

AC 2010-233: A DESIGN-BUILD-TEST-FLY PROJECT INVOLVING MODELING, MANUFACTURING, AND TESTING

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Abstract

This paper describes a junior-level semester-long class project for students in Fluid Mechanics courses. The goals of the project are to introduce students to engineering design, project management, and to incorporate material from other courses in engineering graphics, numerical methods, instrumentation and measurements, and manufacturing processes in a single project. The project focuses on airfoil design using computational tools, and the main emphasis lies on verification of results obtained from computational methods with experimentally measured values. Students will use the airfoil shape they select to make wings to go on a model foam glider. The final part of the project will be staged as a competition where student teams vie to see whose glider can fly the furthest under standard launching conditions.

Introduction

Previously in order to introduce students to engineering design before their senior design capstone experience, a semester-long rocket project was implemented in the junior-level fluid mechanics course at Bradley University as described in the paper by Morris and Zietlow¹. In that project student teams of 3-4 students each had to design and build a small model rocket, with the goal of the rocket landing in a target area on a baseball field on its very first launch. Part of the score for the project was assigned based on the efficiency of each team in using the resources available to them, as measured in the amount of “Bradley Bucks” they spent to complete the project. Note that it is easy to create money for these projects by downloading the template for Monopoly Money from Hasbro² and Photoshopping in the faces of professors in your department. Printing on brightly colored paper works well to discourage counterfeiting. While the rocket project was quite successful and well-liked by the students, it has the limitation of that the best rockets end up all looking the same, as the primary design variables available to the student are the size of the fins and the amount of weight in the nose cone.

To improve upon this, a new project has been designed. The first objective of the new project is to design an airfoil for launch speeds less than 10 mph and for angle of attack from 0 to 10 degrees, to be tested on a glider. A 2D aerodynamics CFD tool, such as the freely available XFOIL³, FOILSIM^{4,5}, or JAVAFOIL⁶ is the computational tool used in the analysis of the lift and drag coefficients. Student can use any airfoil shape they want, but to keep the project simple, the NACA 4-digit series of airfoils is recommended. After finding the airfoil shape that gives the highest lift to drag ratio (L/D) based on the computational results, an airfoil will be built and tested in a wind tunnel to verify the computational results. First a 3D solid model of the airfoil is made in drafting software such as AutoCAD, SolidWorks, or Pro-E, and then the 3D airfoil section is made with a CNC milling machine or a rapid prototype machine. Though not required in the project, some students also made the fuselage of their gliders with the CNC machine. The students must devise a way to attach end plates to the narrow airfoil section to minimize the induced drag effects, and they must also devise a method for mounting the airfoil section in the wind tunnel. If the results of the wind tunnel testing are acceptable to the student team, they may proceed to the final stage of constructing a model glider. If not, they may select a different airfoil

shape and perform additional wind tunnel testing. In the first semester of this project, student teams built from 1-3 airfoils to test.

The final glider each team builds will be made entirely out of foam, and the shape of the glider can be determined by each team. They are limited only in that the overall dimensions must fit into the launch mechanism, which was 28 inches wide. The students can design and build any shape of fuselage they want, and they can select the length, chord, and aspect ratio of the wings. Students are responsible for ensuring the glider design is dynamically stable in pitch, yaw, and roll. An additional constraint on the design is economic. Students are charged “Bradley Bucks” for all material used, and for the use of equipment, including the wind tunnel and CNC milling machine, and consulting fees for seeking help from faculty. The final grade in the project depends on the distance the glider travels, the accuracy of a numerical prediction of glide distance compared to the actual measured distance, the amount of Bradley Bucks spent, and the quality of the final project report. The co-authors of this paper are graduate students who verified the feasibility of the project as a graduate course project the previous semester.

While the emphasis of this project is on the design and construction/manufacturing and not on the actual flight itself, it does bear similarity to other design-build-fly educational projects. The two national design-build-fly (DBF) yearly competitions are the AIAA DBF and the SAE Aero. Five papers were found in the educational literature on the AIAA DBF Competition⁷⁻¹¹, and two on the SAE Aero Competition¹²⁻¹³. These papers would be good resources for a school looking to enter one of these competitions for the first time. Allison et al. at the University of Colorado discuss the challenges of building a flying wing instead of a conventional configuration⁷. Cowin and Kelly¹² discuss the challenges of having students from different majors work on the project, which relates to the ABET outcome to function on multi-disciplinary teams. Seven additional references were found in the literature on internal DBF projects developed by various universities¹⁴⁻²⁰ that include balloon satellites¹⁷ and rocket-propelled gliders¹⁸.

