AC 2012-4118: OPTIMIZATION FROM A WORKING BASELINE: A DESIGN EDUCATION APPROACH

Dr. Nathan Delson, University of California, San Diego

Nathan Delson's interests include mechatronics, biomedical devices, human-machine interfaces, and engineering education. He is Co-founder and Past President of Coactive Drive Corp., which develops novel actuators and control methods for use in force feedback human interfaces. Medical device projects include an instrumented mannequin and laryngoscope for expert skill acquisition and airway intubation training. He received his undergraduate degree in mechanical engineering from University of California, San Diego, and then went on to get a doctorate in mechanical engineering from the Massachusetts Institute of Technology in 1994. He was a lecturer and Director of the Design Studio at Yale University for four years, and then returned to his alma matter, UC, San Diego, in 1999. He is now a tenured lecturer and Director of the Design Center in the Department of Mechanical and Aerospace Engineering. He teaches hands-on design courses including an introductory design class, a mechatronics class, and a capstone design class. His interests in design education include increasing student motivation, teamwork, and integration of theory into design projects.

Dr. Mark Anderson, University of California, San Diego

Optimization from a Working Baseline: A Design Education Approach

Abstract

Optimization from a working baseline is a design education approach that has been adopted at University of California, San Diego after watching years of students attempt overly ambitious designs under tight time constraints. The end results were often that designs were completed without time for optimization or comparison of theory to hardware performance, and the educational message of good design practice was not being conveyed. There was specific concern that analysis was not being applied in hands on design projects, rather under time pressure students often resorted to an unguided trial-and-error approach. To remedy this situation, we separated our mechanical and aerospace senior design courses into two distinct projects. Our first senior design project uses the working baseline approach, where students use analysis to optimize a reduced degree-of-freedom system. In these projects students gain design and analysis skills that prepare them to tackle more complex design challenges. A second project is then addressed, which includes all of the wonderful complexity and uncertainty that are characteristic of open-ended problems in engineering design.

Introduction

Compared to industry projects, students design projects are often compressed into a short time period and restricted to use of low cost hardware. These two factors can have the unintended consequence of encouraging unguided trial and error rather than analysis. It is often easier for students to simply build a range of hardware solutions, try them out and keep the one solution that works without ever fully analyzing the system or justifying their design decisions. We wish to convey the lesson that in real-world design, each trial can be very expensive, and therefore experimentation should be guided by theory. These educational challenges have led us to choose a two project approach. The first project still uses low cost hardware and has tight time constraints, yet the design challenge starts with a *working baseline* that is specifically selected so that analysis can improve optimization results. The working baseline projects we have chosen are reduced degree-of-freedom systems with very specific and quantifiable performance objectives. There still remain many areas of optimization, yet these optimizations relate more to parameter selection and detail design, rather than conceptual changes. We do not intend to minimize the importance of conceptual design, but rather have specifically chosen to have students focus in their first senior design effort on a challenge where the concept generation component of the project has already been determined. The second set of projects is truly open-ended and similar to traditional capstone design courses.

The working baseline approach emphasizes analysis, but is distinct from experimental lab course where students conduct a set of predefined experiments. These lab setups allow students to perform experiments well-suited for comparison with theory, but leave no room for design improvements or optimization. The working baseline approach is a true design effort in that each student group modifies and optimizes their hardware setup.

This paper describes working baseline projects that have been developed for two senior-level engineering design courses. In the mechanical engineering design course, students use microprocessor control to improve the performance of a single degree-of-freedom turntable. Students have the ability to optimize the bearings, drive train, gear ratios, sensors, electronics, and closed-loop control algorithm. In the aerospace engineering course, students optimize the performance of a tethered electric airplane that flies in circles around a pylon. Students modify the lifting surfaces and use recorded sensor data to guide their optimization effort.

