Case Studies in Application of System Engineering Practices to Capstone Projects

Abstract

The Exploration Systems Mission Directorate (ESMD) of the National Aeronautics and Space Administration (NASA) sponsors a faculty fellowship program that engages researchers with interests aligned with current ESMD development programs. The faculty members are committed to run a capstone senior design project based on the materials and experience gained during the fellowship. For the 2010 – 2011 academic year, 5 projects were approved. These projects are in the areas of mechanical and electrical hardware design and optimization, fault prediction and extra planetary civil site preparation. This work summarizes the projects, describes the student teams performing the work, and comments on the integration of Systems Engineering principles into the projects, as well as the affected course curriculums.

Introduction

The Exploration Systems Mission Directorate (ESMD) of the National Aeronautics and Space Administration (NASA) sponsors a faculty fellowship program that engages researchers with interests aligned with current ESMD development programs. By engaging these faculty members in current research projects, NASA gains the benefit of their contribution to technology development. Additionally, the faculty members are committed to run a capstone senior design project based on the materials and experience gained during the fellowship.

NASA ESMD is a proponent of the System Engineering (SE) approach outlined in The NASA Systems Engineering Handbook.[1] Part of the experience for students on these projects is exposure to the principles of SE, and guidance from the faculty mentor in applying these principles to the projects performed. The purpose of this project is to prepare faculty to enable their students to complete senior design projects with potential contribution to NASA ESMD objectives and ultimately increase their competitiveness in the job market for NASA and its contractors. The faculty worked for eight weeks at NASA field centers on a selected ESMD project, convened at Kennedy Space Center (KSC) for one week, and incorporated the ESMD project into an existing senior design course or capstone course at their university during the 2010-2011 academic year.

During the eight weeks at a NASA field Center, each faculty fellow worked side-by-side with NASA technical experts. The faculty gained extensive knowledge on the related ESMD projects and associated requirements, interfaces and issues affecting the design and potential solutions. The faculty developed materials for use at their university during the 2010-2011 academic year in support of the completion of senior design projects using a systems engineering design approach.

At KSC the faculty shared and reviewed all senior design project materials amongst themselves, developed a report compiling their findings, attended a faculty workshop on systems engineering, developed a PowerPoint presentation for the Regional Space Grant Meetings, and participated in the review panel for a Senior Design Course currently in development under a separate contract. At the conclusion of incorporating the ESMD project at their university, in May 2011, the faculty fellows will each produce a white paper.

This paper examines the benefits of applying the SE process in the capstone environment, describes the composition and performance of individual student teams, and draws some conclusions about how to best integrate SE into the capstone experience.

Project Descriptions

NASA X-TOOLSS (eXploration Toolset for Optimization of Launch and Space Systems)

The NASA X-TOOLSS software is utilized for design optimization of conceptual space systems. NASA X-TOOLSS is based on genetic and evolutionary algorithms, which have proven successful for global optimization of complex systems and for applications where unique and innovative designs are sought. An advantage of NASA X-TOOLSS and genetic/evolutionary optimization is that the design space is not limited to existing designs and approaches. Example applications of interest for NASA X-TOOLSS include habitats for the Moon and Mars, lunar surface mobility and power systems, lunar descent module and lander concepts, and thermal/structural design of small satellites and other spaceflight hardware.

The mentor of this project is a female aerospace engineer with a PhD. She is a lecturer employed by a Mechanical and Aerospace engineering department at a state university in Alabama.

The student groups recruited for this project consists of eight male students and two female students - 8 Caucasian, one Hispanic and one other minority. The students represent Mechanical and Aerospace engineering.

Implementation of the ITU G.729 Voice CODEC on FPGA

This project will implement International Telecommunication Union (ITU) standard G.729 (CS-ACELP) speech compression CODEC on a Field Programmable Gate Array (FPGA) target. The CODEC is typically implemented in software on a Digital Signal Processors (DSP). NASA desires to implement the CODEC on an FPGA so that redundant data-bus audio packet management, speech signal extraction and compression can happen on a single chip, minimizing mass, power and size requirements.

The mentor for this project is a male electrical engineer with a PhD. He is a tenure track assistant professor employed by the electrical and computer engineering department at a state university in Mississippi. The student groups recruited for this project consists of seven male students – all Caucasian. The students are all Computer engineering majors.

