Applying Physics to an Undergraduate UAS Design

Andrew Bellocchio, Bobby Crawford, and Lynn Byers
United States Military Academy, andrew.bellocchio@usma.edu, bobby.crawford@usma.edu, lynn.byers@usma.edu

Abstract - The Department of Civil and Mechanical Engineering at the United States Military Academy requires its graduates to complete an integrative capstone design in their senior year. One of these projects involves the design, construction, testing, and demonstration of a small, highly autonomous, Uninhabited Aerial System (UAS). This particular capstone option was added to the list of available capstone projects in the fall of 2005. In the past, while students have been able to complete the design process relatively well, an area of deficiency for all capstone design teams has been the physical modeling of their design before construction. This paper will describe the progression of physical modeling and analysis for the systems’ air vehicles over the course of the three years of the project’s existence. In the first year, the two teams did little or no modeling. During the second year of the project, with three different teams, some modeling was attempted, but not verified through testing once the designs were constructed. At the start of the third year, one of the faculty advisors developed a detailed procedure for aerodynamic modeling and performance analysis, called the “Alpha .60 Laboratory”. To augment the previous year’s design pedagogy with an inductive learning component, the students were required to complete the laboratory on an existing airframe. They were then required to apply the same analysis to each alternative developed through the engineering design process. Upon selection and construction of their final design, the students will be required to validate their analytical predictions through flight testing. Preliminary results have shown marked improvement in the detail of the analysis and the level of the students’ understanding of the underlying physics. An assessment of the laboratory’s impact on this year’s designs will also be presented.

Index Terms – aircraft performance, inductive learning, propeller efficiency, radio controlled airplane laboratory, Uninhabited Aerial System (UAS)

INTRODUCTION

A major component of the mechanical engineering program in the Department of Civil and Mechanical Engineering at the United States Military Academy is a year-long capstone design during the students’ senior year. This component culminates with the fabrication of a prototype and presentation of the design to the customer. Before cadets begin their capstone designs, they are first taught the mechanical engineering design process. This is evaluated through frequent submissions linked to the phases of the design process. While necessary, teaching students the design process immediately before they begin their capstone design project causes an unintended effect. Students tend to focus the majority of their effort on the design process and its related products while neglecting the underlying physics and engineering. In fact, many of the “customers” and other project judges noted that “the projects moved directly from the conceptual and preliminary design phases to the actual construction phase without any modeling or analysis to predict performance.” [1]

A recent addition to the list of available capstone design projects was the design, construction, testing and demonstrations of a small, highly autonomous Uninhabited Aerial System (UAS). Because students did little modeling in the first two years of the project, faculty advisors sought a way to incorporate physics-based modeling into their students’ design project. This was accomplished with the development of a hands-on laboratory that guided cadets through a detailed procedure for aerodynamic modeling and performance analysis.

This laboratory accomplishes two major goals. The first is that, by requiring the students to complete the laboratory on a student built “stock” airframe, they add valuable experience to their schemata with radio control (RC) airframes prior to beginning their design. The “stock” airframe chosen was the Alpha .60 and is shown in Figure 1. The second goal accomplished is that the students can then apply the same laboratory process to their own airframe choices. This knowledge gained with the laboratory teaches students how to add physical modeling and performance prediction to their design.
identifying several learning style dimensions which can be used to describe a given learner. One of these is an Inductive/Deductive dimension. Their research indicates that over half of engineering students and professors surveyed consider themselves to be inductive learners while almost all engineering instruction is geared towards deductive learners. Unfortunately, almost all engineering and science instruction has been historically deductive in nature (i.e. – lecture).

Some of the characteristics of inductive learning identified by Prince and Felder [3] are listed below:

- Is learner-centered, constructivist in philosophy, involves active learning, and is collaborative
- Is never purely inductive – there are still deductive components
- Filters new information through a person’s ‘schemata’ – the sum of prior experiences (knowledge, belief, preconception, prejudice, fear, etc.)

Felder states that no one student is an absolute, but favors one style over another to a certain degree [2]. Information taught in the less preferred method has a greater chance of being ignored and quickly forgotten by the student. Hence, a modification of teaching to encompass multiple styles of learning, can greatly improve students’ attitudes toward a subject matter. Felder favors a multi-style approach to teaching engineering, stating that while students should be taught in their preferred mode, they should still be challenged with other instruction modes to facilitate a more complete development.

Why develop an additional component to an already lengthy senior design experience?

