Spacecraft Systems Engineering Courses for Traditional Engineering Curriculum

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Abstract

Systems engineering is an important skill for future engineers. Systems engineering is a management technology that allows engineers to effectively design, develop, and deploy large scale systems. It is an essential part of engineering education that teaches by demonstrating the utility of many important technical skills such as electronics, communications, controls as well as soft skills such as teamwork, leadership, communication, timeliness, economic impacts. The author developed a systems engineering course called, Spacecraft Systems Engineering, to educate the students in systems engineering concepts. This was a multidisciplinary course with electrical engineering and mechanical engineering students. Satellites consist of mechanical, electrical, and computer-related components, so the students will naturally learned the multi-disciplinary nature of the engineering. The topics included systems engineering methods & process, orbital mechanics, satellite subsystems, and intellectual property issues. The author has offered multiple versions of spacecraft systems engineering courses at two different universities. He will present the lessons learned by teaching systems engineering course in traditional engineering curriculum. In this paper, he will also compare the differences between the courses and suggest an effective method to teach systems engineering.

I. Introduction

A skill set that the industry values, but which is not taught in traditional engineering curriculum is systems engineering concepts. Temple University is taking the initiative to teach systems engineering at the undergraduate and graduate levels by engaging in the design, build, and test of a system. Systems Engineering provides the tools and processes to ensure that correct systems are efficiently engineered. The definition and the need for systems engineering education are given in the literature, see [Sage 2000] and [Parish 1999]. According to International Council on Systems Engineering (INCOSE), there are 82 academic programs that teach systems engineering worldwide, out of which 48 are in the United States. For example, systems engineering department has been one of the most popular and successful undergraduate program at the U.S. Naval Academy [DeMoyer 2004]. There are, however, more than 2000 four year institutions in the U.S. The students in the universities without systems engineering department do not get exposed to the systems engineering concepts. Systems engineering demonstrates that there are more to engineering than technical skills because developing a system involves the interactions of science, technology, organization, environment, and information. Systems engineering has been used in various disciplines: robotics [Boyle 1997], power [Padhy 2004], imaging [Sonka 1998], and avionics [Rankin 1991]. It is an important part of engineering education, because, whether it is a cell phone or an automobile, our students will most likely work on a part of a large system. Moreover, Brown and Scherer compared various systems engineering programs in the U.S. and stress the need more systems engineers [Brown 2000]. They conclude the paper with various opportunities such as jobs in systems engineering. Thus, it is imperative for the traditional engineering programs to educate their students with some knowledge in systems engineering. Some aerospace departments have incorporated systems engineering courses to their curriculum, and systems engineering has also been taught at electrical engineering curriculum at Iowa State using fiber optics high speed systems [Mina 2005]. However, teaching systems engineering with aerospace applications in electrical engineering curriculum seems to be a new concept.

There are four pedagogical aspects to the spacecraft systems engineering course: first, to teach systems engineering concepts; second, to teach the mechanics and dynamics involved in designing, building, and testing a system; third, to teach students how to work in a team environment towards a common goal; and fourth, to teach and learn engineering practices through a spacecraft application. This course is different from the traditional lecture course in the sense that there is significant amount of design.

II. Systems Engineering Methodology

The systems engineering is used in large organization such as the department of defense, NASA, and many commercial companies. Systems engineering allows effective management of a large engineering projects. The main concept in systems engineering is to design, build, and test with documentations so others can track the project. In systems engineering process, the customer generates the user requirement. Then concept of operations describes the overall design criteria. Trade Studies leads to the selection of system, subsystem, and components. Design document is a critical part to the systems engineering process. Here one lay outs the detailed design of the subsystem and system. Design reviews are held after the design is completed. Interface Control Document details the layout of how all the subsystems will connect. Finally, the Test Plan validates the subsystem and system.

After the user requirement and concept of operation (vision for the project) are generated, the system is decomposed into its subcomponents; the system and subsystem Specifications. Trade Studies are conducted within the design phase to analyze and select the best available components for the system. The Trade Studies must take into account performance, cost, weight, power requirements, availability, and reliability of all components that could be utilized. After the Trade Studies several budgets need to be developed and maintained. Obviously, the financial budget needs to be established. Not as obvious, however, are the personnel, weight and size, power, and RF communications link budgets.