Dust Tolerant Connector System

Quick connect functionality for both electrical and fluid connectors used in extraterrestrial applications are desirable for extended surface operations. The ability to accommodate fluids that are both high and low temperature, as well as electrical connections passing anything from low voltage control signals to high voltage power transfer in a common system of hardware will provide necessary infrastructure in accomplishing science missions on the surface of other worlds. Use of commercial off the shelf (COTS) electrical and fluid connectors as a design basis will help in minimizing system costs. The project's goals are to create quick connect/disconnect hardware that is operable by an astronaut wearing a space suit, in any gravity condition. The system must be designed for use with space suit gloves that restrict fine motor skills and isolate the user's sense of touch, and do not require mobility usually restricted when operating in a space suit. The hardware shall operate in zero gravity and near perfect vacuum and be adaptable to non-terrestrial locations with aggressive atmospheres and unusual contaminants. The system shall also include an installation tool to overcome large mating forces, geometry to assure correct connector alignment for engagement and a dust exclusion system to minimize, if not eliminate, any dust that could impinge on the connector interface surfaces. This design effort will include a standardization effort, such that three distinct sizes of connector systems result.

The mentor for this project is a male mechanical engineer with a PhD. He is employed as a tenure track assistant professor in the engineering technology department at a state university North Carolina.

The student group recruited for this project consists of three male students, 2 Caucasian and one Hispanic. The students represent Mechanical Engineering, Mechanical Engineering Technology and Electrical Engineering Technology.

Lunar Regolith Excavation, O_2 Production and Outpost Emplacement

The feedstock required for O_2 production on the moon is Lunar Regolith (soil). One hundred metric tons (MT) of Lunar Regolith will be required each year for Oxygen Production of 1 MT. In addition up to 2,000 MT of regolith excavation will be required per year in the initial stages of Outpost construction. This project will investigate concepts for Lunar Regolith excavation equipment and propose solutions in the form of completed designs and prototypes. This project is split into three design projects. First, a design project to design and build a test bed to measure small scale excavation forces under reduced gravity conditions. Second, a design project to design and build a mobility platform and an excavation system which will be used to enter NASA's Lunabotics competition. Third and last, a design project to design and build a tool for the stabilization of soil to function as a landing pad.

The mentor for this project is a male Civil Engineering PhD candidate. He is employed as a lecturer in the Civil Engineering department at a state university in Colorado. The reduced gravity team consists of 2 females and 4 males. The Lunabotics team consists of 2 females and 5 males. The landing pad tool team consists of 6 males. The students represent Mechanical Engineering, Electrical Engineering and Civil Engineering.

Prognostics for Complex Systems

The Prognostics Center of Excellence at NASA Ames Research Center is conducting research in systems health management. This involves the early assessment of abnormal conditions and damage as well as the estimation of "remaining life" of a component or subsystem. The goal is to contribute towards the state of the art in uncertainty management which is a critical component of prognostics.

The mentor of this project is a male computer engineer employed by the computer science department at a state university in Florida. Ten students took this class, all majoring in Computer Science, all of them male, 8 Caucasian, 1 Hispanic, and 1 other.

SE Framework

One of the main objectives of this project is to introduce Systems Engineering (SE) to the students participating in the project. Systems engineering is a formalism that standardizes the design and development of complex engineering systems. SE is similar to the universally defined phases of the architectural/building design and integration process[2],[3].

Typical SE approaches start with the definition of the system to be designed or built. Capabilities and limitations are defined for use in the architecting and design process. Multiple system design concepts are generated as defined by the agreed upon capabilities and requirements for system functionality. A single design concept is chosen for further modeling and development. Once mathematical and virtual models are verified, this concept is realized with hardware, software and personnel required by the design goals. The concept realization is compared to the models to assure that the design intent has been executed and then the final product is tested and assessed to verify that design goals are attained or attainable.

Figure 1 shows the current configurations of the NASA SE process, now termed an "engine". Using NASA's SE engine, the design process incorporates 3 sets of common technical processes: (1) system design, (2) product realization and (3) technical management. In total there are 17 common technical processes whereby steps 1-9 represent steps in the execution of a project and steps 10-17 are crosscutting tools for carrying out the design process.

