AS NOTED:		SCALE: 2.000	DWG NO.	SHEET 1 OF 1	REV A
		DATE: Jan-14-14			



DRAWN	1/14/14	DRAWING NAME:	REAR WING TAB
	ENDO	FILE NAME:	ARG14_REAR_WING_TAB_001_MILL
		MATERIAL:	4130 STEEL
NO REQ'D	1	2014 CORNELL FORMULA SAE	
EXCEPT AS NOTED:		SCALE: 1.000	DWG NO.
		DATE: Jan-14-14	SHEET 1 OF 1 / REV A



DRAWN	1/14/14	DRAWING NAME:	REAR WING TAB
	ENDO	FILE NAME:	ARG14_REAR_WING_TAB_003_MILL
		MATERIAL:	4130 STEEL
NO REQ'D	1	2014 CORNELL FORMULA SAE	
EXCEPT AS NOTED:		SCALE: 1.000	DWG NO.
		DATE: Jan-14-14	SHEET 1 OF 1 · REV A