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Spacecraft Systems Engineering – The Initiation of a Multidisciplinary Design Project at the University of North Dakota

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Abstract

During this past year, several departments at the University of North Dakota have been focusing on the design of inexpensive spacecraft for atmospheric studies and remote sensing. This multidisciplinary design project emphasizes the systems engineering approach, in which extensive documentation is created prior to any construction or testing. Fourteen undergraduate and three graduate students designed and tested the second build of a spacecraft, known as Scorpio II, to be launched using a zero-pressure balloon. This project will send a 10-kg spacecraft to an elevation of approximately 25-km to collect and transmit real-time sensor and digital image data from the stratosphere. The telecommunications subsystem is responsible for collecting sensor readings, acquiring images from a digital camera, and packetizing this data so that it can be transmitted to a ground station via a radio-frequency (RF) link. The RF link will be implemented using a commercial, off-the-shelf (COTS) transceiver. Furthermore, the telecommunications subsystem will be able to receive uplink telecommands for controlling image acquisition, varying the sampling frequency of individual sensors, and releasing the payload from the balloon. The spacecraft – attached to a parachute – will be tracked with global positioning system (GPS) data so that it may be safely recovered after its descent. The large-scale scope of this project, coupled with the group size, has led to many new experiences for the students, including an appreciation for true teamwork and the positive and negative aspects of group dynamics. The efficacy of applying this systems engineering approach to a variety of large-scale student projects, such as spacecraft or solar-powered vehicle design, will be discussed.

I. Introduction

Undoubtedly, there exists a large gap between the engineering skills that are required by industry and the engineering skills that are taught in our universities. One fundamental skill that is commonly used in industry but almost always neglected in academia is the systems engineering approach to design. The University of North Dakota is taking the initiative to teach systems engineering at the undergraduate and graduate levels by designing small spacecrafts in class. The result of this initiative is called the Scorpio project.

The concept for Scorpio, the first in a series of planned microsatellite launches, stemmed from a proposal to NASA for student-centered satellite missions by the Upper Midwest Aerospace Consortium (UMAC) at the University of North Dakota (UND). The proposed UMAC mission – designated the "Crop Explorer Research and Education Satellite" (CERES) – generated considerable interest within the Department of Electrical Engineering regarding the possibility of designing and building orbiting satellites on the UND campus. This effort was also inspired by the ongoing "CanSat" project within Stanford University's Space Systems Development Laboratory (SSDL), in which operational satellites are designed and constructed to fit within containers the size of an ordinary 12-ounce soda can[1].

There are three pedagogical aspects to the Scorpio project: first, to teach the systems engineering methodology; second, to teach mechanics and dynamics involved in building and launching a spacecraft; and third, to teach students to work in a team environment towards a common goal. This educational model is drastically different from the typical lecture, homework, and exam course format, in which students must compete against one another for their grades.

This paper is organized as follows. In Section II, the systems engineering methodology is described, with spacecraft applications in mind. In Section III, the first build of the Scorpio project, Scorpio Alpha, is described. Section IV follows with the second build, Scorpio II, which was designed and implemented during the 2000 fall semester. Section V discusses the lessons learned from the two Scorpio builds, including new knowledge that was acquired, group dynamics that were an inherent part of the team-oriented projects, and various roadblocks that were faced by the students and faculty. Finally, the paper concludes with future directions and a vision for subsequent system builds.

II. Systems Engineering Methodology

The systems engineering approach was first developed by the military as a process by which large engineering projects could be designed, implemented, and tested prior to deployment[2]. Eventually, a modified version of the military procedures found its way into the commercial world. The philosophy centers around the idea that a project will be designed and documented on paper before any prototypes are constructed. The documentation includes a Concept of Operations that describes the overall system design criteria, Trade Studies that lead to decisions on the subsystem parts, a layout of how all system pieces will interface with one another, and a plan for integrating and testing the complete system[1,3]. Figure 1 shows the general layout of the systems engineering process, from the Concept of Operations through the various stages of the mission.

