AC 2011-868: UNDERGRADUATE CAPSTONE DESIGN: INDUCTIVELY ENHANCED

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Abstract

The Department of Civil and Mechanical Engineering at the United States Military Academy at West Point, New York requires its graduates to complete an integrative, year-long capstone design during their senior year. One of the capstone projects available to the mechanical engineering students in the department's aerospace sub-discipline requires the design, construction, testing, and demonstration of a small, highly autonomous Uninhabited Aerial Vehicle (UAV) for a Department of Defense client. This particular project was added to the list of available capstone options in the fall of 2005.

This paper briefly describes the motivation behind the addition of the UAV capstone design option, resources that were required to start the program, and selected budget data collected during the second and third years of the capstone design. Teams in the first year of the project were limited to a budget of $9,000 each and experienced mixed results during final flight demonstrations. Second year budgets were increased to $12,000 for each team based on feedback from the first-year experience. Performance at flight demonstrations was markedly improved in the second year.

Lessons learned from the first two years were used to significantly modify the program in the third and subsequent years. Students began the design with very little practical, hands-on experience with small aircraft and the associated subsystems. Faculty members spent a significant amount of time researching learning methods and discussing potential modifications to the project structure that would result in a rapid acquisition of foundational knowledge by the students.

In particular, the third year of the program was modified to incorporate an inductive learning experience as part of the project. Students began by building and testing an off-the-shelf, Remotely-Controlled (RC) airplane; modifying it to operate with an off-the-shelf autopilot; and conducting bench and flight testing of the aircraft and its components. The intent of this rapid, three week experience was to develop a cognitive schema that the students could draw upon as they executed the design process and created their original UAVs. This approach, its benefits, and lessons learned are detailed.

Introduction

The content of the Mechanical Engineering program is constantly reviewed in order to ensure it meets the needs of its constituents and satisfies the ABET Engineering Accreditation Commission (EAC) criteria. ABET EAC criterion 4 requires:

> "a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints."[1]

In order to satisfy this criteria, the ME program has developed two semester-long courses that constitute a capstone engineering design experience for its students. The design projects require students to work in teams to design, build, test, and demonstrate a mechanical engineering device. These projects are open ended. The desire is to have students work for an external client on a real world design whenever possible. While the department does have a limited budget to support these projects, external funding is highly desired in order to free up additional funds for projects that may be internally generated. Additionally, there is no programmed space to conduct these projects in the current facilities. This has been solved by converting former laboratories and classrooms to support the addition of these projects.

The best capstone design experiences occur when an external client has a project with the right scope and requirements and this matches up with the right funding and support. In the fall of 2005, the Department of Civil and Mechanical Engineering (D/C&ME) at the United States Military Academy at West Point, New York obtained the necessary external funding to add an autonomous Uninhabited Aerial Vehicle (UAV) design project to the series of capstone design options available to Mechanical Engineering (ME) majors in the undergraduate program. Under this program, two separate teams designed, procured parts, constructed, tested, and demonstrated two unique, small UAVs. These teams, advised by the lead author, consisted of six mechanical engineering undergraduates. The lessons learned from that first year experience were carried over into the second iteration of the project. For academic year 2006 – 2007, the D/C&ME formed three student teams, each team containing four ME majors, with one ME faculty member as an advisor. The capstone was also opened to students in the Department of Electrical Engineering and Computer Science (D/EE&CS). The D/EE&CS faculty approved two Electrical Engineering (EE) majors and three Computer Science (CS) majors for inclusion in one of the UAV design teams. This unique structure offered us the opportunity to not only assess the changes made in the capstone design from the first year to the second, but also the ability to compare and contrast the performance and overhead requirements of a multi-department team to two ME pure teams.

In both years, the initial progress of the design teams was slowed by lack of skills and knowledge that were essential to project success. The team members did not arrive at their capstone design with these tools in their kit and the faculty members quickly realized that the curriculum did not contain opportunities for the students to develop this specialized knowledge and skill set. The summer after second iteration of the design, the faculty members met to discuss how to most efficiently impart the required skills and knowledge to the students and when to do this.

