

AC 2010-1901: NASA SENIOR DESIGN: SYSTEMS ENGINEERING AND REUSABLE AVIONICS

James Conrad, University of North Carolina, Charlotte

James M. Conrad 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 is currently an associate professor at the University of North Carolina at Charlotte. 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 ASEE, Eta Kappa Nu, the Project Management Institute, 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.

NASA Senior Design: Systems Engineering and Reusable Avionics

Abstract

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 a Environmental Control Unit for a Lunar Habitat.

This senior design project included 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 senior design project included a large project team made up of Systems, Electrical, Computer, and Mechanical Engineers/Technologists. The efforts were made up of several sub-groups that each worked on a part of the entire project. The large size and complexity made this project one of the more difficult to manage and advise. Typical projects only have 3-4 students, but this project had 10 students from five different disciplines.

This paper describes the difference of this large project compared to typical projects, and the challenges encountered. It also describes how the systems engineering approach was successfully implemented so that the students were able to meet nearly all of the project requirements.

NASA Faculty Fellow Program

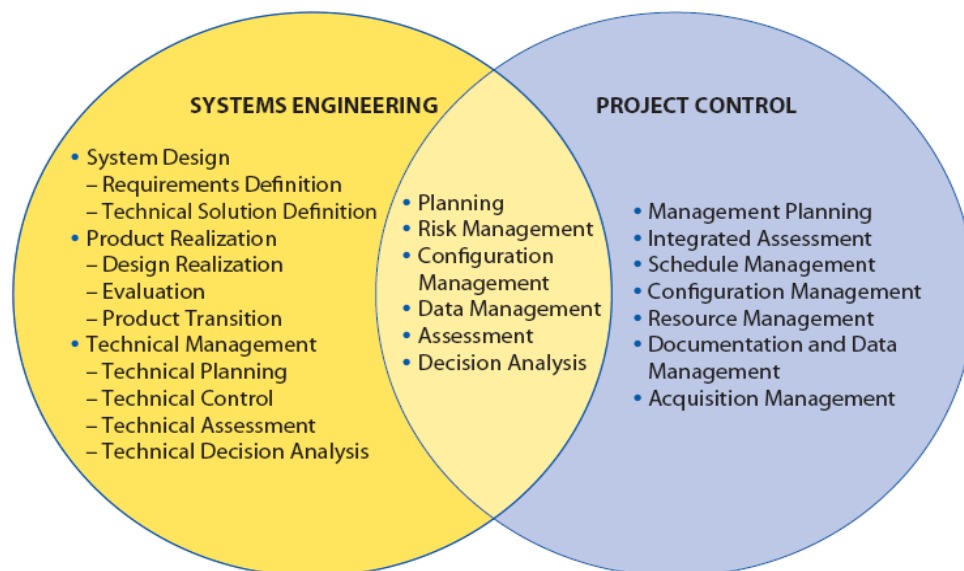
In early 2009, NASA's Exploration Systems Mission Directorate (ESMD) solicited involvement for a summer 2009 higher education opportunity for faculty. The purpose of their program was to prepare faculty to enable their students to complete senior design projects with the potential for contribution to NASA ESMD objectives. The goal of this program was to select five faculty who would work for several weeks at a NASA field center on a specific ESMD project and incorporate the ESMD project into an existing senior design course or capstone course at their university in the 2009/2010 academic year. The course could have all students involved in a single project, or allow a subset of the enrolled students to work on a project.

During the six weeks at the NASA center, faculty fellows worked closely with NASA engineers. The objective of this NASA site assignment was so the faculty could gain extensive knowledge on the specific selected NASA project, including the requirements, interfaces and issues

affecting the design and potential solutions. During the summer the faculty also developed materials for use at their university during the academic year in support of the completion of the senior design project using a systems engineering approach.

Systems Engineering¹

Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. The senior design project teams were encouraged to review the NASA systems engineering handbook² in the early stages of their projects. They were provided with supplemental systems engineering educational materials. The senior design teams were required to focus on the following systems engineering facets and to control their projects:



The system engineering design concepts crucial for 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 should be monitored and assessed during the design project implementation. It should be noted that the UNC Charlotte Senior Design Program included many of these concepts in their existing program^{3,4,5,6}.