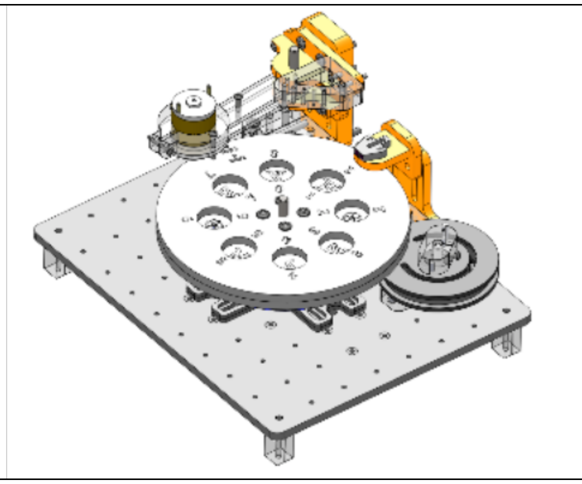
Both the aerospace and mechanical working baseline projects utilize sensors, which allows for comparison of theory to performance as well to quantify the impact of each design change on system performance. In prior years we had introduced sensors and microprocessors into a design course, and we found that the complexity of student projects grew due to the natural tendencies of ambitious students, yet the complex hardware was not well suited to teaching essential design skills. The working baseline approach provides an opportunity for in-depth technical analysis using a configuration that is identical for each project team. Accurate system modeling serves to illustrate how analysis-based optimization can be more productive and less time consuming, than trial-and-error. In addition, it provides a working starting point that motivates the students to strive for an even better solution. Finally, the approach allows a fairly in-depth design problem to be addressed in a relatively short period of time.

Baseline Turntable Project

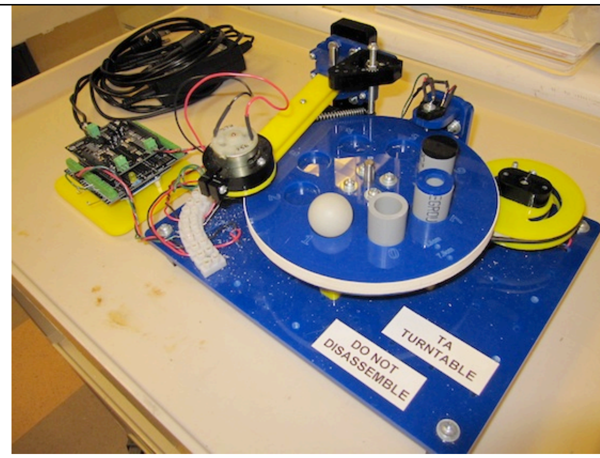
The working baseline project for the senior-level mechanical engineering class is shown in Figure 1. The apparatus consists of a turntable with radius of 79.5 mm. The turntable is driven by a Direct-Current (DC) motor and friction drive. To move the turntable, the motor shaft rotates against an elastic band that grips the outer radius of the turntable. The turntable itself is supported by four thrust bearings located 45 mm from the turntable center. The ratio of the turntable radius to the DC motor shaft radius is 72. The friction drive arm is approximately 127 mm long, and a tensioning spring is located 48 mm from the drive arm pivot point. A pulley and belt system connects the turntable to a potentiometer. The potentiometer provides a measurement of the turntable angular position. The radius of the potentiometer pulley is twice the radius to the turntable pulley. All of the turntable parts are laser-cut from acrylic. The students assemble their own turntable, and have access to the laser cutter to generate design modifications from the baseline.

A microcontroller is used to control the turntable. A 16-series PIC processor was used for many years; however, this year a switch was made to the Aruduino UNO microcontroller. The Arduino offers a software development environment that the students can readily master with very little formal instruction. This capability allows lecture and exercises to emphasize technical analysis and dynamic modeling, rather than software development and debugging.

A specialized dual-channel motor-driver board is used to control the DC drive motor. The motor-driver board accepts a Pulse-Width Modulation (PWM) signal generated by the Arduino microcontroller. The turntable includes eight circular slots that can be used to hold objects. Figure 1 shows a ball and several small sections of PVC pipe. These items are used to develop a contest theme, which will serve to motivate design optimization.