The Kindergarten Approach

Much of what children learn in pre-school and kindergarten is not taught through formal classroom instruction. Significant time is spent in activity centers, outdoors, and on trips. The goal of this activity is to develop the child's *cognitive schemata*; their cognitive framework or concept that helps them organize and interpret information.[2] For example, it is hard to write about a farm if you have never been to a farm or seen pictures of a farm.

Likewise, the faculty members found that it is a lot harder to start a Remote-Controlled (RC) airplane engine if you have never seen one before. Where does the glow plug go? How do you set the throttle? How do you fuel the airplane? How do you prime the engine? Do you have all of the batteries charged? What batteries do you need? What do you do when the engine doesn't start the first time? If you have no experience with small two-cycle engines (most of our students do not), this becomes a daunting part of your capstone if you wait to learn this after you have designed and built your UAV and are ready to test it. In fact, this unfamiliarity seems to breed procrastination.

For this particular project, the students seemed to struggle with the following question: How do you predict your UAV's performance and how do you verify your predictions? Performance prediction is critical in the early phases of the design process and in the selection of the best design concept. An ability to test and verify these predictions is critical to determining if the design's engineering characteristics have been met. While thrilled by the idea of designing and testing a UAV, our students took on this challenge without some of the connecting experiences that would allow them to readily take the knowledge they had and apply it to this particular design challenge.

It is generally accepted that not all students learn in the same manner. Felder and Silverman have proposed a model[3] 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[4] are listed below:

- Includes one or more of 'inquiry learning', 'problem-based learning', 'project-based learning', 'case-based teaching', 'just-in-time learning', 'discovery learning'
- 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.)

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

According to Prince and Felder[4], 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, the hands-on construction and testing components are significant
- 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*. A laboratory exercise designed around the Alpha.60 RC airplane was developed for this purpose.

Resources Required to Start the Program

The success of the first year UAV concepts sparked a growth in the UAV design program within D/C&ME. As interest increased, the number of teams expanded from two to three. Project advisors assigned four mechanical engineering majors to each team. One multi-disciplinary team was supplemented with two electrical engineering majors and three computer science majors. A difficulty associated with the inclusion of students from outside the mechanical engineering department was the integration of graded requirements amongst the three programs.

Each team had its own mechanical engineering faculty advisor, and the multi-disciplinary team incorporated faculty advisors from the electrical engineering and computer science programs. Advisors attempted to synchronize courses milestones and minimize duplicate graded requirements. Despite this effort, multi-disciplinary team members on an end-of-course survey strongly disagreed with the statement "Departmental submissions were standardized." Due to this, standardization was a priority for year three and accomplished before cross enrolling cadets.

Advisors allocated the remaining Year 1 funding not directly spent on airplanes toward program improvements as shown in Table 1. Expansion of the program to three teams accounted for 19% of the expenditures. The lead author reinvested the remaining 81% back into the program as upgrades and improvements. A portion (12%) of the spending, to include $1,950 for multiple Alpha 60 RC model planes for training and $600 for team copies of an RC flight simulator, supported the training of new student pilots to fly RC model airplanes.

Table 1: Year Two Program Improvements

Improvement	**Cost**
Piccolo II Autopilot System	$11,515
Alpha.60 Ready To Fly RC Model Airplanes for pilot training (qty 5)	$1,950
Laptop computer	$1,602
Storage Cabinets ($357 x 4)	$1,428
Digital Video Camera	$1,350
Portable Gasoline Generator	$972
Great Planes Real Flyer RC Flight Simulator (3)	$600
Earthmate GPS Blue Logger (2)	$580
Electrical System Tool Kit	$529
Handheld GPS (2)	$370
Two Way Radios (8)	$336
RC Airplane Field Kit with Starter (2)	$218
Total	$21,450

The flight trainer RC airplane and simulator provided the opportunity to train new student pilots prior to flying the concept planes. While the cadets ultimately ended up using a D/C&ME faculty member as their RC pilot, the initial flight simulator purchased (which came with the trainer airplane) was of relatively low quality. The upgraded flight simulator, along with the RC flight trainer, if used early enough by the teams, could provide the teams with some trained RC pilots. While it requires a significant time investment, the payoff would be that the cadets are not restricted by the schedule of a single faculty member who, although extremely generous with his time, was flying for five RC airplane capstone design teams. Similar programs may also tap into a university or local RC club for experienced pilots.

