

2009 ESMD Space Grant Faculty Project

Final Report

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July 24, 2009

**“The Moon is the first milestone on the road to the
stars.”
– Arthur C. Clarke**

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EXECUTIVE SUMMARY

The strength of the National Aeronautics Space Administration (NASA) Exploration Systems Mission Directorate (ESMD) Faculty Project lies in its ability to meet **NASA's Strategic Educational Outcome 1** by developing a sustainable and long-term integration of student involvement at academic institutions with NASA Centers. This outcome is achieved by a four-fold approach: 1) by the faculty working on various senior project related areas at NASA centers, 2) by engaging students at Minority Serving Institutions in the art of systems engineering and systems design of technologies required for space exploration, 3) by identifying the issues and requirements for senior design projects for students, and 4) by preparing faculty members to advise students in their senior design projects. The objectives of the ESMD Faculty Project are to:

1. Enable Space Grant institution faculty to better prepare their students to meet current and future NASA needs
2. Enable faculty to gain extensive knowledge on the ESMD senior projects and associated requirements.
3. Enable faculty to develop materials emphasizing the system engineering approach for use in their respective universities in their senior design course.
4. Enable better matching of ESMD required needs and knowledge of the faculty and students involved in the senior design projects.
5. Provide the Space Grant Consortia an opportunity to strengthen relations with the NASA Centers
6. Develop better collective understanding of the U.S. Space Exploration Policy by the Center, Space Grant, faculty, Education Office, and students
7. Aid NASA in gaining a greater and more detailed understanding of each of the Center activities

Senior Design projects are intended to stimulate undergraduate students on current NASA activities related to lunar, Mars, and other planetary missions and to bring out innovative and novel ideas that can be used to complement those currently under development at respective NASA Centers. Additionally, such academic involvement would benefit the prospects for graduating seniors to pursue graduate studies and to seek careers in the space industry with a strong sense for systems engineering and understanding of design concepts. These projects will also be helpful in the creation of educational materials to upgrade the senior design course topics.

Five faculty members, each from a Space Grant Consortium-affiliated university, worked at four of NASA Centers for six weeks between June 1 and July 10, 2009. The project objectives listed above were achieved successfully. In addition, faculty reviewed a senior design course developed by an ESMD faculty under a separate contract.

NASA'S EDUCATIONAL OBJECTIVES

Three outcomes serve to align all agency education activities:

Outcome 1: Contribute to the development of the STEM workforce in disciplines needed to achieve NASA's strategic goals through a portfolio of investments.

Outcome 2: Attract and retain students in STEM disciplines through a progression of educational opportunities for students, teachers, and faculty.

Outcome 3: Build strategic partnerships and linkages between STEM formal and informal education providers that promote STEM literacy and awareness of NASA's mission.

A conceptual basis for examining, guiding, and coordinating the NASA education portfolio (The Education Framework) is depicted in Figure 1 and provides a strategic management tool that allows monitoring participant movement through educational activities. Educational programs and projects draw from the category below them, as a key source for participants, and they connect participants to the category above them, thereby providing a more experienced and focused group and creating a measurable pipeline.

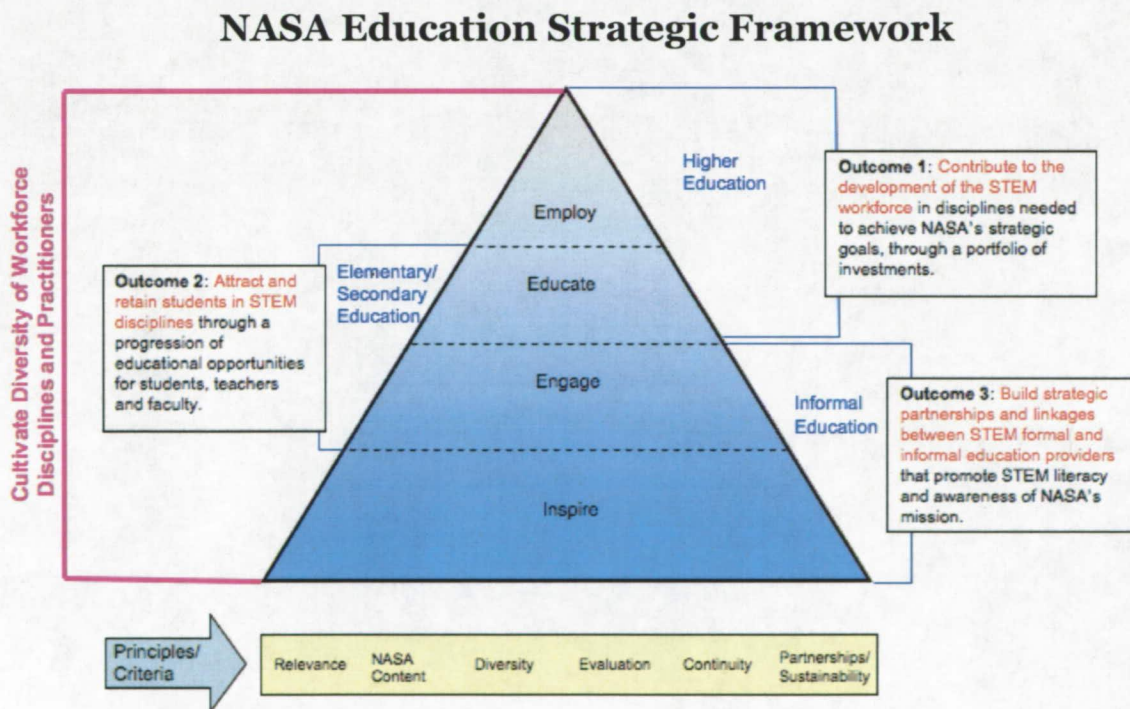


Figure 1. NASA's Strategic Education Framework

Description of the Four Categories of Involvement

Inspire—Activities focused on promoting awareness of NASA’s mission among the public, primarily through informal education and outreach activities. This category is heavily supported by the outreach activities of other NASA organizations, such as the Office of Public Affairs. *Inspire* level efforts are broad, with the goal of reaching a large number of people, but are not limited to “in-person.” This category forms the base of an education structure that becomes more focused at progressively higher levels of the framework “pyramid.””.

Engage— Education activities that in some manner incorporate participant interaction with NASA content for the purpose of developing a deeper understanding. Participants are strategically identified and targeted.

Educate—Focused education support that promotes learning among targeted populations. Education activities focus on student learners, or pre- and in-service educators, and are designed to develop and/or enhance specific STEM knowledge and skills using NASA resources. *Educate* activities promote new knowledge acquisition and strengthen an individual’s skills. NASA’s elementary and secondary education efforts are supplementary to formal classroom instruction. NASA’s higher education efforts may include development of specific university curricula in support of the NASA mission and student-built instruments.

Employ—Targeted development of individuals who prepare for employment in disciplines needed to achieve NASA’s mission and strategic goals. Through internships, fellowships, and other professional training, individuals become participants in the U.S. Space Exploration Policy and NASA science and aeronautics research. At the apex, they have acquired sufficient mastery of knowledge for employment with NASA, academia, industry, or within STEM fields of teaching.

2009 ESMD Faculty Project Educational Objectives

The work performed for the ESMD Faculty project is primarily focused on *Outcome 1: Higher Education: Employ and Educate* of the NASA Education Outcome and Objective Hierarchy. In particular two secondary outcomes, *Objective 1.2 Student Support* and *Objective 1.3 Student Involvement, Higher Education* are the primary areas in which this project addresses the objectives of the guiding framework of the NASA Education Portfolio. In addition, project personnel are also involved in *Outcome 3: Informal Education – Engage and Inspire* to promote awareness of NASA’s mission among the public, primarily through informal education and outreach activities, for instance, by working with local public broadcasting personnel to create content.

CONSTELLATION PROGRAM ASSIGNMENTS AT NASA CENTERS

The 2009 ESMD Faculty Project is designed to address needs of the NASA's Constellation Program by guiding senior design projects in conjunction with NASA technical experts. The Constellation Program is describe below.

Constellation Program

The structural model that most closely resembles the current mission is the Apollo "5-box" (shown in Figure 2) management structure and was selected because it worked effectively. These five organizational functions are comprised of program planning and control; test and verification; operations integration; systems engineering and integration; and safety, reliability and quality assurance. This was adapted and tailored to the Constellation Program's more evolutionary objectives.

Constellation is envisioned to have developmental aspects throughout its life cycle in that new developments to support the next mission will start in phases as current developments become operational. For instance, lunar outpost development will start after the low Earth orbit portions of the Program are operational. The adapted organizational structure is shown in Figure 2. Note that an advanced development function (Advanced Projects Office) has been added to the Apollo "5-box" structure. This organization houses research and development activities for "pre-projects" envisioned to support lunar missions and beyond. Organizations outside of NASA, such as international and commercial partners, could be involved in these later phases of the Program.

The Constellation Program was staffed with recognized leadership within the Agency (e.g., from the ISS Program, Space Shuttle Program, and Mission Operations Flight Director Office) and the contractor/DoD space community between November 2005 and March 2006, seeking project managers with demonstrated experience in executing projects and discipline area leaders able to assemble strong teams, articulate a clear vision of the task, and integrate horizontally and vertically.



Constellation Program

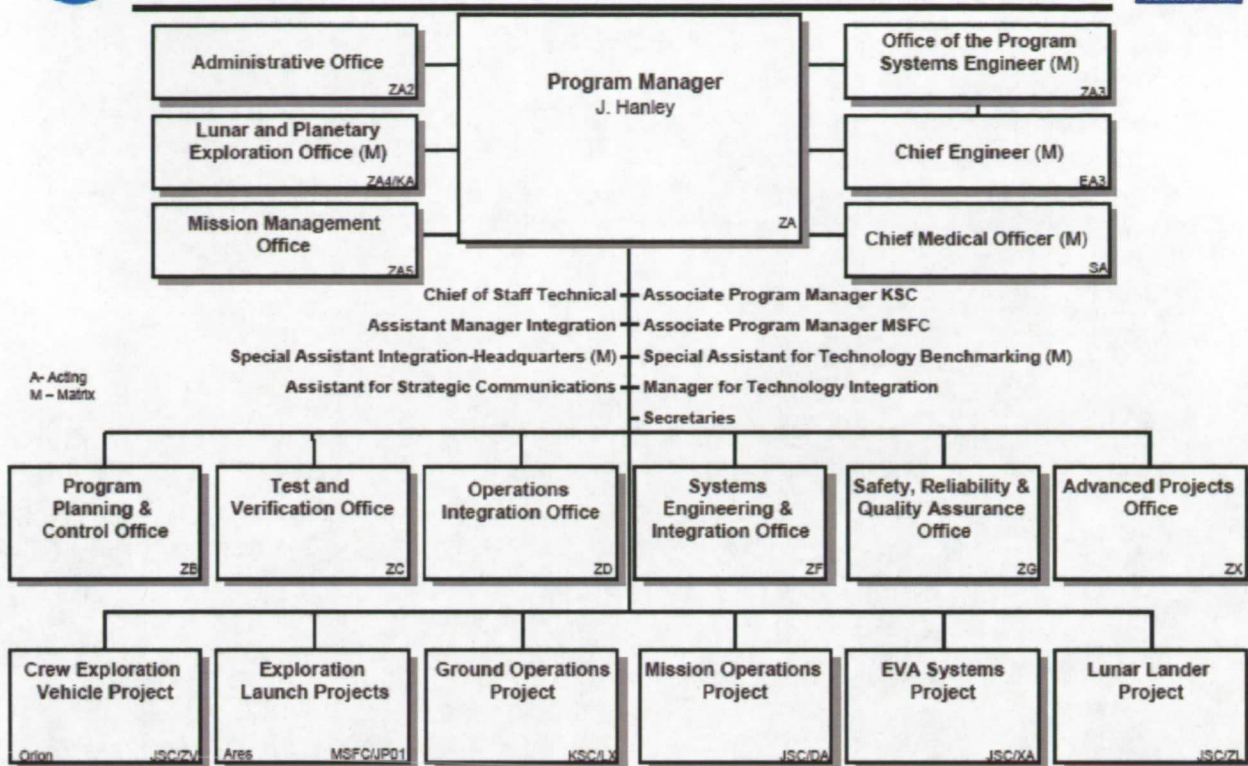


Figure 2. Constellation Organization Structure. Program Management (first row boxes); the Program Offices adapted from the Apollo 5-box structure (second row boxes); Project Offices (third row boxes).