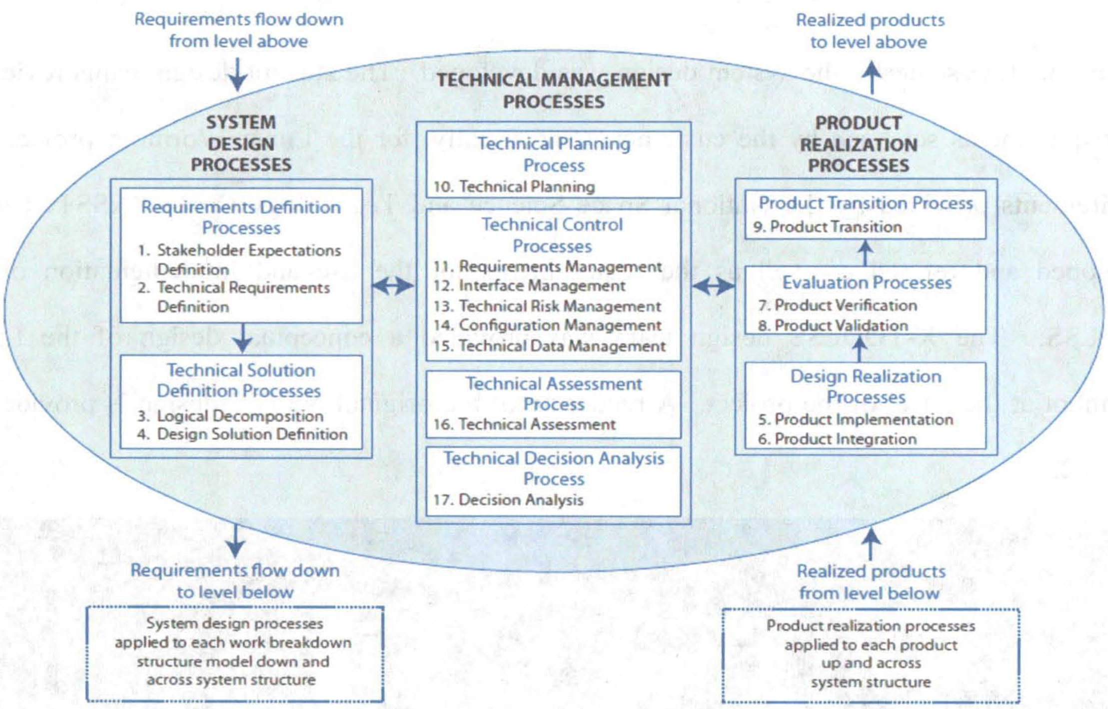

Figure 1. NASA's SE Engine.

NASA X-TOOLSS

The NASA X-TOOLSS design optimization software was applied during development of a lunar regolith burrowing device – also referred to as a Lunar Wormbot - as well as a 1/3 scale Gemini style space capsule during the 2010-2011 academic year. The SE Principles integrated into the NASA X-TOOLSS project follow the outline provided by the NASA SE engine shown in Figure 1.

The X-TOOLSS project was completed over a two semester design sequence. The system design was completed during the first semester and the product realization was completed during the second semester.

During the first semester the system design was developed. The student design teams reviewed the requirements set forth by the customer. Specifically, for the Lunar Wormbot project, the requirements provided by the National Space Science and Technology Center (NSSTC) were developed and refined as well as the requirements for the use and implementation of X-TOOLSS. The X-TOOLSS design team was provided a conceptual design of the Lunar Wormbot at the onset of the project. A rendering of the original NSSTC design is provided in Figure 2.