According to Prince and Felder [3], a project-based exercise is one of several inherently inductive learning vehicles. The UAV capstone project contains almost all of the features identified in their paper:

- A major project provides the context
- Active learning is inherent, it is almost entirely hands-on
- Motivated by a complex, ill-structured, open-ended real-world problem
- Questions/problems provide the learning context
- Students discover/shape the course content
- Primarily self-directed
- Team-based collaboration

In order to facilitate the accumulation of new knowledge in the capstone exercise, the faculty wanted to find a way to enhance the students’ schemata. The Alpha .60 laboratory exercise was designed for this purpose.

THE NEED FOR MODELING AND PERFORMANCE PREDICTION

The students learn the mechanical engineering design process during the first 13 lessons of their course, Mechanical Engineering Design. This course teaches students to applying the mechanical engineering design process to an individual project in preparation for the students’ participation on their year-long capstone design project. The end result of their capstone design is a student-built, working prototype. The course text [3] takes the students through the design process from problem definition to detail design (Figure 2) [4]

As part of the conceptual design phase, early in the design process, the students generate a Quality Function Deployment (QFD), which is a tool that translates the customer requirements into engineering characteristics. These engineering characteristics feed into the design specification list that is a measurable description of the design. The design specification list includes the engineering characteristics and their target values or range of values. At this point in the design process, the only information the students have to set these engineering characteristic targets is information they have obtained by benchmarking similar existing designs.

During the second year of the project, one capstone design team constructed a mathematical model of their design in order to refine the engineering characteristic target values and predict some aspects of performance of their design. The team used the aircraft design process as outlined in Anderson’s book [5] with limited success. However, due to the challenges described later, the results were questioned and never verified once the prototype was constructed.

DEVELOPMENT OF THE LABORATORY

In an effort to inject more engineering early into the design process, the authors introduced a physics-based, aircraft
performance laboratory. The timing could not have been better. As the teams entered the conceptual design phase, the aerospace engineering members were studying aircraft performance in the undergraduate course ME481 Aircraft Performance and Static Stability. This created an excellent opportunity for cadets to apply their new aircraft design skills in a practical setting to the capstone UAS design.

The authors based the performance model on Anderson’s aircraft design process [5] as taught in ME481; however, the nature of the UAS capstone design presented several unique challenges for predicting the performance of the low-speed, radio-control sized airplanes:

- **Complex Undergraduate Design:** The UAS capstone demands complex, multi-disciplinary design that goes beyond the level of traditional undergraduate design found in AIAA’s or SAE’s “Design, Build, Fly” competitions. Building a completely autonomous airplane required teams to install an autopilot, independent electrical power system, and communication systems to a ground station. With much to do, time was short; therefore, any physics-based model had to be relatively simple to use and learn in a couple of weeks.

- **Selection of an Airframe:** Since the project is limited to only two semesters and a good portion of cadet time is occupied with computer science and electrical engineering tasks, teams selected commercial, off-the-shelf radio control (RC) airframes. Although this ensured a flight worthy airplane, it forced teams to approach the design process backwards. Instead of designing wing and airplane geometry to meet engineering targets, teams must, in essence, reverse engineer a commercial airframe in order to predict its performance.

- **Limited Manufacturing Data:** RC airplane manufacturers typically only publish empty weight, span, chord, propeller size and pitch, and engine size. Power curves, drag polar, and engine performance are usually unknown even to the manufacturer. It is an industry of hobbyists who design from best practices and experience. As a consequence, the physics-based model must generate the design parameters from the limited specifications available.

- **Low speed flight:** RC airplanes fly at low speeds with Reynolds Numbers between 300,000 to 1,000,000 [6]. At these low Reynolds Numbers, a wing’s lift curve and maximum coefficient of lift decrease. Additionally, there is limited published airfoil data at such low speed flight. Fortunately, [6] and [7] are excellent sources of low-speed airfoil charts and aerodynamics specific to RC flight.

### Drag Polar

The drag polar is an expression of the airplane’s aerodynamic efficiency. Hence, determining an aircraft’s drag polar is a key step in predicting its performance.

Traditional drag polar development analyzes the flow over the wing, tail, and sections of the fuselage as outlined by Lan and Roskam [8]. Wind tunnel testing then supplements these preliminary results. This drag polar at subsonic flight takes the form

\[
C_D = C_{D_0} + KC_L^2. \tag{1}
\]

where

- \(C_{D_0}\) is the zero lift drag coefficient
- \(K\) is the proportionality constant
- \(C_L\) is the coefficient of lift

Unfortunately, RC airplane manufacturers do not publish the detailed geometry required for traditional drag analysis. Neither is it practical, in terms of time or money, to have undergraduate students conduct extensive wind tunnel testing for each potential airframe. The solution is a hybrid of drag models taken from the commercial software MotoCalc, ElectriCalc, and Gyles AeroDesign Drag Estimator. This drag estimate sums the zero lift drag, \(C_{D_0,body}\), of the body (minus wing) based upon drag contributions of an airplane component’s attributes. An example for the Alpha .60 airplane is shown in Table I [9] where \(C_{D_0, body}\) totals 0.040.