CAD Model



Photo

Figure 1 Baseline Turntable

Each two-person team builds a turntable from a supplied kit parts. The students are expected to analyze each component, as well as the completed turntable, and write a detailed technical report. The equations of motion for the turntable are shown in Table 1. These equations can be seen to represent a single degree-of-freedom system. Methods are available to estimate each modeling parameter both analytically and experimentally. For example, the turntable moment of inertia can be estimated analytically using its physical dimensions and the material density. It can be estimated experimentally by accelerating the turntable using a known applied torque.

Table 1 Turntable Equations of Motion

$$\left(\frac{L_a}{R_a}\right)\frac{di_a}{dt}+i_a=\left(\frac{1}{R_a}\right)\left[V_a-K_b\left(\frac{r_L}{r_m}\right)\frac{d\theta_L}{dt}\right]$$

$$J\frac{d^2\theta_L}{dt^2}+B\frac{d\theta_L}{dt}=\left(\frac{r_L}{r_m}\right)K_t i_a$$

$$J=J_L+J_m\left(\frac{r_L}{r_m}\right)^2 \qquad B=B_L+B_m\left(\frac{r_L}{r_m}\right)^2$$

V_a = applied armature voltage
i_a = armature current
t = time

R_a = armature resitance
L_a = armature inductance
K_b = back EMF constant
K_t = motor torque constant

J_m = motor moment of inertia
B_m = motor friction
r_m = radius of motor shaft

θ_L = turntable position
J_L = turntable moment of inertia
B_L = turntable friction
r_L = radius of turntable

Figure 2 shows an open-loop time response for the baseline turntable. This response plot was obtained by commanding maximum duty cycle to the motor-driver board. The commanded motor direction is reversed at the 0.5 second elapsed time.

The blue line in Figure 2a illustrates the potentiometer position, in analog-to-digital converter counts, as recorded from the actual turntable. The blue line in Figure 2b shows the potentiometer position that is obtained by simulating the turntable equations of motion in Table 1. By comparing these two plots, one sees that the analytical model provides a reasonably accurate representation of the actual system dynamics.

The green lines in Figure 2a and 2b provide further evidence of model fidelity. The green line in Figure 2a was obtained by adding known weights to the turntable, thus changing its moment of inertia as well as the friction of the supporting thrust bearings. The green line in Figure 2b is obtained by adjusting the associated model parameters to reflect an increase in the turntable weight. Students are expected to generate similar comparisons as part of their technical report.