After the Trade Studies, Design Documents are created that illustrate the actual pin-outs, connections, and schematics of the components and how they will connect with one another. Next, the Interface Control Documents (ICDs) are generated to describe the subsystem interface specifications. The ICDs state the electrical, mechanical, and logical parameters that are needed for each subsystem to communicate with its connected subsystems. A particular ICD includes the specific voltages, data sentences, data structures, and connectors that will be used for communication at one subsystem interface. Then the Test Documents are drawn up, which govern the tests that must be conducted during the multilevel integration of the various subsystems. These documents help to guarantee that, at each step of integration, proper testing is performed to ensure that the complete system is operating correctly.

Moreover, Risk Mitigation is performed at each stage of the mission, particularly during the design stage, to develop a “game plan” to follow for each foreseeable risk. Risk Mitigation is used to ensure that the risk of project and financial failure, as well as human injury and physical damage, are minimized.

Periodic design reviews are essential parts of systems engineering process. Depending on the program, different review processes exist [Wertz]. In NASA program, Mission Concept Review and Mission Definition Review are conducted in the beginning phase. A Preliminary Design Review (PDR) is conducted to critique the preliminary paper design of the system. Prior to reaching the point of no return in terms of the design changes, Critical Design Review (CDR) is conducted to ensure that the design is systematically sound. Most people involved in the project including engineers, customers, outside consultants participate in the review. After the Test Plan has been successfully carried out and the total system has been assembled, Operational Readiness Review (ORR) is conducted. The ORR ensures that all subsystems are working properly and that the complete system is ready for operation. After the lifecycle of the system has been exhausted, a Decommissioning Review (DR) should be conducted to critique the performance of the system.

III. Satellite Design Course at University of North Dakota: Design, Build, and Test a Spacecraft

Here we repeat the description given in [Won et al. 2001] of the spacecraft systems engineering course taught at the University of North Dakota in 2000. During the 2000 fall semester, a course entitled "Satellite Design" was taught to 14 undergraduate and 3 graduate students. This was a multidisciplinary effort involving six faculty members from electrical engineering, mechanical engineering, computer science, and space studies. The 90-minute lecture course format included feedback and guidance by the instructor at the beginning of each class for approximately 20 minutes, with the remainder of the class spent on subsystem team meetings or a group discussion. In this course, students designed, implemented, and tested a remote sensing platform and its payload under the project name "Scorpio II." The mission objective was to provide the students with an opportunity to learn the systems engineering approach by developing an operational remote sensing platform and launching it via a free-flying weather balloon. A summary of the Scorpio II specifications is provided in Table 1.

Table 1: Summary of Scorpio II Project

Weight	Gondola: 10 kg
Size	49 cm x 49 cm x 49 cm (W x D x H)
Total Current Draw Capacity	5800 mAh
Payload	Digital Camera, Temperature Sensors, Pressure Sensor, GPS, Compass
Financial Budget	Equipment: $5000 (approximately) Labor: $0
RF Link	Frequency: 900-MHz Carrier, 26-MHz Bandwidth Data Rate: 115.2 kbps Coverage Radius: 80.0 km

Students were divided into ten teams, as shown in Figure 1, with a class member serving on more than one team. Each team had a Team Lead, who was responsible for inter-team communications and deliverables. The spacecraft bus was designed to carry the following payloads: (1) digital camera; (2) temperature sensor; (3) pressure sensor; (4) digital compass; (5) accelerometer; (6) humidity sensor; (7) voltmeter; (8) ammeter; (9) solar cell voltmeter; and (10) GPS receiver.