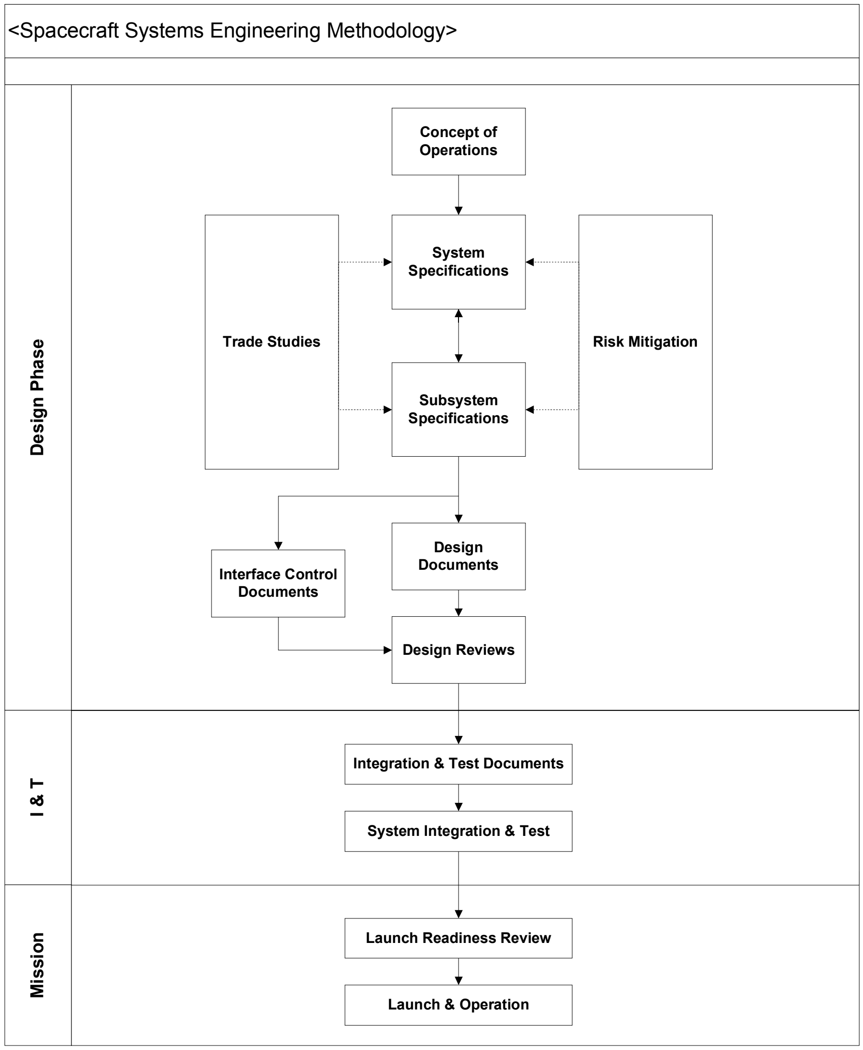

Figure 1: Spacecraft Systems Engineering Methodology

Every project must have a well thought-out vision in order to be successful. The document that lays out this vision is known as the Concept of Operations (ConOps). The ConOps drives the project by setting the requirements and defining the parameters that guide the design process. In the case of the Scorpio project, these parameters include the radio-frequency (RF) communications link specifications; image acquisition and sensor specifications; software data structures; launch requirements; and environmental conditions of operation.

Once the ConOps has been generated, the system is decomposed into its minor components. Starting with the System Specification, continuing on to the Unit Specifications, and ending with the Subsystem Specifications, the system is defined on a smaller and smaller scale until requirements of how each subsystem will operate have been laid out. After the system specification is complete, several budgets need to be developed and maintained. First, the monetary budget needs to be established. Not as obvious, however, are the personnel, weight and size, power, and RF communications link budgets that also need to be maintained.

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.

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.

Once the components have been selected, 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. Finally, Integration and Test (I&T) 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.

Periodic design reviews are essential parts of all successful engineering projects. In the systems engineering process, several design reviews are conducted at different points in the project. Initially, a Preliminary Design Review (PDR) is conducted to critique the paper design of the system. Prior to reaching the point of no return, a Critical Design Review (CDR) is conducted to again ensure that the design is systematically sound. Once the Integration and Test Plan has been carried out successfully and the total system has been assembled, a Launch Readiness Review (LRR) is conducted. The LRR ensures that all subsystems are working properly and that the complete system is ready for launch. After the lifecycle of the system has been exhausted, a Decommissioning Review should be conducted to critique the design and performance of the system.