NASA Reusable Avionics Project

The initial proposal for this activity was to develop a General Purpose Measurement Tool for use on the lunar surface. However, the need for hardware/software for the Johnson Space Center Electronics (JSC-EV) branch had changed quite a bit since the original proposal was written in January 2009. There were more immediate needs than the measurement tool (specific) that can help NASA, specifically proof-of-concept technologies (general). The general technology activities could help guide the development of specific devices. Therefore, this original proposal was changed.

With his technical manager (Greg Hall), Dr. Conrad discussed the technical areas of interest to JSC-EV, including 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 investigated the feasibility of this concept.

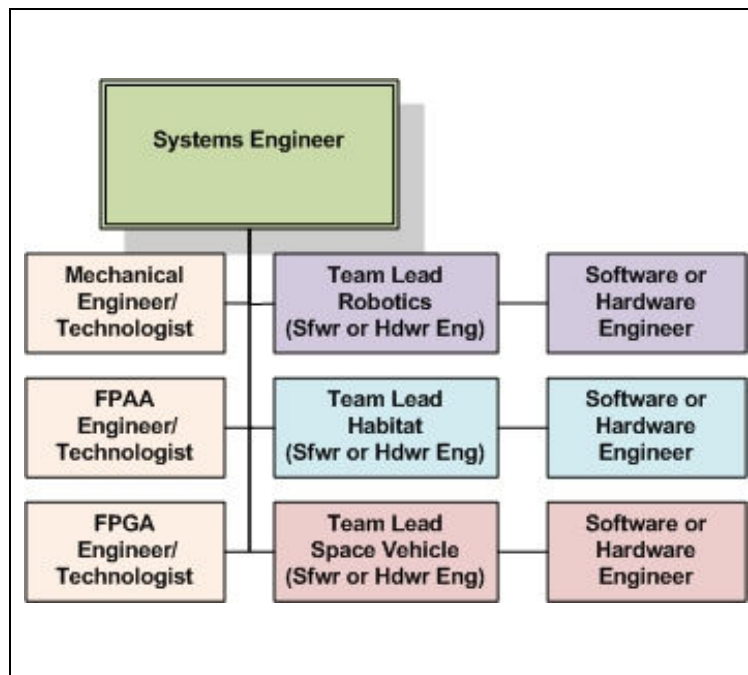
Dr. Conrad investigated in more detail the avionics planned and already in the Constellation vehicles (Orion, Altair, habitat, Lunar Electric Rover). Many documents are in the public domain, but many are also contractor designs and are thus not accessible. Dr. Conrad is continued with a "generic" design of the different avionics vehicles and approximated, as best possible, the hardware and software design. An additional area of investigation was Real-time Ethernet, or Time-triggered Ethernet.

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 a Environmental Control Unit for a Lunar Hab.

This final identified project was to include the investigation of a wide range of functions of space vehicles and possible uses. Specifically, this included:

- 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 required a large project team made up of Systems, Electrical, Computer, and Mechanical Engineers/Technologists. The efforts were to be made up of several sub-groups that each worked 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 was one of the most complex projects offered by the University of North Carolina at Charlotte for the senior design program. Students working on this project were be given the experience of working on a typical industry effort, with respect to size and scope.

