

The Capstone Engineering Systems Design Process at the United States Air Force Academy

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Abstract

This paper describes the overall experience of offering a capstone, senior-level, engineering systems design course at the United States Air Force Academy from the perspective of both technical and non-technical students, along with their instructors. The course is designed to introduce cadets of all majors to the engineering design process and the Air Force acquisition process. The cadets are expected to apply knowledge from past courses at the United States Air Force Academy to design, build, test, and deliver a project that the instructor assigns to them, which benefits a real-world user. Along the way, the cadets also meet certain milestones, give briefings and demonstrations, and prepare technical reports. The course is geared so that technical and non-technical cadets can team up to perform meaningful work in an engineering design format. In the midst of a unique and often challenging group dynamics environment, the cadets are challenged to find their own solution to an ill-defined problem, and then actually perform hands on fabrication and testing of their project. Examples of past projects and the performance of cadets in building those projects will be evaluated to provide some insight into cadet performance. Data will be analyzed to determine whether cadet performance is tied to the technical complexity of a given project. Some insight into teaching this course is discussed, and finally, the paper will discuss the benefits and the challenges involved in a course like Engineering Systems Design. The paper will conclude with some feedback from recent graduates of the United States Air Force Academy and a look toward the future of the course.

Background

Every cadet graduates with a Bachelor of Science degree from the USAF Academy, whether majoring in science and engineering (technical majors) or the humanities and social science (non-technical majors.) As part of the curriculum, each cadet takes six engineering courses, from the civil, electrical, aeronautical, astronautical, and mechanical engineering departments. For the last 31 years, the USAF Academy has offered a capstone, senior-level, engineering systems design course to tie these courses together, known as Engineering 410 (Engr 410). Since its inception, Engr 410 has been a part of the core curriculum at the USAF Academy. The initial designers of the course felt that it

was important for every cadet that graduates from the USAF Academy to have experienced some form of engineering design whether he/she was a technical major or a non-technical major. Engineering 410 is the course that fulfills this requirement. The official educational goals and outcomes of Engr 410 are listed below, excerpted from the Department of Astronautics Course Goals and Requirements.

Operational Goal:

By the end of this course, you will be able to:

- (1) Apply knowledge acquired in previous core engineering courses to design, build, test, and deliver an operational engineering prototype system.
- (2) Apply knowledge acquired in previous management courses and leadership experiences to form a contractor team and successfully meet all milestones of the acquisitions and design process.

Curricular Outcomes:

- (1) Define and explain the phases of the DoD Acquisition process and identify associated milestones
- (2) Given a request for proposal (RFP), you should be able to:
 - a.) validate the user's requirements and present various design alternatives, highlighting how each will meet the user's requirements
 - b.) develop a technical, cost and management proposal that will demonstrate how your selected design will be developed through studies, engineering analysis, subsystem fabrication, system integration, and testing.
- (3) Once a design has been selected, demonstrate through oral and written presentation that it meets the user's specifications
- (4) Demonstrate independent learning by identifying and researching unknown information dealing specifically with your project (ie. safety standards, building materials, hazardous materials)
- (5) Demonstrate competence in the timely and professional completion of your task by creating a schedule to meet all required milestones
- (6) Demonstrate competence in teamwork by ensuring that all team members are gainfully employed to meet all required tasks
- (7) Demonstrate competence in resource management by completing your project within budget and material constraints.

In addition to the goals and outcomes listed above, the following course description also provides some insight to the multi-disciplinary aspects of Engr 410.

Course Description from Curriculum Handbook:

Engr 410. Engineering Systems Design. 3(1). Application of the core disciplines to the overall systems analysis and design process in a capstone engineering design environment. Includes introduction and application of the Air Force systems acquisition process to completing a design project. Projects require attention to the engineering technical details of systems design as well as the economic, management, and social aspects of the process. Course includes a

qualifying examination to assess the cadets' understanding of the acquisition and design process prior to starting the course project. Final report and briefing. Sem hrs: 3 fall or spring.

With some history and information of Engr 410 complete, let's look at how Engr 410 is actually administered and some of the challenges associated with this course.