Constellation Projects that comprise the Constellation Program are listed in the bottom row of Figure 2. Table 1 describes major responsibilities for each project in the development and operational phases of the Program.

It is known from agency history that its success depends on a strong program leading strong projects. As soon as the program office was staffed, a process began of negotiating roles and responsibilities between the Program and projects. All recognized the importance of having a program office integrate project interfaces, as well as the importance of allowing projects maximum flexibility in managing their assigned element. However, a detailed examination of integration processes was necessary to truly understand and assign responsibilities. The program and project deputies conducted integration process decomposition in order to understand and agree upon ownership for each step in the integration processes. This understanding is paramount for implementation of hardware and software interface agreements and is a key element leading into the design definition phase.

Table 1. Constellation Project Descriptions

Constellation Project	Lead NASA Center	Function	
		Developmental Phase	Operational Phase
Project Orion	JSC	Develop and test the Orion (CEV) spacecraft to transport crew to and from space.	Provide Orion spacecraft.
Project Ares	MSFC	Develop and test the Ares I (CLV) and Ares V (CaLV) launch vehicles.	Provide Ares launch vehicles.
Ground Operations Project	KSC	Perform ground processing and integrated testing of launch vehicles. Plan, construct and/or reconfigure integration, launch, and recovery services for Orion Crew Module, Ares I and Ares V.	Provide logistics and launch services. Provide post-landing and recovery services for the crew, Orion Crew Module, and spent Ares Solid Rocket Boosters.
Mission Operations Project	JSC	Configure, test, plan, and operate facilities, systems, and procedures. Plan missions and flight operations.	Train crew, flight controllers, and support staff. Coordinate crew operations during missions.
Lunar Lander Project	JSC	Develop and test the Lunar Lander to transport crew to and from the lunar surface and to provide a habitable volume for initial lunar missions.	Provide Lunar Lander.
Extravehicular Activities (EVA) Systems Project	JSC	Develop EVA systems (spacesuits, tools, and servicing and support equipment) to support crew survival during launch, atmospheric entries, landing, abort scenarios, and outside the space vehicle and on the lunar surface.	Provide spacesuits and tools.
Future Projects	To be determined	Develop systems for future applications including Lunar Surface Systems (equipment and systems for crew operation on the lunar surface) and systems for future human exploration activities.	Provide future systems as needed.

The Constellation Program has been formulated, and must execute, during continuous operations of the space shuttle (through 2010) and ISS.

Moreover, NASA must be prepared to make best use of the expertise resident in the space shuttle workforce, when it becomes available as that program phases out. Constellation has developed a phased development program in anticipation of this workforce availability.

The Program Office workforce is comprised of engineers, scientists, and administrative personnel and was sized utilizing experience from past programs as well as guidance on availability of key personnel to support three human spaceflight programs at the Johnson Space Center. The initial size estimate was based on previous human spaceflight programs and was set at approximately 8% of the total program content. After the Program System Requirements Review, there was sufficient experience in the office to attempt a reduction in the budget to only approximately 6.5% of the total Program content. This was based on expected workload and products and a better

understanding of the Program integration responsibilities. The Program team continues to track risks incurred with this funding level and to reprioritize work as needed to meet the Program milestones.

The projects are staffed by leveraging expertise across the Agency. Project work assignments at the NASA Centers (and the White Sands Test Facility/White Sands Missile Range) are described in Figure 3.

It is recognized that managing a team distributed to this extent is a daunting challenge; indeed it is only now possible with current communications technology that enables real-time electronic meetings, single-source record keeping, and maintenance of the requirements baseline in a single database accessible by all program elements. All members of the workforce must use the selected electronic tool suite in order to make this distributed team work.

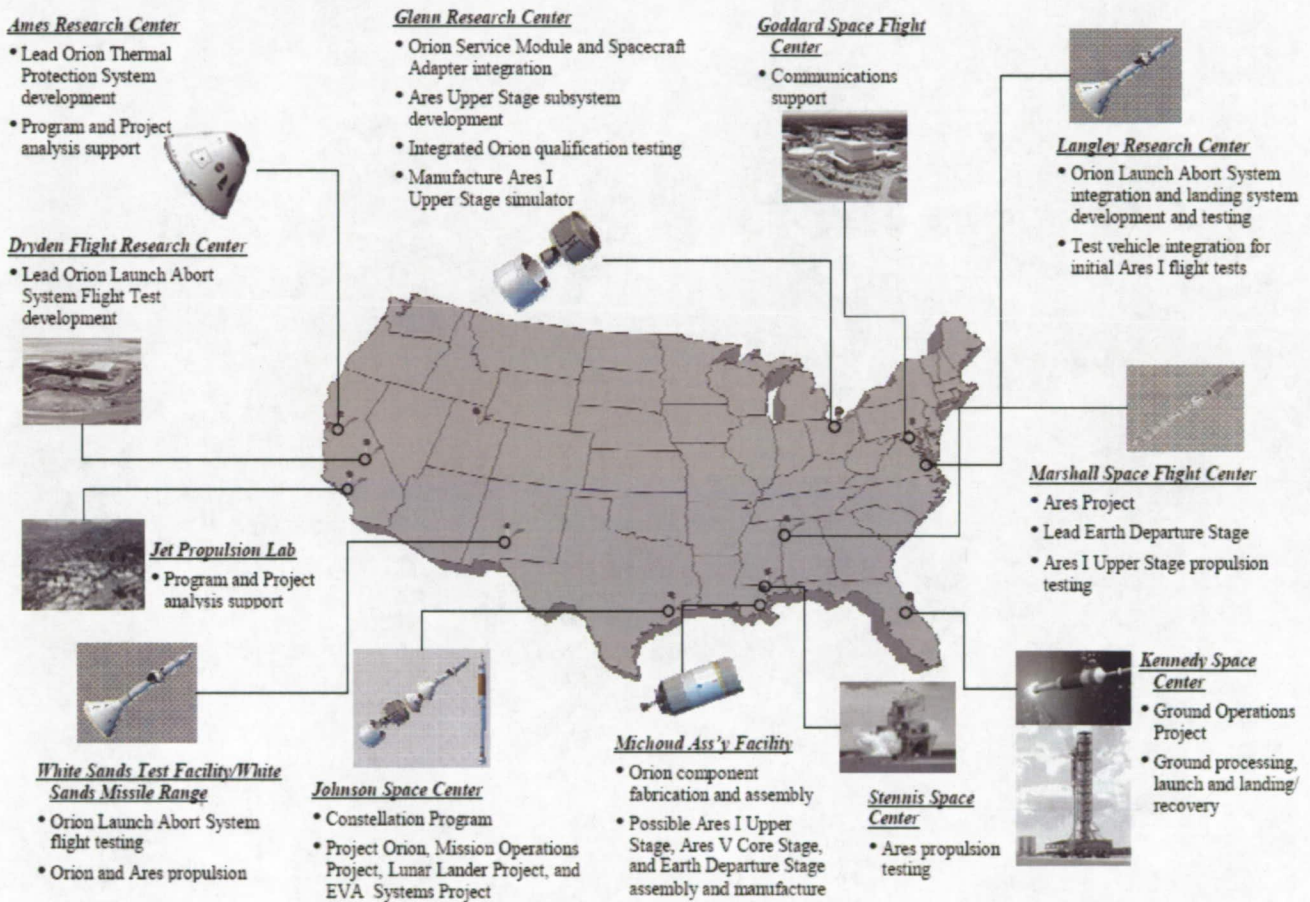


Figure 3. Constellation work assignments at NASA Centers

CONSTELLATION PROJECT ASSIGNMENTS AT NASA CENTERS

In June 2006, NASA announced Agency center responsibilities associated with the Constellation Program for robotic and human exploration of the Moon and Mars. The distribution of work across NASA's centers reflects the Agency's intention to productively use personnel, facilities and resources from across the Agency to accomplish the U.S. Space Exploration Policy.

In addition to the primary work assignments each Center will support the Moon and Mars surface systems conceptual designs. Constellation Center assignments are:

Ames Research Center, Moffett Field, CA, leads the Crew Exploration Vehicle (CEV) Thermal Protection System Advanced Development Project. Ames is developing information systems to support the Constellation Program Safety, Reliability, and Quality Assurance Office.

Dryden Flight Research Center, Edwards, CA, leads CEV Abort Flight Test integration and operations including Abort Test Booster procurement and integration with the Flight Test Article.

Glenn Research Center, Cleveland, OH, leads the CEV Service Module and Spacecraft Adapter integration, providing oversight and independent analysis of the prime contractor's development of these segments. Glenn has lead responsibility for the design and development of several crew launch vehicle (CLV) upper stage systems.

Goddard Space Flight Center, Greenbelt, MD, provides co-leadership of the Constellation Program's System Engineering and Integration navigation team and software and avionics team.

Jet Propulsion Laboratory, Pasadena, CA, leads a multi-center activity in support of the Mission Operations Project to plan systems engineering processes related to operations development and preparation. JPL provides co-leadership for the Constellation Program Office Systems Engineering and Integration Software and Avionics team.

Johnson Space Center, Houston, TX, hosts the Constellation Program, the CEV Project and the Mission Operations Project. The Constellation Program manages and integrates the program and all projects. The CEV Project Office manages and integrates all CEV elements including prime contractor work. The Mission Operations Project manages and integrates all activities related to mission operations.

Kennedy Space Center, FL, hosts the Ground Operations Project. The project manages all activities related to ground operations for the launch and landing sites, including ground processing, launch, and recovery systems.

Langley Research Center, Hampton, VA, leads Launch Abort System integration supporting the CEV Project, providing oversight and independent analysis of the CEV prime contractor's development of the system. Langley leads the Command Module Landing System Advanced Development Project for CEV. Langley provides vehicle integration and CEV test article module development for the CLV Advanced Development Flight Test-o.

