AC 2007-1340: EVOLUTION OF A CLASS IN SPACECRAFT DESIGN: EXPERIENCES GAINED OVER A DECADE OF TEACHING

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Evolution of a Class in Spacecraft Design: Experiences Gained over a Decade of Teaching

Abstract.
Spacecraft Design at the University of Colorado at Boulder is a project-based approach to the design of an unmanned spacecraft mission, focused at the senior and graduate level. Teams of students produce a Concept Study Document and series of oral presentations for a hypothetical NASA Announcement of Opportunity. The class incorporates subsystem lectures and student presentations with the goal of imparting a systems engineering view to the design of a spacecraft without attempting to teach systems engineering. Strengths and weaknesses of a classroom approach to developing competence in the subject matter are discussed. Similarities and differences between the experience of a classroom environment are contrasted to the Student Nitric Oxide Explorer (SNOE) student spacecraft build. Plans for expanding the class to include the study of a future NASA/ESA mission are reviewed.

The approach for designing a spacecraft, and the knowledge of process and procedures needed to do so, have been developed from experiences gained from trial-and-error learning since the space age began more than half a century ago. Systems that go into space are varied, and can be designed to be unmanned and manned, with a historical difference being the cost premium that the presence of a human in the system puts on safety and reliability. Unmanned satellites within the NASA environment, the focus of the class and this paper, were once treated in a substantially different way from a safety and reliability approach, but given significant costs for even the simplest of spacecraft, the differences in the design process for unmanned and manned vehicles are disappearing as safety and reliability requirements evolve to be similar to manned vehicles. This change across NASA is principally due to processes implemented following the Challenger disaster, and further modified after the Columbia accidents, and has resulted in a pronounced risk adversity within NASA in all areas. It also seems to be the case that as the first generation of space engineers enter retirement, the hands-on lessons learned experiences are also being lost. To offset the loss of expertise, the focus within NASA today is on process and procedure, with the intent that by following established approaches to design and implementation, that this will keep reliability in place. The viability of this approach is debated broadly today as ever increasing costs and longer schedules erode the available budget resources.

Universities have played a key role in space and can continue to do so. Universities have been a place where the undertaking higher risk projects within stricter funding guidelines have been accomplished with two goals: 1) to accomplish the task to the best of the available ability; and 2)
to educate the participants and provide experience in space hardware development. This approach to hardware development within a university has been a way to provide a broad education to future space workers, but fewer of these opportunities exist today. Despite current NASA trends to the contrary, universities can continue to provide an environment for higher risk developments within a rich teaching environment for today’s students, who are the future employees within the space business, with hope that

Many areas of the space business have changed over the past decade. One specific challenge is getting into space, made difficult by the limited availability and cost of launch vehicles. The number of US launch vehicles are less, and while there is hope and optimism for a number of small start-up companies to develop alternative launch vehicles that are more economical, today’s cost to get the smallest of payloads into low orbit on a US manufactured vehicle exceeds $30M, and for the largest of satellites can approach ten times that amount. Shuttle launches, once the hope for low cost space transportation, have not proven to be so. The focus on risk aversion, and the high cost of launching payloads, are two of the factors that have changed in the spacecraft development environment over the past decade.

Teaching spacecraft design in this changing environment has been both interesting and challenging: interesting in that incorporation of the changes into the course keeps the lecture presentations and discussions fresh from year to year. The teaching challenge has come from interpreting these changes, and structuring increasing amounts of lecture materials that inform, but don’t overwhelm the students. One area in particular, project management, has evolved. Risk management, as one example, is becoming a formal embedded process within a project to help the project manager to more effectively manage programs. Assessing and managing risk is proving to be one of the most effective way to identify and manage issues. Ten years ago this methodology was in its infancy. Earned value management (EVM) is becoming a requirement on all programs – independent of project value. Where it was once applied only to very high dollar programs, it is now being used in smaller efforts where schedules and budgets are tied together to better track progress and performance. There have been corresponding changes in each of the discipline areas, ranging from new design, analysis, and manufacturing tools to improved understanding of the on-orbit environment.

