Learning to Innovate Across Disciplines: A Case Study on Three Team Project Experiences

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Abstract

This is a student-led paper summarizing a case study on how present-day engineering students learn what is needed to innovate solutions, going well beyond what is usually taught in course lectures. It is set in the context of an aerospace engineering school in an American university, with typically large class sizes and a school culture that emphasizes research and instruction. Three projects are included in the study, progressing in level of complexity. There was some commonality in participants between the three. The first is a large open-ended advanced concept development exercise in an upper-division course. The second is a Capstone Design course. The third is a professional society’s international level vehicle design team competition. The results show where and how students acquired the knowledge, skills, confidence and experience to build through the years and reach a level where they could innovate and perform with excellence at the level of the international competition. The case study is aimed to benefit instructors who are interested in improving the depth of their courses as well as improving their students’ ability to innovate in a meaningful way.

Introduction

The case study described in this paper examines a vertical sequence of experiences where students learned to innovate with rigor and depth, broadened their horizons by applying the skills that they learned, and then went on to compete successfully against the best from around the world, in an arena demanding innovation with depth. These students advanced through the curriculum at the School of Aerospace Engineering, Georgia Institute of Technology. Each student learned to deal with uncertainty when innovating, exploring outside their disciplines, and satisfying common sense while thinking outside the box. Most importantly, students learned to work in a team where self-discipline, initiative, and leadership traits are developed.

There is a critical need to build excellence\(^1,2\) and enable our best students to perform much better than their predecessors. The case study documents the progression of the students’ learning from a core engineering course, to the capstone design experience, and on to the intensely challenging environment of an international design competition.

The open-ended course assignment involved the conceptual design of a missile defense system for the continental United States with particular focus on aerodynamics aspects. Students were divided into teams of two and given six weeks to complete the assignment with mandatory weekly reporting. Discussion and integration of course material was learned just in time to do the high speed aerodynamics portions of the project. Thus, the learning for this project was integrative. Students had to investigate current technologies, available programs and make
engineering judgments to design an advanced concept system where there is no precedent in the published literature. The capstone design course is part of the core curriculum. Here students learn to work in an environment similar to that in industry. Emphasis is on learning the principles and processes of design, and the workplace issues of working in diverse teams. The third case is an international vehicle design competition held annually under the auspices of an international professional society. Details are suppressed to allow blind review.

**Open-Ended Project**

A short primer on strategic defense issues was given in the high speed aerodynamics course to set the context for this particular assignment. These issues began with the Cold War concept of Mutually Assured Destruction (MAD), the treaties on anti-ballistic missiles and space weapons, the Strategic Defense Initiative (SDI), the end of the Cold War, and the rise of other threats leading up to the present, with upcoming capabilities and threats discussed. The objective of the project was to create a solution for a defense system for the specific case of an attack from an intercontinental ballistic missile (ICBM). The premise is that in times of tension, some aircraft would patrol at about Mach 0.6 and 40,000 feet, offshore and over the US.

The system was composed of a transonic patrol, a supersonic unmanned combat air vehicle (UCAV), and a hypersonic weapon. The large transonic patrol would carry the other two components. Up to four uninhabited combat air vehicles (UCAV’s) can be launched on warning from the carrier. Several such carriers would fly over the periphery of the US at an efficient altitude of 40,000 ft (~12,000 meters). The supersonic UCAV would accelerate and climb up to altitudes of 150,000 ft (~46,000 meters) in order to put its four hypersonic weapons, at an appropriate altitude with time left to hit the incoming warheads. The supersonic UCAV’s are expected to accelerate to Mach 4. The UCAVs would then glide to landing. The air breathing supersonic-combustion ramjet hypersonic weapons would quickly accelerate to collide with any incoming warheads. Teams of two students each were formed. Weekly reports updating the team’s progress were expected.

Performance parameters studied were the total weight, range, endurance, maximum speeds, critical Mach number, lift to drag ratio, service ceiling, rate of climb, turn rates and radius, and drag estimates. Figure 3 illustrates the different types of vehicles involved in the design is shown in The carrier aircraft is likely to be much bigger than pictured, and powered by turbofan engines.

