AC 2011-1009: SYSTEMS ENGINEERING AND SPACECRAFT SUBSYSTEMS MODELING AS PREREQUISITES FOR CAPSTONE DESIGN

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Lisa Guerra has 25 years experience in the NASA aerospace community. Ms. Guerra is currently working with the UTeach Engineering Program. She recently completed a 4-year assignment from NASA Headquarters to establish a systems engineering curriculum at The University of Texas at Austin, as a pilot for national dissemination. Ms. Guerra's most recent position at NASA Headquarters was Director of the Directorate Integration Office in the Exploration Systems Mission Directorate. In that position, her responsibilities involved strategic planning, international cooperation, cross-directorate coordination, architecture analysis, and exploration control boards. Prior to this assignment, Ms. Guerra worked in the Biological and Physical Research Enterprise and the Space Science Enterprise in the capacity as Special Assistant to the Associate Administrator. While in the Space Science Enterprise, she managed the Decadal Planning Team a precursor effort to enabling the Bush Administration's Vision for Space Exploration. Ms Guerra also spent 3 years at the Goddard Space Flight Center as Program Integration Manager for future high-energy astrophysics missions, particularly the James Webb Space Telescope.

Ms. Guerra started her career at Eagle Engineering Corporation in Houston focusing on conceptual design of advanced spacecraft for human missions to the Moon and Mars. Ms. Guerra continued working on space exploration-oriented assignments at SAIC (Science Applications International Corporation) in support of NASA's Johnson Space Center.

Ms. Guerra earned a B.S in Aerospace Engineering and a B.A. in English from the University of Notre Dame. She received a Master of Science degree in Aerospace Engineering from the University of Texas at Austin. Her Master's thesis, "A Commonality Assessment of Lunar Surface Habitation", was performed under a research grant from the Johnson Space Center. Ms. Guerra is also a contributing author to the McGraw Hill textbook, "Human Spaceflight, Mission Analysis and Design". Her current efforts in systems engineering curriculum can be located at http://spacese.spacegrant.org.

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Growing up in Ocean Springs, MS, Martin Brennan developed a passion for science and in particular, flight. He entered Mississippi State University after high school with a keen sense of problem solving, which lead to earning a double major in Aerospace Engineering and Physics. His interest has been further ignited by graduate studies in spacecraft design and orbital mechanics at the University of Texas at Austin, where he is currently pursuing a PH.D.

Systems Engineering and Spacecraft Subsystems Modeling as Prerequisites for Capstone Design

Abstract

A NASA project to improve university design education curricula has resulted in the addition of an undergraduate introduction to systems engineering and a spacecraft subsystems modeling laboratory as prerequisites to the capstone spacecraft/mission design course in aerospace engineering at the University of Texas at Austin. The systems engineering course materials, created by the second author, are based on NASA systems engineering practices and available in the public domain on the internet (http://spacese.spacegrant.org). The current paper summarizes the content of the systems engineering course, as well as a companion lab on modeling spacecraft subsystems, and focuses on the positive effects of introducing systems engineering prior to the capstone design course. The student designs since the introduction of the systems engineering prerequisite have been more complete, better conceived, better documented, and much more professional than before. The student design team leadership has functioned more effectively and student oral presentations have been markedly improved. The effects of the systems engineering introduction are most apparent in the final written design reports. Summary information from an example student report is included here and the full report is available.

NASA's Project

In fall 2006, the second author, a NASA engineer, came to the University of Texas at Austin on an Interagency Personnel Act (IPA) appointment for the purpose of finding ways to increase the systems engineering awareness of graduating engineering students. The goal was to work at both the undergraduate and graduate levels. The first author had been teaching the capstone space/mission design course at UT Austin since 1984. During the two initial semesters, the NASA engineer attended the capstone design classes and provided lectures on systems engineering topics at the appropriate times during the semesters. Meanwhile, she was developing course materials and planning for a full course that introduces systems engineering at the undergraduate level.