Electric field starting kits saved time and effort in starting and breaking-in new engines. The electrical tool kit was mainly used by the ME pure teams as the electrical engineering majors had their own tools and laboratory space in the D/C&ME academic building. The lockers helped secure and organize an overcrowded workspace, but did not truly overcome problems in competing for space and equipment. A video camera, generator, handheld GPS, and two way radios supported field operations during flight testing and project demonstration.

During the course of execution in the second year of the project, the faculty advisors ascertained that there were several additional purchases that would be beneficial to the continuation of the project. The first was the purchase of an electronics bench. All previous electronics testing (even for the pure ME teams) had to be done in the D/EE&CS electronics laboratory, which is in a separate academic building. This resulted in the cadets spending a significant amount of time walking between the two buildings on campus. A power supply for the electronic bench was also ordered once the necessary funding was confirmed at the end of the fiscal year.

External constraints forced the movement of the team into a smaller 20’ by 15’ workspace. With three teams, associated equipment, and up to 12 students at a time, the space proved grossly inadequate. Tight spacing led to accidental damage to planes and the mixing of team equipment and parts. Student feedback indicated each team should ideally have their own 20’ by 15’ area.

Although flat, clear space for RC controlled flight can be found at athletic fields or parks, a full test of autonomous flight controlled by an autopilot requires a large, unpopulated area. D/C&ME expanded autonomous testing by using airspace within the West Point training area and the installation’s range complexes. A local RC airfield was also used by coordinating with a local RC flying club. Use of airspace required several months of coordination with the owning state or federal agency and the Federal Aviation Administration.

Results of First Two Years

To support three teams and to encourage greater autonomous flight and inclusion of different technologies, D/C&ME acquired additional funding that increased each team’s budget to $12,000. First year designs under a budget of $9,000 included pilot Radio-controlled (RC) fixed-wing (F/W) flight as well as autonomous flight by a commercial autopilot using Global Positioning Systems (GPS). With greater funding, students built upon year one concepts by exploring technologies such as onboard wireless video, radio frequency homing, inertial guidance, and laser designated ground objects (Table 2).

Table 2: Summary of Student UAV Concepts

	Team	Type	Propulsion	Autonomous Flight Mode	Demonstrated Technologies	Cost
Year 1	**ME Team A**	F/W	Electric Powered Propeller	Kestrel autopilot with GPS	Onboard wireless video	$7,531
	ME Team B	F/W	Glider	MicroPilot autopilot with GPS	Weather balloon release	$9,826
Year 2	**Multi-Disciplinary Team**	F/W	Gas Powered Propeller	Xbow autopilot with GPS	Frequency homing, inertial backup	$4,560
	ME Team C	F/W	Gas Powered Propeller	Kestrel autopilot with GPS	Onboard wireless video	$9,250
	ME Team D	F/W	Electric Powered Propeller/glider	Kestrel autopilot with GPS	Onboard wireless video, laser designated landing point	$11,650

All three teams built and tested their UAV concepts using primarily commercial, off-the-shelf products. They took their UAV's to China Lake, California for a demonstration hosted by the supporting federal agency.

The additional team members, advisor support, and resources of the multi-disciplinary team fostered the development of a new, fully autonomous flight mode using frequency homing to an object emitting a signal. Frequency homing demonstrated by the multi-disciplinary team was functional, despite difficulties encountered in determining altitude from the vertical signal reading.

ME Team D demonstrated short range landing point laser designation using a lasing ground station with laser recognition facilitated by a UAV wireless video link. Autonomous video/laser tracking, however, proved too difficult for a team without graduate-level education and additional time and resources.

Third Year Inductive Learning Experience

While student experiences during the first two years of the UAV capstone design were rewarding, there were many goals that were not achieved due to the inadequate schemata of the students. The application of physics to model and analyze their design alternatives in the early stages of the design process was woefully inadequate to ensure that students were making the best design choices. As construction and testing progressed, the lack of experience in working with small aircraft engines and servo controls led to delays and student frustration throughout the process. The faculty believed that a well-designed, hands-on *laboratory* experience early in the course might fill some of the gaps in the students' collective schemata.