### Table I: Profile Drag Estimate

<table>
<thead>
<tr>
<th>Airplane Section</th>
<th>Baseline Smooth Configuration (add 0.022)</th>
<th>Drag Modifiers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage</td>
<td>Circular or Elliptical (add none)</td>
<td>Rounded Corners (add 0.003)</td>
</tr>
<tr>
<td></td>
<td>Rectangular (add 0.005)</td>
<td></td>
</tr>
<tr>
<td>Surface Finish</td>
<td>Smooth (plastic film) (add none)</td>
<td>Average (fabric) (add 0.003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rough (bare wood) (add 0.005)</td>
</tr>
<tr>
<td>Landing Gear</td>
<td>None or Retractable (add none)</td>
<td>Fixed with Pants (add 0.003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fixed (add 0.010)</td>
</tr>
<tr>
<td>Protrusions</td>
<td>None or few (add none)</td>
<td>Some (scale details) (add 0.003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Many (wires, struts) (add 0.010)</td>
</tr>
<tr>
<td>Column Sum</td>
<td>0.022</td>
<td>+0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+0.015</td>
</tr>
</tbody>
</table>

The zero lift drag, \(C_{D_0, wing}\), from the Alpha .60’s Clark-Y airfoil at a low Reynolds Number is from wind tunnel testing at the Massachusetts Institute of Technology in 1924 [6]. Assuming the interference drag between body and wing is negligible; the zero lift drag is the sum of the body and wing drag

\[
C_{D_0} = C_{D_0, body} + C_{D_0, wing}. \tag{2}
\]

The second term in (1) is the induced drag, which is the square of the lift coefficient times a proportionality constant \(K\):
where

\[ C_{Dj} = KC_l^2 \]  (3)

with the drag polar (5) known, teams can predict the airplane’s total drag and, hence, power required to fly at a given airspeed (Figure 4).

\[ e \quad \text{is the Oswald Efficiency Factor} \]
\[ AR \quad \text{is the wing’s aspect ratio} \]

Low-wing planes average an Oswald Efficiency Factor of 0.6 while high-wing planes, such as the Alpha .60 average 0.8 [10]. For the Alpha .60 this yields a K of 0.070 and a total drag polar shown in (5) and Figure 3.

\[ C_D = 0.058 + 0.070C_l^2. \]  (5)

Lift to drag ratios calculated from the drag polar measure the airplane’s efficiency with a quantifiable number. Table II shows these ratios and other key performance parameters of the Alpha .60.

**Table II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds Number over wing</td>
<td>Re</td>
<td>560,000</td>
<td>[-]</td>
</tr>
<tr>
<td>Zero Drag Coefficient</td>
<td>C_D</td>
<td>0.058</td>
<td>[-]</td>
</tr>
<tr>
<td>Proportionality Coefficient</td>
<td>K</td>
<td>0.070</td>
<td>[-]</td>
</tr>
<tr>
<td>Lift to Drag Ratio</td>
<td>L/D</td>
<td>7.85</td>
<td>[-]</td>
</tr>
<tr>
<td>Lift to Drag Ratio (L/D)max</td>
<td>L/D</td>
<td>8.54</td>
<td>[-]</td>
</tr>
<tr>
<td>Maximum Lift Coefficient</td>
<td>C_l,max</td>
<td>1.12</td>
<td>[-]</td>
</tr>
<tr>
<td>Wing Loading</td>
<td>W/S</td>
<td>1.58</td>
<td>lbf/ft²</td>
</tr>
<tr>
<td>Thrust to Weight Ratio</td>
<td>T/W</td>
<td>0.70</td>
<td>[-]</td>
</tr>
<tr>
<td>Maximum Static Thrust</td>
<td>T_{max,static}</td>
<td>7.31</td>
<td>lbf</td>
</tr>
<tr>
<td>(tested at 10,270 rpm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Shaft Horsepower</td>
<td>P</td>
<td>0.72</td>
<td>shp</td>
</tr>
<tr>
<td>(estimated at 10,270 rpm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Power Available</td>
<td>P_max</td>
<td>0.47</td>
<td>hp</td>
</tr>
</tbody>
</table>

**Power Available**

The power available is the full throttle power provided by the propeller at a given airspeed. Any power greater than the power required, or excess power, may be applied to maneuver at load factors greater than one such as turn or climb.