In spring 2007, the first offering of the three semester-credit-hour prototype systems engineering introductory course occurred. There were twenty five students in the class, with most having taken the capstone design course or were taking it simultaneously. There were only a few students who had neither taken nor were enrolled in the capstone course. This meant that the experiences of this set of students could not be used as typical of the planned course sequence.

The systems engineering course materials were organized into PowerPoint modules so that they could be made available as a resource for instructors across the nation via the internet. As part of the materials development process, engineering faculty from the University of Colorado at Boulder reviewed the course materials and provided feedback. In October of 2008, a conference was held at NASA JSC in which the course materials were first presented to the national academic community.

Now available online, the materials include twenty-seven systems engineering lecture modules, example assignments and examinations, reference documents including NASA and other government handbooks, recommended readings, two video lectures about systems engineering by Gentry Lee of the Jet Propulsion Laboratory, and links to other related systems engineering resources. The materials are available on the National Space Grant Foundation website[1]. The website is updated periodically with additional material contributed by faculty who use the materials. In addition, NASA is sponsoring the development of twelve new modules in related topics, such as human factors engineering and virtual teaming. These additional modules, as well as a graduate-level systems engineering course will be available in 2010. The website also includes a FORUM on which users can share information.

UT Austin Implementation

In fall 2006, the Aerospace Engineering Department at UT Austin began planning for curriculum revisions to be effective in the 2008-2010 course catalog. The first author chaired the curriculum committee. In the 2006-2008 catalog, students chose between an aeronautics technical area and a space flight technical area, each of which had seven hours of courses. In the new catalog, each technical area was expanded to contain thirteen hours of courses, with a second design course being added to each area. The faculty in the space flight area chose to require the Space Systems Engineering Design (SSED) course as the prerequisite for the capstone spacecraft/ mission design course. Also, a computational laboratory attached to the orbital mechanics course was revamped to focus on the modeling of spacecraft subsystems. The course was renamed as the Spacecraft Systems Laboratory (SSL) to better reflect the new course content. These courses were formally adopted for inclusion in the curriculum as prerequisites for the capstone design course effective in the fall 2008 semester.

Space Systems Engineering Design (SSED)

This course is a three semester-credit-hour course taught on a twice per week basis. The course modules developed for the SSED course are Introduction, Teamwork, Project Life Cycle, Scope and Concept of Operations, System Architecture, System Hierarchy and Work Breakdown Structure, Analytical Hierarchy Process, Requirements–Basics, Requirements–Writing, Requirements-Configuration and CM, Functional Analysis, System Synthesis, Design, Interfaces, Margins, Technical Performance Measures, Cost, Risk, Technology, Trade Studies, Reliability, Verification, Technical Reviews, Schedule, Management, and Ethics. All modules are available to the students on the course website and remain available to them in the capstone design course.

Space Systems Laboratory (SSL)

The SSL is a one semester-credit-hour laboratory course, created by the third author, which focuses on the modeling of spacecraft subsystems. This course is taught concurrently with the SSED course and consists of a 1.5 hour lecture and a 1.5 hour guided computer lab each week. Students in the SSL course step through 12 different week-long modules that cover important topics in the analysis of spacecraft performance. Topics include modeling and simulation, all the major spacecraft subsystems (e.g. power, communications, propulsion, thermal, etc.), the space environment, launch vehicle selection, Monte Carlo analysis, and a few other specialized modules. The class discussion focuses one week to each of the following topics.

- Introduction to Modeling & Simulation
- Introduction to Spacecraft Subsystems
- Space Environment Modeling
- Launch Vehicle Selection
- Atmospheric Entry and the Thermal Protection Systems
- Propulsion Subsystems
- Attitude Determination and Control Subsystems
- Communications Subsystems
- Command and Data Handling Subsystems
- Power Subsystems
- Structure and Thermal Control Systems
- Parachutes, Landing, and Impact Attenuation Systems

Student work during the last month of the course is focused on an extensive individual project that looks at a trade study involving two subsystems for an interplanetary mission. This final project gives the students an opportunity to exercise the tools they learned in the SSL course and provides a glimpse of what they will be doing on a larger scale as part of a team in the capstone design class.