Project Description

For the students, the main objective of the project is to design and build a glider that will travel further than their classmates’ gliders, with the additional educational objectives of:

- To understand the fluid forces of lift and drag.
- To use a numerical method to solve an ordinary differential equation,
- To work on a team and use design methods to solve an engineering problem.
- To use engineering equipment (wind tunnel) to make engineering measurements.

The students have complete control over the glider design and fabrication. The students can select the airfoil shape and aspect ratio of the wings. The grade for the rocket project is divided into the following categories: Final Written Report (40%), Accuracy of Glider Trajectory Prediction (20%), Distance Glider Traveled (20%), Economic Efficiency (15%), Aesthetic Appeal of Glider (5%). A Preliminary prediction report is due the class period before the glider launch, in which the students must show a 2D glider trajectory prediction. The final project report is due the week after the launch. The final project report must include a Budget Report, a Predictive Model Report (including all MATLAB codes used), an Aerodynamics Testing Report that includes a summary of wind tunnel testing, and a report on the Final Measured Performance of the Glider. Accuracy is based on how close the computed prediction of glider flight distance

comes to the actual distance traveled in final testing. For the economics part of the contest, students pay Monopoly Money according to the following rates:

Materials	<u>Rate</u>	<u>Minimum Charge</u>	
1. Foam	\$1 per in ³	\$5	
Facility fees			
1. Wind tunnel	\$60/hour	\$10	
2. Launch fee	\$20/launch	\$20	
Consulting fees			
1. Professor	\$40/hour	\$10	(first visit free)
2. TA	\$20/hour	\$10	
3. Students	\$10/hour	\$5	

The glider should be build almost entirely out of foam. Glue or adhesive may be used to attach pieces of foam to each other. There should be no sharp or pointy edges on the gliders. The students must use solid modeling software (AutoCAD, Solidworks, or Pro-E) to create a model to import to the CNC machine. Either the lab TA or Professor must be present at all tests. Lab time is scheduled on a first-come, first-served basis.

Students were assigned into teams of 4 to build a glider. There were 32 students in the course and 8 gliders were built. The only constraints on the project were that the glider be made solely of foam (glue or adhesive was allowed to attach the different pieces of the gliders. Each team's glider was built from a single piece of 2 ft by 4 ft by 2" thick foam. The students thus had to consider the way in which they cut glider pieces out of the sheet in order to maximize the usage. As this was the first experience using a CNC milling machine for all of the students, many groups decided to make test pieces to test their manufacturing skills before beginning on the final glider. They discovered the importance of tool path, tool size, and tool shape in the quality of the final parts made. The project also used material from their numerical methods course and their drafting course. CAD software used by the student teams included AutoCAD, SolidWorks, and Pro-E.

The facilities that are available to the students to complete this project include a low-speed subsonic wind tunnel, a CNC milling machine, the facilities of the machine shop (band saw, drill press, manual lathe, scroll saw, etc.) and general work space in the Fluid Mechanics Lab and the Project Lab. Computer software used will be XFOIL or FOILSIM for CFD simulations and MATLAB or EXCEL for trajectory simulations. Additional reference material that may be useful to the students include texts on wind tunnel testing, such as that by Barlow²¹, a general aerodynamics textbook^{22,23}, an aerodynamics reference book such as Hoerner²⁴ or Blevins²⁵, and the original NACA report on airfoil section shapes²⁶ or the summary from the NASA History Office by Talay²⁷. Students are responsible for any necessary calibration of wind tunnel measurement equipment.

Each member of the team must contribute something tangible to the project. Each person should have a primary area of specialization listed in the team report. These areas could include: Prototype assembly, Modeling, Report Writing, Experiments, Launch Specialist, etc.