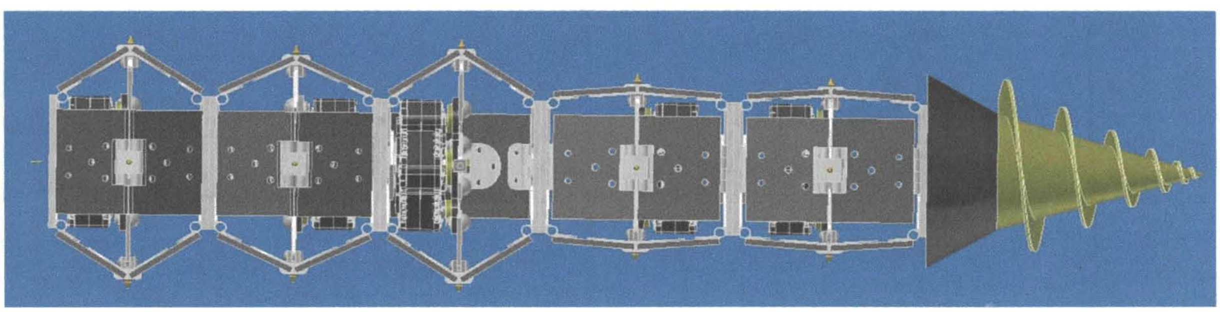

Figure 2: Original NSSTC Lunar Wormbot design optimized using X-TOOLSS.

The NSSTC Lunar Wormbot design consists of an ultra-sonic conical drill bit, with an auger, connected to a robotic body that mimics the peristaltic motion of an earthworm. During the system design phase the student team conducted numerous patent searches and market surveys in order to clearly define the requirements based upon the complexity, costs and manufacturing capabilities available to the team. Various conceptual designs were developed that met the requirements. Trade studies were completed and, via numerous evaluation matrices, a design was selected for further development. The criteria utilized to evaluate the conceptual designs included performance, costs, design complexity, manufacturing and tooling availability, system safety, durability, reliability, human factors and maintainability. During the initial system design phase, conducted and completed during the first semester, the student team conducted numerous telephone conferences and maintained email correspondence with NASA and NSSTC technical advisors. The X-TOOLSS design optimization process was begun by understanding and learning how to use the program in order to apply the software to the optimization of the Lunar Wormbot. The first semester culminated with a Preliminary Design Review (PDR) conducted at NASA's Marshall Space Flight Center (MSFC) in Huntsville, AL. The NASA and NSSTC advisors provided guidance for the next phase of the design process and were completely satisfied with the progress made by the student design team.

The next phase, conducted during the second semester, constituted the product realization phase within the SE engine. Early in the semester a Critical Design Review (CDR) was conducted whereby detailed design drawings, a complete technical analysis including the X-TOOLSS design optimization, system safety, detailed costs and a complete manufacturing schedule was presented. Upon approval of the NASA and NSSTC technical advisors the student team commenced parts procurement and fabrication of the Lunar Wormbot. Upon final testing and verification of the hardware requirements the team conducted a Product Readiness Review (PRR) at MSFC. Additionally, the team traveled to Kennedy Space Center (KSC) at the end of the second semester in order to test the hardware at KSC's lunar regolith simulant test bed.

As the student design team progressed through the system design and product realization processes, the technical planning processes, as specified in the SE engine, were continually addressed and maintained. Communication and documentation of the design process are critical aspects of technical planning. Once the technical plans are initiated they may evolve due to changes in requirements. Adherence to NASA's SE engine during the design process emphasizes the need for proper technical management – an aspect of design that is often neglected due to the emphasis that is placed upon system design and realization. However, in order to assure proper transfer of information and maintain system safety it is imperative to follow the technical management processes as dictated within the SE handbook. As the X-TOOLSS team developed their design and resulting hardware, the technical management processes were implemented and, as a result, a more efficient design process ensued.

Implementation of the ITU G.729 Voice CODEC on FPGA

Processes described in the NASA Systems Engineering Handbook (henceforth handbook) are being used during the project. Section 4.2 of the handbook was consulted during the requirements definition process. Students considered functional, sustainability, health and safety, economic, and political constraints when deriving requirements. Performance, interface, and safety requirements were developed for the senior design project. Requirements used the words shall and must when defining requirements to avoid verb confusion and strengthen requirements. Requirements were validated by faculty members, other student design teams, and by consulting with NASA engineers. Additionally the requirements validation check list (Appendix C of the handbook) was used to confirm defined requirements conform to NASA system engineering guidelines.