Capstone Design Course

The capstone design course is a three semester-credit-hour course taught in both the fall and spring semesters. In this course, students do a conceptual design of a space system and mission. The design course deliverables were sequenced to allow (force) the teams to follow good systems engineering methodology. The deliverables, in the order assigned, are:

- Design Scope Oral Presentation
- Design Proposal - 20 to 30 pages
- Team e-mail Progress Reports – weekly
- Team workload management reports as appropriate
- Design Requirements Briefings
- Trade study oral/written reports
- Mass/Volume/Power oral/written report
- Design Oral Mid-Semester Presentation
- Design Written Mid-Semester Report
- PowerPoint of the Oral Presentation
- Peer reviews: Mid-term Reports & Presentations
- Design Oral Final Presentation
- Design Written Final Reports
- Design Poster and/or Models (if appropriate)

Implementation and Effects

The SSED course has been taught every fall and spring semester at UT Austin beginning in spring 2007 and the SSL course was first taught in the fall of 2008. The transition period, in which some students were taking the SSED course and/or the SSL course concurrently with or after the capstone design course is complete. During the fall 2008 semester, only four students in the class had taken the SSED course, and none had taken the SSL. Each of these students took the role of the Systems Engineer on a design team such that there were four teams comprised of seven students, six of whom had not taken the SSED course. The results in this semester seemed better than those of earlier semesters, but the real improvements occurred when almost all of the students in the capstone course had completed the prerequisite courses in the new sequence.

In spring 2009, more than half of the students in the capstone course had taken the SSED and SDL courses and the student work was perceptibly better. In fall 2009, only one of 28 students had not taken the two (now prerequisite) courses. The quality of the student final reports was much improved. The work was more complete, better thought out, and more professional. Effects of the SSED and SSL courses on the capstone design course include the following:

- Student teams are effectively organized and function more smoothly. Using the team structuring model from SSED, teams now have a Project Manager, a Chief Engineer, and a Systems Engineer.
- Students now develop improved and more comprehensive requirements than before. The emphasis placed on requirements development in SSED has resulted in a much greater appreciation for the role of precise requirements in design.
- Students implement trade studies in more detail. The coverage of trades in SSED and the modeling of subsystems in SSL give the students a strong appreciation for the need for trades and the ability to quickly and accurately model subsystems.
- Students develop preliminary Concepts of Operations (ConOps) and later refine them based on requirements developed earlier in the course.
- Teams are much less prone to decide on a single mission-architecture early in the formulation process. They are much more willing to revise their design concepts than students were in earlier semesters. This indicates a better understanding of the role of iteration in engineering design.
- Students seem much more aware of the importance of looking at heritage systems. However, they measure heritage systems against their own requirements and often reject or suggest modifications to heritage systems if chosen as part of their designs.
- The depth of analysis of the various subsystems in each team project has increased markedly, with many subsystems now including candidate hardware, performance criteria, and choices of specific hardware for their designs. In previous semesters, this was a rare occurrence.

An Example of Student Work

The written design report is the primary tangible product of the capstone design course. The example is from a student team in the fall 2009 semester. The project topic chosen was suggested by an engineer at the Jet Propulsion Laboratory and involved a Neptune orbiter that deployed a lander on Neptune's moon, Triton. The two vehicle names reflect their missions. The main spacecraft is named NEWTON (Neptune Exploration With Triton ObservatioN), and the Trition lander is named EINSTEIN (Exploration Into Neptune's Satellite Triton Examining its Internal Nature). The example student work consists of the Table of Contents, List of Figures, and List of Tables (without page numbers) of the design team's final report. These items provide insight into the influence of the SSED and SSL courses on the student work without presenting the entire final 100 page report[2]. Note the Table of Contents entries are compressed here. They were not compressed in the student report.

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Note the close correlation between the items in the student report and the module topics in the SSED course. The addition of the SSED and the SSL has resulted in improved design products for the UT-Austin aerospace engineering capstone design course. By introducing these prerequisites, the students have the opportunity to understand and exercise critical tools and techniques prior to implementing their capstone design.