To find the available power and calculate the excess power, the teams first modeled the propeller-engine performance. Engine brake shaft horsepower for a 2-cycle engine such as the Alpha .60 or 4-cycle engines also found in RC airplanes, remains constant with respect to velocity (any ram effect is negligible). Propeller performance, unfortunately, is more difficult to model because as forward velocity increases

- **Thrust decreases.** While engine power remains constant with increasing airspeed, propeller thrust decreases linearly.
- **Propeller efficiency changes.** A propeller has a changing propulsive efficiency (or propeller efficiency), \( \eta_{pr} \) with respect to the direction of the relative wind across the propeller. The relative wind direction is a function of forward flight and the propeller’s rotational velocity. The ratio between the two wind velocities is called the advance ratio, \( J \). Since the advance ratio represents the direction of the relative wind, propeller efficiency is also a function of \( J \). This is because propellers are designed for optimal performance at a given pitch and advance ratio. Thus, a fixed-pitched propeller installed in RC airplanes is inefficient at lower speeds of forward flight, then increases to an optimal point at one airspeed before it decreases at high velocities (Figure 5).

\[ \text{FIGURE 3} \]

**DRAG POLAR OF THE ALPHA .60 RC AIRPLANE**

\[ \text{FIGURE 4} \]

**POWER CURVE OF THE ALPHA .60 RC AIRPLANE**

\[ \text{Velocity (ft/s)} \]

Power Required
To account for the aerodynamics across the propeller, a designer needs experimental test data or a propeller performance model. This laboratory makes use of the software PropSelector [11]. PropSelector is shareware software that models propeller performance for RC model airplanes at low Reynolds Numbers. It is developed from propeller data collected for NACA in the 1939 [12]. Given the propeller diameter and pitch at a given velocity and speed, the program predicts engine shaft power, thrust, propeller efficiency, and propeller power (power available). Using the program, the Alpha .60 laboratory requires cadets to:

- Predict engine shaft horsepower from a simple static thrust test with speed measured by a tachometer. The Alpha .60’s engine is rated at 0.72 shp at 10,270 rpm.
- Build a propeller efficiency curve as a function of the advance ratio, J. Figure 5 shows the Alpha .60’s 12”x4” 3-bladed propeller efficiency curve.

With the propeller efficiency curve plotted as show in Figure 5, the power provided by the engine driven propeller becomes the product of the efficiency and shaft horsepower. Notice that the power available curve in Figure 4 is not a horizontal line normally found for a variable-pitch propeller. The fixed-pitch propeller power curve has the same shape as the efficiency curve in Figure 5.

Even though shaft horsepower is constant with airspeed, it is dependent on the rotational speed, n. Some “wind milling” occurs at high velocities as the incoming air begins to drive or autorotate the propeller. This has the effect of off-loading the engine’s torque and resulting in an approximately 14% increase in engine rpm at maximum velocity.

**Performance Predictions**

Analysis of the power curves answers the engineering characteristics of maximum airspeed, range, endurance, and maximum rate of climb summarized in Table III. Teams found the fuel consumption needed for range and endurance calculations from static testing.

Use of the lift equation at maximum coefficient of lift yields the stall velocity. To account for tip vortices, the maximum coefficient of lift for a 3D wing, $C_{L,max}$, is taken as 90% of the 2D airfoil [5].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stall Speed</td>
<td>$V_{stall}$</td>
<td>34.5</td>
<td>ft/s</td>
</tr>
<tr>
<td>Landing Distance</td>
<td>$s_{L,land}$</td>
<td>278.1</td>
<td>ft</td>
</tr>
<tr>
<td>Take-off distance</td>
<td>$s_{L,T/O}$</td>
<td>59.0</td>
<td>ft</td>
</tr>
<tr>
<td>Maximum Endurance</td>
<td>$E_{max}$</td>
<td>66:36</td>
<td>minutes:seconds</td>
</tr>
<tr>
<td>Maximum Endurance Airspeed</td>
<td>$V_{E,max}$</td>
<td>35.0</td>
<td>ft/s</td>
</tr>
<tr>
<td>Maximum Range</td>
<td>$R_{max}$</td>
<td>24.9</td>
<td>nm</td>
</tr>
<tr>
<td>Maximum Range Airspeed</td>
<td>$V_{R,max}$</td>
<td>42.5</td>
<td>ft/s</td>
</tr>
<tr>
<td>Maximum Airspeed</td>
<td>$V_{max}$</td>
<td>80.5</td>
<td>ft/s</td>
</tr>
<tr>
<td>Maximum Rate of Climb</td>
<td>$R/C_{max}$</td>
<td>1,023</td>
<td>fpm</td>
</tr>
<tr>
<td>Maximum Static Thrust</td>
<td>$T_{max,static}$</td>
<td>6.69</td>
<td>lbf</td>
</tr>
<tr>
<td>Power Limited Minimum</td>
<td>$V_{min}$</td>
<td>11.9</td>
<td>ft/s</td>
</tr>
<tr>
<td>Velocity*</td>
<td>$V_{min}$</td>
<td>7.1</td>
<td>knots</td>
</tr>
<tr>
<td>Maximum Rate of Climb</td>
<td>$V_{R/C,max}$</td>
<td>47.8</td>
<td>ft/s</td>
</tr>
<tr>
<td>Airspeed</td>
<td>$V_{R/C,max}$</td>
<td>28.3</td>
<td>knots</td>
</tr>
</tbody>
</table>