The senior design project also includes design verification tasks. Section 5.4 of the handbook was consulted during product validation. A key validation requirement was for the FPGA ITU G.729 CODEC to have equivalent output to the ITU G.729 reference model provided by ITU for all stimulus provided G.729 specification. Students used the reference model provided by ITU to generate intermediate stimulus and output results to be compared to sub-module functionality during the design process. This approach allows students to implement the design piece meal and verify functionality of individual pieces as they are implemented. Integrated sub-modules are also validated against the test suites provide by the ITU. Section 5.4 of the handbook will be used to assist in development of the validation report after completion of project.

Finally, section 6.1 of the handbook was consulted for project management. Students developed a schedule for the project which considered required tasks, the duration of required tasks, and the dependence tasks upon other tasks. Students meet weekly with a faculty advisor to review progress against the project schedule and discuss setbacks.

Dust Tolerant Connector System

The capstone program hosting this project encourages multidisciplinary teams. This project is comprised of an Electrical Engineering Technology Student, a Mechanical Engineering Technology Student as well as a traditional Mechanical Engineering student. This group has integrated their different backgrounds and approaches well, forming a cohesive team of peers dedicated to development of system.

This team has considered the lifecycle of their system in the concept development phase, and realizes that their output should be repairable in a harsh environment. While the Concept of Operations (CONOPS) developed is weak, there is evidence of systems integration thinking displayed. The review process with NASA sponsors is ongoing, and this aspect of systems engineering is illustrating to the students that design is an iterative, collaborative process.

The students have demonstrated both synthesis and discovery in the architecting of their design. Biomimetic principles (use of whale baleen as a model for collecting small particles) and application of new technologies (carbon nanotube surface treatments) are a part of the design concept being developed.

Because these students have had little prior exposure to system engineering concepts, their ability to decompose their system into subsystems is limited, and their ability to assign budgets (performance as well as resource) is unsophisticated.

System interface definition has also been a challenge. Even though this is a simple interface to define (a male and female connector), the students have trouble grasping this concept.

Design margin, contingency and the concept of "Fail Safe" are also new to these students.

Lunar Regolith Excavation, O_2 Production and Outpost Emplacement

The entire senior design class consists of 235 Students of which 225 were classified as seniors, 10 as juniors. The class consists of 123 Mechanical Engineering students, 15 Environmental Engineering students, 61 Civil Engineering students, 34 Electrical Engineering students, 1 Engineering Physics student (who is a double major in Mechanical Engineering) and 1

Petroleum Engineering student (who also is a double major in Mechanical Engineering). The class consists of 51 females, leaving 184 males. The entire class was given a one hour lecture on introduction to NASA System Engineering. After the lecture, almost all students were convinced that a certain level of system engineering was required for engineering projects and 74% of the class could identify System Engineering as "The process to turn a need into a capability". The three teams comprising a total of 19 students that are working on NASA projects are multidisciplinary in configuration and consist of Mechanical, Electrical and Civil engineering students. The three teams and some additional interested students attended an additional optional lecture about system engineering methods. An increase in awareness of the whole project (big picture thinking) was definitely noticeable in the meetings after the System Engineering lecture. Due to the size and complexity of the project the emphasis is very much on the design and realization process, but an increased emphasis on project management and control could also be observed due to the increase in awareness of its importance with regards to successful projects. Methods used were among others the making of a Work Breakdown Structure which formed the basis for the schedule (in Microsoft Project) which is updated every week. Resource allocation in the form of manpower, location and time as well as budget was based on the preliminary design ideas. Lessons from the past were introduced by the faculty advisor and another faculty member who has helped with previous space related projects. Optimization of the design ideas has been performed using modeling and analysis as well as the building and testing of simple prototypes to get more experience with particular mechanical methods (e.g. the building of a mobility platform using tracks and the building of a lunar stimulant dumping mechanism based on mining engineering designs). Review sessions and feedback sessions were very helpful and are critical to give the team feedback and assess if they are performing successfully. Methods such as requirement management are not being used in a project of this scale even though a customer needs and stakeholder analysis was done resulting in requirements for the systems. Some of the methods feel very contrived in smaller scale projects and the students fail to see the need to use such methods in small scale projects.