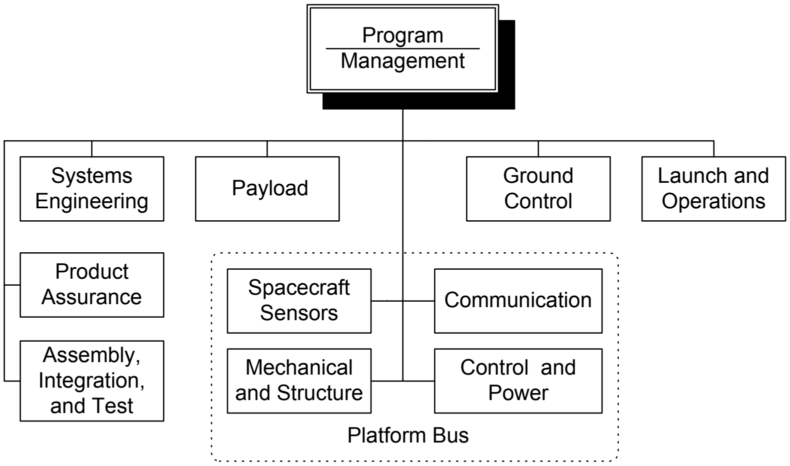

Figure 1: Organization Chart of Spacecraft Development Project

The spacecraft telemetry includes data from all payload sensors, the digital camera, and the GPS unit. The GPS data is also sent through an amateur radio transmitter, which serves as a backup tracking system. The spacecraft telecommands include: (1) a time interval change command for acquiring digital pictures; (2) a download image command; and (3) a cut-down command to separate the gondola from the balloon for retrieval. The Communications Subsystem (Comm) has the most complex interface in Scorpio II. All sensor data enters the Comm, and all telecommands are processed by the Comm. When the download image command is initiated from the Ground Control Subsystem, the Payload Subsystem receives the telecommand and sends the image directly to the airborne transceiver in the Comm. After completing the image download, a "download complete" acknowledgement is sent to the Comm. Originally, the Scorpio II airborne unit, shown in Figure 2(a), was scheduled for launch in December 2000, but because of project timeline overruns and severe weather, the launch date was delayed until spring.

Scorpio II was launched on Friday, May 4, 2001. The weather was perfect, with no wind, clear skies, and a cool temperature. A 3000-gram latex balloon was filled from two large helium tanks, which generated about 24 pounds of lift. Everything went smoothly, and we managed to transmit about fifteen "take picture" tele-commands and two real-time image reception tele-commands. Around 10 minutes into the ascent, with the gondola about 1,800 meters high, the cutdown mechanism was triggered unexpectedly. The parachute was activated and the gondola descended, landing about 1.6 km North of the launch site. Two real-time image transfers were downloaded to the ground station, and thirteen images were stored in the digital camera. Figure 2(b) shows one of the in-flight images, in which the launch site is visible in the upper-left corner.

The Ground Control Station was designed using LabVIEW and PCommPro. LabVIEW handled the primary ground control tasks including all telemetry reception and telecommand capabilities. PcommPro, a serial port communications utility, was used for the real time image transfer command. Unfortunately, the LabVIEW graphical interface was accidentally closed instead of running in the background. When the applications were switched from PCommPro to LabVIEW, the cutoff mechanism was activated. We suspect that opening LabVIEW initialized the serial port buffers and sent erroneous data, which was interpreted as a cutdown command.

Figure 2: (a) Scorpio II Airborne Unit; (b) Scorpio II In-Flight Image

IV. Spacecraft Systems Engineering Course at Temple University: Design Only

Aerospace-related projects are an outstanding educational tool to motivate and train undergraduate students. The course, Spacecraft Systems Engineering, synthesized traditional engineering concepts with nontraditional topics such as intellectual property and systems engineering methods. The other course topics included space environment, dynamics of a spacecraft, satellite attitude & orbit control, orbital mechanics, communications, space power systems, and a hands-on aerospace project. The developed modules are (1) mathematics and astrodynamics; (2) satellite subsystems; (3) systems engineering methodology; (4) picosatellite development modules; and (5) intellectual property. Table 1 mentions the modules and their objectives. In a 15 week semester, the instructor taught all five modules outlined in Table 2 (12 weeks) and other miscellaneous topics (3 weeks) such as introduction, space environment & ground station. Moreover, this course was offered as a general engineering course which included electrical engineering and mechanical engineering. Offering the course to students in different discipline was appropriate because satellites are multidisciplinary subject.

Table 2: Modules and Student Learning Goals

No.	Modules	Student Learning Goals	Time
1	Mathematics and Astrodynamics	To know how mathematics (calculus) is used in deriving orbital motion of the satellite	2 weeks
2	Satellite Subsystems	To appreciate how a system is comprised of parts from multidisciplinary fields	2 week
3	System Engineering Methodolgy	To understand why systems engineering method is needed for effective development of a large system	3 weeks
4	Picosatellite Design	To learn system engineering by designing, building, and testing a small satellite in laboratory	4 weeks
5	Intellectual Property	To understand the importance of intellectual property and learn the process of applying for a patent	1 week

The biggest difference between this course and the one offered at the University of North Dakota was that we did not actually build the spacecraft in this course. The course ended with a Critical Design Review. The instructor divided the class into six teams as shown in Figure 3. Then he assigned about three students per team. The satellite was called PaperSat because it was just designed on paper without implementation.