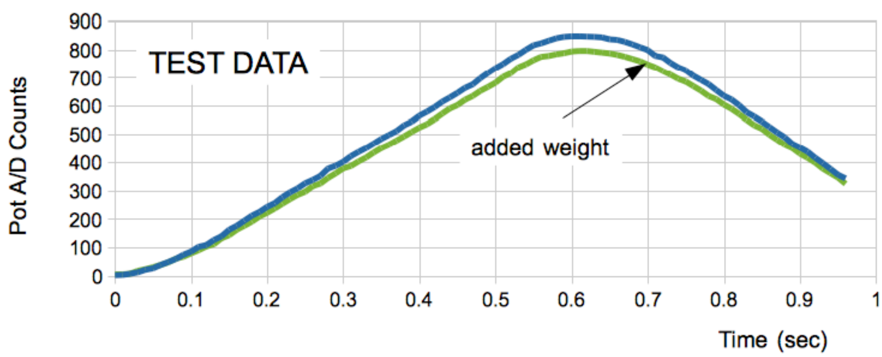


Figure 2a Measured Turntable Position from Step Input

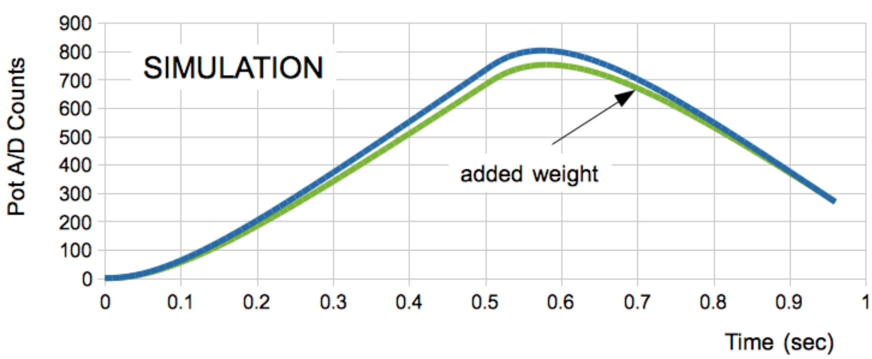


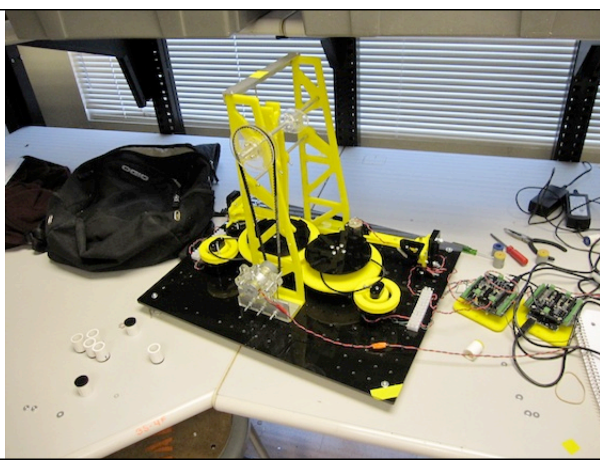
Figure 2b Simulated Turntable Position from Step Input

Turntable Optimization

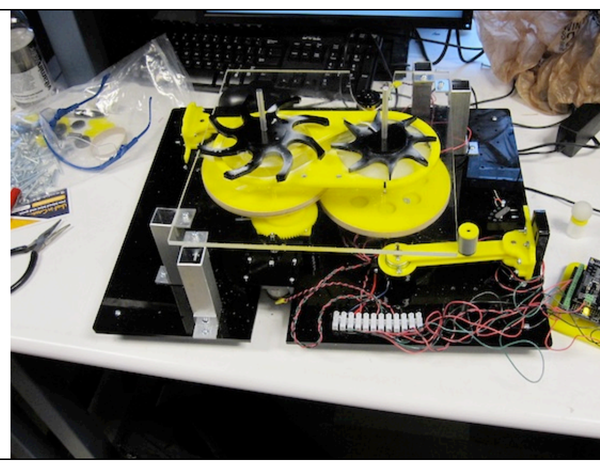
Goals of optimization are motivated by a themed competition. Teams of four students are established by combining two of the paired turntable teams. The result is a four-person team that has two turntables to work with. At this point, additional construction materials are provided, including geared DC motors and additional acrylic material. A shopping cart is also provided, allowing teams to purchase additional items from a fixed budget allowance.

The contest theme and rules are varied yearly to keep the designs fresh and avoid duplication of previous efforts. However, the common element of each contest is to design and build a transfer mechanism that moves items from one turntable to the other as quickly as possible.
Precise control of the turntable position is needed to implement a fast transfer mechanism. This requirement tends to drive optimization efforts, and usually necessitates use of a closed-loop feedback control system. Optimization metrics might include minimum time to achieve a given set point, or a requirement to minimize response overshoot or acceleration levels. Students typically implement a Proportional+Integral+Derivative (PID) control system, but other nonlinear or open-loop control schemes have been attempted. Performance optimization may require tuning the control system gains. However, student teams may also modify turntable components, such as the friction drive ratio, thrust bearing materials, or the turntable itself.