In an effort to inject more engineering early into the design process and develop hardware skills, 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 UAV design.

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

- **Complex Undergraduate Design:** The UAV 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 power 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, there are a few excellent sources of low-speed airfoil charts and aerodynamics specific to RC flight[6,7].

Laboratory Performance Modeling

To overcome the above difficulties, the authors developed a performance model that first started with the aerodynamics (namely drag) of the total airplane. The drag, or resistive force the air exerts on the airplane as it pushes through the air, is quantified using the drag polar equation. Accurately estimating this drag polar equation without lengthy and expensive wind tunnel testing became the foundation of the performance model.

The second step quantified the power required by airplane to overcome this drag at a given airspeed. To maintain steady, level flight, this power consumption must be matched by the propulsive power available; thus, the final step was to estimate the power generated by the engine-propeller system. This engineering model embodied the analysis necessary for making sound performance predictions of the lab's Alpha.60 airplane.

Analysis of the data revealed the engineering characteristics of maximum airspeed, range, endurance, and maximum rate of climb summarized in Table 3.

TABLE 3 Alpha.60 Predicted Engineering Characteristics

Parameter	Symbol	Value	Units
Stall Speed	V_{stall}	34.5 20.5	ft/s knots
Landing Distance	$s_{g,Land}$	278.1	ft
Take-off distance	$s_{g,T/O}$	59.0	ft
Maximum Endurance	E_{max}	66:36	minutes:seconds
Maximum Endurance Airspeed	$V_{E,max}$	35.0 20.7	ft/s knots
Maximum Range	R_{max}	24.9	nm
Maximum Range Airspeed	$V_{R,max}$	42.5 25.2	ft/s knots
Maximum Airspeed	V_{max}	80.5 47.7	ft/s knots
Maximum Rate of Climb	RC_{max}	1,023	fpm
Maximum Static Thrust (at 10,272 rpm)	$T_{max,static}$	6.69	lbf
Power Limited Minimum Velocity*	V_{min}	11.9 7.1	ft/s knots
Maximum Rate of Climb Airspeed	$V_{RC,max}$	47.8 28.3	ft/s knots

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

As part of the lab, teams had to assemble a Ready-To-Fly (RTF) Alpha.60, verify the center-of-gravity location, break in the engine, measure the static thrust produced by the propeller using a spring gage, and calculate the fuel consumption needed for range and endurance calculations from static testing. Following the static testing, the faculty advisors took the students out and flew the Alpha.60 model until it crashed with a hard landing…on purpose. The lab experience concluded with the students repairing the model to return it to flying condition; a skill that is critical to this capstone design and is best learned early.

Results of Third Year

The two teams that participated in the UAV capstone design in their third year saw marked improvement over earlier teams. Both teams deployed their UAV's to the DoD testing site in the California desert and were successful in beyond-visual-range autonomous flight on the first attempt. Integration of on-board systems worked as designed and the teams spent significantly less time on final, on-site design fixes and troubleshooting. The students were much more confident and comfortable with the hardware and required less intervention from the faculty advisors.

Conclusions

The implementation of an inductive learning experience in the capstone design course at the United States Military Academy at West Point, New York required a minimal amount of funding from the project budget; the cost of an Alpha.60 RTF RC airplane and fuel. It did require significant planning and preparation on the part of the faculty advisors. It also required several dedicated lessons out of the beginning of the capstone design. While the cost in time was significant, both the faculty advisors and the students agreed that it allowed the design team to achieve greater efficiencies of learning and produce a much better final product.

The structured learning experience at the beginning was initially viewed by the students as encroaching on their design time. Once they became involved with working on the hardware, they quickly realized how valuable the experience was. The lab experience relieved some of the anxiety and later frustration that had been experienced in the past.

This year, the program's Wind Power capstone design team faculty advisors are adopting the same approach towards their team's design. Results are pending at the end of this semester.

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