Marshall Space Flight Center, Huntsville, AL, hosts the Constellation Launch Vehicle projects. The projects are responsible for project management of all CLV and cargo launch vehicle related activities. Marshall provides the CLV first stage design, and is responsible for launch vehicle demonstration testing including the Advanced Development Flight Test-o.

Stennis Space Center, MS, manages and integrates rocket propulsion testing for the CLV Project. Stennis leads sea-level development, certification, and acceptance testing for the upper stage engine, sea-level development testing for the upper stage main propulsion test article, and sea-level acceptance testing for the flight upper stage assembly.

The pilot testing of the ESMD Faculty Project began in 2007 with five faculty members, each assigned to two NASA Centers. The outcome of this pilot testing was very successful in that a large number of Senior Design topics and internships were identified.

This trial project was followed by the initial ESMD faculty project in which ten faculty members, each from a Space Grant Consortium-affiliated university, worked at ten NASA Centers for five weeks between June 2 and July 3, 2008, collected data on Senior Design ideas and identified possible internships that would benefit NASA/ESMD.

SCOPE OF PROJECT

The purpose of the ESMD space grant project is to train and develop the highly skilled scientific, engineering and technical workforce of the future needed to implement US space exploration missions. Four potential areas critical to future space explorations have been identified and these are described as below:

Spacecraft: Guidance, navigation and control; Thermal; Electrical; Structures; Software; Avionics; High-speed re-entry; Modeling and simulation; Power Systems; Interoperability/commonality; Advanced spacecraft materials; Crew/vehicle health monitoring; Life support.

Propulsion: Propulsion Methods that utilize materials found on the Moon and Mars; "Green" Propellants; On-orbit propellant storage; Motors, Testing, Fuels, Manufacturing, Soft Landing; Throttleable Propellants; High Performance and Descent.

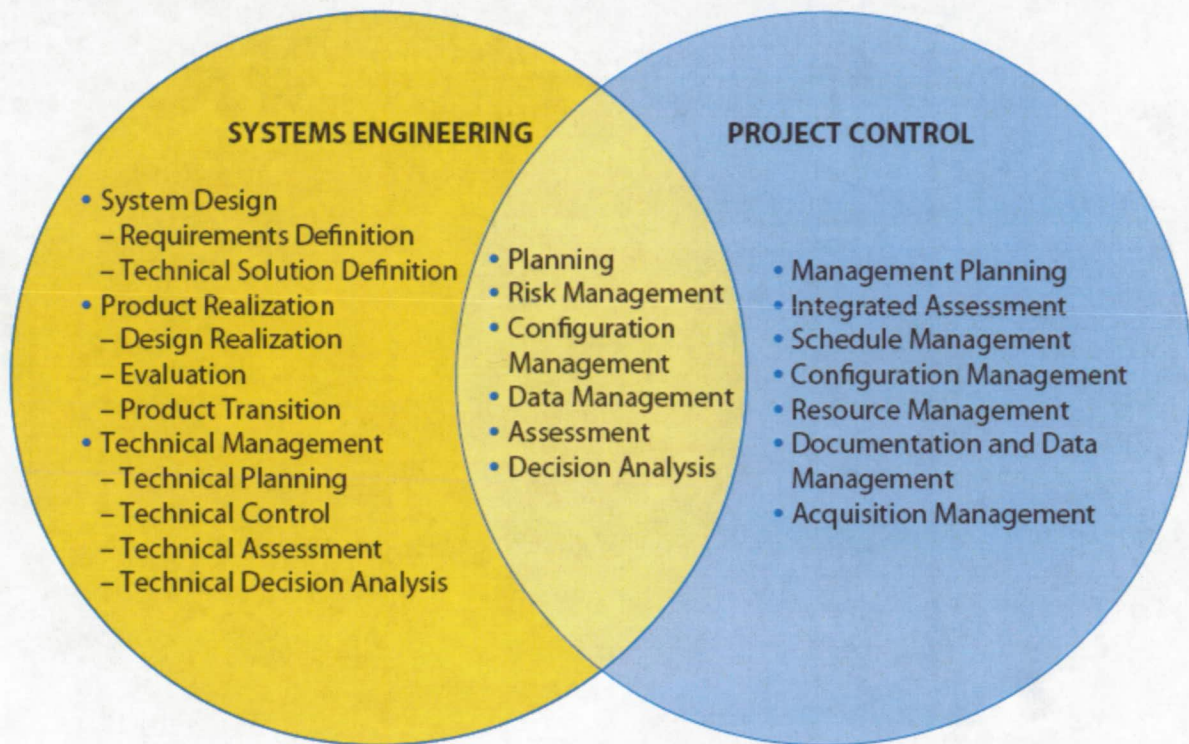
Lunar and Planetary Surface Systems: Precision landing Hardware, Software; In-situ resource utilization; Navigation systems; Extended surface operations; Robotics; Environmental Analysis; Radiation protection; Spacesuit, Life Support; Power Systems.

Ground operations: Pre-launch, launch, mission operations, Command and control Software Systems, communications; Landing and Recovery.

The specific purpose of the 2009 ESMD Faculty Fellowship is to prepare faculty to enable their students to complete senior design projects with potential contribution to NASA ESMD objectives. The faculty will work for six weeks at a NASA field Center on a selected ESMD project, convene at Kennedy Space Center (KSC) for one week, and incorporate the ESMD project into an existing senior design course or capstone course at their university in the 2009/2010 academic year. During the six weeks at a NASA field Center, each faculty fellow will work side-by-side with a NASA technical expert. The faculty will gain extensive knowledge on the ESMD project and associated requirements, interfaces and issues affecting the design and potential solution(s). The faculty will develop materials for use at their university during the 2009/2010 academic year in support of the completion of senior design project(s) using a systems engineering approach.

SYSTEMS ENGINEERING APPROACH TO SENIOR DESIGN PROJECTS

Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. The senior design project teams will be encouraged to review the NASA systems engineering handbook in the early stages of their projects. They will be provided with supplemental systems engineering educational materials. The senior design teams will be required to focus on the following systems engineering facets and to control their projects:



The system design keys crucial for the project success are:

- Successfully understanding and defining the mission objectives and operational concepts are keys to capturing the stakeholder expectations, which will translate into quality requirements over the life cycle of the project.
- Complete and thorough requirements traceability is a critical factor in successful validation of requirements.
- Clear and unambiguous requirements will help avoid misunderstanding when developing the overall system and when making major or minor changes.

- Document all decisions made during the development of the original design concept in the technical data package. This will make the original design philosophy and negotiation results available to assess future proposed changes and modifications against.
- The design solution verification occurs when an acceptable design solution has been selected and documented in a technical data package. The design solution is verified against the system requirements and constraints. However, the validation of a design solution is a continuing recursive and iterative process during which the design solution is evaluated against stakeholder expectations.
- These key areas will be monitored and assessed during the design project implementation.

SUMMARY OF FACULTY PROJECTS AT NASA CENTERS

**Professor Ghanashyam Joshi
Ames Research Center**

Initial Project Proposal

The Prognostics Center of Excellence at 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 useful life (RUL)” 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 ESMD is dedicated to creating enabling technologies and research for sustained and affordable human and robotic exploration. This project will help support the ESMD goal in the area of prognostics and damage modeling. In addition, the project will help train and develop the highly skilled engineering workforce of the future needed to implement the Vision for Space Exploration. This will be achieved through the participation of engineering faculty and students in technical problem solving through the application of engineering design process and the systems engineering approach.

Activities On-site at Ames Research Center

1. Dr. Kai Goebel (kai.goebel@nasa.gov)

Dr. Goebel works at RIACS for Ames Research Center in the Discovery and System Health group which is part of the Intelligent Systems Division where he coordinates the Prognostics Center of Excellence. This Center of Excellence is involved with elements of Systems Health Management as it applies to Aeronautics and Aerospace. He uses engineering, physics, and methods from artificial intelligence to achieve the project goals. Kai’s particular focus is in Health Management integration, uncertainty management, and prognostics for particular applications that have not been sufficiently tackled yet (e.g. space algal farms, etc.) and post-prognostic health management.

2. Dr. Bhaskar Saha (Bhaskar.Saha@nasa.gov)

Bhaskar Saha is a Research Scientist with Mission Critical Technologies, Inc., whose research at Ames Prognostics Center of Excellence is focused on applying state-of-the-art classification, regression and state estimation techniques for predicting remaining useful life of systems and their components. He has

developed an integrated Bayesian framework to estimate present damage and damage growth rates as a function of operational parameters to determine remaining-useful-life probability densities. He has also developed a hardware-in-the-loop testbed to benchmark prognostic algorithms using run-to-failure tests on Li-ion batteries. He has also formulated a comprehensive set of metrics to evaluate the performance of prognostic algorithms in order to standardize research in prognostics and advance the state-of-the-art. He completed his Ph.D. from the School of Electrical and Computer Engineering at the Georgia Institute of Technology in 2008. He received his M.S. also from the same school and his B. Tech. (Bachelor of Technology) degree from the Department of Electrical Engineering, Indian Institute of Technology, Kharagpur.

3. Dr. Abhinav Saxena (abhinav.saxena@nasa.gov)

Prognostics Algorithm Development: A Gaussian Process Regression based prognostics algorithm has been developed. GPR provides the flexibility to combine different models to construct a more complex realistic model that may explain a system's behavior better. It also accounts for various uncertainties that may arise due to environment and modeling noise. Predictions are accompanied with corresponding variance. The algorithm has been applied to several application datasets and shown to work effectively when compared to other data-driven methods.

Prognostics Performance Evaluation: As Prognostics matures, it is essential to develop methods that are simple yet cater to prognostics applications in evaluating the prediction performance. A set of new metrics were developed and are being applied to different applications. This efforts includes developing metrics that can track the evolution of performance with time as more predictions are made. These metrics are capable of accounting for and quantifying uncertainty information that may be available in the form of probability distributions from the algorithms.

Composites Prognostics: In recently started efforts carbon-carbon composites are being subjected to tensile fatigue tests and corresponding data are being collected from pristine and failure injected (cracked and de-lamination) test coupons. Piezoelectric sensors are being used to collect data using lamb wave propagation methods that has been shown to effectively detect cracks and de-lamination. The focus of this study is to collect fault evolution data that can then be used to develop prognostics data.

4. Edward Balaban (Edward.Balaban@nasa.gov)

Edward Balaban is a researcher in the Diagnosis and System Health group at NASA Ames Research Center. His main areas of interest are diagnostics and prognostics of physical systems. He is currently the lead for actuator prognostics with the Diagnostics & Prognostics Group in the Intelligent Systems Division. During his years at Ames he participated in research and development of

diagnostic and other autonomy elements for the X-34 experimental reusable launch vehicle, International Space Station, robotic astronaut assistants, autonomous planetary drills, and the future generation of autonomous micro-spacecraft. He received the Bachelor degree in Computer Science from The George Washington University in 1996 and the Master degree in Electrical Engineering from Cornell University in 1997.

5. Scott Poll (scott.poll@nasa.gov)

Scott Poll received a BSE degree in Aerospace Engineering from the University of Michigan, Ann Arbor, in 1994, and a MS degree in Aeronautical Engineering from the California Institute of Technology, Pasadena, in 1995.