Teaching spacecraft design has much in common with teaching the design of any engineering system. A spacecraft begins with high level requirements and objectives, and often the mission dictates the form and function of the design. Near earth missions can often be less efficient in terms of mass, power and data than those further from earth. These high level requirements
generate a second level of measurement requirements for the mission, i.e. resolution, wavelengths, reliability, lifetime, etc., including a baseline minimum performance that the mission must meet. These level 2 requirements are key to managing the systems engineering effort as they place performance requirements on all elements of the mission, and when verified and validated, assure the project that the mission will perform as specified. These second level requirements are further evolved into level 3 performance requirements on the space and ground segments of the mission, and these are often specified in contracts to the suppliers. Level 3 requirements include considerations such as launch loads, the environment the satellite will see when on orbit, the spacecraft lifetime, testing requirements, and other conditions that will can affect the design. One condition that separates spacecraft design from many engineering tasks is the inability to retrieve and service the spacecraft (with the exception of software changes); this places a premium on the overall system design of a spacecraft including a well developed strategy for graceful degradation of the system.

A search on the internet will return a number of university programs that teach spacecraft design with a variety of approaches: some focus on hands-on hardware experimentation; some are multi-semester efforts, and some involve academic study of a spacecraft design. The University of Colorado’s program falls into the latter. With the growing interest in teaching systems engineering as part of the engineering curriculum, teaching spacecraft design provides a rich opportunity to stress systems engineering approaches to problem solving within a defined context.

Within the University of Colorado’s Aerospace Engineering curriculum, ASEN 4148/5148 Spacecraft Design has been taught as a one semester class since the 1980’s. The class originated with encouragement from industry, and in its early form engineering professionals from local aerospace companies presented lectures in their specialty subsystem. Charles Brown was the originator of the class, and for each subsystem that Brown didn’t teach, a professional would give lectures followed by homework. The student’s grade was based on the homework, a midterm, and the final exam. The “book” was a bound copy of the lecture notes that were contributed from each of the lecturers. In the early 1990’s, with a growing focus on team-based learning and group work, Brown modified the class format from the lecture/homework/exam approach to a team project-based project format where students worked together to create a spacecraft design. The lecture approach was unchanged, and the class was further supported by professionals returning to help groups with their projects. Class response was very positive to this approach. I had little teaching experience when I assumed the teaching role from Brown in
1996, and chose to keep the class format of a project-based team project. The changes made since that time are described later in the paper.

Spacecraft Design is offered as an aerospace elective in the School of Engineering and is intended to provide an introduction to the topic. The class treats the subject broadly, emphasizing first design principles; students desiring to explore topics further can do so in the graduate curriculum. The class is intended primarily for aerospace engineering students, but mechanical and electrical engineers along with engineering physics majors have taken the class. The one prerequisite for the class is senior standing. Students are graded on the quality of their Phase A spacecraft proposal, along with their formal presentation of the design at the end of the semester. The student’s individual grade comprises their individual contribution to the proposal, the overall quality of the completed proposal itself, and peer evaluations from their team. Ten years ago there was a homework component to the class, and each lecture had an assignment pertaining to the lecture, but not related to the proposal effort. That homework has been removed in favor of evolving the final project with more deliverables. The class is crosslisted as an undergraduate/graduate class, and is taken by both undergraduate and graduate students and more recently by professionals from industry. There are no prerequisites with the exception of senior standing: experience has shown that while juniors and sophomores are able to perform the work, they tend to not engage the group as well as an older student does. Enrollment of 16 students in 1996 grew to 52 students in 1998, too many students in my opinion to relate to effectively. Enrollment is now capped at around 30 students. The class is offered across the engineering school, but the limited enrollment keeps the class rich with aerospace engineering majors. The cap at 30 results in 3 teams of 10 students/team, and the class is small enough to provide individual attention to students when needed. Teams of 8 and 9 students have also been highly functional. Teams larger than 10 are not as cohesive, and teams of 7 or fewer students have not been as successful. Teams are selected to be a mix of undergrads and grads.