Course Format

Engineering 410 is a course that every senior-level cadet at the USAF Academy is required to take during his/her senior year. Engr 410 is part of the Academy's core curriculum, making the course a graduation requirement for every cadet whether that cadet is an Astronautical Engineering major or a Political Science major. Each semester an average of 425 – 450 cadets take Engr 410, and each class is broken down into individual class sizes of between 14 – 19 students.

The ideal make-up of each section would be a 50-50 mix of technical and non-technical cadets. However, while cadets may request spring vs. fall or afternoon vs. morning, they are essentially randomly assigned to a given section. Each section is given a perhaps different ill-defined problem, usually some type of engineering product for the local Colorado Springs community or the local base community. Projects to benefit the handicapped are most preferred. However, the cadets have no knowledge of the project itself prior to the start of the semester. Likewise, the cadets have no choice of instructors. The 20+ instructors who teach Engr 410 come from the four engineering majors at the Academy.

To bring in even more realism to the class, each project has a real-world user/client that is expecting the class to produce a product. The user/client has a close working relationship with the cadets because they eagerly await the results of the cadets' work. Whether it's a Pinewood Derby Racetrack for a Cub Scout Pack or a Hands-On Solar System for an Elementary School, the user/client is an important part of Engr 410. Also, each time the cadets give a formal briefing (usually four times during the semester), a Senior Reviewing Official (SRO) is required to be there. The SRO provides an outside source of feedback to the cadets and essentially gives them permission to proceed through each phase of the course.

The layout of the course is shown in Figure 1 and is known as the Engr 410 Roadmap, which resembles two phases in the actual DoD/Air Force acquisition process. Beginning with Lesson 1, the class is presented with their design challenge, which is their project for the entire semester. After receiving their project, the cadets then proceed to start organizing themselves and brainstorm ideas for solving the project, a phase known as Concept Exploration/Ideation. Defining and understanding the requirements of the project are also a part of this phase. "While mission requirements focus on the big picture items (the reasons for and results of the project), system requirements focus on the individual elements of the system architecture to describe in more details what we expect of each mission for success."¹