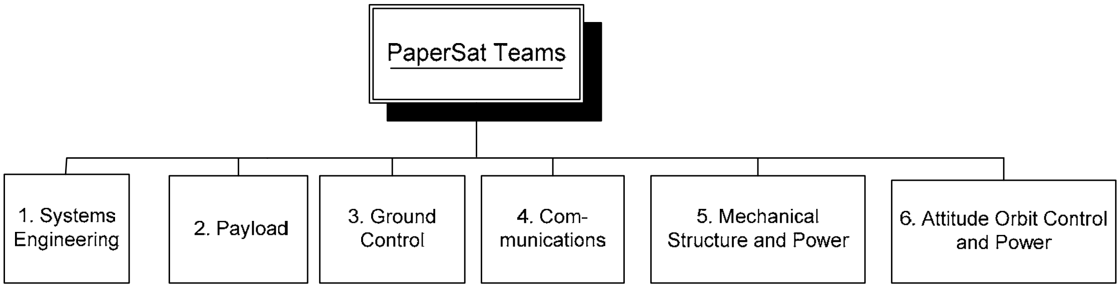

Figure 3: Paper Satellite Team Names

The PaperSat was to perform a remote sensing mission of taking images around the Temple University region in order to track the green space in and around campus. The student generated concept of operations, requirements, specifications, tradestudy documents, and design documents. Figure 4 show the mechanical design of the spacecraft. The student decided to use a weather balloon as the launch vehicle. The course ended with a Critical Design Review.

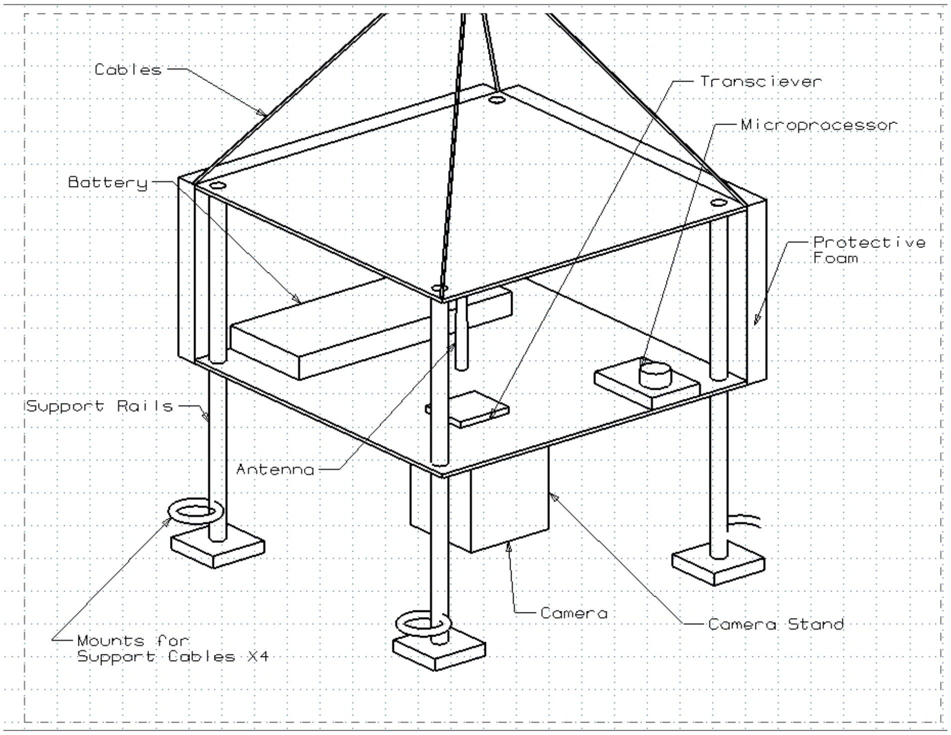

Figure 4: Mechanical Design of the PaperSat.

V. Lessons Learned

The following items summarize the lessons learned through the two iterations of Spacecraft Systems Engineering courses at two different universities.