Airfoil Geometry Generation

While any airfoil shape or group of airfoil families can be used, the NACA-4-digit series has the advantage that the geometry is completely and easily determined from the airfoil name. The following discussion of the NACA 4-digit airfoil series is adapted from the fluid mechanics textbook by Post²⁸. The first attempt to systematically characterize airfoil shapes performed by the National Advisory Committee on Aeronautics (NACA), which was the predecessor organization to NASA. NACA created specifications for airfoils classified in the 4-digit series, 5-digits series, and 6-digit series, among others. The more complex 5 and 6 digit series will not be discussed here. In the NACA four digit series, a four-number designation is used to define each airfoil uniquely by specifying the geometry. The first number of the 4 digits specifies the maximum camber, **m**, of the airfoil as a percentage of the chord length, *c*. The second number in the name specifies the position, **p**, of the maximum camber from the leading edge in tenths of the chord length. The camber is the amount of curvature in a wing. A wing with zero camber is symmetric. The last two digits together specify the thickness, **t**, of the airfoil as a percentage of the chord. So for example, a NACA 4515 airfoil has a maximum camber of 4% of the chord, located 50% of the chord back from the leading edge (halfway back), with a maximum thickness of 15% of the chord. As another example, a NACA 0012 airfoil is a symmetric airfoil, with a maximum thickness 12% of the chord. A symmetric airfoil generates no lift at zero angle of attack, and thus must be flown at positive angle of attack in order to generate lift. The NACA 2412 airfoil has 2 percent camber at $x = 0.4 c$ from the leading edge and is 12 percent thick. The 4-digit number is sufficient to generate the shape of the airfoil. The four digits can be written as NACA **mptt**. From the values of *m* and *p*, the equation for the mean camber line can be generated as

$$y_c = \frac{m}{p^2}(2px - x^2) \quad \text{for } 0 < x < p$$

and

$$y_c = \frac{m}{(1-p)^2}(1-2p+2px-x^2) \quad \text{for } p < x < c \quad (1)$$

Here *x* is the axis along the length of the airfoil running from the leading edge to the trailing edge, and *y* is the height above (or below) the *x*-axis. To generate the profile of the airfoil the thickness above and below the mean camber line must also be known. By definition, the thickness above and below the mean camber line at each point *x* is the same. The equation for the local thickness, *y*, as a function of the *x* location is

$$y = \frac{tt}{0.2}(0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4) \quad (2)$$

The locations for the upper and lower surfaces of the airfoil at each axial location *x* is taken by adding or subtracting *y_t* to *y_c* respectively. Further geometric constraints on the NACA 4 digit airfoil are that $y_c = 0$ at $x/c = 0$ and $x/c = 1$. The maximum value of $y_c = \mathbf{m} * c / 100$ occurs at $x/c = \mathbf{p} / 10$, and also at this point $dy_c/dx = 0$.

With Equations (1) and (2) the 2D geometry of the airfoil section can be defined, using software such as MATLAB. MATLAB can be programmed to output the coordinates in a file

that can be imported to solid modeling software such as Pro-E. When an analysis is to be conducted on an airfoil with a chord lengths not equal to one, the coordinates for the airfoil must first be found for a chord length of one and then multiply the coordinates, both x and y, by the desired chord length. As referenced in Figure 4, the coordinates for the upper surface can be found with the following equations:

$$\begin{aligned} x_u &= x - y_t \sin \theta \\ y_u &= y_c + y_t \cos \theta \end{aligned} \quad (3)$$

Likewise the lower surface coordinates can be found using the equations below:

$$\begin{aligned} x_l &= x + y_t \sin \theta \\ y_l &= y_c - y_t \cos \theta \end{aligned} \quad (4)$$

where x is the position along the chord, y_t is the corresponding thickness distribution and θ is the local angle between the previous point and current point. The leading edge radius of the four-digit airfoils is defined by the equation:

$$r_t = 1.1019t^2 \quad (5)$$

where the center of the circle this radius defines is located at 0.05 percent of the chord on the mean line. Through the use of the above equations any number of four-digit airfoil coordinates for the upper and lower surfaces can be defined.