The most significant change in the class has been movement away from a class of professional guest lecturers. While the idea of having outside professionals lecture each of the topics makes sense, in practice the quality of the lectures, and coverage of materials is more difficult to manage. Having gained experience though my professional work, I now give all the lectures, and it’s the exception when I invite an outside speaker in. This class has responded well to this, and students seem to appreciate seeing the same person each lecture. An important part of this class is creating an atmosphere conducive to creating a meaningful teamwork experience for the students.
The preliminary unmanned spacecraft design can be accomplished with knowledge of 8 areas: 1) mass-efficient mechanical structure design, 2) steady state thermal design in the absence of convection, 3) basic orbital mechanics, 4) control of the spacecraft’s translation and rotation maneuvers (attitude control), 5) power generation and energy storage, 6) operability of the spacecraft systems (command and data handling), 7) telecommunications, and 8) propulsion. Two other areas, project management and systems engineering, are important components of a satellite design, and in the ideal team one individual assumes the responsibility for either a subsystem, the systems engineering role or the project manager position. A highly functional group will have mastered the basics of each of these areas in one semester.

Given that each of these topics can be taught as a semester-long class, and given that most students who take the class have had no previous exposure to the topics, the teaching challenge is to provide enough information to enable them to do design work, but not overwhelm their ability to retain the information. Many texts are available as resources for teaching, and I’ve alternated between the original notes from the class, Space Mission Analysis and Design (SMAD)iv and Elements of Spacecraft Designv. SMAD is a particularly useful reference owing to the breadth of coverage, and it’s a text that I recommend to have as a reference, and most professionals in the industry have a copy. Student evaluations of both texts, however, are consistently low, so there remains an opportunity to create yet another introductory text. There are a handful of other texts that are useful for reference as wellvi. Much of the contemporary information about spacecraft is conveyed in the professional setting (with much of the information being proprietary) so most texts on the subject are basic at best. International Traffic in Arms (ITAR) regulations have further restricted information flow – so web sites that used to be readily available are no longer accessible. From this perspective the subject is more difficult to teach than it was a decade ago and without access to web sites – more challenging for the student to complete the design.

Each semester begins with a mission concept for the class to “propose to”. Using NASA’s Announcement of Opportunity (A/O) for Discovery Missionsvii as a guide, requirements for a selected mission are put together. Each year a planet is chosen and science goals and objectives are outlined. A minimum of requirements are put into the A/O to provide a design framework to work from, and each team is permitted to work within the constraints of the requirements. Each mission has a specified payload, typically consisting of a camera and a sensor in a particular wavelength. The requirements (mass, data, power, field of view, interfaces, etc) placed on the mission by sensors quickly add complexity, so the number of instruments are kept to a minimum. Outer planet missions with one camera sensor provide considerable challenge. Since 1996 the
class has accomplished missions to each planet (including the then planet Pluto), with the 
exception being Mercury. Missions at Earth, to Venus and to Mars are less complex from a 
mission design perspective, and as solving the interplanetary transfer is the first priority for 
going to another planet, Venus and Mars are straightforward to calculate. With this solved teams 
can pull together the top level design. Missions to the outer planets are more challenging owing 
to propulsion requirements to get into orbit. They offer increased challenge in all subsystem 
areas, but seem to create more interest with students. A mission to Mercury has an interplanetary 
transfer (flybys) that is beyond the scope of the lectures. The environment is also quite 
challenging – particularly the increased thermal loads with closer proximity to the sun.

The semester consists of 2 teaching segments. The first segment prior to spring break is taught in 
lecture format. There are two lectures per week, and each of the 8 subsystems has 1 or 2 lectures. 
In each lecture the basic design approach is discussed along with appropriate basic calculations. 
Following spring break each of the students is required to give a standup presentation on a topic 
of interest in spacecraft design. Written feedback is provided to each student following their 
individual talk.