Figure 3 show examples of transfer robots designed and built by student teams. The example shown on the left side of Figure 3 implements a transfer arm, that is activated by a rotating camshaft. The transfer arm slides sections of PVC pipe from one turntable to the other. One microcontroller is used to control both turntables, while a second microcontroller controls the camshaft and transfer arm. Optimization is required in this design to insure that the turntable index slots are aligned when the transfer occurs. The right side of Figure 3 shows an example where rotating guides are used to shift objects from one turntable to the other. A single microcontroller is used to synchronize motion of both turntables. Optimization of this design requires careful consideration of shape of the rotating guides.



Cam-Activated Transfer Robot



Slider-Guide Transfer Robot

Figure 3 Optimized Transfer Robots

For the first time the student reports include realistic plots comparing theory to experimental results. Oral presentations and discussions with students demonstrate an increased understanding of how engineering fundamentals apply to their design. There is a sense among the students that application of theory has a role alongside trial and error.

Baseline Airplane Project

The working baseline airplane project was developed by modifying a commercially-available model airplane kit. The baseline airplane has a wingspan of 46 cm, and fuselage length of about 44 cm. It is powered by a small brushless motor coupled to a ten-ampere electronic speed controller. A student-built example of the working baseline airplane is shown in Figure 4. The airplane is constructed of laser-cut balsa and plywood parts, and is covered with heat-shrunk plastic. The mass of the completed airplane is approximately 150 grams.

Additional components have been added to each airplane kit in order to support technical analysis objectives. Several of the added electronic components can be seen under the left wing of the airplane in Figure 4. The on-board instrumentation includes a three-channel analog signal data logger, a two-axis accelerometer, and a two-channel radio receiver.

The airplanes are flown by attaching wires to a connector on the left wingtip. These wires provide twelve-volt direct-current power to the airplane and its instrumentation. They also restrict airplane motion so that it rotates around a stationary pylon as it flies. The motion is therefore constrained to lie on the surface of cylinder centered at the pylon. The student pilot can control elevator position and motor speed using hand-held, two-channel transmitter that is linked to the receiver onboard the airplane.

Figure 4 Baseline Airplane

Four-person teams are organized so that one student leads in each of the typical aerospace sub-disciplines: aerodynamics, structures, propulsion, and control. Technical reports are required in each of these areas. These reports establish the performance and dynamic characteristics of the working baseline airplane. They also provide a foundation for analysis-based optimization efforts.

Table 2 lists the equations of motion for the tethered airplane. These equations represent the motion of the airplane as it travels around the stationary pylon. The motion characteristics of the airplane are governed by the non-dimensional aerodynamic coefficients. Analytical expressions are available to relate these coefficients to the geometry and mass distribution of the airplane.

Table 2 Airplane Equations of Motion

$$\frac{d\alpha}{dt} = q + \frac{1}{V}\left[g\cos\theta + \frac{F_z}{m}\right]$$

$$\frac{dq}{dt} = \frac{M}{I_{yy}} \qquad \frac{d\theta}{dt} = q$$

$$F_z = -\bar{q}S\left[C_{L0} + C_{L\alpha}\alpha + C_{L\delta}\delta\right]$$

$$M = \bar{q}S\bar{c}\left[C_{m0} + C_{m\alpha}\alpha + C_{mq}\left(\frac{q\bar{c}}{2V}\right) + C_{m\dot{\alpha}}\left(\frac{\dot{\alpha}\bar{c}}{2V}\right) + C_{m\delta}\delta\right]$$

α = angle-of-attack
q = pitch rate
θ = pitch attitude
δ = elevator deflection
t = time

V = airspeed
$\bar{q}$ = dynamic pressure
m = mass
I_{yy} = moment of inertia
g = gravity

F_z = vertical force
M = pitch moment
S = reference area
$\bar{c}$ = mean chord
C = aerodynamic coefficient

A model validation example is illustrated in Figure 5. This example represents the type of analysis results that are expected as part of the student technical reports. The airplane is trimmed at an airspeed of approximately 8 m/s. The pilot applies a full deflection, Trailing-Edge-Up (TEU) elevator input and then returns the control to the trim position. The pilot control input is captured by the on-board data logger and is shown as the orange line in Figure 5a.