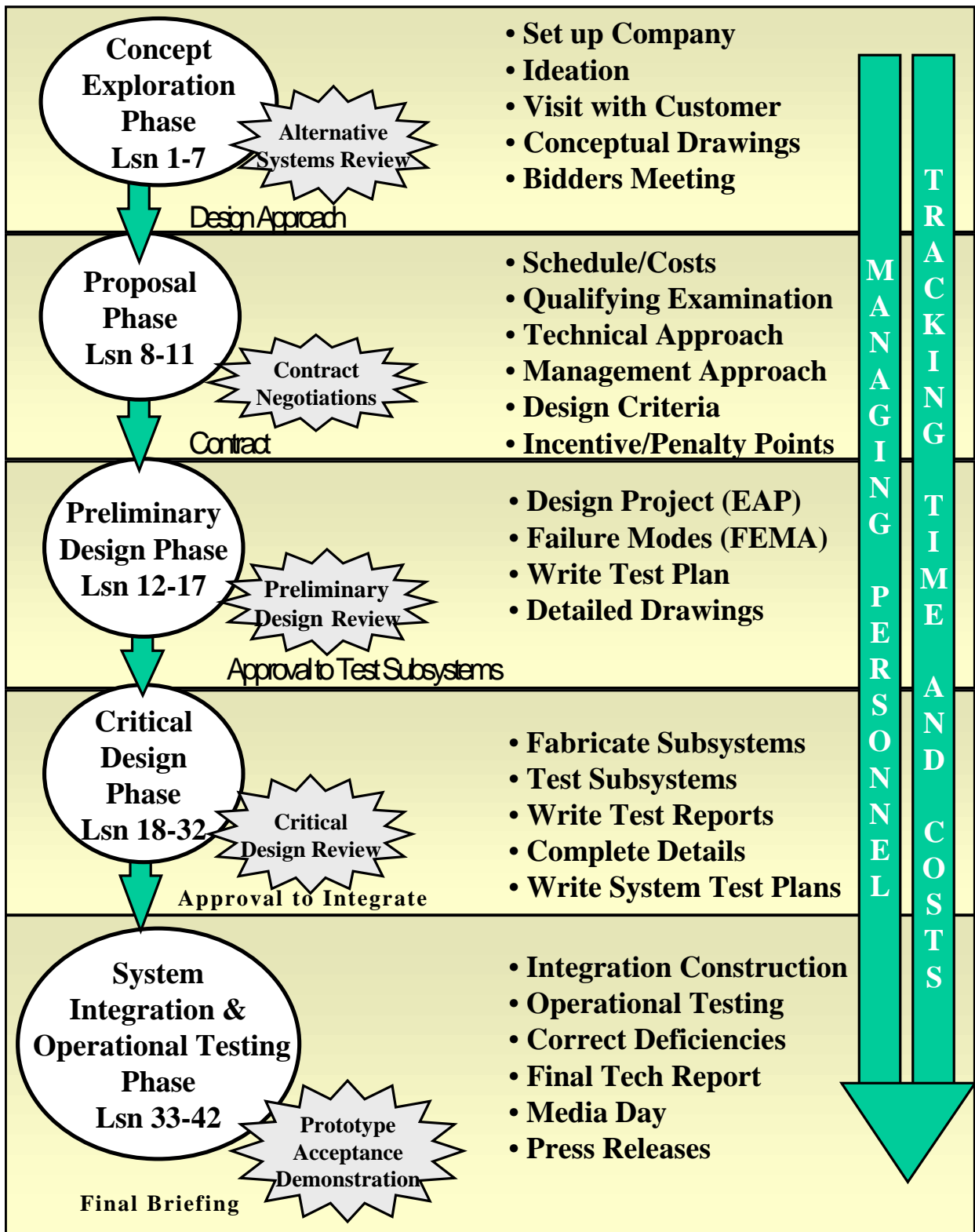


Figure 1: Engr 410 Roadmap – 42 Lessons

In order to simulate a real world environment, the instructor represents the government and the class is modeled after a typical government applied research contractor. From the beginning, the cadets are expected to manage the project and ensure the project is not over budget (~\$500 total funds for hardware purchases). However, if the project is large enough, outside funds can be utilized to complete the project. Typically, the class is organized with a Program Manager that leads the entire effort. The project is broken down into various subsystems, with the rest of the cadets assigned to work in these areas. An example organization chart is shown in Figure 2 for a mobile rocket launcher, where the management team would be in charge of project schedule, reports, presentations, and cost.

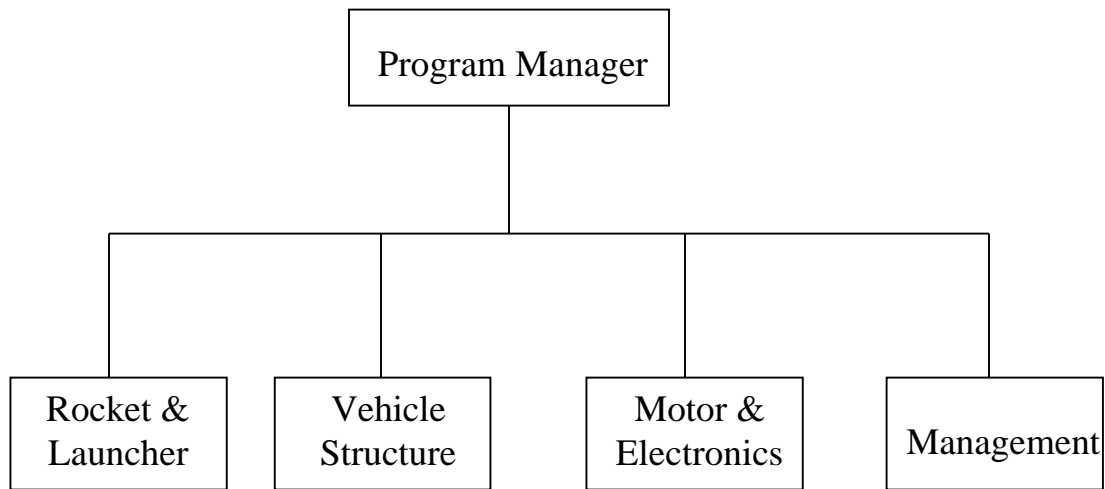


Figure 2: Example Organizational Structure

With their solution in mind, the class moves into the Proposal phase where they start doing some analysis and set up their fictitious company to provide the details for how they're going to operate the entire semester. After their Proposal has been approved, the cadets move into the Preliminary Design Phase where the real engineering analysis work begins. Cadets are required to perform a detailed Engineering Analysis and Failure Modes Analysis of their proposed solution. Once this is complete, the students present their plan in a formal briefing where they request permission to proceed with fabrication of their subsystems. The Senior Reviewing Official (SRO) plays an important part in this briefing and all subsequent formal briefings.