- The satellite project taught the students many concepts that simply cannot be introduced in conventional lecture and laboratory courses. From proper documentation techniques and the systems engineering philosophy to teamwork and systems-level integration, students learned valuable lessons in both the technical aspects of engineering and the group dynamics of a large-scale project.
- Large-scale system integration also rarely takes place in either undergraduate or graduate education. The satellite project allowed the students to gain valuable experience that is generally not found in either the on-campus curriculum or through cooperative (co-op) education.
- Dealing with group dynamics helps students to polish their "soft skills," which are vitally important in today's business world. Soft skills, including oral, written, and interpersonal communications, are often the most important skills that a person must possess in order to advance one's career. Working in large groups as a part of the undergraduate curriculum provides students with a chance to hone their people skills, which generally occurs only in an industrial cooperative education setting.
- Students learned how to make informed group decisions and to deal with the ramifications of their decisions. Since each student was responsible for a major portion of a subsystem, she or he also learned how to depend on others to complete the mission. If only one person did not fulfill her/his tasks, the mission would be unsuccessful, as opposed to most undergraduate design projects in which one or two students usually do the majority of the work and the others just "get by." Part of the dependence on other team members was grounded in the integration and test deadlines. Delaying one test of a subsystem directly impacted everyone else's schedules. Students were also responsible for adhering to the cost, size, and weight budgets set forth in the design and documentation phase of the project.
- The first iteration of the course was more effective in teaching the systems engineering concepts, but the lack of time made the experience full for just a few students who actually finished the project in the following semester. In the second iteration the course ended on time, however, the full systems engineering experience was not given due to the lack of implementation, test, and launch part.
- Grading was a challenge. In the first iteration, the PI assigned grades individually, and in the second iteration by the teams. Either way students were not fully satisfied with the grading scheme.

There were some major obstacles (roadblocks) and some minor challenge (speedbumps) that arose during the Spacecraft Systems Engineering course. The second iteration of the satellite project encountered major roadblocks, namely a failed integration and test schedule and severe weather, which delayed the launch to the spring of 2001. There were a number of speedbumps in both builds, including a lack of experience with the systems engineering methodology, some negative group dynamics, and problems with consistently driving open issues to closure. The following is the summary of the speedbumps.

- The systems engineering methodology is dramatically different from the way students conventionally tackle design projects in undergraduate courses. In most undergraduate courses, students first build a system, crudely debug and test the device, and finally document what they have accomplished after the fact. In the systems engineering process, documentation laying out the system design must be written before any part is ordered or any subsystem is built. Some resistance to this philosophy existed at first, but the students quickly grasped and appreciated the utility of systems engineering.

- A problem with consistently driving open matters to closure during the meetings was a speedbump that the satellite project faced over its entire duration. The meetings or class times were originally set up to discuss progress on the project and to assign action items to individual team members, who would then be responsible for finding solutions. If the individual assigned a specific duty needed help solving a dilemma, she or he was supposed to consult with other team members outside of the meeting time, in order to make the meetings more productive and efficient. However, most of the meetings were consumed by the discussion of detailed design issues, rather than a critical examination of the overall project progress. By dealing with detailed design issues during the general team meetings rather than in the laboratory with the relevant subsystem team, valuable time was wasted for the group members not concerned with a particular problem.
- The lack of a common work schedule may be partly to blame for the problems encountered during the meetings. Because the students had not only full class loads but also outside jobs, there were very few common work hours among the group. The only times that the whole group was assembled were during the meetings and class time, which made them the most convenient times to discuss problems with the other team members. The different schedules also had a negative effect on the workings of the group, because it became difficult to discover information about unfamiliar subsystems. In essence, it was quite difficult for undergraduate engineering students to work in this environment, because of their tremendous workloads.
- Teaching students how to act on a design review was a big challenge. Students were reluctant to criticize the peers. The instructors became the “devil’s advocate” during the design reviews, which lead to slight resentment by the students.

VI. Future Directions and Conclusions

The systems engineering is an important topic for future engineers. There are a number of systems engineering departments in the American universities, but teaching systems engineering in traditional engineering curriculum is an important issue. Students seem to enjoy learning about the topic, however effective method of instruction is not yet found for the traditional engineering program. In the next iteration, the instructor will let students design, build, and test a much simpler system.

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