![Figure 1: Schematic illustration of the 3 vehicles in the missile defense system.](image1.png)

![Figure 2: Area coverage issues](image2.png)

As a stated requirement, the team also calculated...
an average area that the transonic patrol would cover given a two minute warning to launch the UCAV’s. In this two minute period, the aircraft is assumed to be going the opposite way and turn around and follow the ICBM. The area that the patrol would cover was found by integrating the velocity of the transonic patrol with respect to time from zero to 120 seconds. An estimated weight breakdown of the complete system was developed and shown by figure 3 below. The complete system includes the transonic patrol’s fuel and crew weight, its empty weight, the weight of 4 UCAV’s and 16 hypersonic weapons.

![Weight of Carrier](image)

**Figure 3:** Weight estimation of the carrier aircraft

**The Engineer’s Toolbox**

Knowledge from several courses and tools were used throughout this project in order to facilitate and perform the required analysis in the given amount of time. Figure 4 is an estimated visual representation of the many tools and courses used ranked in percentages based on their use during the development of the defense system.

Some particular examples include the knowledge and skills developed in the drafting course with AutoCAD in ME 1770, while using knowledge from Compressible Flow to find Mach angles. This mixture of unrelated knowledge allowed for “ball park” estimates of the shape and size of the system components. The supersonic airframe was designed using MATLAB according to the shape of the Sears-Haack body shape, shape for minimum wave drag, shown in Figure 2. This process was extrapolated to other components of the defense system.

![Courses and tools used in the conceptual design of the defense system](image)
In this case, the unfamiliar material came from the high speed aerodynamics course as it was being taught throughout the semester. Thus, students had to go well beyond what is learned in the classroom. Open ended projects teach students how to begin making “back of the envelope calculations” and decisions well before a final configuration solution is known. This pushes students to pull tools out of their “engineering toolbox”. Weekly reports not only encouraged students to keep up with the material in class but to go beyond and learn as much as possible in all aspects of this field.

Capstone Design Course

The capstone course is a two semester, 8 semester hour course, that constitutes the culmination of four years of engineering education. Students must choose rotorcraft, fixed wing, or space as their senior capstone course. The experience reported here is that of rotorcraft design. Students experience team-based design under conditions that closely resemble those encountered in industry. Students are exposed to an experience in which they have to specify, design, and produce a full-system beginning from relatively ill-posed needs as stated by a customer. The first semester focuses on the fundamentals of helicopter theory. The individual project involves sizing a helicopter given a set of requirements and mission. Each week, a mandatory three hour lab was held by an expert in order to focus on a particular field of study. These sessions allowed for each student to find an area in which their interests fall under. Each student would choose a field to serve as the expert on their team. Table I breaks down the labs offered.

Table I. Subject areas and skills involved in the Capstone Design course

<table>
<thead>
<tr>
<th>3D Modeling</th>
<th>Structural Analysis</th>
<th>Cost Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational Fluid Dynamics</td>
<td>Rotor Dynamics</td>
<td>Stability and Control</td>
</tr>
<tr>
<td>Flight Simulation</td>
<td>Design</td>
<td>Optimization</td>
</tr>
</tbody>
</table>
An example of these technical skills is shown through Figure 5. This figure contains visual representations of some of the tools used in industry to produce high fidelity results. Computational fluid dynamics flowing through the fuselage of a helicopter using Fluent is shown in the top left corner. The top right shows finite element analysis performed on the landing gear of a helicopter to ensure the structural integrity and load paths using the ANSYS software. At bottom left is 3D modeling of a helicopter structure using CATIA, and at right bottom is a performance analysis of a helicopter using momentum theory using MATLAB.

Figure 5: Several screenshots of software learned in the capstone design course
International Student Design Challenge

The 2012 annual student design competition request for proposal (RFP), sponsored by American Helicopter Society International, stipulated the desire for a lightweight, highly maneuverable rotorcraft system. This rotary wing pylon racer was expected to perform at levels similar to the fixed-wing red bull competition aircraft, in order to spark interest in a helicopter racing sport. Fitting well with the rotorcraft design capstone course, a team of students who were enrolled in the rotorcraft design capstone course was formed and an innovative solution to this proposal was initiated.