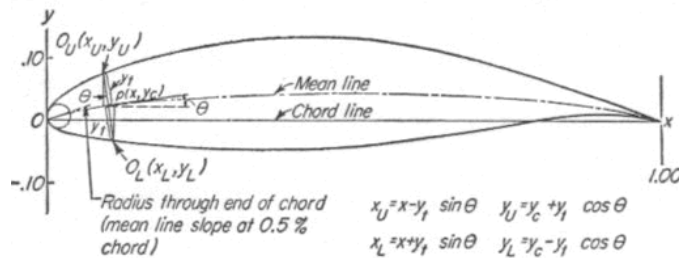


Figure 1: Visual definition of four digit airfoil geometry.²⁶

Aerodynamics Simulations

XFOIL is an interactive program for the design and analysis of subsonic isolated airfoils. XFOIL was developed by Prof. Mark Drela, Massachusetts Institute of Technology, and is freely available for download as open-source software. XFOIL also includes several standard airfoils in its database, including the NACA 4-digit series. Once the airfoil geometry is selected or defined, the user has to specify the Reynolds number, Re and the angle of attack, α, to perform a simulation. The results that are outputted by XFOIL include a plot displaying the pressure distribution along the airfoil, and the following data are displayed on the plot:

1. Lift coefficient,

2. Pitching moment coefficient,
3. Coefficient of Drag,
4. Lift/Drag ratio.

XFOIL can run a series of simulations at different angles of attack and output the results to a text file, which can be read in MATLAB. See the Appendix for an example of exact commands to be entered into XFOIL. A screenshots of the results for a NACA 2412 airfoil is shown in Figure 2. Some student groups alternatively chose to use JAVAFOIL or FOILSIM, screenshots of which are shown in Figures 3 and 4, respectively.

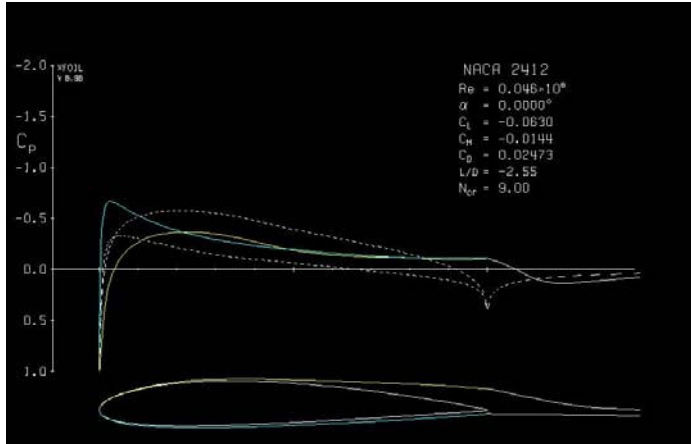


Figure 2: NACA 2412 XFOIL PRESSURE DISTRIBUTION ($\alpha = 0$)

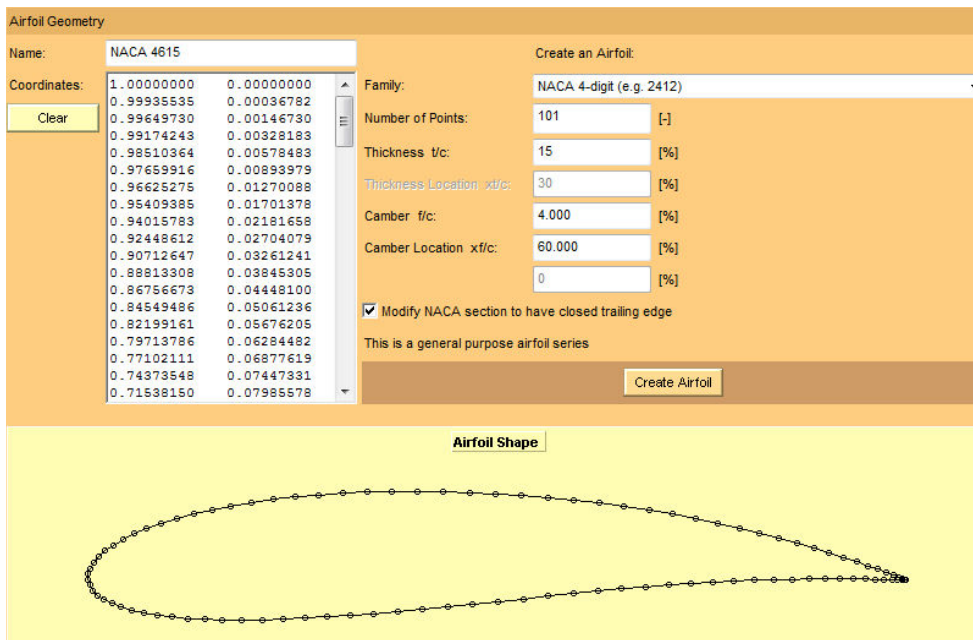


Figure 3: NACA 4615 Airfoil modelled in JAVAFOIL.