III. Scorpio Alpha: Summer 2000

On July 29, 2000, a team of seven undergraduate electrical engineering students from UND launched Scorpio Alpha, a microsatellite that was documented, designed, built, tested, and launched over a period of 11 weeks. A summary of the project specifications is provided in Table 1.

Table 1: Summary of Scorpio Alpha Project

Weight	Gondola: 2.88 kg Complete Package: 4.5 kg
Size	28 cm x 31 cm x 40 cm (W x D x H)
Total Current Draw Capacity	3100 mAh
Payload	Digital Camera, Inclinometer, Temperature Sensor, Pressure Sensor, GPS, Compass
Financial Budget	Equipment: $4,663 Labor: $15,583 Ground Control Station (Notebook Computer): $2,000
RF Link	Frequency: 900-MHz Carrier, 26-MHz Bandwidth Data Rate: 9.6 kbps Coverage Radius: 32.3 km

The Scorpio Alpha airborne unit, launched using a moored weather balloon, contained a communications link that allowed for real-time data retrieval from its on-board sensors. These sensors, which measured acceleration, inclination, interior and exterior temperature, and compass direction, collected data that was transmitted in real-time to the ground station unit, consisting of a notebook computer connected to a transceiver. A digital camera capable of acquiring still images was also contained in the airborne unit to store in-flight images. The digital images were subsequently accessed and viewed upon recovery of the satellite.

The system performed admirably for the first 56 minutes of flight. As shown in Figure 2, strong winds began deforming the weather balloon, which caused the primary mooring line (50-pound test) to break. The secondary mooring line failed immediately thereafter. Luckily, the team had implemented an emergency cut-down mechanism. An uplink telecommand was sent from the LabVIEW-based ground station over the wireless communications link to the rapidly rising spacecraft payload. The ground station recorded telemetry data during the entire mission, and data was still being recorded by the system at the time of payload recovery. The payload container and internal electronics are depicted in Figure 3. The Scorpio Alpha project team has provided an excellent starting block for continuing spacecraft development and the creation of a Spacecraft Systems Engineering program at UND.

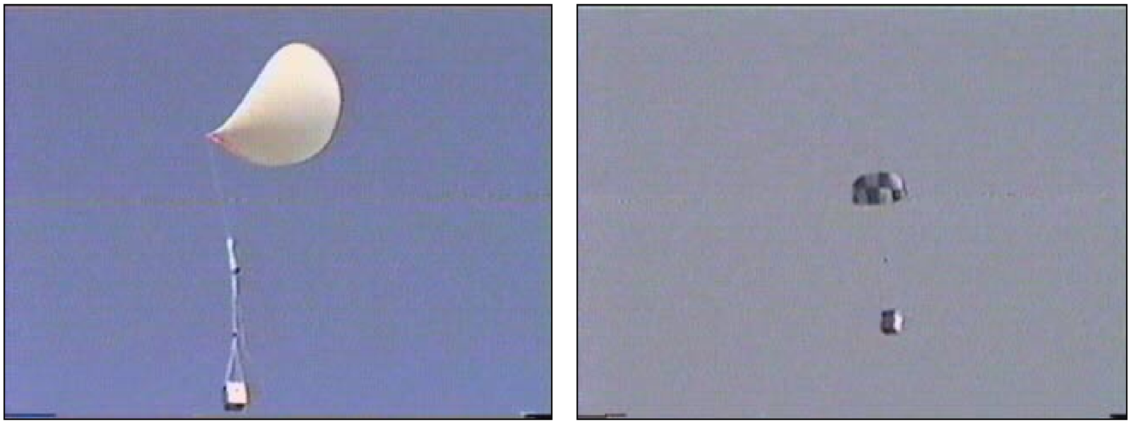

Figure 2: Scenes from the University of North Dakota Scorpio Alpha microsatellite launch. *Left:* Airborne unit in-flight, including the weather balloon, parachute, and container. Note the deformation of the weather balloon due to excessive wind gusts, immediately prior to failure of the tether lines. *Right:* Descent of the parachute and airborne unit container, after activation of the cut-down mechanism from the ground station.