After approval of their preliminary design, the cadets are required to actually go out and fabricate their subsystems, with limited options for subcontracting. Laboratory facilities with full-time lab technicians are specifically assigned to support the Engr 410 class projects. Students who may have never operated a band-saw before are given the opportunity to do some hands-on construction. The cadets are expected to spend their entire classroom time and even outside of class time in the labs building their project.

As they proceed through the Critical Design phase, cadets encounter the problems of going from a paper design to building actual hardware and integration, with all the

students expected to contribute to the group's effort. No one is allowed to be assigned to full-time paperwork or management. Once fabrication and testing of the subsystems are complete, the class presents another briefing where they request permission to proceed with Integration and Testing of the project. The semester ends with a Prototype Acceptance Demonstration for the user/client and a Final Briefing to discuss what was learned throughout the semester.

Example Projects

Prior to the start of each semester, Engr 410 instructors are required to submit a description of the project they plan on using for their section. These submissions are then reviewed by a group of experienced Engr 410 instructors to ensure the project meets all the requirements for Engr 410. Also, since the cadets will have significant interaction with the user/client, the instructor must choose a project where the user/client can play an integral part.

Past projects in Engr 410 have varied widely and involved different engineering disciplines. Cadets have built projects for the local community as well as organizations located on the USAF Academy. Additionally, the success of these projects has varied and cadet performance has been tied to a number of factors.

- Instructor Motivation for the Project
- Perceived Benefit to the User
- Perceived Level of Difficulty
- Cadet Motivation

When the instructor is motivated for the project and the students perceive that the project will have a real benefit for the user/client, then the class usually turns out to be fairly successful. If cadets are not motivated and the project seems to be too technically challenging then the cadets tend to struggle. Below in Table 1 is a list of some recent projects - Fall 2001, their perceived difficulty level and an estimation of their success.

A number of things determined the difficulty level of these projects. First, the individual instructors' overall perception of the difficulty level was very important. Also, the number of engineering disciplines being applied in the project was considered. The greater number of disciplines, the greater the difficulty. Finally, the background of individual cadets was taken into account.

Performance was first and foremost determined by the grades the cadets received on the required turn-ins. In pretty much all cases, the cadets who worked hard on the turn-ins produced a better product than those cadets who received poor grades on their turn-ins. How the cadets critiqued each other also influenced their performance. The instructor's perception of the cadets and his/her critiques also played a role in determining grades as well as performance.

<u>Project</u>	<u>User</u>	<u>Difficulty Level</u>	<u>Performance</u>
Pinewood Derby Racetrack	Cub Scout Pack 187	Easy to Moderately Difficult	Good
Small Satellite Gravity Gradient Boom	USAFA Small Satellite Program	Difficult	Excellent
Rocket Launcher/Trailer for 20' Rocket	USAFA Rocket Program	Very Difficult	Outstanding
Mobile Kitchen Demonstrator	Air Academy High School	Easy	Poor
Mobile Handicapped Elevator	Colorado Springs Household	Difficult	Good
Handicapped Toddler's Walker	Colorado Springs Household	Moderate	Average

Table 1: Recent Engr 410 Projects

From an initial inspection, the above table seems to indicate that more difficult projects seemed to result in better cadet performance. However, each project seemed to have something unique to it that resulted in better performance. For example, the Small Satellite Gravity Gradient Boom project was an entire class effort. All the cadets contributed to the project even though it was difficult. On the other hand, the Mobile Kitchen Demonstrator suffered from a lack of group participation. In the end, one cadet was taking on a majority of the work and thus the project suffered. The Rocket Launcher/Trailer had the benefit of a motivated and dynamic instructor who helped the cadets every step of the way.

Pedagogy and Instructor Challenges

As you can see, Engr 410 is unlike most other college courses. Certainly it differs from others that are taught at the Academy. Lecturing is limited to an early discussion of the DoD acquisition process, but from there, the instructors supervise, observe, and evaluate cadet work. No in-class exams are given, nor is there any outside homework.