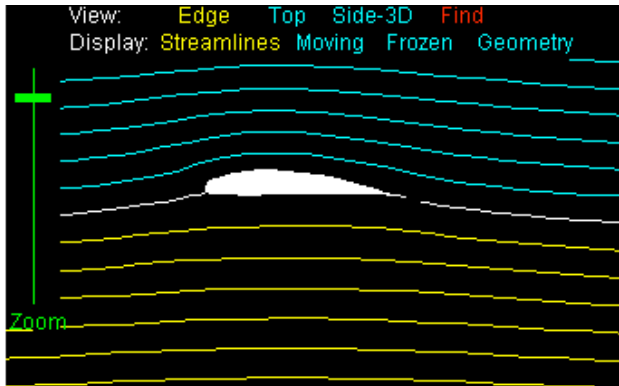


Figure 4: FOILSIM prediction of air flow around SG6043.

Glider Construction and Manufacturing

Two graduate students validated that it was in fact possible to make wing sections from solid foam insulation using the available facilities before the project was implemented in the junior-level undergraduate course. Suitable proportions, based on the size of available foam, were used to design the airfoil on ProE Wildfire 3.0, and CNC code was generated with the appropriate post processor. Figures 5 and 6 show a screenshot of the solid model created and the actual machined airfoil section. Foam was the material used to machine the airfoil on the CNC machine due to its low weight and ease of machinability.

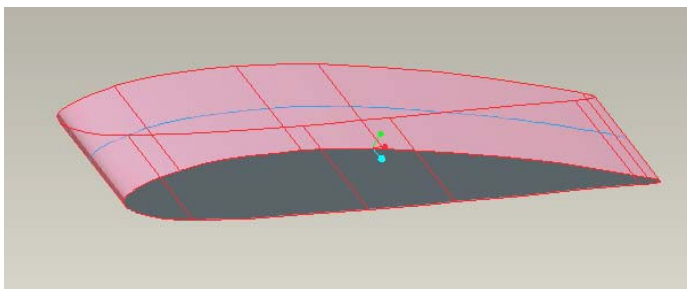


Figure 5: Surface profile used by CNC milling machine.

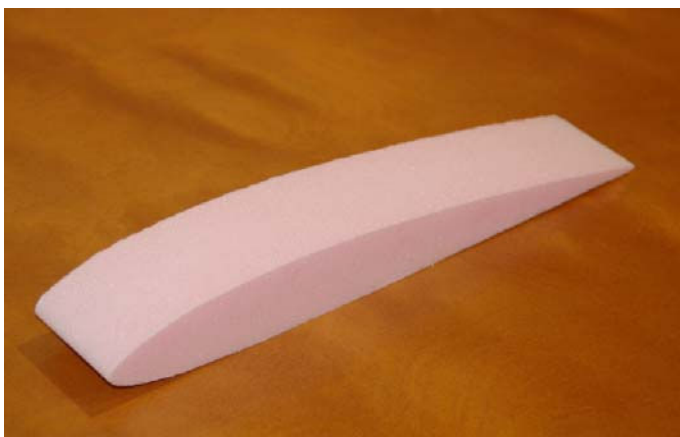


Figure 6: Completed foam wing section created by CNC milling machine.

Though not required in the project, some groups also chose to make the fuselage on their glider in the CNC to ensure a smooth, controllable surface geometry. Figure 7 shows an example of a fuselage half being made in the CNC from the block of foam. Due to the limitations of the size of the CNC working volume, the fuselage sections typically had to be made in two or more segments, which were then assembled.