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

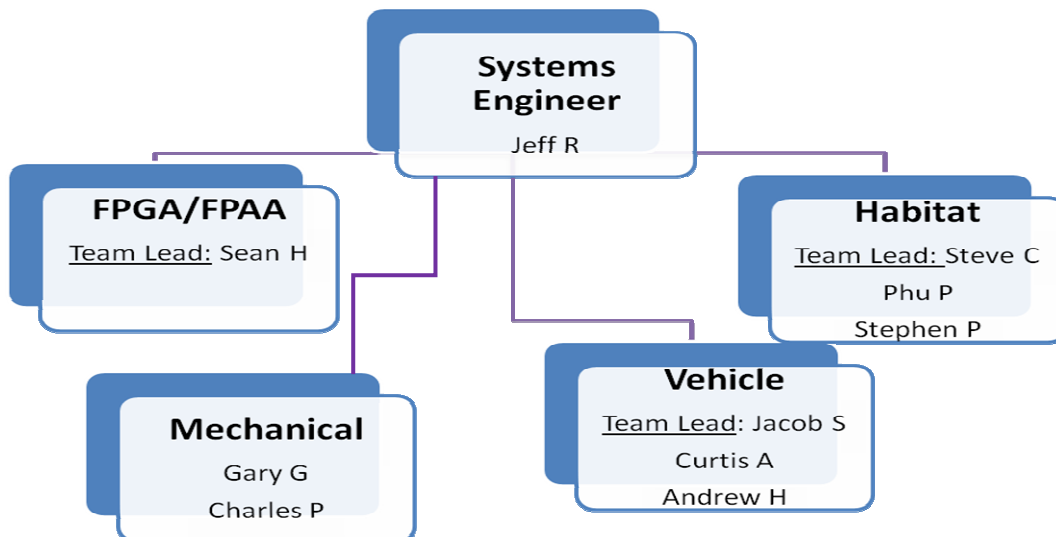
1. A robotic vehicle that uses the common FPGA and FPAA boards
2. A simulated lunar habitat that uses the common FPGA and FPAA boards
3. A simulated space vehicle that uses the common FPGA and FPAA boards
4. A programming and test fixture for the FPGA and FPAA boards

Results - Student Involvement

This project was implemented in the UNC Charlotte College of Engineering Industrial Senior Design Course. It was offered as one of several projects that students could choose to work on over the course of the fall 2009 and spring 2010 semesters.

Students were invited to apply to participate in this project before fall courses even started. The objective of this early advertising was to ensure enough students would select this project as their first choice. Apparently our advertising approach and the allure of working on a NASA project was VERY successful. Twenty-five students applied early for the ten project positions, including four for the coveted Systems Engineer position. One half of the students were encouraged to apply for the project on selection day (two weeks into the course). Sixteen applications were submitted on selection day, and ten were assigned to the project. Several students were turned away so that they could work on other industry projects.

One of the first things that the team did was to organize themselves into different teams than had been initially formulated by the faculty advisor. This was necessary since three fewer electrical and computer engineering students were allocated to the project as first proposed. The final assigned number of students also necessitated that the "deliverables" be reduced to three - the simulated space vehicle was removed from the requirements.



The student selected as the Systems Engineer has an extensive background in industry and had a strong interest in project management.

Results - Project Implementation

Students who were selected for this project completed the requirements document, built a work breakdown structure of the effort, planned the project activities and designed the devices and vehicles in the fall, as described in the UNC Charlotte Senior Design publications^{3,4,5,6}. Students implemented the designs in the spring semester (which was not complete at the time of publication of this paper). The Faculty Advisor, Dr. Conrad, worked closely with all team members to ensure success.

Due to the size of team, it was necessary for the sub-teams to have separate meetings, with an occasional "all-hands meeting" of the entire team when needed. The Systems Engineer and Team Leads also meet with the faculty advisor on a regular basis. The team leads were responsible for gathering all requirements and designs for their sub-project, then forwarding these requirements and designs to the Systems Engineer. Any technology interfaces between teams were directly handles by team members - they did not go through the team leads for such detailed efforts.

The team had the same problems and successes that typical large industry teams encounter, including the well know forming-storming-norming-performing team behavior. All storming behavior was resolved by the end of the first semester.

This team, using Systems Engineering approaches at a more pronounced level than other senior design teams, was able to outperform nearly all other teams in first semester performance.