Figure 5b compares the actual response of the airplane to the response predicted by numerically simulating the equations of motion in Table 2. The blue line in Figure 5b stems from simulation of the analytical model, using the recorded control input (Figure 5a) to drive the model. The orange line in Figure 5b is the aircraft response recorded by the vertical-axis accelerometer. This data is logged at a rate of fifty samples per second. Much of the noise seen in the flight data stems from electric motor and propeller; however, the mean shape of the recorded acceleration response clearly follows the simulation model.

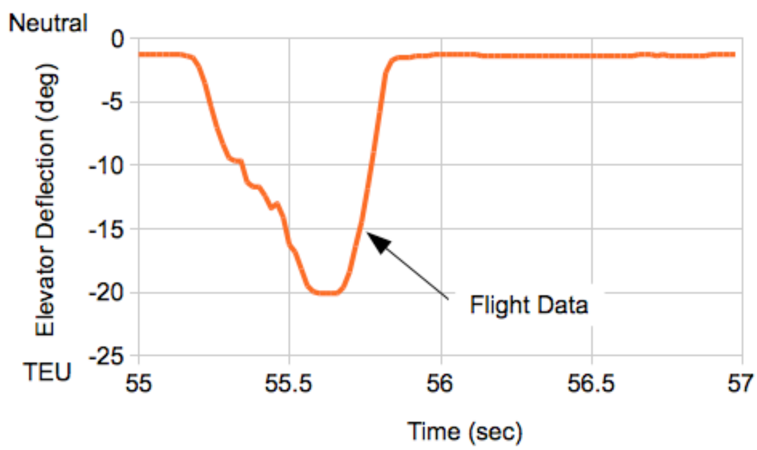


Figure 5a Elevator Input Command Recorded in Flight

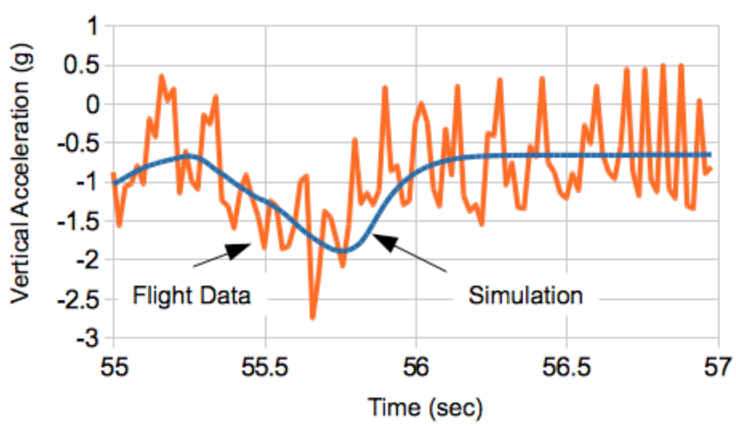


Figure 5b Airplane Flight Data and Model Simulation

Airplane Optimization

Airplane optimization is also motivated by a contest theme. The design metric for the most recent class was to maximize the ratio of time needed to complete three slow laps to the time needed to complete three fast laps. This metric is intended to replicate typically requirements of a carrier-based fighter airplane. Carrier aircraft must be capable of flying at high speeds to complete its intended mission, but also must fly slowly to land on the carrier. These conflicting requirements have led to swept-wing fighters such as the F-14. Wings are swept for high-speed flight and unswept for approach and landing.

Student teams may choose to optimize slow flight by increasing wing span and camber; or they may optimize high-speed flight by reducing wing span and camber. Teams were allowed one pit stop between the timed slow and fast laps so that a configuration change could be made. However, the configuration change could not add or remove items from the airplane. Sweeping or unsweeping wings from a fixed pivot is one obvious configuration change that could be attempted. Other possibilities include deploying wing flaps or other aerodynamic control surfaces.