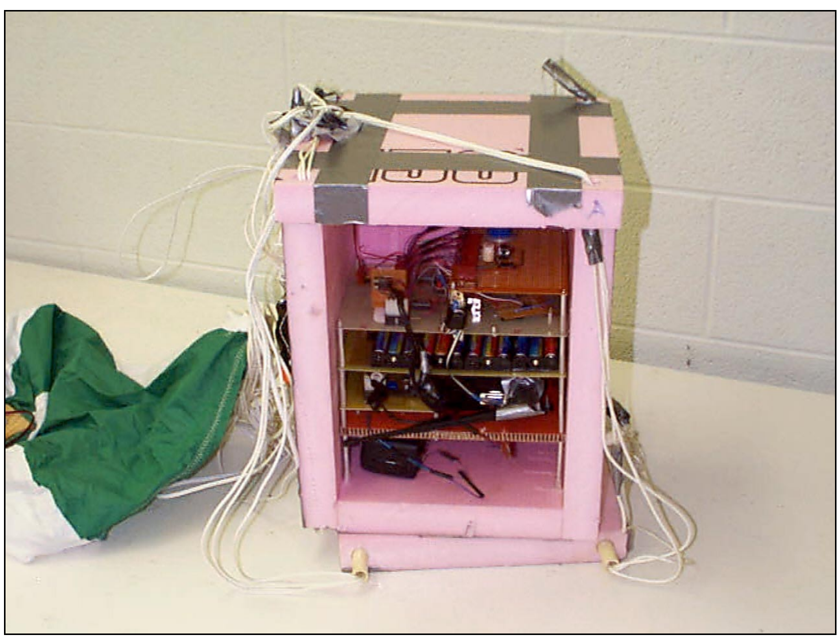

Figure 3: Scorpio Alpha Airborne Unit

IV. Scorpio II: Fall 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 announcements and comments 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 spacecraft bus and its payload under the project name "Scorpio II." A summary of the Scorpio II project specifications is provided in Table 2.

Table 2: 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

The mission objectives were:

1. To provide the students with an opportunity to learn the systems engineering approach by developing an operational spacecraft and launching it via a weather balloon.
2. To develop a fully operational remote sensing spacecraft which will:
   - take digital pictures of farm land
   - determine crop health using a multispectral camera
3. To develop a space/atmospheric platform which will be capable of:
   - spacecraft tracking using GPS and ranging
   - real-time telemetry and telecommand
   - performing station-keeping maneuvers in the stratosphere

Students were divided into ten teams, as shown in Figure 4. Each team had a Team Lead, who was responsible for inter-team communications and outputs. 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.