He is currently a Research Engineer with the National Aeronautics and Space Administration (NASA) Ames Research Center, Moffett Field, CA, where he is the deputy lead for the Diagnostics and Prognostics Group in the Intelligent Systems Division. He is co-leading the evolution of a laboratory designed to enable the development, maturation, and benchmarking of diagnostic, prognostic, and decision technologies for system health management applications. He was previously the Associate Principal Investigator for Prognostics in the Integrated Vehicle Health Management Project in NASA's Aviation Safety Program. He has experience with model-based reasoning tools Livingstone, TEAMS, and RODON, which use different diagnostic strategies, behavior descriptions, and levels of abstraction to model and diagnose a system. Previously, he led a team in a real-time simulation of fault detection, isolation, accommodation, and situational awareness of aircraft flight control system failures. Prior to that, he was a researcher and the assistant project director for a multi-phase wind tunnel test program to study the Reynolds number effects on the externally blown flaps of a C-17 transport aircraft.

People I did not meet, but received e-mail communication

1. Mengshoel, Ole J. (Ole.J.Mengshoel@nasa.gov)

One overall theme of my current work is “Probabilistic Reasoning and Machine Learning for Aerospace System”. One long-term goal of this research is automatic detection, diagnosis, and re-configuration of aerospace vehicles and systems when components fail or fail to work as originally anticipated. Bayesian networks, which model multi-variate probability distributions, are a key component in our approach. Bayesian networks enable efficient machine learning, knowledge acquisition, and efficient inference algorithms, and also play a central role in a wide range of other probabilistic reasoning applications, for example in medical diagnosis, language understanding, intelligent data analysis, and spam filtering.

There are many opportunities for collaborations in ongoing research on probabilistic model-based diagnosis utilizing Bayesian network techniques. The

research utilizes both model-based and data-driven techniques, and is applicable to a wide range of systems and sub-systems in aerospace. As an example, consider the real-world (hardware) electrical power system, namely the Advanced Diagnostic and Prognostic Testbed (ADAPT) located at the NASA Ames Research Center. ADAPT provides a controlled environment in which to inject failures, either through software or hardware, in a repeatable manner. The testbed facilitates benchmarking the effectiveness of different technologies, including our probabilistic techniques.

Additional background information, project information, Bio, etc.:

<http://www.cmu.edu/silicon-valley/faculty-staff/mengshoel-ole.html>

<http://ti.arc.nasa.gov/people/omengshoel>

<http://ti.arc.nasa.gov/project/pca/>

<https://dashlink.arc.nasa.gov/>

2. Matthew Daigle (Matthew.J.Daigle@nasa.gov)

My technical background is as follows. I have a BS in Computer Science and Computer & Systems Engineering, an MS in Computer Science, and a PhD in Computer Science. My graduate work focused on model-based diagnosis of physical systems, and was applied to formations of mobile robots and the electrical power system testbed here at Ames. I have been at Ames for a year and the work has been focused on modeling, diagnosis, and prognosis for propellant loading systems for Shuttle/Constellation. Let me know if you need any other information.

In addition to these meetings, several technical seminars and discussions were attended as detailed in the weekly reports.

Final Project Proposal

The senior design projects of interest at Southern University under NASA-Ames supervision are:

1. Composite materials (or corrosion) prognostics testing and modeling project
2. Battery prognostics testing and modeling project

Further discussions are in progress to define details of project requirements and timelines.

Professor Jiang Guo

Jet Propulsion Laboratory

Activities On-site at the Jet Propulsion Laboratory

Jet Propulsion Laboratory (JPL) located in Pasadena, Los Angeles, California, is leading NASA's robotic space exploration efforts by constructing and operating automated planetary spacecraft. Some recent notable projects at JPL have been the Phoenix Mars Lander, the Mars Exploration Rovers Spirit and Opportunity, and the Spitzer Space Telescope.

From June 1 to July 10 Prof. Guo visited the Mission Assurance Directorate at NASA JPL and worked with his mentor, Dr. Jose Macias, Mission Assurance Manager (MAM), for Operations, to identify the requirements of a **Mission Assurance Management Environment (MAME)**.

Prof. Guo is very grateful to his mentor, Dr. Jose Macias, for the strong support and valuable advice he provided.

Prof. Guo's work at JPL was to investigate and integrate approaches to implement a high level software system to support JPL's mission assurance (MA) activities. Some of these activities included scheduling and monitoring the mission assurance function. His research goal was to improve the performance of mission assurance management and provide a software-supported management environment—MAME.

While on lab, Prof. Guo worked with many mission assurance personnel, such as Burt Sigal, Mission Assurance Training Coordinator, Jittendra Mehta, Chief Mission Assurance Manager, Kim Plourde, Chief Mission Assurance Manager, David Guarino, Mission Assurance Section Manager, Grant Faris, Chief Mission Assurance Manager for Operations, Tom Frascchetti, Mission Assurance Division Manager, Thuy Nguyen-Onstott, Quality Assurance Section Manager, Cynthia Kingery, Reliability Section Manager, Cami Vongsouthy, Safety and Environmental Section Manager and Robert Menke, Electronics Parts Engineering Deputy Section Manager to conduct research on mission assurance activities and improve his related technical background.

Prof. Guo's understanding of the function and scope of the mission assurance activities at the JPL site will allow him to advise his students in the implementation of a web-based software environment to support the mission assurance activities at JPL. This is the subject of the software systems senior design project to be developed at California State University, Los Angeles, in the 2009-2010 academic year. The project will challenge Prof. Guo's seniors to synthesize the knowledge they have gained during their undergraduate program and apply that knowledge in solving real-world engineering problems. Prof. Guo

will help students to devise solutions that meet the JPL's mission assurance management needs.

To identify the requirements, Prof. Guo started with interviews. He discussed the workflow with mission assurance senior experts and managers. These interviews were basically targeted to gather information about mission assurance managers' activities. Prof. Guo acquired knowledge about the various components of mission assurance including Quality Assurance, Reliability Engineering, Electronic Parts Engineering and Environmental Engineering. From the interviews, Prof. Guo also understood how mission assurance managers interact with other teams that have different disciplines in the area of safety and mission success.

Prof. Guo devoted much time on document analysis, a very important step in gathering requirements. This helped in the study of concepts, the identification of requirements and description of work activities of mission assurance managers. Prof. Guo read through many papers, reports and presentation materials including those prepared by Grant Faris, Jose Macias and Jittendra Mehta. He also analyzed the Marvel Proposal to understand the overall function of mission assurance of a complete project. Lastly, he studied safety and missions success related handbooks, such as JPL's FPP and DP.

Prof. Guo spent three days attending JPL mission assurance manager monthly report meetings. He collected the information of managers' work items, including work agreement, red flags or potential red flags, failure/problem reports, the 5 X 5 risk assessment matrix, Incident/Surprise/Anomaly reports, and medium and high risk waivers.

He took extensive notes, more than 100 pages, as part of the requirements eliciting phase. Based on these notes, Prof. Guo created a use-case model for the Mission Assurance Management Environment (MAME). This model is a simplified representation of a MAME system that is intended to facilitate understanding of system functions and mission assurance features. Prof. Guo combined textual description and diagrams to describe the system requirements. The use-cases and step-based scenarios provided a context for discussing the requirements for the MAME system with the mission assurance managers.

Prof. Guo wrote the draft version of the requirement of the MAME system based on the use-case model and submitted it to the JPL mission assurance managers for review and used the storyboard approach to collect the inputs and feedbacks of the first version of requirements of the MAME system. Prof. Guo discussed with the reviewers individually their feedbacks and used a set of drawings to describe mission assurance managers' activities that occur in an interaction of the system. Storyboards are a kind of paper prototyping. Prof. Guo started by drawing pictures of the screens, dialogs, toolbars, and other elements on papers to discuss the functions and features that the MAME system should provide. Storyboard is an inexpensive and efficient communication tool.

After a discussion with reviewers, Prof. Guo completed the requirements of the MAME system. This document will be the start point and guideline of the year long senior design project that will be finished in 2010.

Senior Design Project Plan

MAME Project Goals

To increase the efficiency of the Mission Assurance Managers, the project's goals are as follows:

- Provide a web-based infrastructure to support MAM's work
- Provide a Framework for MAM's work
- Provide MAMs with a Work Environment

To implement MAME successfully, the following aspects and design requirements need to be taken into consideration:

- Dynamic – All items in MAME are editable and adaptable.
- Extensible – the MAME system should provide a capability to add new functions in the future.
- Traceable – Everything in the MAME system is recorded and can be tracked. This is a reliability requirement.
- User friendly – MAME should provide default items such as a pre-defined work list. MAMs can easily tailor items according to the projects they are working on.
- Maintainability – Easy to fix bugs, update to new versions and install on different platforms.

MAME Major Features

• Create Role Model

MAME has two kinds of users: Administrators and Users. Users are organized according to pre-defined role models. These models will be used to control: Approval and Permission. The pre-defined role models should be editable.

The administrator can add new roles and new relationships. These relationships will be defined in a matrix. Current roles: OSMS engineers, specialists, consultants, mission assurance managers, chief mission assurance managers, section managers, division managers.

• Create Process Definition

MAME will provide an editable process definition based on pre-defined work item lists. Users can edit process definitions using a graphical user interface. MAME will provide an ability to re-use a process definition. When creating a new project, the user can select previous process definitions. MAME will provide a schedule view. The scale of the schedule should be adjustable. MAME will provide Process Definitions tailored to various project classifications such as

Class A, B, C, D or E. It should also consider long term or short term missions, Earth, moon or deep space environments, etc.

- **Execute Defined Process**

MAME will provide different process definitions for different roles. MAME will create reminders for work items that have not been completed when due. The reminders are automatically generated for overdue work items. Two reminders: email and red alert displays on the screen. Users can select to display the reminders later, or simply ignore them. MAME will provide screen navigation driven by process definition execution. MAME will allow users to view and complete work items (upload documents) that have been assigned to them.

- **Track Process Execution**

MAME will provide upper level managers a "radar view" that allows them to monitor process definition progress including: project status, pending work items, work item ownership, how long each work item has been waiting, etc. MAME will also provide users the ability to track related work items and documents for example for a given document, find all documents that were used to create it and all documents that will use it as a source. Another example would be for a user to find all his assigned work items and all his completed work items.

- **Log Process Execution**

MAME will log all the changes to the work items. MAME will log all the work item execution status for later analysis. MAME will log ready time for work items. That is the input available time. MAME will log end time for work items. This is output available time.

- **Analyze Process Execution**

MAME will help the managers to compare the defined process vs. the actual process execution. It will also help managers to analyze where the bottlenecks are. MAME will provide managers the ability to analyze the performance of teams and some statistic data, such as waiting time, number of changes, etc.

- **Monthly Report**

MAME will provide mission assurance managers' monthly report support. This includes generation of graphic reports of Waivers, Problem/Failure Reports, ISAs, Document Traceability, and Non-Conformance Report.

Applying System Engineering Approach to MAME Project

The system engineering approach plays an important role in MAME project implementation. System engineering is involved in MAME project at two levels.