Figure 6 shows two example airplanes designed and constructed by student teams. The left side of Figure 6 illustrates a modified wing planform. The area of the wing has been reduced, as well as the thickness of the wing airfoil. The most unique aspect of this optimized airplane configuration is the design of the horizontal tail. The surface area of the tail has been reduced and the elevator control surface has been eliminated. Thrust vectoring provides pitch control for this airplane. A wire control arm extends over the wing and attaches the motor to a control servo mounted just behind the wing trailing edge. This control servo controls the pitch attitude of the airplane by changing the thrust line of the motor and propeller.

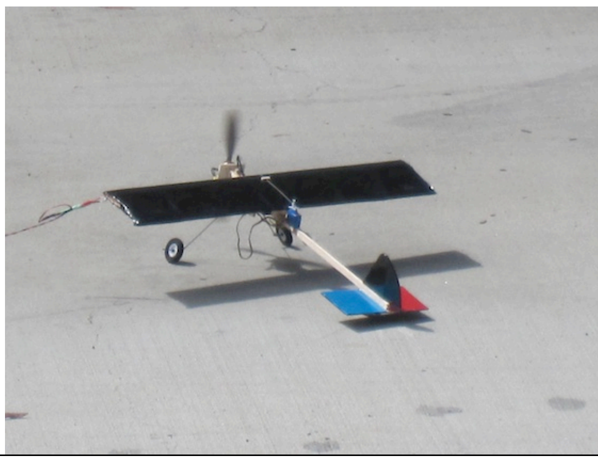
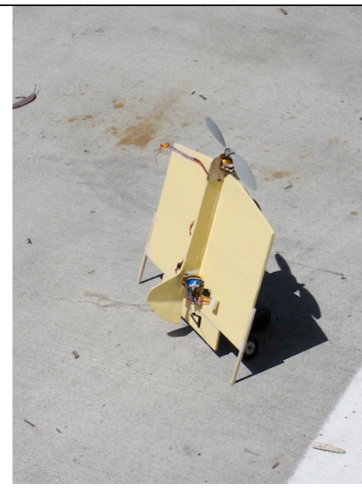
	
Thrust Vector Airplane	VTOL Airplane

Figure 6 Optimized Airplanes

The right side of Figure 6 illustrates an optimized Vertical Take-Off and Landing (VTOL) configuration that was designed by one of the student teams. This ambitious flying-wing configuration completely eliminates the vertical tail. Pitch control is provided a large flap located along the trailing edge of the wing. This design takes advantage of the fact that the thrust-to-weight ratio of the working baseline aircraft is slightly greater than unity. Students were able to analyze and verify this design possibility by testing the baseline aircraft propulsion system using an instrumented propeller test stand.

<u>Concept Generation</u>

Concept generation is a critical part of the design process, as a poor initial concept can lead to lost time and money. This key element is not included in educational design projects that are developed from a baseline. However, the experience that a student has gained from baseline optimization exercise helps to underscore the importance of a good initial concept.

A second design project allows students to gain experience in concept formation. In mechanical engineering, the second design project is an open-ended project that is provided by an outside sponsor. These design problems are solicited from the local community of manufacturing, research, and development companies. The projects typically require delivery of a working prototype, and the majority of the projects represent new, clean-sheet design solutions.

Students in the mechanical engineering design course are formed into teams of typically four to five students. The student teams meet regularly with the industry sponsor, including a "kick-off" meeting at the very beginning of the project. This project kick-off meeting is where design requirements are set. Afterward, the student teams spend several weeks studying the design requirements and developing initial concepts. This activity culminates with a "risk reduction" presentation wherein the student teams describe the design problem along with a short list of promising concepts. They are also expected to identify technical challenges and areas of high risk. Construction of a final prototype takes place during the second quarter of the two-quarter course sequence.