Assigning grades is thus an interesting challenge in Engr 410. Except for an initial “qualifying exam” given during the first few weeks of the course, to assess their understanding of the course and the acquisition process, cadets have no individual assignments. Cadets are graded as a class and assessed based on their class performance. The cadets submit formal technical reports and give formal and informal briefings that are considered their graded events. Their performance on these events forms their grades in the course. In addition, to simulate the real Air Force, cadets are required to rate themselves as well as their classmates. Each cadet is required to comment on their own performance in addition to how their classmates are performing. Thus, numerous things are used to determine an individual cadet’s grade in Engr 410.

Another huge instructor challenge is providing a worthwhile and challenging project to the class. The project must have some complexity to require engineering analysis (which

should be able to be performed by even non-technical cadets), and yet it must be capable of being built by cadets in a single semester timeframe within a tightly constrained budget and minimal sub-contracting. The required engineering analysis must reflect material that cadets have learned in the core engineering classes throughout their USAF Academy career. The project is best if it can be broken into individual subsystems. Also, the instructor needs to have a possible solution to the problem already in mind.

Likewise, even with a perfect project, the challenges of motivating students and choosing projects of appropriate difficulty remain. Trying to motivate both technical and non-technical cadets to get excited about engineering design is not easy. It is vital for the instructor to be able to adapt to the individual class – some need to be “coached” while others can survive more autonomy. Course critiques have shown that instructors with this adaptable style have been able to produce a better-motivated student.

Group dynamics is yet another challenging aspect of Engr 410. Since cadets are randomly assigned to each section, there is often a wide-range of backgrounds in each Engr 410 class. Both the instructor and the cadets are challenged to work together as a group and produce the required product. There are times when friction in the group causes problems and the instructor can be very tempted to step in. However, past experience has shown that it’s best to relinquish some control over the class and allow the cadets to work out their problems on their own. Two examples of Engr 410 section backgrounds are given in Table 2 below.

<u>Engr 410 Section A</u>		<u>Engr 410 Section B</u>	
<u>Major</u>	<u># of Cadets</u>	<u>Major</u>	<u># of Cadets</u>
Political Science	2	English	2
Astro Engineering	1	Basic Science	1
Humanities	1	Political Science	3
Management	2	Computer Engr	1
Engineering Mech	1	Legal Studies	1
Behavioral Science	3	Geography	1
History	1	Biology	2
Physics	1	Social Science	1
Legal Studies	1	Behavioral Science	1
Biology	1		
Ops Research	1		
Economics	1		

Table 2: Engr 410 Section Backgrounds

To sum up the instructor challenges, whoever administers the entire course then has the unenviable task of ensuring that the range of required workload is not too vast between various projects. Likewise, instructors from five different departments need to be coordinated, with those rather objective grades brought into line with the rest of the course.

Conclusions

Despite all the challenges of taking, teaching, and administering this course, “Throughout the United States Air Force, previous graduates of the USAF Academy agree on one recurring theme – the value Engineering 410 had on their careers in the Air Force.”² Whether it’s the exposure to hands-on fabrication and construction, the exposure to the engineering systems design process and the DoD acquisitions process, experience working with cadets from different backgrounds, or the fabrication of worthwhile projects and interaction with the local community, Engineering 410 has been well worth the time and effort that goes into the class. Graduates remember their projects (even suggesting their own when on active duty), and the overall experience not only helps them throughout their careers as Air Force officers but also the rest of their lives.

A quote from a 1984 graduate of the USAF Academy sums up the Engineering 410 experience: “I have been in charge of mergers and acquisitions for the technology sector of a major London bank for the past 5 years. Engineering 410 provided me analytical skills that I use in my job every day. The group dynamics, analytical skills, and project management techniques I learned by applying it to a real-world scenario gave me tremendous experience at an early age. It was the best course I have ever had, even compared to my Ivy League MBA courses.”

Another quote from a 1988 graduate who now teaches on the faculty: “E410 is a challenge, but I found as a student, and the students that I now have in class have for the most part felt that it is the best course they have had at the Academy. Unfortunately, the cadet critiques don’t reflect this since they take the critiques while they are still caught up in the exercise of trying to finish their project, but after getting some real-world experience, they realize it is a great course to prepare them for the real world. Getting a group of people together to solve an ill defined problem is not easy, but neither is life ☺”

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Biographies

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