First, the students will follow the system engineering process to implement the MAME project. In the concept development phase, students will use prototyping and visualization technologies to build a concept model and use case models. These models will serve as the fundamental basis of project development. After the team and NASA technical expert review the requirements, students will work

on the preliminary design phase of the project. For the preliminary design, students will choose the design platforms and finish the design of data schema. They also need to complete workflow model and interoperability analysis. NASA technical expert will review preliminary design report. Based on review results, students will improve their preliminary design. Next, in the final design and fabrication phase, students will divide the system into subsystems, and design and implement subsystem modules and components. At this phase, students will conduct unit testing and interface verification. NASA technical expert will review the output of this phase. Then, at system assembly and integration phase, students will assemble and integrate individual modules and components to achieve specified system requirements. Next, in the validation and test phase, students need to complete system testing and validation testing and demo system functions to NASA technical expert. In addition to that, students will be required to document the full project in the form of a high-quality final report and make a final presentation and demonstration to NASA technical expert.

Second, the main goal of MAME project is to support critical system engineering activities, including Concept Development, Preliminary Design, Final Design and Fabrication, System Assembly, Integration, Validation and Test. MAME provides aid to MAM to complete high quality milestone and deliverables, such as: SRR – System Requirements Review, PMSR – Project Mission System Review, PDR – Preliminary Design Review, CDR – Critical Design Review, SIR – System Integration Review, SMSR – Safety and Mission Success Review, FRR – Flight Readiness Review, V FRR – Launch Vehicle Flight Readiness Review, and LV LRR – Launch Vehicle Launch Readiness Review.

Professor James Conrad Johnson Space Center

Initial Project Proposal

The initial proposal for this activity was to develop a General Purpose Measurement Tool. Specifically: "In current and future space travel, electronics will play an important part. These electronics are increasingly complex. Occasionally, an electrical or electronics system will fail. In order to troubleshoot the problem, a single handheld instrument is needed. It should have the combined capabilities of a multi-meter, oscilloscope, protocol analyzer, network analyzer, spectrum analyzer, hand held computer, and technical reference database in a rugged, radiation tolerant, easy to use unit. This tool would be the Swiss Army Knife of the International Space Station, Crew Exploration Vehicle and Lunar Habitat Electrical and Electronics Installation and Test. Some capabilities include:

- Unit should be easily used by an astronaut, with a user interface that can be used in bright sunlight, or dimly lit environment.
- Use of high reliability universal front end electronics and virtual instrument interface coupled with field programmable analog arrays, and FPGA to maximize universality."

The need for hardware/software for the JSC-EV branch has changed quite a bit since the proposal was written. There are more immediate needs than the measurement tool (specific) that can help NASA, specifically proof-of-concept technologies (general). The general technology activities will help guide the development of specific devices. Therefore, this original proposal was changed.

Activities On-site at Johnson Space Center

With his technical manager (Greg Hall), Dr. Conrad discussed the technical areas of interest to JSC-EV, including the wireless sensor networks, RFID sensing, system engineering, middleware networking, lunar vehicle, and measurement tools projects. There is an underlying technology question about reusing hardware between all of the lunar assets. For example, the lunar descent vehicle, the lunar habitat, and the lunar electric rover will all need electronic interfaces and computer controller boards. Rather than have three separate sets of electronics (and the spares that might be needed), a good design would reuse the one-use only lunar descent vehicle's computer controller board so that it could be used in the habitat or rover. The new project will investigate the feasibility of this concept.

Dr. Conrad investigated in more detail the avionics planned and already in the Constellation vehicles (Orion, Altair, habitat, Lunar Electric Rover). Many documents are in the public domain, but many are also contractor designs and

are thus not accessible. Dr. Conrad is continuing with a "generic" design of the different avionics vehicles and approximate, as best possible, the hardware and software design. An additional area of investigation is Real-time Ethernet, or Time-triggered Ethernet. Dr. Conrad did finally have a good conversation with Kevin Somervill at Langley on the "Common Systems Architecture" for all Constellation vehicles (well, theoretically all vehicles). This discussion was attended by six NASA engineers and all involved have a plan for continuing collaboration.

Dr. Conrad presented his summer progress and Senior Design project plan to Kam Lulla, Gail Chaplane (Engineering Division) and Helen Lane (External Relations Office). He described the differences between last year and this year's program. The attendees expressed that they needed a process to best handle requests for senior design projects (some schools are going straight to the NASA sites).

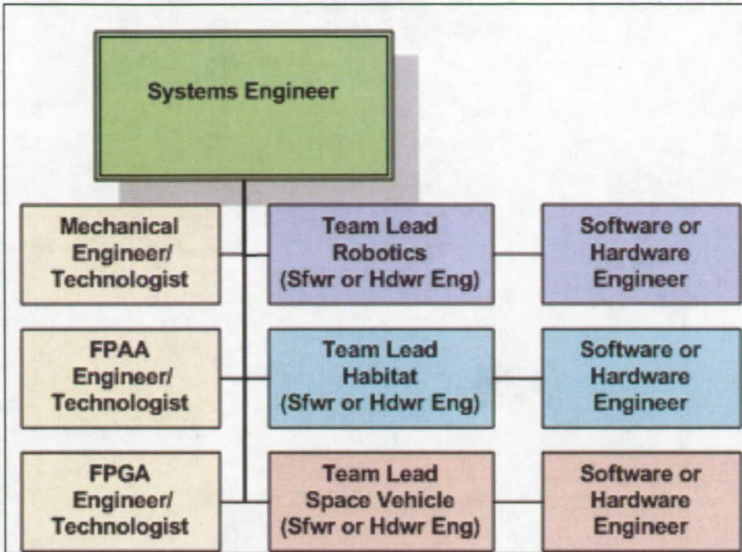
Final Project Proposal

One concept for future space flights is to construct building blocks for a wide variety of avionics systems. Once a unit has served its original purpose, it can be removed from the original vehicle and reused in a similar or dissimilar function, depending on the function blocks the unit contains. For example: Once a lunar lander has reached the moon's surface, an engine controller for the Lunar Decent Module would be removed and used for a lunar rover motor control unit or for an Environmental Control Unit for a Lunar Hab.

This project will include the investigation of a wide range of functions of space vehicles and possible uses. Specifically, this includes:

- Determining and specifying the basic functioning blocks of space vehicles.
- Building and demonstrating a concept model.
- Showing high reliability is maintained.

The specific implementation of this project will require a large project team made up of Systems, Electrical, Computer, and Mechanical Engineers/Technologists. The efforts are made up of several sub-groups that each work on a part of the entire project.



General support (4): Systems Engineering, FPGA Engineer/Technologist, FPAA Engineer/Technologist, Mechanical Engineer/Technologist

Project 1 (2-3): Robotic Sensing, Control, and Communications

Project 2 (2-3): Lunar Habitat Sensing, Control, and Communications

Project 3 (2-3): Space Vehicle Sensing, Control, and Communications

FPGA = Field Programmable Gate Array,
FPAA = Field Programmable Analog Array

This is one of the most complex projects offered by the University of North Carolina at Charlotte senior design program. Students working on this project will be given the experience of working on a typical industry effort, with respect to size and scope. The Faculty Advisor, Dr. Conrad, will work closely with all team members to ensure success. Students who participate in this project will also be co-authors on several technical papers which will be written to describe the effort and results. This effort will truly be a bright spot on anyone's resume.

Students working on this project will have the opportunity to work at NASA's Johnson Space Center as an intern in the summer of 2010. Interested students will need to apply for the internship in the fall of 2009. Summer employment is not guaranteed, but working on this project will provide proof of a strong commitment to NASA's goals.

The project has four subprojects. The main objective is to demonstrate that the same FPGA and FPAA board can be moved between three different systems. Each of the Systems will have some basic functionality, i.e. the Robotic Vehicle will move in its environment and avoid obstacles. There are four deliverable products from this project:

1. A robotic vehicle that uses the common FPGA and FPAA boards
2. A simulated lunar habitat that uses the common FPGA and FPAA boards
3. A simulated space vehicle that uses the common FPGA and FPAA boards
4. A programming and test fixture for the FPGA and FPAA boards

Professor Alak Bandyopadhyay Marshall Space Flight Center

Initial Project Proposal

Study of the propellant loading system is a very important part of the pre-launch ground operation of space vehicle. In order to find out various design parameters and to obtain an optimal time line, a numerical simulation of the entire loading system is very desirable and important. An integral numerical model has been developed in NASA using Generalized Fluid System Simulation Program. The main objective of the current model is to develop an efficient algorithm to improve upon the existing model as well as finding optimal parameters for smooth ground operations during the loading process. The system consists of optimal performance of various components such as the storage tanks, propellant tanks, ground system fill and vent lines, flare stacks, the valves etc. The physics involved is quite complex too as it involves interaction of flow-heat-mass transfer, phase change, conjugate heat transfer and unsteady behavior. The numerical simulation is complex as well as time consuming. However, as intense computation is expected, even in a faster computer, the computational time needed is enormous (a typical run with one set of parameters may be 11 to 12 hours). The main objective of the proposed work is (i) to optimize the design parameters to solve such complex systems and (ii) to reduce the computational time by introducing more efficient nonlinear solver. The learning outcome from this simulation gives a great opportunity for the students in the senior design course to understand the concepts of system engineering, learning new algorithms, how to optimize design parameters, data collections and post processing of large volume of data.

Activities On-site at Marshall Space Flight Center

Prof. Bandyopadhyay has primarily worked with his mentor Dr. Alok Majumdar, Thermal Analysis branch at Marshall. However, during this project he got support from several personnel including Ms. Melissa Van Dyke, Thermal Analysis Branch Chief, and Mr. Rick Moore for technical assistance. Dr. Majumdar is the primary developer of the Generalized Fluid Flow Simulation Program, the code used for the analysis of this work. Dr. Majumdar and Dr. Andre LeClair of NASA MSFC have originally developed the Propellant Loading Model to support the Preliminary Design Review (PDR) of ARES I upper stage main propulsion system [1]. Prof. Bandyopadhyay has first studied the existing model thoroughly and tried to understand the design issues, identify the key design parameters and in the beginning started using the GFSSP simulation with simplified models involving conjugate heat transfer which plays an important role in the loading model.

From the second week onwards Prof. Bandyopadhyay started working on the algorithm modification for optimization of the code with suggestions and guidance from my mentor. The conjugate heat transfer modeling between solid and fluid has been changed and the code has been suitably modified. This has been done to see if the simulation time can be improved from the existing model, however, even though the new algorithm produced accurate solutions, but could not reduce the computational time. The algorithm for the solver modification using Broyden method instead of Newton Raphson might be able to reduce the simulation time and Dr. Majumdar has been working on this to implement the Broyden scheme into GFSSP. Prof. Bandyopadhyay would be testing the new scheme and possibly implement in the senior design course.

Prof. Bandyopadhyay has been also running various cases by varying the time steps to reduce the simulation time without losing accuracy of the solutions. The work will give the students in the senior design course an integrated system level design ideas, concepts and learning and they would be primarily working on the parametric study to obtain an optimized time line for the loading of propellant.

Prof. Bandyopadhyay has attended the weekly meeting of ER43/Thermal Analysis group and discussed with all the Engineers and members of this group about the work. He has also participated in the internal meetings of the GFSSP where various other problems using the code were discussed and this also will help his in implementing the ideas in the senior design course.