References

1. Ghanashyam Joshi, Jiang Guo, James Conrad, Alak Bandyopadhyay, William M. Cross, and Gloria Murphy, 2009 ESMD Space Grant Faculty Project Final Report, October 2009.
2. NASA System Engineering Handbook,
<http://education.ksc.nasa.gov/esmdspacegrant/Documents/NASA%20SP-2007-6105%20Rev%201%20Final%2031Dec2007.pdf>
3. James M. Conrad, "Determining How to Teach Project Management Concepts to Engineers," Proceedings of the 2006 ASEE Conference, Chicago, IL, June 2006.
4. James M. Conrad, Daniel Hoch, and Frank Skinner, "Student Deliverables and Instruction for a Senior Design Program Course," Proceedings of the 2007 ASEE Conference, Honolulu, HI, June 2007.
5. James M. Conrad, Daniel Hoch, William Heybruck, Peter Schmidt, Martin Kane, Linda Thurman, and Frank Skinner, "Working with Industry Sponsors in a Multidisciplinary Senior Design Program," Proceedings of the 2008 ASEE Conference, Pittsburgh, PA, June 2008.
6. James M. Conrad, Nabila Bousaba, Daniel Hoch, William Heybruck, Peter Schmidt, Martin Kane, Linda Thurman, and Deborah Sharer, "Assessing Senior Design Project Deliverables" Proceedings of the 2009 ASEE Conference, Austin, Texas, June 2009.

Appendix - Initial Project Statement of Work (starting on next page)

Title: Field Reprogrammable and Reusable Avionics Unit

Sponsor: NASA Johnson Space Center, Engineering Directorate, Avionics Systems Division

Personnel: 10-12 Comp/Electrical/Mechanical Engineers/Technology

Expected person-hours: 2500-3000

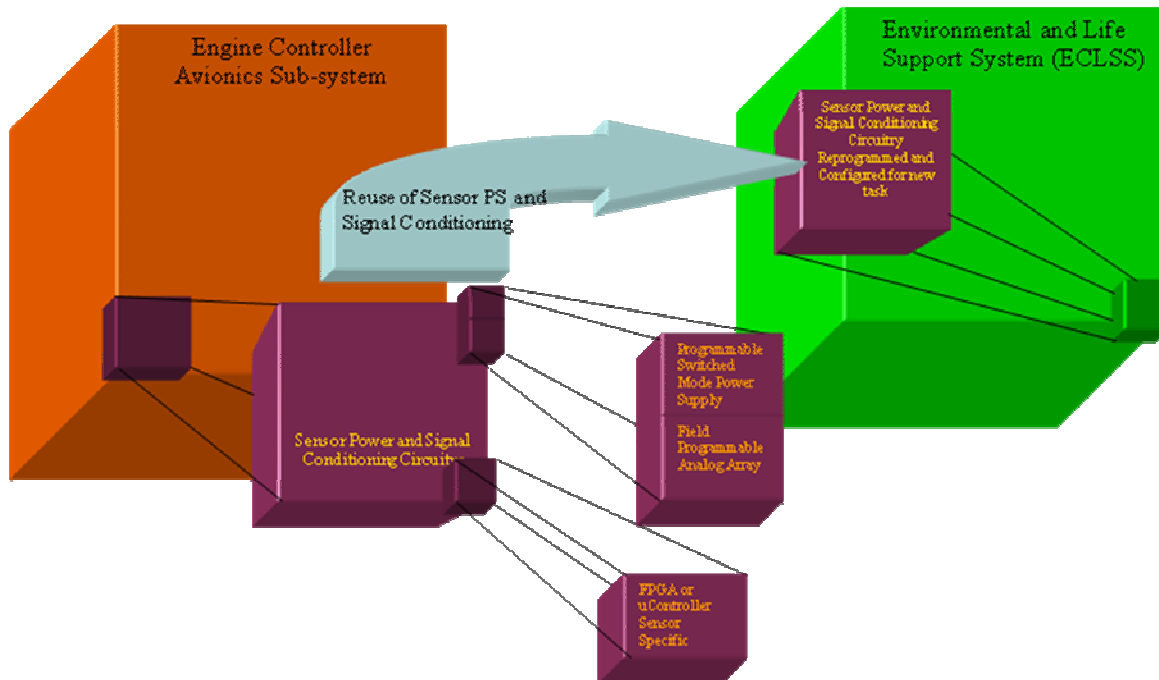
Deadline: Spring 2010

Project Overview and Motivation

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 a 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:

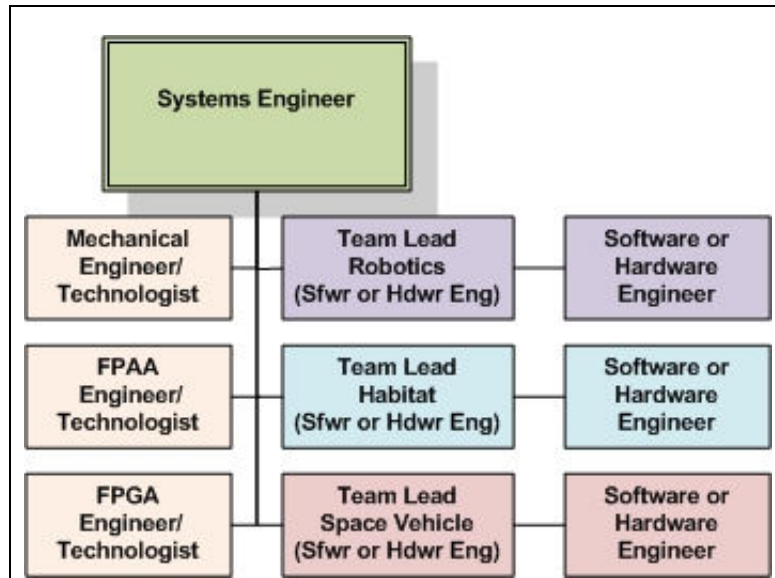
- Determining and specifying the basic functioning blocks of space vehicles.
- Building and demonstrating a concept model.
- Showing high reliability is maintained.



Example of Sensor Sub-element of Engine Controller Avionics package, note the sensor sub-element may be further divided into fundamental functioning blocks.

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.

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



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

Project Benefits

This is one of the most complex projects offered by the 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.

Expectations of Students

It is expected that any skills not yet learned but required for the job will be either taken as a course during the first semester of this project, or will be learned on the students own time. In any case, the student must have a "Practitioner" level of knowledge by December.

The entire project team will meet once a week to report progress. Other one-on-one meetings will be needed to discuss and work on technical matters. Students are encouraged to seek

assistance if technology poses a specific problem. Nonetheless, this is NOT a project for students who expect to coast during their project. You will work, but not for excessive amounts of time. It is expected that student effort will be consistent during the semesters and not with a large peak at the end of the semesters.

Job Descriptions

Each position below lists certain skills needed for the project. Please indicate which position interests you in your cover letter. Make sure you address your skills and how they map to the requirements below.

Systems Engineer (1): This position requires a solid background in multiple disciplines, i.e. computer, software, electrical, and mechanical engineering or technology. This person will be responsible for ensuring that the project not only stays on track but also remains technically sound. As a result, this person will need to have a working understanding of all of the technologies in the project (of at least an "apprentice" rating). While this person will not necessarily be writing code, designing circuits, or drawing mechanical parts, they should understand the underlying technologies. This person will also have excellent leadership and organizational skills. This is especially suited for a mature student with previous work experience.

FPGA Engineer/Technologist (1): This position requires a solid background in developing electronic systems using skills learned as a junior, including analog and digital circuits. This person must also have additional knowledge of computer architecture and hardware. Knowledge of VHDL/Verilog and the Xilinx tool set is required. This person will help in the selection of an off-the-shelf FPGA development board and will be responsible for creating the programming and test fixture interfaces. This person will also assist the hardware engineers in the project sub-teams.

FPAA/Analog Processor Engineer/Technologist (1): This position requires a solid background in developing electronic systems using skills learned as a junior, including analog and digital circuits. This person must also have additional knowledge of analog-to-digital and digital-to-analog conversion hardware. Knowledge of VHDL/Verilog and the Xilinx tool set is required. This person will help in the selection of an off-the-shelf FPAA development board and will be responsible for creating the programming and test fixture interfaces. This person will also assist the hardware engineers in the project sub-teams.

Mechanical Engineer/Technologist (1): This position requires a solid background of the design of mechanical enclosures, cabling, and air-handling equipment for the electronics industry. This person will create the enclosures for all three of the subprojects and will ensure that, mechanically, the main processor boards can be easily removed and inserted into each of

the projects. This person will also work with the FPGA and FPAA positions to build the test fixture and cabling needed for the sub-projects. They will also help with the robotic vehicle and other sub-projects that need mechanical assistance.