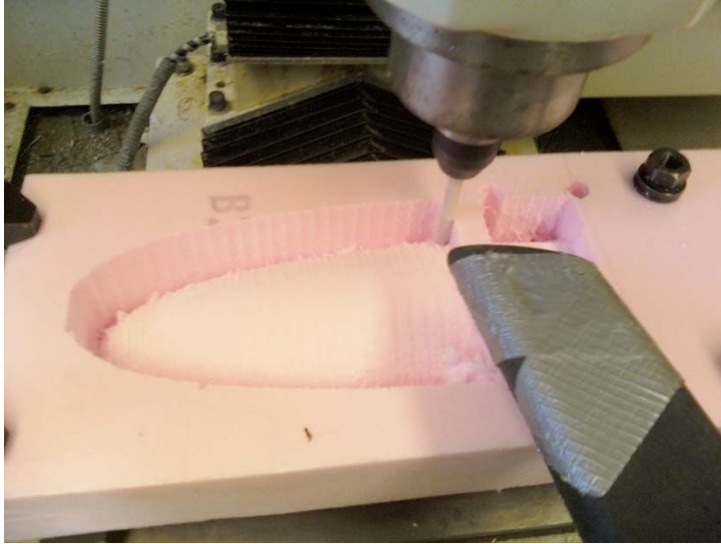


Figure 7: CNC Mill Machining Half of the Fuselage.

Wind Tunnel Testing

One requirement of the project is that the students validate the 2D CFD simulations with experimental data. Teams either made an airfoil section of the wind they used, or some teams made an additional scale model of the final wind used on the glider. Figure 8 shows a picture of a foam airfoil in the wind tunnel. The wind tunnel results typically showed significantly lower L/D ratios than the model predictions. Students attributed this to the rough surface of the foam.

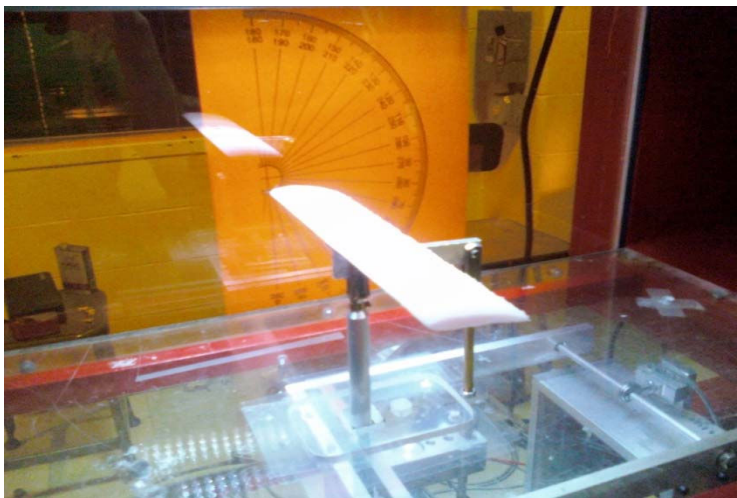


Figure 8: Airfoil section being testing in wind tunnel to verify 2D CFD simulations.

MATLAB Trajectory Simulations

Figure 9 shows an example of basic nearly parabolic trajectory of the students' MATLAB codes. In discussions with the students after launch, it was found that they typically assumed a ballistic trajectory and did not account for the possibility in changes of angle of attack after the glider was launched.

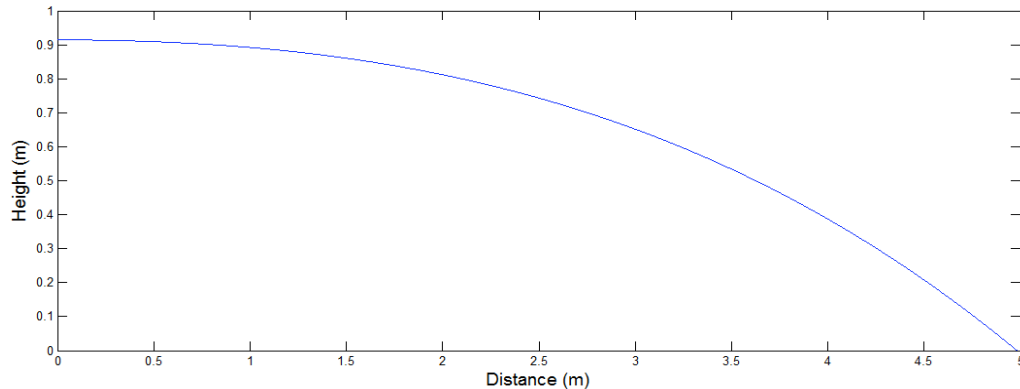


Figure 9: 2D MATLAB glider trajectory prediction.