Final Project Proposal

The senior design class students in Algorithms will be involved in several sub-problems based on the senior design project learned under the ESMD space grant. The main emphasis of this work is complete system design using numerical tools and general understanding of the physics. The work will be distributed into two or three project categories:

- (i) Algorithm issues, modeling simpler problems using the complex algorithm, with improved runtime than the existing algorithm.
- (ii) Parametric study of the Propellant Loading Model using GFSSP and find out an optimum timeline.
- (iii) Optimization of the code using various time steps and find out an optimal runtime.

However, all the students will be taught the preliminary concepts, the numerical algorithms involved, the fundamental mathematics needed to understand the problem and the solver. Students might have to learn FORTRAN programming skills before using the code. The method of discretization, the control volume approach, and the various numerical techniques such as Newton-Raphson, Substitution methods, 1st order, second and higher order differencing schemes and the partial differential equations will be taught to make the students comfortable with the complexity of the project. Then the GFSSP code will be introduced. The students will not directly solve the complex problems. They

would be given simpler models to simulate and have a feel about the solution process. The concepts of Systems Engineering and the various aspects of it will be discussed in the class.

The students will then proceed to start working on individual projects; they will present informally to the entire class about their progress and also will be participating in ESMD teleconferencing to talk about the progress. The students will also be given home works and other assignments to help them in improving their understanding of the theory and the numerical algorithm. Students will also learn how to work in a team and how the work can be integrated.

Professor William M. Cross
Marshall Space Flight Center

Initial Project Proposal

While many of the specifics are yet to be developed, crushing and grinding to convert terrestrial materials to LRSMs will be necessary. The primary issue with using these methods is that for many mineral types, the particle fracture mechanism is primarily abrasion. This produces a small fraction of angular fines at the small area on the particle that the jaw or roll contacts, while leaving the remainder of the particle essentially intact. Using more energetic crushing operations leads to different fracture mechanisms first cleavage and with sufficient energy the mechanism becomes shatter. Initial work will focus on determining which fracture mechanism will lead to the optimal shaped particles. The shape of the particles will be determined from optical microscopic visualization and from calculation of the average particle shape factor. The shape factor ($\psi = d_v^2/d_s^2$) can be calculated from the ratio of the average surface diameter. The size distributions will be characterized using the Rosin-Rammler distribution. Statistical comparison between the size and distribution moduli of the possible LRSM and the chosen lunar material will be used to quantify their correspondence. In addition, the composition of the size fractions will be determined by x-ray diffraction and energy dispersive x-ray fluorescence, which is a part of SDSM&T's field emission SEM. SEM will also be used to estimate liberation of mineral constituents for comparison with liberation estimates determined from micrographs of previously obtained lunar materials.

The design project will also examine how decreased gravitational attraction affects separation processes, such as jigs, cyclone separation, dense media separation, magnetic separation and flotation. This will primarily be accomplished through analytical modeling of the separation process.

An important aspect of the design process will be to understand the scale-up of the process to produce the desired amount of LRSM and to determine the cost of manufacture of the LRSM. Scale-up will be begun through determination of dimensionless quantities using Buckingham's pi theorem. In addition, MODSIM, a modular simulator of mineral processing applications will be used to develop the scale-up process in more detail, and with suitable code revisions explore the effect of reduced gravity on separations.

Activities On-site at Marshall Space Flight Center

Prof. Cross worked primarily with three people at the National Space Science and Technology Center, Dr. Douglas Rickman, Mr. Christian Schrader and Mr. Rashidi Hunter. Dr. Rickman is the primary technical expert associated with the design project being developed. Meetings were held with Dr. Rickman at least

weekly when his schedule permitted. Meetings were held more informally with Mr. Schrader, a researcher who is currently finishing his Ph.D. degree and with Mr. Hunter who is an engineering major at Morehouse University. In addition, bi-weekly group meetings for all relevant workers from the various projects Dr. Rickman oversees.

In addition, Prof. Cross had a meeting with researchers from NSSTC, Marshall Space Flight Center and Teledyne Brown Engineering concerning specifics of the Figure of Merit calculation in determining how well terrestrial simulant materials match existing Apollo mission gathered lunar materials. The Figure of Merit calculation is of considerable importance in understanding the relation between simulant and lunar material. As such, this meeting and subsequent discussions will be important in the final simulant material produced during the design course.

Finally, Prof. Cross presented a seminar covering his areas of expertise and its application to lunar work primarily to the members of Dr. Rickman's team on June 23, 2009.

Final Project Proposal

The final anticipated design project has three areas of possible work. The first and most important is utilizing separation technology to reduce the cost of current simulant materials. Primarily this would be aimed generally at removing minerals that do not occur on the moon. This would include all hydrothermally-altered minerals. In addition, separation methods to obtain very pure samples of plagioclase, having a high calcium to sodium ratio and pyroxene materials containing primarily orthopyroxene rather than clinopyroxene will be examined.

Those minerals that are in the earth-based ores similar in composition to lunar regolith that do not occur on the moon have been identified. Primarily, these are hydrothermally-altered minerals, including:

- albite ($\text{NaAlSi}_3\text{O}_8$),
- illite $((\text{K,H})(\text{Al,Mg,Fe})_2(\text{Si,Al})_4\text{O}_{10}[(\text{OH})_2,(\text{H}_2\text{O})])$,
- biotite $(\text{K}(\text{Mg, Fe})_3\text{AlSi}_3\text{O}_{10}(\text{F, OH})_2)$,
- epidote $(\text{Ca}_2\text{Al}_2(\text{Fe}^{3+};\text{Al})(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH}))$,
- chlorite group minerals general structure $((\text{Mg,Fe})_3(\text{Si,Al})_4 \text{O}_{10} (\text{OH})_2 \cdot (\text{Mg,Fe})_3(\text{OH})_6)$

Of next greatest importance is better understanding of the major mineral constituents of the lunar surface, particularly related to how these minerals fracture under load. Typically size and shape of the fractured mineral vary as the

load is increased and both of these characteristics (size and shape) are critical to obtaining the highest fidelity lunar simulants. Methods to achieve the correct simulant shape have been examined. Mineral breakage is a complex function of the bond strength of the atoms within the material, the mineral particle size, the conditions (mineral pretreatment, dry or wet comminution, temperature and humidity, etc.) and the type of equipment used. One of the most important mineral related criteria is the Bond work index. A variety of methods for determining the Bond work index has been found, and these are being critically evaluated.

Of at least equal importance to the size and shape issues, understanding how mineral beneficiation processes are altered by lunar conditions is critical to successfully achieving future mission goals. In general these methods are likely to be, at least initially, simulations. Terrestrial crushing and grinding have been simulated quite extensively and altering the gravitational force should be relatively straightforward. The environment effect will be more challenging. For terrestrial unit concentration operations, modeling is less well understood. As such, initial work will concentrate on relatively simple physics-based, sum of forces simulation. More complicated models will be considered as time and necessity warrant. One possibility involved with this aspect of the design project, is performing validation testing through the Systems Engineering Educational Discovery (SEED) Reduced Gravity Education Flight Program.

Applying System Engineering Approach to the Senior Design Project

Implementation of systems design principals into the South Dakota School of Mines and Technology Metallurgical Engineering Design project will be accomplished in two ways. First, at the beginning of the course, Dr. Cross will present several lectures covering the systems engineering process. This portion will be presented to all students enrolled in MET 351 (Engineering Design I, fall semester junior design) and MET 464 (Engineering Design III, (fall semester senior design) to any non-Metallurgical Engineering students involved in the ESMD project design.

After this introduction to systems engineering, the ESMD project team members will implement systems design processes. In particular, systems design (including stakeholder expectations and technical requirements), technical solution definitions (logical decomposition and design solution definitions), technical decision analysis, risk assessment and management, decision analysis, assessment, schedule management, validation and verification. Depending upon the size and complexity of the final design project planning and control issues will be dealt with using a systems engineering approach if needed.

SENIOR DESIGN COURSE AND REVIEW

As defined by the Accreditation Board for Engineering and Technology, Inc. (ABET) ABET “Engineering design is the multi-disciplinary process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.” This definition clearly delineates the differences between a *design project* and a *research project*. A critical element for ABET accreditation is that university engineering programs must implement a capstone senior-design course. Here students are expected to engage in a culminating major design experience that requires cross-disciplinary efforts and a physical design realization. This broad-based comprehensive approach is not the objective of most research efforts that are typically directed and specific in nature. Many university engineering programs satisfy this criterion to varying degrees of success by requiring a “capstone” senior-design class or project. This capstone design project is often at odds with university promotion and tenure process (P&T) requirements for faculty. Capstone design projects are incredibly time consuming, and have the potential to detract from faculty time that would otherwise be dedicated to specific research projects. The P&T process emphasizes publishable, funded research. These conflicting requirements lead many university departments to do a ‘minimal’ job on senior-design by substituting a senior year research project for a full-scale capstone course.

To help resolve these intra-academic conflicts, and to promote student interest in NASA related engineering topics, during the fall of 2008 the NASA office of exploration released a request for proposals (RFP) for development of a Senior Design Capstone course. A primary requirement is that the course materials can be packaged, and with minor modifications, implemented and instructed at any United States educational institution with an ABET accredited engineering program. The Mechanical and Aerospace Engineering Program at Utah State University, Logan Utah, was selected to develop the required course material. Summaries of both the developer comments and the review by the ESMD Faculty Fellows are provided below.

The Senior Design project under NASA sponsorship requires the following elements: (i) Clear delineation of top-level requirements and hierarchy for the space mission at hand within imposed constraints; (ii) Itemization of major phases, tasks and engineering specifications associated with the project, as well as reviews, within the context of a holistic approach and an overall timeline of milestones/Gantt Chart; (iii) Design expectations; (iv) Allocation of responsibilities to group members for specified activities and processes in order to realize the customer expectations & produce an integrated design; (v) Testing,

validation and verification of design as proof of compliance with customer requirements; (vi) Simulation/demonstration & presentation of the implemented design; (vii) Detailed documentation with references (including websites).

Utah State University Course Developer Objectives and Comments

This course is developed as partial fulfillment of the requirements of a grant funded by the NASA Office of Education. The final outcome is a “packaged” senior design course that can easily be “moved laterally” and incorporated into universities across the nation. The course materials must adhere to the standards of the Accreditation Board for Engineering and Technology (ABET), and be relevant to one of four areas identified by NASA’s Exploration Systems Mission Directorate (ESMD).

- *i) Spacecraft Systems,*
- *ii) Propulsion,*
- *iii) Lunar and planetary surface systems,*
- *iv) Ground Operations.*

This specific design project will target item *i) – Spacecraft Systems* – and will develop senior design concepts for a Lunar and Planetary Surface Landing Research Vehicle (*LPSRV*) (*ESMD# DFRC1-15-SD*). Per NASA specifications concepts must account for reduced lunar gravity, and allow simulated terminal stage of lunar descent to be flown either by remote pilot or autonomously. The design project will challenge students to apply systems engineering concepts to define research and training requirements for a terrestrial-based lunar landing simulator. This free-flying platform should allow for both sensor evaluation and pilot training. The selected concept must allow a small-scale prototype-demonstrator to be constructed within the time and budget constraints of a university-based senior design project. A prototype of the system concept will be constructed and flight-tested. Selected concept must be scalable to a full-size planetary landing research.