The scoring function given by the RFP is a combination of time, fuel weight, and engine power. Thus, careful consideration was taken at each step of the design process in order to strike a balance between fuel efficiency, engine power, load factor, and speed, all while maintaining safety for the pilot and spectators. According to the RFP, the three most stringent requirements are that the helicopter must be sized to successfully hover at 103°F at Sea Level, achieve a minimum of 60 knots sideward flight, and achieve a minimum of 125 knots at 90% MRP at 103°F at Sea Level. The course is assumed to be flown at 80°F at Sea Level (autumn). The 225lb pilot has 10 minutes to warm up and 5 minutes to takeoff. The pilot starts the course at no more than 100 kts. Then, the helicopter is required to perform 6 different maneuvers throughout the track. A list of mission segments was provided. Each maneuver requires a certain amount of maneuverability and agility from the helicopter. Speed, turning radius, load factor, control power, and acceleration/deceleration clearly became the most important characteristics for this racing rotorcraft. A detailed breakdown of all of the requirements found in the RFP was developed. They are separated between performance, mission, and miscellaneous requirements.

Team Dynamics

The Badger team was an international alliance with nine undergraduates and three graduate students. The team was mentored by two professors. Weekly Thursday evening meetings were designed so that students could discuss their progress and brainstorm problems together. Each student’s voice was heard equally. International students were able to join student meetings in the form of video calls through the Skype software.

The team divided the work equally based on the interests and experience of each student. A team leader and a chief engineer were assigned. The team leader was to arrange meetings and analyze the team’s progress using a progress chart while the chief engineer was to oversee the entire design, assist students in their endeavors, and finalize the technical paper. Monthly in-progress reviews (IPR’s) were held where both the team leader and the chief engineer were in charge of creating a professional presentation of their current work. Every member was required to attend this meeting and time arrangements were made to accommodate the international students. During every meeting, a set of designated experts and professors posed as judges. Their jobs were to question, critique and evaluate the team’s progress. At the end of each meeting, judges gave key points that they wanted to see for the next month’s review.

Examining Different Configurations
The team, therefore, decided to examine and compare the capabilities of the conventional helicopter, compound helicopters, tandem rotor helicopters, coaxial and intermeshing helicopters. To generate the advanced rotorcraft concept, a morphological matrix was generated, with a total of 77,760 configurations options available. From there, the list was narrowed down to 4 different configurations and a baseline model was chosen. Once the chosen configurations were known, it was time to begin looking at the best one in order to begin an optimization analysis.

![Figure 6. Design Process Flow Map](image)

Radar plots are used to graphically show how given designs perform against the various criteria such as operational cost, acquisition cost, safety index, MRP and time. The next step in TOPSIS selection is to determine how close each configuration is to the ideal and how from the worst. Based on the TOPSIS methodology and engineering estimates, the intermeshing rotor configuration was chosen as the best fit for this particular mission. The coaxial rotor was a very close second. The preliminary design led to the intermeshing design concept, aiming to score on the RFP’s originality grading criterion. This design is the first synchropter design to come from Sikorsky Aircraft and is unconventional for highly maneuverable aircraft. All things considered, it was concluded that the intermeshing design was the most original and optimal configuration for this mission and competition. The design process flow map is illustrated in Figure 7.

**Integrated Product/Process Development (IPPD)**

In the conceptual design procedure, the IPPD methodology assists the designers in investigating the requirements set by the RFP and attaining promising solutions. The IPPD works by organizing the very iterative design process in a systematic way. Normal IPPDs contain four loops: the conceptual design loop, initial product data management loop, preliminary design iteration loop, and the process design iteration loop.

The process starts with analyzing the requirements set by the RFP and selecting a baseline model. An RF
(required fuel) method is then used the size the baseline vehicle. After the vehicle’s size was assessed, the even more iterative process of analyzing the individual components began. Several trade studies were completed. Examples of these are basic helicopter configurations, auxiliary propulsion types, main rotor airfoils, hub configuration and transmission selection. Once the most ideal solutions were obtained and integrated within the CATIA model, the revised design was scored using the RFP overall evaluation criteria (OEC) shown by Equation (1) above. This process was repeated until the minimal OEC was achieved thereby marking the final design. The Badger’s final score is 1380.6.

**Performance Results and Specifications**

The Badger design outperforms RFP performance requirements with the use of auxiliary propulsion in the form of a pusher propeller for both increased acceleration and deceleration properties. Modified model was based on Leishman’s model for tandem rotors.⁵

**Table II. Performance Summary**

<table>
<thead>
<tr>
<th>Parameter (103F)</th>
<th>GW = 2500lbs</th>
<th>GW = 2800lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best range speed</td>
<td>119.83 knots</td>
<td>123.56 knots</td>
</tr>
<tr>
<td>Best endurance speed</td>
<td>68.58 knots</td>
<td>73.12 knots</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>175.87 knots</td>
<td>174.27 knots</td>
</tr>
<tr>
<td>Speed at 90% MCP</td>
<td>165.73knots</td>
<td>164.13knots</td>
</tr>
</tbody>
</table>

It offers 176 kts maximum speed at 103F temperature, 60kts in sideward flight, 166kts maximum speed at 90% maximum MCP, and hovers at sea level on a 103F day with a 300 lb payload. Table VI above summarizes performance while Table VII below is the summary of the overall specifications of The Badger.