Prognostics for Complex Systems

At this stage, the 2010 - 2011 academic year senior project on "Prognostics for Complex Systems" is focused on software development, without building the hardware components, which are assumed to exist. This assumption has two important consequences. First, it is crucial to either identify an existing equipment, for which the respective software could be built, or involve an adequate simulator, which would generate data for later analysis of system health and conduct prognostics. Secondly, applying the NASA Systems Engineering Handbook to software development is – to the instructor's knowledge – rather uncommon and creates quite a challenge to the student teams.

Regarding the first issue, the accepted resolution is two-fold. Due to non-availability of easy online access to NASA generated real-time data for studying system health, the team decided to look for adopting an existing system of a slightly different nature, but similar enough in continuity of operation, so health data it generates could be uses for health management and prognostics. Additionally, a simple simulator is being developed, which uses related models, so faults and failures could be generated randomly providing a platform for health management. Building our own hardware is also being considered, but is an issue of lower priority with prospects for the next edition of this course.

The second issue, using the NASA Systems Engineering Handbook for software development, has been resolved by comparing its respective parts with the IEEE Software Engineering standards, regarding four software development stages of the simple waterfall process model: (1) Software Requirements Specification; (2) Software Design; (3) Software Implementation, and (4) Testing, with respective reviews after each stage. The NASA model has been mapped onto the IEEE standards model as follows:

Software Requirements Specification: IEEE Std 830 – NASA Handbook Sections 4.1 and 4.2

Software Design Description: IEEE Std 1016 – NASA Handbook Sections 4.3 and 4.4

Software Implementation: no IEEE standard (interim standards applied) – NASA Handbook Section 5.1

Software Testing: IEEE Std 829 – NASA Handbook Sections 5.3 and 5.4.

Additionally, proper project management has been ensured by applying IEEE Std 1058 ad comparing it with selected section of Chapter 6 of the NASA Handbook.

The student team involves ten students divided into two groups, with students playing different roles throughout the semester. Meetings are recorded in minutes, with action items assigned on a weekly basis and verified by the project manager.

Project Outcomes

NASA X-TOOLSS

Successes - Two design teams utilized X-TOOLSS to optimize the design of a Lunar Wormbot and a 1/3 scale Gemini style capsule. Both projects allowed mechanical and aerospace engineering students to incorporate NASA's SE design process during the course of their work.

Opportunities for Improvement – The use and understanding of NASA X-TOOLSS requires an initial period of completing various tutorials developed at NASA MSFC. More tutorials describing the implementation of other software such as Patran/Nastran® will greatly benefit students.

Lessons Learned - Opportunities for transferring knowledge and information gained via the NASA ESMD fellowship program from the participating faculty fellows to the students have proven to be beneficial and will continue in future years. Overwhelmingly, the senior design students were enthusiastic and appreciative of the willing collaboration and support that NASA and NSSTC technical advisors provided. The advice and guidance provided by the technical advisors created a sense of relevance and importance with respect to the hardware developed. As a result, fostering future collaborative efforts between NASA and senior design students will be a priority.

Implementation of the ITU G.729 Voice CODEC on FPGA

Successes - This project has generated a large amount of excitement among the student body within the Electrical and Computer Engineering department and proved to be very successful learning tool for the students chosen to work on the project. The project was first announced to student in an email soliciting team member volunteers during the summer of 2010. Approximately half of the students enrolled in the upcoming term of the department's senior design class volunteered. One team was chosen. A second team was formed to join the in the spring of 2010. Again, approximately half of the students enrolled volunteered to join. Currently, there are 7 students are working on the project.

Opportunities for Improvement - The Implementation of the ITU G.729 Voice CODEC on FPGA project is a large undertaking. One setback was originally starting with two students on the team. This was quickly apparent and a second team was added the next semester.

Lessons Learned - The most difficult aspect of the project is preparing students to be successful. The Electrical and Computer Engineering department offers two courses related to digital hardware design. The first of these classes, titled Digital Devices and Logic Design, required by both Electrical engineering and Computer engineering majors, includes an introduction to digital logic including binary and hexadecimal number systems, Boolean algebra, and basic digital circuit building blocks such as combinatorial gates (AND, OR, XOR, etc) and flip flops, latches, and memory elements. is required by only Computer Engineering majors and

The Digital Devices and Logic Design class does not prepare students to participate in a large scale digital design project which uses Verilog HDL and requires knowledge higher level digital design concepts. Since, electrical engineering majors are only required to take the Digital Devices and Logic Design course most were not prepared to work on this senior design project. Students which have completed both the Digital Devices and Logic Design and the Digital System Design courses were better prepared for this project. However, the scale of the project made circuit validation important and highlighted that students should be better prepared not only to design digital circuits but also to validate their functionality.