The goal of a this capstone senior-design project is to provide students with a rigorous and educational design experience that mimics the challenges they will face in an entry level engineering position while still providing structure, support and resources appropriate for the level of education achieved by a senior in mechanical or aerospace engineering. Creating a course structure that motivates individual achievements and provides thorough and valuable feedback is critical to the design project success. It is also critical that the framework of the class provides motivation and rewards for individual, as well as group, effort and accomplishment

The suggested team size for this project is 15-25 students, and the project should include students from at least three discipline areas, *mechanical/aerospace engineering, electrical engineering, and computer engineering/science*. The multidisciplinary nature of the vehicle design will provide a wealth of real-world engineering challenges for the undergraduate students in the areas of propulsion, thermodynamics, aerodynamics, navigation, guidance, structures, flight dynamics, measurements, and communication systems. Because the vehicle design will require the synthesis of sub-systems from a variety of disciplines, rigorous systems engineering methods must be used to guide the design process and prevent mission “requirements creep.” Specific systems engineering concepts such as requirement verification, design trade spaces, functional block diagrams, and work breakdown structures will be introduced and applied.

One of the major “failure modes” of a senior-design project is that the students try to “do too much” for the time and resources available to them. Thus it is critically for the instructor to focus the early efforts to limit the design space, requirements, objectives, and systems engineering to levels appropriate for undergraduates to accomplish in an academic year. With an excessively open senior-design course, students must be responsible for inventing client requirements, the design methodology, and then eventually constructing a design to meet their own requirements. Students must learn how to deal with design constraints in this class. These constraints may, for example, involve cost or performance considerations in the implementation or platform size restrictions imposed by the intended NASA. These issues will be addressed in the lectures, and students should be consciously aware of these considerations. Here the class instructor must be careful not to “hijack” the design away from the students themselves. Too many constraints or mandates from the instructor prevent students from developing a sense of ownership for the final design project. A strong sense of responsibility and ownership is critical to both motivation and the overall project experience.

Fall Semester 2009 will introduce students to design and systems engineering concepts, and will develop sufficient theoretical background to allow design and fabrication of a prototype demonstration vehicle. Apollo-era lunar mission designs will be examined in detail as a point of departure for this design. A minimum maximum teams will break off into small development teams. The end of fall semester will culminate with a Preliminary Design Review (PDR) being presented to NASA technical personnel (via web-conference, and USU Faculty.

Spring semester 2010 will emphasize detailed theory for specific sub-system relevant to the vehicle design, as well as fabrication and testing of the prototype article. Group lectures will be held at least one hour per week. Internal project design reviews will be held on a bi-weekly basis. As required, technical interchange videoconferences or web casts will be conducted NASA technical and

administrative points of contact in attendance. A final report will be submitted for the NASA Systems engineering competition. *The final deliverable from this report is a working LLRV prototype.* A goal of a successful test flight before end of Spring Semester 2010 will be targeted.

Upon completion of this design class students will be able to synthesize mathematics, science, engineering fundamentals, and laboratory and work-based experiences to formulate and solve engineering problems in both thermal and mechanical systems areas. Students will have proficiency in computer-based engineering, including modern numerical methods, software design and development, and the use of computational tools. Students will be prepared to communicate and work effectively on team-based engineering projects. Students will recognize the importance of, and have the skills for, continued independent learning.

ESMD Faculty Fellows' Comments

- 1) I was expecting more on systems engineering – this is not really a criticism, but more of a statement of my expectations. What might reconcile my expectations with the course is explicit connection of examples etc. to the definitions either the requirements or solution definitions whichever is more appropriate.
- 2) In the end, the course is likely to succeed on how the instructor interacts with the students to help the students understand the various aspects of the systems engineering design process. As such, some examples written or taped would be useful for illustrating ways in which this could be or has been accomplished.
- 3) Was there any assessment of the course by its participants? I did not see any, but may have missed this.
- 4) The number of significant digits used is inconsistent, I believe. While keeping extra digits for calculation is fine, I would like to see these marked clearly to remind the participants about the number of significant digits that are justified in the calculation.
- 5) If possible, I would like to see section 12 cover the log-normal distribution and/or non-parametric statistics too. I find these very useful, often more useful than normal distribution based distributions.
- 6) This is a very specialized course that can only be taken by Mechanical Engineers and, as such, does not offer an opportunity for truly multi-disciplinary activities. The topics of introduction, systems engineering, and the space environment are general enough for engineering seniors, but other topics require extensive coursework in topics that Computer, Electrical, and Civil Engineers will likely not have taken. A more generalized approach could make this course available for more disciplines.

- 7) This is a very rigorous course. There is so much information packed into each set of slides that a student may have difficulty taking it all in. Further, it is not clear from the slides if the course is solely lecture, or if you intersperse discussion, small exercises DURING class time. Research has shown that pure lecture is not effective. I would have liked to see short "group" exercises (i.e. 10 minutes) to demonstrate the points described in class. For example, in the systems engineering section, actually introduce a toy problem that students create a sample trade study.
- 8) Please examine the PowerPoint Slide format. That big stripe of black ink at the top of each page may eat up many ink cartridges. It also takes up ¼ of the page, sometimes forcing the page text and graphics to be smaller (and unreadable). I suggest a new format.
- 9) Syllabus: ABET now requires that instructors list prerequisite knowledge for each course, not just classes. It would be helpful for other universities if you listed the types of topics students have had, i.e.
 - Fluids
 - Thermo
 - Failure Analysis
 - Basic Electronics
 - Basic Programming
- 10) ABET Linkages: The desired outcomes look like the ABET a-k. If so, you should probably list it as such. Pages 8-10 of the syllabus look like the ABET assessment metrics. If you want this to be adopted by other universities, you need to be more specific of the specific measures and what translate to expert
- 11) Most of the space policy section is not needed. The background is interesting, but how important is it for the course goals? You do not have an assessment metric for this material and knowledge.
- 12) Systems Engineering I: This section is so packed with stuff that I am not sure students would be able to get much out of it. I suggest keying on several concepts and developing a "toy problem" that you can show examples of how Systems Engineering is involved in each step of the process.
- 13) Systems Engineering II: I really liked this section. It had good tools for students to use, plus lots of good examples. Some of the text/graphics were too small to be useful as printed in the handbook.
- 14) Space: The Final Frontier: Interesting information, but again a lot of information with little there to be used in a design.
- 15) The "avionics" section does not really have much avionics in it. Avionics includes sensing, control, guidance, power, and communications. Nearly all the material in the two sets of slides is mechanically-based - it does not even look at circuitry, computers, etc. Spacecraft Avionics II: This section is very "mechanically-based transmission" and does not address anything beyond

- signaling. There is no info on CODECS, protocols, differences in radio frequency (why this frequency versus that one from a DATA standpoint).
- 16) The course modules have enormous information. I assume students are going to take other classes while doing these two senior design courses. Is the plan to expose this information to students in relevant courses so that the senior design course will recap and reinforce learning and practice?
 - 17) Is this a required senior design course pair in one engineering department or is it available to other interdisciplinary team members in the college of engineering?
 - 18) Guidance about adoption of this course or modules will be helpful.
 - 19) How will students choose their role in teams and co-ordinate work to make a complete verified tested prototype?
 - 20) Is there a plan for multi-university partnership/team?
 - 21) Exposure to traditional designs such as fasteners, gears, mechanisms, etc. and civilian/commercial (ASME, ASTM, commercial vendors) information and standards is minimal. Is it intentional to encourage lifelong learning and research?
 - 22) Curriculum is very focused on NASA mission and provides Department of Defense and government agency information. How might this curriculum be applied to well-grounded earthly civilian applications?
 - 23) Using examples is a very efficient way to teach students to learn knowledge and apply it. A good example will enable them to follow how to design and implement a project. Section 4, 5 are very wonderful chapters. They include many examples. I especially like the parts named "Friday Design". However, not all chapters include this part.
 - 24) There are some examples can add to Section 7, such as Voyager I and II. They are good examples. Voyager 1 is currently the farthest human-made object from Earth, traveling away from both the Earth and the Sun at a speed that corresponds to a greater specific energy than any other probe.
 - 25) A complete example from beginning to end will be better; also, some new NASA projects can be integrated into this senior design course, such as Opportunity, Spirit and Phoenix.
 - 26) In general, I found the course material has lot of information, but teaching in a senior design course all these information seems very hard, and students might lose interest time to time.
 - 27) It also seems to me, that the author has taken lot of material and has simply put together, rather than editing and putting only enough information for the students. For example. In section 1, is it needed to give all the detailed history about US space mission?
 - 28) The course has one chapter on systems engineering, which is good, but how these concepts are being implemented was not very clear.

- 29) If this course is intended to be a multidisciplinary course, then I find it is going to be quite tough for students other than Mechanical and Aerospace Engineering, as the prerequisites to understand the course contents are not known to other discipline students such as the concepts of gas dynamics in section 6.1 is normally taught to ME and Aerospace Engineering students.
- 30) One of the typical problems I find about the formatting, and type of files. Some of the power point slides were created using MS2003, some are MS 2007, and also some of the chapters do not have pdf documents where some does. Even though this is easily correctable and convertible, I think it is important to be consistent in fonts, styles and document types. For example chapter 8 and another chapter there is no pdf file and power points are created using 2007 version only. Some other chapters I saw that too.
- 31) Even though there are some examples given in the course, however, I wanted to see one Engineering design example that will demonstrate to the students how the basic science and Engineering concepts and mainly the system Engineering approach could be implemented. Many chapters are missing examples.
- 32) As this course is intended for senior undergraduates, I feel the course material is too much especially when in the senior years, students go through several courses where they have to be really busy with project work (research type), and also other career development activities such as interviews, internships etc.
- 33) The course must clearly state what knowledge units students must be very familiar with before taking this course, especially this is important for students other than ME and AE.
- 34) The course should be organized in a general way, so that students can take projects using this material in other area other than space explorations.
- 35) There are so many different topics, I wonder how the students will be evaluated, and if there has to be given a final examination; can students be able to remember that much material?

LESSONS LEARNED AND RECOMMENDATIONS

“Prognostics of complex systems” is a new challenging technical area. It requires significant training and development of highly skilled engineering faculty and students who can integrate the science of system degradation with engineering disciplines, statistics, management, and economics. Significant curriculum renewal and improvement are necessary to meet these challenges. Sponsored research, senior design projects, and curriculum development projects are necessary to reap the potential of this vitally important area to support global progress, security, and economic vibrancy. The effort must be continuous and unrelenting to achieve maximum potential success.

Attending meetings proved to be the best way to collect requirements. The time spent at the monthly report meetings was particularly useful to understand the overall mission assurance activities at JPL, how the mission assurance managers work, and what are the products they deliver to upper management on a monthly basis.

There is an important difference between academic research and engineering work at JPL. Academic research focuses heavily on doability while for JPL, even though the main issue that motivates mission assurance is risk-reduction /risk-avoidance, affordability seems to be the most important issue on the table that is, the price to be paid for reducing risks needs to be compatible with project budget.