Some observations about teaching the class:
Projects. The design of the interplanetary trajectory, velocity changes and required propellant is a 
key to developing the design, and missions near Earth are the easiest for the class to accomplish, 
The two earth orbiting missions that have been done were not favorites of students, but were 
good projects to gain teaching experience. Earth orbiting missions make a good starting point as 
launch requirements are easily met, the thermal environment is well understood, space effects are 
easily quantified, communication distance is small, attitude control disturbances are easily 
quantified, and magnetic torquing against the earth’s field can remove the need for onboard 
propulsion. In increasing order of challenge and complexity are Mars and Venus, then the outer 
planets and finally Mercury. Mars has a straightforward interplanetary transfer, with significant 
public information on past and current Mars missions for students to use. In this sense it has 
good resources for the student. The one disadvantage of Mars is that students are strongly 
influenced by the Lockheed Martin spacecraft designs for Mars, and some of the proposals 
during that mission study seemed remarkably similar to the Lockheed Martin design. Venus is 
slightly more complicated interplanetary transfer, but is a comparable to design complexity as 
Mars. The outer planets – Jupiter, Saturn, Uranus, Neptune – create challenges due to launch 
energy requirements, transit time to the planets and restrictions to data rate because of distance. 
Thermal and power generation are more difficult as distance from the sun increases. Outer 
planets require nuclear power sources. Most students don’t have a background in mission design
so missions to Mercury, and the need for planetary flybys to get to the planet are beyond the scope of the introductory class.

The Announcement of Opportunity. Using a NASA document as a guide has worked well for the class, and following the selection process used by NASA in evaluating proposals adds an element of realism to the class. Early distribution of this document is important to give the class time to read and ask questions before moving too far into the subject material.

Classroom. Presentation of spacecraft design materials strongly benefits by being in an electronic classroom, with a projection system and board to write on. The information delivery benefits by being able to use video. In the past decade a wealth of video has been developed, accessible on the internet, adding significantly to static viewgraph presentations. A PowerPoint presentation with embedded short videos is effective in making a point that otherwise would require significant time to explain.

Selection and Size of Groups. Student teams are selected to be a mix of undergraduate and graduate student. Over the years questionnaires, Myers-Briggs assessment, similarities in life history, preference for Coke or Pepsi, grade point averages, birthdates and random selection of team members from the class list have been used to select teams; no one approach has revealed a discernable difference in team performance or quality. Keeping balance between each team with similar percentages of undergrads and grads on each team avoids some arguments between teams. Team people who don’t have a previous relationship so that all groups start with more-or-less equal familiarity with each other. There has, however, been clear preference for group size. In ten years the class has created approximately 45 teams of between 6 and 11 students, with most averaging 8 to 10 – the latter being preferred. For a number of reasons, including one student covering too many subsystems, groups of 7 or fewer struggle.

Ice Breaker. I assign the same 4 part ice breaker homework to each team in the second week of class. Each team is reimbursed for a team dinner at a restaurant. To get reimbursed each team has to provide a set of photos documenting the evening that include everyone at dinner, everyone wearing a hat, everyone wearing sun glasses, and everyone with someone famous. This elicits a number of groans at first, until I point out the specific requirement of needing photos with these attributes with the suggestion that there might be software that could help with this task. I also ask for individual pictures of each student; these I use as flashcards to learn the student names.
Lecturing. The first year of teaching involved weekends and evenings to build and rehearse lectures for the coming week. Despite the time spent, only a few of the lectures in the first semester year were satisfying to present. Most seemed inadequate. In the second year less preparation work was required, and somewhat surprisingly the flow and quality of the lectures in class seemed improved. The student evaluations supported this. With increased confidence the 3rd year included preparation, polish and practice for each lecture before going into the classroom. The experience was pleasing in that the quality of the lectures was much higher in my opinion. In addition I was able to increase the content of each of the lectures to better match with my own learning over the three years. Student evaluations, however, did not support this. Thinking the materials needed further improvement the 4th year had even better charts, but when presenting it became clear that many in the class were not listening. It was at that point that I found my teaching style – the style I use today. I realized that in the effort to make my presentation materials perfect, and my lectures equally as refined, I lost contact with the students. What I found out was that they weren’t looking for perfection, they were look for participation.

Lectures. Each lecture is a mix of PowerPoint presentation, board work and discussion of a contemporary issue in spacecraft design. Some of the best discussions come from issues arising in my work environment, including technical and management problems on our ongoing space projects. If, in the course of lecturing the class seems unresponsive, I’ll often stop and introduce a discussion topic to get the students back into the lecture.

Student Feedback. Spacecraft Design is one of the highest evaluated classes in the University of Colorado’s School of Engineering. Students clearly enjoy the class, the process of learning to design a spacecraft, and the feeling of accomplishment – despite the significant workload -- by completing the class. For some students the work in this class has been discussed at job interviews and has become the basis for a job offer. Two aspects of the class receive criticism each year: a) the in-class presentations and b) the book. A small percentage of the class, particularly those who do a good job with public speaking, view the in-class presentations as a waste of time. Most students, however, show marked improvement in speaking capability by going through this process.