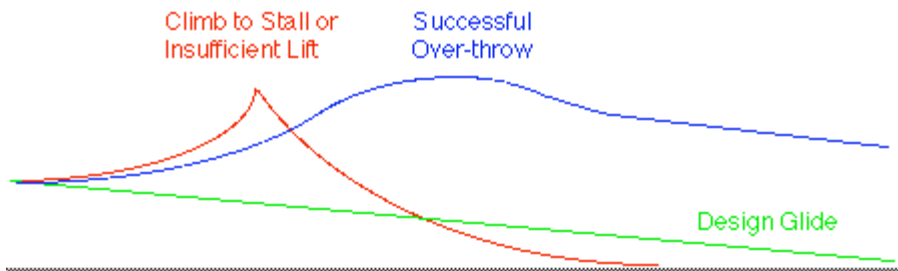


Figure 10: Possible glider paths. (does not show possibility of loop-de-loop).

Results

While most groups built fairly conventional designs, there were some interesting variations. One group built an adjustable tail. One group's glider performed a loop during the test launch. One team stretched the rules by adding a large amount of glue to the nose of the glider to move the center of mass forward and insure stability. All of the 8 teams went with a conventional design with a basic tail. 6 of the teams went with a straight-wing design while 2 went with a swept-wing design. One team made their fuselage body hollow so as to be able to change the center of mass without changing the aerodynamics. The MATLAB predictions varied from 6.5 ft to 19.5 ft, with an average of 14.0 ft predicted. Actual travel distances varied from 7 ft to 68 ft, with an average of 32 ft. The students were surveyed about the project at the end of the semester and asked the following question:

The amount I learned from doing the Glider Project was worth the time and effort I put into it.
a) agree b) disagree

a – 87%, b – 13%



Figure 11: Final Launching. Initial launch speed was measured with a radar gun to confirm the initial launch velocity used in MATLAB simulations, which was found by measuring the spring constant of the elastic band.

Conclusions

This paper outlines a design-build-fly project that can be used by educators to teach engineering design, and also includes aspects from many disciplines of mechanical engineering, including engineering economics, engineering graphics and solid modeling, instrumentation and measurements, numerical methods and simulation, and manufacturing. Most schools will have sufficient hardware on hand to perform the project, and the only actual cost incurred will be that for the material (foam). An additional reference that may be useful to students is the UIUC airfoil geometry database²⁹.

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APPENDIX - XFOIL procedure for NACA 2412 Airfoil

Once XFOIL has been installed to load an airfoil we just type in the standard airfoil. For example, we have used NACA 2412 in this project. So, we just type in

```
XFOIL c> NACA 2412
```

XFOIL returns some specifications of the selected airfoil when this command is typed. Pane command can be used to smoothen out the airfoil geometry. This ensures that the airfoil obtained does not have panels that create very sharp edges. OPER sublevel produces a prompt

```
.OPERi c> - The 'i' next to OPER indicates that XFOIL is in inviscid mode. To go to viscous mode we type 'visc'. This produces the prompt:
```

```
.OPERv c> - The user is prompted to enter the Reynolds Number for the flow. We now input different values for angle of attack. The command used for the same is
```

```
.OPERv c> - alfa 6
```

This command results in a plot displaying the pressure distribution along the airfoil. There is a dashed line plot besides the normal plot. The dashed line plot displays the inviscid flow model and the normal line plot displays the viscous flow model. Thus, we could easily compare viscous and inviscid flows. To generate a simulation for a series of angle of attack, we follow the following steps:

```
.OPERv c> - iter 1000
```

is used to increase the number of iterations. This done so that we can avoid any unconverged solutions for a particular angle of attack.

```
.OPERv c> - pacc
```

enables point accumulation and is used to create a text file where data such as Pitching moment coefficient, coefficient of lift and coefficient of drag are stored. We would also be prompted to enter a file name. This text file could be imported to MATLAB for any analysis. Pressing enter when prompted to enter a polar dump filename would result in the command prompt: .OPERva c> - Next we type the command:

```
.OPERva c> - aseq 0 10 .5,
```

which XFOIL runs for a series of angles of attack from 0 to 10 with increments of 0.5 degrees. Next we type in

```
OPERva c> - pacc
```

which disables the point accumulation. To quit XFOIL we press enter until we reach the command prompt XFOIL c> and then type

```
XFOIL c> quit
```