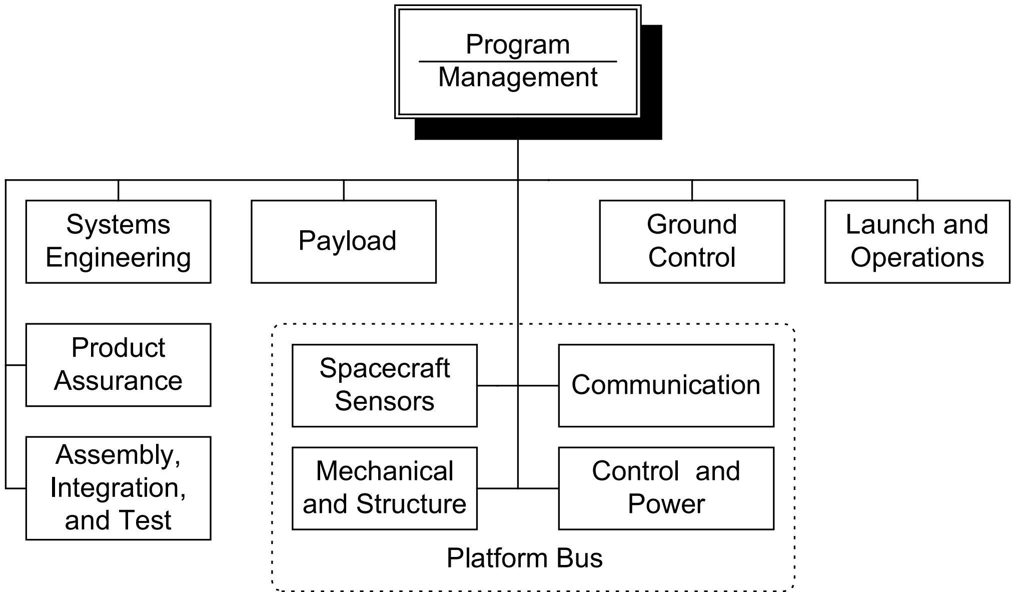

Figure 4: Organization Chart of Spacecraft Development Project

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 interfaces between each subsystem are shown in Figure 5. 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 6, was scheduled for launch in December 2000, but due to project timeline overruns and severe weather, the launch date was delayed. The intent is to launch this spacecraft into the stratosphere using a zero-pressure balloon in the spring of 2001.

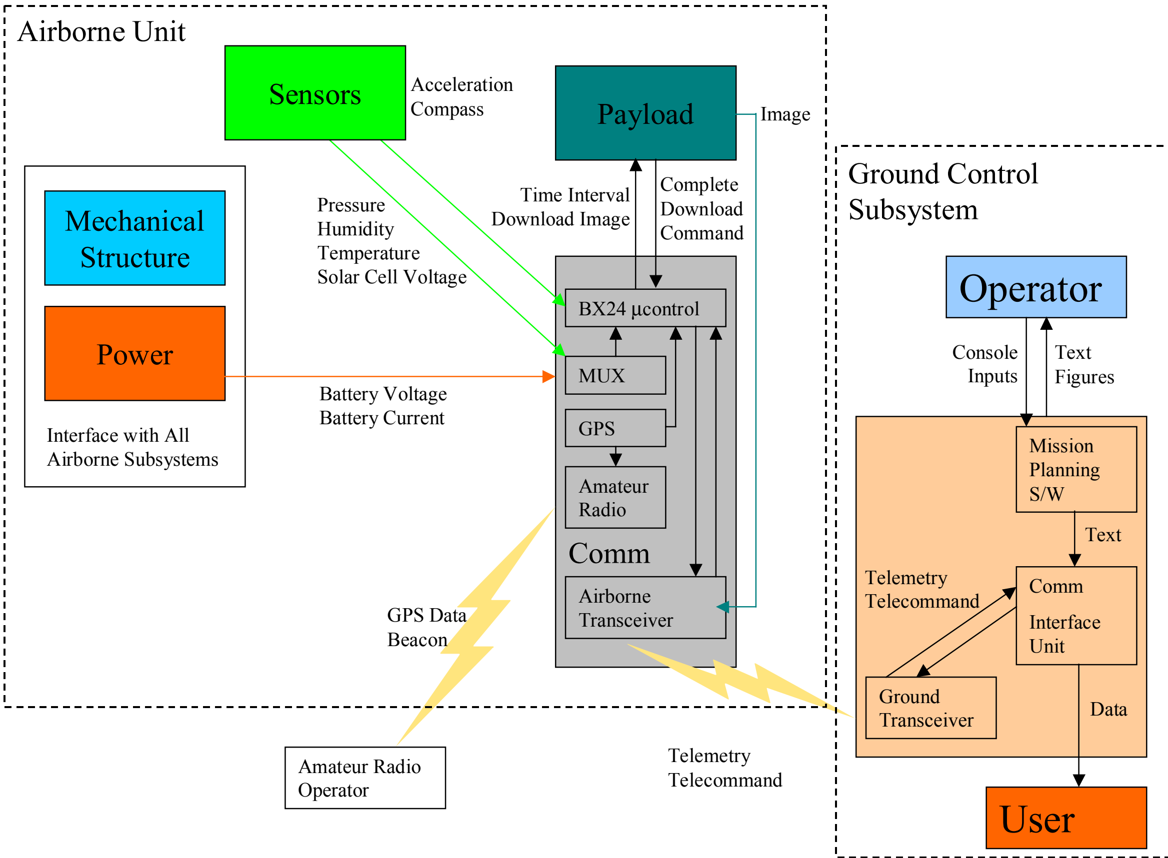

Figure 5: Interfaces Between Scorpio II Subsystems

Figure 6: Scorpio II Airborne Unit

V. Lessons Learned

1. New Knowledge

From an educational perspective, the Scorpio 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.