The addition of the SSED and SSL courses clearly resulted in improved design products for the UT-Austin aerospace engineering capstone design course. With this early mastery of systems engineering topics and modeling methods, the students can tackle more complex mission capstone designs in the second semester of the sequence.

NASA's investment in this project offers an opportunity to markedly improve aerospace (and other) engineering design education nationally. The entire SSED course can be adopted or individual modules can be integrated into existing courses. NASA's project was designed so that, though one university served as the site of the courseware development, all universities have access to the materials. By using the modules, adopting them to local constraints, and then sharing the results through the FORUM, design instructors can participate in the ongoing evolution of the systems engineering course materials.

Although NASA's primary purpose in initiating the pilot program was the production of future aerospace employees with a general awareness and understanding of systems engineering prior to entering the workforce, the primary aim was not to develop a group of students interested in becoming systems engineers. However, many of the UT students have voiced a career interest in this sub-discipline of engineering as well as graduate schools that enable further education in systems engineering. Although it takes years of experience and exposure to space missions and the relevant disciplines to truly be a competent systems engineer, being aware of the discipline at the start in one's career can only benefit the aerospace workforce in general. A recent graduate of the design sequence reported "I am still learning, but I can't even imagine being here (Odyssey Space Research) without having learned and worked systems engineering. Everyone is treating me as if I understand all of the systems concepts (I was afraid I might be "babied" since I was straight out of college), and I believe I am holding my own."

Assessments of Student Work

The work of student teams having the systems engineering course prior to the design course (SE) was formally and informally compared to the work of earlier teams (nonSE) that did not take the systems engineering course. The first author has taught the capstone design course, usually twice per year, since 1984, and maintains an archive containing all of the student design reports produced during that period. The changes noted stem from a comparison of nonSE reports with SE reports. The changes attributed to the introduction of the systems engineering prerequisite are listed below:

- The SE students quickly developed concepts of operations. This took about two weeks longer for nonSE students.
- The SE students wrote good draft requirements almost immediately and developed rationales for them. In the past, the nonSE students usually only implied requirements for

the first half of the semester and rarely wrote rationales for them. In addition, the final requirements developed by the SE teams were much more detailed than those developed by the nonSE teams.
- The SE teams were organized earlier and better than their nonSE predecessors. The SE teams seemed to function better at all stages of the semester.
- The SE teams planned from the beginning to conduct trade studies on critical design elements and were quick to decide which design elements were critical for their projects. The nonSE teams were much slower to recognize which design elements required trade studies and the resulting trades were much less complete than those for the SE teams.
- The mass, volume, and power budgets were developed earlier for the SE teams than for the nonSE teams. The SE teams had draft budgets as part of their mid-term oral presentations and their mid-term written reports. The nonSE teams usually developed these budgets in the last half of the semester.
- The overall quality of the mid-term and final design presentations and reports is markedly higher for the SE teams than for their nonSE predecessors.

The following assessment of the way that the design class has changed and the effects of the addition of the systems engineering prerequisite to the course sequence was made by Ravi Prakash, an aerospace engineer at the Jet Propulsion Laboratory in California.

> I was a student in the aerospace design class at UT Austin in Fall 2002, and I have been participating in a JPL collaboration with the current senior mission design class since the Spring 2009 semester. Throughout the UT-JPL collaboration, I have been increasingly impressed by the quality of work being produced in the senior design class.
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> The teams in the Spring 2009 semester far exceeded the work that my team in the Fall 2002 semester accomplished. Even more impressive is that every semester since then has continued to produce higher quality work. I attribute this to the greater amount of structure that has been added to the class, as well as the addition of the Systems Engineering curriculum that students take prior to the Senior Mission Design class. Students come out of the class having successfully performed trade studies and used spacecraft design tools, making them much better equipped for the aerospace workforce or graduate studies.

References

1. http://spacese.spacegrant.org/
2. Prine, Rebekah, Dustin Walker, Kevin Ferrant, Davis Varghese, Joshua Albers, and Richard Garodnick, NEWTON, Neptune Exploration With Triton ExploratioN, Final Report, ASE 374L, Spacecraft/Mission Design, The University of Texas at Austin Spring 2009. Available from the first author.