This experience leads to two recommendations for faculty in other Electrical and Computer engineering departments. First, Electrical Engineering majors should be encouraged to take more digital design courses. FPGA and other digital device implementation technologies are as a common used tool in many industries. Second, advanced classes digital design courses should include more material related to circuit verification and validation.

Dust Tolerant Connector System

Successes - This team successfully integrated different backgrounds and disciplines to form a cohesive systems engineering unit.

Opportunities for Improvement – Students in this group have had difficulties in bridging the gap between software realizations of their design concepts. Student concepts to date are non-functional by inspection.

Lessons Learned – Systems engineering principles are complex and non-intuitive for students trained in traditional Engineering and Engineering Technology curricula. This content should be incorporated into design courses early in the student's academic career.

Lunar Regolith Excavation, O_2 Production and Outpost Emplacement

Successes – All three teams are enthusiastic, motivated, efficient and integrated well into a well-oiled engineering team. They understand the principals of system engineering and apply them when appropriate for their scale project.

Opportunities for Improvement – Narrowing down from the solution space to a feasible conceptual design faster and not being stymied by the myriad of possible options is something the students find hard. More prototyping and failing often and early in the design process is crucial to get to a correct system choice. Paper designs look great but have often many problems in the construction stage.

Lessons Learned – The students have learned to ask for help from experts (with theory and machine shop work) and incorporate the answers into their designs. They have learned to deal with open-ended problems and this now includes a sense of system engineering and a big picture mentality. The relationship between the technical details and big picture is hard for the students to grasp and system engineering helps to bridge that dichotomy.

Prognostics for Complex Systems

Successes – Despite the lack of equipment sophisticated enough to conduct system health management and make the prognostication process meaningful, the team resolved the issue by ensuring online access to real-time data of the solar system and additionally decided to build a software simulator to generate health related data. Understanding of the NASA Systems Engineering Handbook applied to a software project is significantly enhanced when mapped on much simpler IEEE Software Engineering standards, making the development process feasible for a one-semester academic course.

Opportunities for Improvement – While online access to existing equipment at a NASA center to study system health management would be of significant advantage, in case such access is unavailable building in-house equipment is being considered based on Instructor's experiences from the Summer 2010 fellowship. Project management issues are always a challenge for undergraduate student teams and better coordination of respective activities has to be paid more attention to, both by students and the Instructor.

Lessons Learned – The project on prognostics turned out to present a significant difficulty to undergraduate students due to the lack of sufficient math and computational background to understand the relevant theories applied in system health management. Nevertheless, identification of respective educational gaps is considered an important step in making the next edition of this project more successful.

Conclusions

Integration of SE principles into capstone courses at 5 different universities has been discussed. Faculty experience has shown three major areas of engineering education improvement.

1. Multidisciplinary teams were formed successfully in every case. Use of SE principles encourages team members with different backgrounds to consider the technical portions of their project from other areas. The SE process encourages communication between disciplines and fosters consideration of the nature of subsystem integration to create a successful end product.
2. Project management is viewed as an important skill for successful completion of the capstone experience. As stated in The Engineer of 2020[4], engineering practitioners must enter the workforce with the ability to manage projects in order to be successful in the global economy.
3. Students have been made aware of documentation and standards required for successful completion of complex projects. The NASA SE handbook provides an example to students of the structure necessary in the work place to deliver a successful project. Students have become more aware of codes, standards, specifications and statutes that govern engineering work in practice.
4. All projects benefited significantly from the 2010 ESMD Summer Faculty Fellowships at respective NASA centers, as well as from direct or indirect interactions with NASA engineers in the post-fellowship phase. The knowledge acquired by faculty during their

fellowships and connections made with the NASA staff have a lasting impact on all projects involved and the increase of quality of our teaching.

Additionally, several engineering programs have benefitted from the implementation of this approach, along with the NASA project structure to identify areas of opportunity in their curricula.

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