*Stall will occur prior to $V_{min}$

**Future Work**

Preliminary results of the laboratory are promising. For example, predicted maximum airspeed is within 2% of recorded flight data and predicted static thrust was 8% lower than tested. Still, extensive in-flight testing is needed to verify major assumptions and validate the model. Additional refinements include:

- Further calibration of the simplified zero lift drag estimate using the traditional drag polar development method.
- In-flight fuel consumption tests at best range and endurance airspeeds. The use of a static fuel consumption test may be causing overly optimistic endurance times.
- Accounting for increased engine rpm due to the “wind mill” effect. This will improve the fuel consumption estimate and the engine power estimate.
- Adjustment of the rolling coefficient of friction used for the landing and take-off ground runs. The current value underestimates the impact of friction on the ground rolls. This is causing lower than expected take-off distances and higher than expected landing distances.

**ASSESSMENT OF THE LABORATORY**

The impact of the Alpha .60 laboratory on this year’s UAS capstone designs was assessed using quantitative feedback from a student survey, as well as anecdotal feedback from project judges and faculty.
The UAS design teams completed a student survey that addressed the Alpha .60 laboratory goals. Five of the six questions were formulated mirroring the learning levels in the cognitive domain of Bloom’s Taxonomy [13]:

A. I was involved in the Alpha .60 laboratory
B. The laboratory introduced new knowledge I can apply to UAV mathematical modeling
C. The laboratory improved my understanding of the physics that apply to UAVs
D. The laboratory assisted my team in applying physics to model UAV performance mathematically
E. The laboratory assisted our team in setting the performance specifications for our UAV design
F. The laboratory improved my team's evaluation of its final design

The results of the survey are shown in Figure 6.

Involvement ratings in the Alpha .60 laboratory ranged from ‘1’ to ‘5’ with three of seven students indicating significant participation. The average of the scores was ‘3’, indicating the group as a whole had a moderate investment in the physical modeling of their designs. Using this aggregate approach to analysis, the figure indicates a positive benefit from this emphasis on physical modeling at all levels of Bloom’s hierarchy. The largest benefit from the students’ perspective was at the application level closely followed by the synthesis level of learning. The fact that the students rated the improvement to their knowledge and understanding lower is not surprising since the laboratory content is primarily a reinforcement of theory taught in previous foundation courses.

Project judges were universal in the observation that there was a ‘huge’ improvement in project presentations from the previous year.

- “this year had better results”
- “it was good to see equations (physics) and hear them explained”

Feedback from faculty members advising the UAS capstone design teams supports the quantitative student assessment. Faculty members noted that team members significantly improved their application of underlying physics to model the performance of their UAS airframes, compared to teams from prior years. Despite this improvement, teams did not fully take advantage of the information learned in the laboratory. They failed to reach the two highest levels of Bloom’s Taxonomy with regard to the synthesis of the performance specifications and quantitative evaluation of concept alternatives. Better time management and faculty guidance should push the student learning into these higher levels in the future.

REFERENCES

[12] Lesley, E, P, “Propeller Tests to Determine the Effect of Number of Blades at Two Typical Solidities,” Stanford University, Daniel Guggenheim Aeronautical Laboratory, NACA Technical Note 698, April 4, 1939.

AUTHOR INFORMATION

Andrew Bellocchio, Assistant Professor, United States Military Academy, andrew.bellocchio@usma.edu.

Bobby Crawford, Assistant Professor, United States Military Academy, bobby.crawford@usma.edu.

Lynn Byers, Assistant Professor, United States Military Academy, lynn.byers@usma.edu.