Classroom Management. Being an adjunct, and having a professional position, clearly influences how the class is managed. The class is less academic, and more typical of a work environment. First names are used, including mine. Students are treated in ways similar to how interactions are with colleagues at work. This approach minimizes the need to adapt between work and the classroom, and simplifies things. I make one request of each student in the beginning of the
semester in that they email me if they are going to miss class. I let the groups work independently over the semester, and the first meeting I have with the students is before spring break. At that meeting we informally review their proposal progress. If progress is not where it is expected, future meetings will be planned following the break. Most groups don’t need this oversight.

Guest Lecturers. Because the class is a one semester effort, it’s important that each lecture cover the appropriate material. The results from the use of guest lecturers have been mixed, with some being excellent, and some less so. With less capable lecturers the continuity of the class is disrupted, and the follow-up lecture has to cover the material that wasn’t previously covered. The tendency over the years is to use fewer guest lecturers.

Final Presentation. The final presentations are a highpoint of the class, and adds a significant educational component to the class. All presentations are presented on one evening. All members of the class attend and are present for each team’s presentation. Each student is given an evaluation form to grade the other teams. Each team is allocated 90 minutes to describe their proposal. Invited professionals from industry are often present to evaluate and question each of the teams. Former students often are in attendance as well. All day presentations are a way of life in the spacecraft design business, and the evening of presentation is authentic to industry. Dinner is catered, and the evening is both an education and social occasion.

ITAR. The most impactful change over the past decade has been the impact of the International Traffic in Arms Regulations, and the chilling effect these have had on the public availability of information related to spacecraft design. A decade ago the equivalent of a Google search for spacecraft components would return catalogs of information; today there is almost no technical information on websites. Vendor response to students, once quite easy to develop a conversation with any of the spacecraft component vendors, is now more difficult. The inability to obtain information on spacecraft and launch vehicles has been the single largest change that has made accomplishing the semester long project significantly more challenging.

Life as an Adjunct. There are a number of books written on teaching as an adjunct with excellent advice and observations. My professional life has greatly benefited by teaching the class. There have been opportunities for enlightenment, and working with students has been rewarding. Some students have come into our organization to work with us, and many who have gone out into our industry. Balancing working and teaching is a constant challenge, particularly
during periods of project reviews and heavy travel. From the viewpoint of a professional looking at academia, I’d reverse the old saying, “Those who can’t, do; those who can, teach.”

Picking a Winning Group. All of the proposals are evaluated against a mock selection process patterned after that used by NASA. A principal component of the NASA selection process is evaluation by a panel of experts called TEMCO. Each proposal is evaluated for technical and cost realism, and the proposals are ranked according to risk. Each of the students receives a certificate for completing the class patterned after a long standing tradition in NASA where all team participants receive recognition for their work.

Lessons Learned. Each year a new group of students comes into the class, most without any previous knowledge of spacecraft design, and over the course of a semester most exceed expectations for supporting their team’s development of a mission spacecraft proposal. One of the most important roles in industry in the development of a spacecraft design is the systems engineering role where the overall top level design is managed. In this class each group is required to designate a project manager and a systems engineer, and it’s usually the case that the project management responsibilities are well understood, but the systems engineering role is more difficult to carry out. It’s been challenging over the years to effectively teach the systems engineer role, and it usually isn’t carried out well within the teams. Over the years this confusion has become less of a concern, as there has been almost a uniform response by each of the systems engineers at the end of the class where they recognize, looking back on the project, what the true value of that role is. For that matter most students recognize the value of the class when they go out to aerospace industry, participate in the design process and have a chance to look back on the class. Having gone though the process once, they seem better prepared to take on the challenges that industry presents.

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i NASA Integrated Action Team (NIAT) Report
ii NASA Columbia Accident Investigation Board (CAIB) Report
iii Charles D. Brown, Elements of Spacecraft Design, AIAA
iv Larson and Wertz, Microcosm
v Charles Brown, AIAA
vi JPL Introduction Text, APL text, UK Text, etc.
vii NASA HQ Web Site
viii Books