**Final Product**

The RFP required a more maneuverable rotorcraft than arguably any rotorcraft made before. This proposal presented the conceptual, preliminary, and final design process of an extremely unique rotorcraft. Through several iterations of the design process focusing on maneuverability, this configuration has become an effective racer. Because The Badger was designed with maneuverability in mind, it is an effective racing rotorcraft. Not only does the Badger meet the criteria stated, but it also successfully outperforms the competition. Figure 8 shows the final rendering of the successful design that won the __th international student design competition.
Discussion of Educational Aspects

As stated at the outset, this is a case study tracing what a team of students who shared common experiences did in a vertical subset of the curriculum and beyond in the general area of technical innovation. Two of the experiences were parts of regular coursework, but tuned to bring in innovation towards advanced concepts. The third was an international competition that used the learning from the prior courses in an intense real-world competitive setting, contributing its own learning. A reviewer of the abstract of this paper demanded to know the educational value and the scientific method in this work. The educational questions ask how students learn to innovate at the level of the international competition, where they learn the habits that lead to bold innovation across disciplines, accompanied with in-depth, rigorous analytical skills. The scientific methods applied are in developing the curricular experience that allows students to learn and perform far beyond what was possible even a few years ago. In upper level courses, the number of students decreases significantly than that of the core courses. Thus, the most useful scientific approach is to examine the performance of these students and obtain their own introspections of what worked.

Technical Depth

The aerodynamics course AE3021, like the rest of the core curriculum, was focused on subject area depth. The AE3021 course provided an advanced concept development exercise to integrate the subject knowledge. Perhaps for the first time in the curriculum for these students, a course expected students to bring in knowledge and skills gained in other courses and merge it with their explorations of new areas in order to synthesize a new conceptual design in a completely new area. Thus in this course, the technical depth needed to make innovations was emphasized.

The capstone design experience further educated the students in the lore, terminology, methods and practices of aircraft design. As seen from the work presented, this included system design and optimization methods. Thus, students now had the capability to bring design tools into their repertoire, making the innovation process more systematic. The design competition experience
gave students the intense practical experience of making the innovation process highly quantitative, and “letting the requirements drive the design” rather than depend on just intuitive innovation. This closes the cycle, now equipping the students with the depth, the tools and the quantitative metrics to conduct engineering innovation.

**Breadth of Domain** The students got early exposure to the need for breadth when they had to consider various issues including strategic deterrence history and global military realities, in the course assignment. The capstone design course required them to bring in several considerations to meet the design requirements, and learn to use professional-level tools in several disciplines simultaneously. The design area taught them how to consider the entire design space and a large number of possible configurations, while systematically narrowing down to a final design.

**Individual Initiative, Teamwork and Communication** The single and twin team assignments in the aerodynamics course and the individual performance assignments in Rotorcraft Design demanded individual initiative. The two-person teams in AE3021 demanded communications and coordination, and this was expanded to the larger (5 to 10) teams in the Capstone Design course. Students had to deal with team dynamics, and learn the communication skills needed not only to get work done in teams but to interact with the rest of the class and the reviewers through their work.

**Conclusion**

The three projects together had one goal in common: Prepare the next generation of aerospace engineers to deal with uncertainty when innovating new solutions to problems that have never before been looked at. Within the constraints of a standard engineering curriculum, the depth, breadth, tools and quantitative metrics needed to conduct innovation within a large system context, are all successfully conveyed.

The paper conveys the sequence of learning needed for successful innovation. First, depth in technical subjects is conveyed through core engineering courses, along with a free-form exploratory experience of advanced concept design. In the capstone design course, the process of design is codified so that students can organize their approach much better in the design process. The experience of international level design competitions, in teams including both graduate and undergraduate students, then allows the students to grasp and use professional-level tools along with quantitative metrics to allow the requirements to drive towards a winning design, providing the students with the background and confidence to practice innovation in real life situations.

**References**