The systems engineering philosophy places a premium on documentation and "thinking through" a design before heading into the laboratory. This is a thought process that is often encouraged by professors, but in reality is rarely followed by students. In most undergraduate design projects, the students head into the laboratory with only ideas in their minds as to their design methodology. When taking on a large-scale project, a well-planned design is vital, so that when integration finally takes place all of the various subsystems will work together properly. The systems engineering philosophy forces the students to make sure that every subsystem of the project fits together, especially at the interfaces, before parts are ordered and implementation commences.

The documentation process that is involved in systems engineering is rarely introduced to engineering students in the undergraduate curriculum. Rather, it is usually learned on the job after graduation. The students working on the Scorpio project learned which documents need to be created, the expected contents of each document, the need for the strict reliance on documentation for answers to questions, and the necessity to keep documents current. Typically, when students participate in a design project, they build the system and then document what they have done after the fact. Because there were a number of students working on this project with a wide variety of classes and extracurricular work schedules, group members were not always around to answer questions about a particular subsystem. With access to the proper documentation, the students were able to find answers to most questions without one-on-one meetings. Consequently, the need to keep documentation current for the present design is of utmost importance, so that others can work with the latest generation of design changes.

Large-scale system integration also rarely takes place in either undergraduate or graduate education. The Scorpio 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. While some cooperative education experiences do indeed involve systems integration tasks, the vast majority of co-op students are never exposed in-depth to the methodology and processes involved in this aspect of engineering design. As far as systems integration in undergraduate education is concerned, most design projects are undertaken by groups of three or four students, which greatly limits their scope. By working with a group of 7 to 20 team members, the scale of the Scorpio project was substantially increased beyond what a typical undergraduate design team could accomplish. Working in a large team also introduced the students and faculty to many aspects of group dynamics, a relatively new experience for the team members.

2. Group Dynamics

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. Additionally, students working on a large-scale design project have to deal with significantly more responsibility and accountability than what is normally placed on co-op students.

Group design projects in the undergraduate curriculum usually consist of small numbers of students working together, generally with no more than three or four students in any single group. Typically, these groups are either handpicked by the professors or self-selected among friends and study partners. Although students do learn some teamwork skills from these interactions, they lack the experience of working in larger groups, as well as working with students with whom they may not socialize. Scorpio taught the students important lessons in teamwork and its necessity in the successful completion of large-scale engineering projects with short timelines.

Team members had more responsibility and accountability placed on their shoulders than they had ever encountered previously in an engineering project. They were responsible for making decisions on everything from the project mission to the components used in the system to the launch date and location. 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.

3. Roadblocks and Speedbumps

"Roadblocks" and "speedbumps," the major and minor hurdles that must be overcome during the course of any project, are the most common sources of frustration and delays in large-scale design projects such as Scorpio. Roadblocks are large problems that cause a project to come to a complete standstill until they are resolved, while the minor obstacles that slow down the pace of a project's progress are considered speedbumps. The Scorpio Alpha project was fortunate to experience no real roadblocks. The Scorpio II project, however, 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 first speedbump that arose was the students' lack of experience with the systems engineering methodology. Because the topic of systems engineering was new to all the students and many of the faculty involved on the project, the team members needed to be taught how to perform every step in the process. Essentially, no background experience could be assumed. The primary lead instructors on the Scorpio project had the responsibility of ensuring that the students understood every step of the systems engineering process and completed them correctly. Having to teach every last detail of the systems engineering methodology significantly extended the learning curve period, thus slowing the project progress.

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.