Students in aerospace engineering also gain concept generation experience using a second open-ended project. This second project is formulated such that its solution requires integration of the primary sub-disciplines: structures, aerodynamics, propulsion, and control. Teams generally consist of three to five students. The design problem is developed by the student team and concepts develop only after the problem definition has been approved by the instructor. This second design experience is focused on a full-scale aerospace system. Consequently, the design experience focuses almost all effort on conceptual design. Students prepare a design proposal and participate in a Preliminary Design Review (PDR) at the end of the course.

Open-Ended Design Experiences

A legitimate pedagogical question is whether indeed the working baseline projects improve students design skills in their open-end capstone projects. While it is difficult to quantify performance on different projects with different groups of students, the following examples are presented where students applied noteworthy design skills in their capstone design projects after their working baseline projects.

A recent open-ended design project required a team of mechanical engineering students to design and build an apparatus to test Micro-Electro-Mechanical (MEM) accelerometers. The students had to build a two degree-of-freedom system that rotated a test fixture at specific velocities and angular orientations. When the students began the process of selecting motors, they contacted a vendor who offered a common rule-of-thumb guideline for motor selection and inertia matching. The students were told that the gear ratio should not be less than a certain amount if they have a high inertia to move, and therefore directed them to a direct drive motor with a weight of 9 kg to rotate the 3 kg test platform. Since this was a 2 DOF system, the 9 kg motor would have to be added onto the 3 kg test platform, effectively quadrupling the overall mass that the base motor would have to move. The students were challenged by the instructor to properly model the system rather than rely upon the vendor's rule of thumb. The students developed the equations of motion of the system, and numerically solved the resulting ordinary differential equation. The student team validated their numerical model with a test system and ultimately selected a 2.5 kg motor that satisfied the specifications of the system. The ability of the student team to move beyond a reliance on vendors' rules of thumb and apply fundamental analysis is they type of skills we hope to install in our graduates.

In aerospace engineering, student teams are expected to develop a concept proposal that is intended to solve a "full-scale" design problem in the aerospace industry. Example problems include Single-Stage-To-Orbit (SSTO) vehicles, electric-powered airplanes, and micro-aerial vehicles. The experience of a recent student team helps to illustrate the connection between the baseline optimization and the open-ended design activities. The team was developing a new concept for an environmentally-friendly transport that would eventually replace the C-17. The team spent extra time, early in the project, to parameterize their blended-wing configuration so that its geometry could be described with only fifty-three parameters. Changing any one of these parameters produced an entirely new CAD model that could be subsequently used for aerodynamic analysis. This upfront modeling effort led to significant time saving when many competing configurations were under study.

Conclusion

The approach of starting from a working baseline has been developed after watching years of students generated overly ambitious designs under tight time constraints. The end results were often designs based upon trial and error without sufficient analysis, and the education messages of good design practice were not being conveyed as well as we wanted. In parallel, the introduction of sensors and microprocessors to design projects had many advantageous, but also tended to increase student project complexity and make it even more difficult to apply analysis to design.

The baseline optimization approach briefly separates application of theory from the problem of tackling an open-ended design problem. The key aspect of using a working baseline has been to reduce the complexity of the design challenge. Students are presented with a very clear and focused optimization challenge, which leads them to delve into the engineering details of their system. A reduced degree-of-freedom system can provide a rich resource for teaching the elements of design optimization. Even a single degree-of-freedom turntable can provide a valuable first hand experience in issues such as the relationship between bearing stiction and feedback control gains. Use of such a system provides a way to tie together many of the other technical areas students have pursued during academic studies.

Engineering design courses must expose students to open-ended challenges yet, at the same time, foster an approach to design that is based upon a strong foundation in modeling and analysis. Open-ended challenges can lead to creative solutions that become functional only during the end of the project -- leaving no time for optimization or comparison of theory to experimental performance. The working baseline optimization activity helps students make a successful transition to truly open-ended problems in engineering design.

Acknowledgement

Developing unique and interesting design projects requires special dedication from both the faculty and supporting staff. The authors would like to acknowledge contributions made by Chris Cassidy, Steve Roberts, Tom Chalfant, and a long list of graduate teaching assistants.