General “administrative things” were a disappointment. Dr. Conrad never was issued an official badge and never had a NASA email address. This process should really be fixed in the future. These administrative problems were not experience last year when Dr. Conrad was a participant at JSC.

One of the problems faced is getting the computer account and computer access at Marshall. Even though my mentor, the branch head and others gave considerable support, still it took more than a month to get my computer account. The simulation for the propellant loading model involves rigorous computation and in a 2.6 GHZ multiprocessor, 8 GB memory machine a typical run takes more than 11 hours. In order to optimize various parameters, and with code modification several runs were required. In my personnel laptop, it takes 10 times as much time and also the code produces large size files, where memory is an issue and writing onto output file takes long time.

One possible problem that was envisioned involved the acquisition of sufficient quantities of minerals for these tests. Large amounts of the minerals in question are only available (in the United States) from the Stillwater mine in Montana. This issue was addressed. The US Geological Survey in Denver has several tons of ore which can be shipped to the South Dakota School of Mines and Technology when the senior design requirements are more fully fleshed out.

The participants from the 2008 ESMD Faculty Project made several recommendations for improving the program. Some of the recommendations were rendered moot due to changes in the program, but the following comments on the recommendations that were applied to this year's activities are:

- For successful implementation of Senior Design courses, there should be a financial incentive for faculty provided by the institutional Space Grant. Merely providing small amounts that cover the design costs may not play out favorably, since the faculty must invest a substantial amount of time in direction and oversight. With a full load of teaching, there may not be sufficient time for faculty to engage students at the level of direction needed. The equivalent of 4-5 weeks of summer support would at a minimum entice faculty toward engaging seriously in the design process and in achieving a positive outcome. *This recommendation was implemented, although not through the institutional space grant consortia. The 2009 program allowed faculty to delve into a NASA problem in great detail and will allow them to better address NASA's needs. The summer support included in the grants was increased over the previous year.*
- A five-week rotation barely allows one to touch the surface of the immense number of engineering and science projects at the NASA Centers. The fellowship time period needs to be extended to at least 6-8 weeks, if possible. This will enable more than one meeting with potential mentors and establish a level of trust and common understanding of the purpose and the mutual benefits of the program. *This recommendation was partially implemented, since the assignment was six weeks long. Some 2009 participants thought this amount of time spent at the center was still too short.*
- The role of faculty is to ensure that Senior Design projects comply with ABET requirements. In this context, uniform expectations should be developed for Senior Design Projects for the benefit of the NASA POC. This would result in projects being defined at the proper level of technical complexity and those that can be completed without requiring that the NASA POC's be continuously involved in the project as technical advisors. *This recommendation was implemented. Again, the 2009 program allowed faculty to delve into a NASA problem in great detail and will allow them to better address NASA's needs. However, it will still be up to the faculty members to ensure the project comply with ABET requirements.*
- The thrust of the ESMD Faculty Project should be maintained towards enhancing NASA's Strategic Educational Outcome 1. As the 2008 Faculty Project has demonstrated there is a need for faculty to closely interact with NASA Center personnel to identify relevant exploration topics and to develop senior design course materials. It is recommended that the 2009 Summer Faculty Fellowship be awarded to faculty fellows who can glean

ideas relating to exploration and bring back to their respective institutions information that could be used to improve their curricula. . *This recommendation was implemented. The 2009 Project allows faculty to become more involved with NASA personnel relating to exploration topics for the senior design projects. The 2009 Project was specifically directed towards NASA's Strategic Educational Outcome 1.*

- Faculty Fellows seeking Senior Design ideas should fruitfully collaborate with industry partners, so that the design effort is of mutual interest to both industry and NASA. This will help facilitate interaction between the industry technical expert and the university faculty teaching the senior design course, which will reduce the time required from the NASA POC. Future Faculty Fellows could spend a portion of their assigned time at an industry partner in the vicinity of a NASA Center. *This recommendation was not implemented. However, the 2009 faculty do not feel this was possible due to the way that the 2009 Project was set up.*

The participants in the 2009 ESMD Faculty Project involved five faculty from throughout the USA, which include two faculty that were involved in the 2008 ESMD Faculty Project. The 2009 participants have several observations/recommendations concerning the program:

- Weekly telecons were very helpful and useful for understanding the project.
- Some participants thought the number of this year's participants was good, some thought the number was too small.
- All faculty were happy with the level of detail they were able to achieve this year. The faculty who participated both years were not able to delve into problems with such detail last year. They think that it is a good model to have one year general and the next year detailed, with respect to identifying and solving NASA problem needs. Perhaps another model would be to spend ten weeks at a center, and spend four weeks identifying projects at a site, then spend six weeks concentrating on one problem. Another alternative would be to mix the faculty to have one as a generalist and another as a specialist.
- Better or more interactions with NASA Systems Engineers would have helped faculty to prepare for implementation of systems engineering skills into the fall senior design projects.
- More time is needed between final contracting and the beginning of the work assignment. This affected several aspects of the visits, including badging, computer access, travel plans, and housing.
- It may be useful to have one or two students who will be participating in the faculty's senior design project travel with the faculty to the participating NASA Center. This would allow this team to develop more detail concerning the project and to more readily "hit the ground running" when the design project starts.

CONCLUSIONS

The Constellation Program is the medium by which we will maintain a presence in low Earth orbit, return to the moon for further exploration and develop procedures for Mars exploration. The foundation for its presence and success is built by the many individuals that have given of their time, talent and even lives to help propel the mission and objectives of NASA. The Exploration Systems Mission Directorate (ESMD) Faculty Fellows Program is a direct contributor to the success of directorate and Constellation Program objectives. It is through programs such as the ESMD Space Grant program that students are inspired and challenged to achieve the technological heights that will propel us to meet the goals and objectives of ESMD and the Constellation Program. It is through ESMD Space Grant programs that future NASA scientists, engineers, and mathematicians begin to dream of taking America to newer heights of space exploration. The ESMD Space Grant program is to be commended for taking the initiative to develop and implement programs that help solidify the mission of NASA.

With the concerted efforts of the Kennedy Space Center educational staff, the 2009 ESMD Space Grant Summer Faculty Fellows Program allowed faculty to become more involved with NASA personnel relating to exploration topics for the senior design projects. The 2009 Project was specifically directed towards NASA's Strategic Educational Outcome 1. In-situ placement of Faculty Fellows at the NASA field Centers was essential; this allowed personal interactions with NASA scientists and engineers. In particular, this was critical to better understanding the NASA problems and begin developing a senior design effort to solve the problems.

The Faculty Fellows are pleased that the ESMD Space Grant program is taking interest in developing the Senior Design courses at the university level. These courses are needed to help develop the NASA engineers and scientists of the very near future. It has been a pleasure to be part of the evaluation process to help ensure that these courses are developed in such a way that the students' educational objectives are maximized. Ultimately, with NASA-related content used as projects in the course, students will be exposed to space exploration concepts and issues while still in college. This will help to produce NASA engineers and scientists that are knowledgeable of space exploration.

By the concerted efforts of these five senior design projects, NASA's ESMD Space Grant Project is making great strides at helping to develop talented engineers and scientists that will continue our exploration into space.

FACULTY BIOGRAPHIES

Ghanashyam Joshi



Dr. Ghanashyam Joshi is a professor of Mechanical Engineering at Southern University and A & M College, Baton Rouge, Louisiana. He received his bachelor's degree in mechanical engineering from the Indian Institute of Technology, Mumbai, master's degree from North Dakota State University, Fargo, and doctorate degree from Michigan Technological University, Houghton. He has served on fellowships at the National Institute of Standards and Technology (NIST), Oak Ridge National Laboratory (ORNL), Air Force Research Laboratory (AFRL), The Boeing Company, Hewlett-Packard Company, and the Ford Motor Company. Dr. Joshi is a registered Professional Engineer (PE) in the state of Louisiana. He has published numerous research papers in journals and conferences.

Jiang Guo



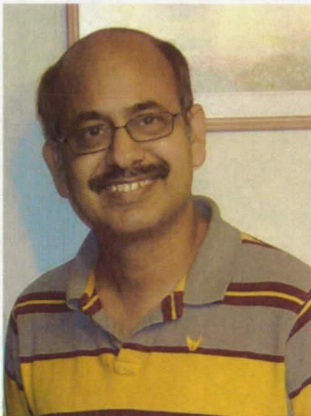
Dr. Jiang Guo is an Associate Professor of Computer Science at California State University Los Angeles. Before he joined California State University Los Angeles in 2002, Dr. Guo had been an Assistant Professor of Computer Science of California State University Bakersfield for two years. Before that, he had been a Research Associate of US National Research Council for three years from 1998 to 2000. Dr. Guo received his B.S., M.S., and Ph.D. degrees of Computer Science respectively in 1989, 1992, and 1996. Then, Dr. Guo spent a year and a half as a post-doctor with the Institute of Software at Chinese Academy of Sciences. Dr. Guo's research areas include software engineering, software reengineering, web-based systems and software system interoperability. Dr. Guo is the author of over 60 papers on computer science and software engineering deriving from his research. He got the best paper award of SEKE1999. He has served as the program committee member for more than 50 conferences. Dr. Guo was awarded outstanding professor commendations two years in a row in 2005 and 2006 in the College of Engineering, Computer Science and Technology of California State University Los Angeles.

James Conrad



Dr. James Conrad is an associate professor of Electrical and Computer Engineering at the University of North Carolina at Charlotte. He received his bachelor's degree in computer science from the University of Illinois, Urbana, and his master's and doctorate degrees in computer engineering from North Carolina State University. He has served as an assistant professor at the University of Arkansas and as an instructor at North Carolina State University. He has also worked at IBM in Research Triangle Park, North Carolina, and Houston, Texas; at Ericsson/Sony Ericsson in Research Triangle Park, North Carolina; and at BPM Technology in Greenville, South Carolina. Dr. Conrad is a Senior Member of the IEEE and a Certified Project Management Professional (PMP). He is also a member of Sigma Xi, Eta Kappa Nu, the Project Management Institute, the American Society of Engineering Education and the IEEE Computer Society. He is the author of numerous books, book chapters, journal articles, and conference papers in the areas of robotics, parallel processing, artificial intelligence, and engineering education.

Alak Bandyopadhyay



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Dr. William M. Cross is an associate professor of Materials and Metallurgical Engineering at the South Dakota School of Mines and Technology. He received his bachelor's and master's degree in Metallurgical Engineering from the South Dakota School of Mines and Technology, and his doctorate degrees in metallurgical engineering from the University of Utah. Prior to his faculty appointment, Dr. Cross was a research professor in the Materials Engineering and Science graduate program at the South Dakota School of Mines and Technology. In addition to a large variety of research funding (primarily in polymer matrix composite materials), he has consulted for a number of national and international companies and worked with the South Dakota State Crime Laboratory. Dr. Cross is a member of the Materials Research Society, the Society for Advancement of Material and Process Engineering and the Society for Mining, Metallurgy and Exploration. He is the author of numerous journal articles, and conference papers in the areas of hydrometallurgy, mineral flotation, polymer matrix composite interphase formation and properties.

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