One step in the systems engineering methodology – the creation of design documents – was essentially omitted, because the faculty sensed that the students were becoming disenchanted with only creating documents, and the end of the semester was rapidly approaching. They decided to let the students loose in the laboratory, with the understanding that they would create design documents as the project progressed. However, this did not happen as planned, as the students regressed to their previous ways of building and then documenting after the fact. This led to some problems as the project advanced to integration. If the primary designer of a subsystem was not present at a critical time, it became difficult to troubleshoot problems that arose, simply because there were no documents outlining the workings of the system. If the design documents had been in place, troubleshooting may have been greatly accelerated.

A problem with consistently driving open matters to closure during the meetings was a speedbump that the Scorpio 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. However, the master's-level graduate students involved in the project could be depended on to essentially manage the project and to complete their technical tasks on time.

VI. Future Directions

The Department of Electrical Engineering at the University of North Dakota has developed a vision for a Spacecraft Systems Engineering program. This vision utilizes a bottom-up design methodology to generate experience in designing spacecraft packages, in which the airborne units and launch vehicles will gradually increase in complexity. The first step of the vision, already successfully accomplished by Scorpio Alpha, calls for a moored weather balloon launch. The second generation of launch platforms will be free-flight (unmoored), zero-pressure balloons. This will involve flying an airborne unit with the zero-pressure balloons in the stratosphere to test the robustness of the design. Once satisfactory success has been achieved with the airborne units, the next logical step will be to develop low-cost orbiting satellites that can be tested in environmental test chambers.

The first generation of Scorpio Alpha was completed during the summer of 2000. The airborne unit was flown with a moored weather balloon, while real-time telemetry data was recorded by the ground station, in-flight digital images were captured, and an uplink command was executed, allowing for the safe recovery of the package. The entire procedure was well-documented using systems engineering principles, which should provide an excellent foundation for the next-generation satellite project. Moreover, the airborne unit and ground station were constructed for under $10,000, which is an extremely small budget for a satellite mission[4], even for a student-centered satellite mission. The student team members learned many valuable skills, including the systems engineering approach, proper documentation methodologies, multilevel systems integration, group dynamics, and how to successfully handle the hurdles which inevitably occur on a large-scale project.

The second generation of Scorpio was developed during the fall semester of 2000, in an electrical engineering seminar course entitled "Spacecraft Systems Engineering." Scorpio II improved upon the Scorpio Alpha design: longer RF range, heavier payload, higher mission altitude (25-km), real-time image download, and spacecraft tracking using GPS. As the airborne units of subsequent Scorpio builds increase in complexity, the Spacecraft Systems Engineering class will evolve into a multidisciplinary effort between the electrical engineering, mechanical engineering, computer science, space studies, physics, aviation, and business departments on the UND campus.

In the Scorpio project, the labor consisted of both undergraduate and graduate students. Because of the students' class loads, part-time jobs, and extracurricular activities, it was difficult to rely on the undergraduates to complete the projects according to schedule. On the other hand, the graduate students could be relied upon to lead and complete the necessary tasks. From this experience, graduate students should be the core work force behind such a project. A handful of excellent master's-level graduate students with interests in aerospace engineering applications are critical for the success of the spacecraft type projects. Consequently, UND Electrical Engineering is currently working on recruiting additional graduate research assistants to continue the aerospace-related projects that have been started on the University of North Dakota campus.

In order to provide students with the proper resources to effectively design, build, and test satellite systems, a number of labs and workstations need to be developed at the University of North Dakota. To protect the sensitive electronic components during the integration and test segment of the systems engineering process, electrostatic discharge (ESD) stations need to be acquired. This will help to minimize the damaging effects that ESD can have on sensitive electronic components. Development and test stations are required for work with embedded systems, the ground station, and printed circuit boards. In order to design and test the airborne unit structure, environmental testing laboratories will also need to be developed. These labs will house a thermal chamber, anechoic chamber, altitude chamber, and additional equipment to conduct vibration and shock experiments. Since computer simulations are a large part of the design and test procedures, computers running the proper simulation packages are also a requisite component of the needed infrastructure. Finite element modeling of the airborne unit package will provide virtual mechanical and thermal simulations of the structure to aid in its design and manufacture, and mission planning software will assist in the eventual launch of student-designed orbiting satellites.

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