Software Engineer (3): This position requires a solid background in embedded systems and software development. The person in this position is expected to know the C programming language and basic computer architecture. Knowledge of Linux and VHDL is helpful but not necessary. This person will program the microprocessors to use the hardware developed by team members.

Hardware Engineer (3): This position requires a solid background in developing electronic systems using skills learned as a junior, including analog and digital circuits. This person must also have additional novice knowledge of analog-to-digital and digital-to-analog conversion and computer hardware. Knowledge of VHDL/Verilog and the Xilinx tool set is required. This person will program the FPGA and FPAA boards, with the help of the FPGA/FPAA support Engineer/Technologist. They will also build any other hardware needed

Other skills, helpful but not required, are:

- Linux and Linux tools
- Communications hardware/software like RS-232, USB, CAN, Wi-Fi, ZigBee/802.15.4, Bluetooth
- Robotics and motor control (or plan to enroll in the Introduction to Robotics course in the spring of 2010).

Project Requirements

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:

5. A robotic vehicle that uses the common FPGA and FPAA boards
6. A simulated lunar habitat that uses the common FPGA and FPAA boards
7. A simulated space vehicle that uses the common FPGA and FPAA boards
8. A programming and test fixture for the FPGA and FPAA boards

General Requirements

All projects will use the same FPGA and FPAA board. All systems will be based on the Linux Operating System.

Robotic Vehicle Requirements

This vehicle can be either a small electric (0.75 by 0.60 meters) vehicle or an All Terrain Vehicle, both of which are available from Dr. Conrad's lab for use by the team. This vehicle will need to be controlled by the avionics (FPGA, FPAA, and other added electronics and cabling).

This device should also demonstrate the ability to:

- Communicate via 802.15.4 or 802.15.4/ZigBee
- Communicate via Ethernet (on the bench)
- Communicate via USB (on the bench)
- Communicate via CAN bus
- Sense its environment with Ultrasound, compass, accelerometer, and gyroscope (Inertial Measurement Unit)
- Sense its environment (temperature, humidity, light).
- Sense the battery temperature and voltage during charging and operation.
- Report on the vehicle's status via wireless messages every 10 seconds.
- Perform a movement and sensing mission (i.e. move in a 100 meter by 100 meter square).

Lunar Habitat Requirements

This "habitat" will need to be controlled by the avionics (FPGA, FPAA, and other added electronics and cabling). This device should also demonstrate the ability to:

- Communicate via 802.15.4 or 802.15.4/ZigBee
- Communicate via Ethernet (on the bench)
- Communicate via USB (on the bench)
- Communicate via CAN bus
- Sense its environment (temperature, humidity, light).
- Sense the battery temperature and voltage during charging and operation.
- Report on the habitat's status via wireless messages every 10 seconds.
- Maintain a constant temperature in the "habitat" by controlling air flow (fan) and a heater.
- Control LED-based lighting in the "habitat" based on times programmed by the user and motion.
- Charge batteries using a solar collector.
- Provide a touch screen-based display to show this same status and allow the user to change the temperature via the touch screen

Space Vehicle Requirements

This "vehicle" will need to be controlled by the avionics (FPGA, FPAA, and other added electronics and cabling). This device should also demonstrate the ability to:

- Communicate via 802.15.4 or 802.15.4/ZigBee
- Communicate via Ethernet (on the bench)

- Communicate via USB (on the bench)
- Communicate via CAN bus
- Sense its environment with Ultrasound, compass, accelerometer, and gyroscope (Inertial Measurement Unit)
- Sense its environment (temperature, humidity, light).
- Sense the battery temperature and voltage during charging and operation.
- Report on the vehicle's status via wireless messages every 10 seconds.
- Perform a movement and sensing mission (i.e. open a valve to maintain its position above the moon's surface).

Programmer/Test Fixture Requirements

This fixture will need to program and test the avionics (FPGA, FPAA). This device should also demonstrate the ability to:

- Communicate via Ethernet
- Communicate via USB
- Communicate via CAN bus

Appendix B: Designs Published for the December Poster Session (Two Posters)



Avionics

Jeff Rotberg
Andrew Hamilton
Jacob Spahr
Curtis Austin
Charles Pritchard

Stephen Chapman
Stephen Pocher
Phu Phong
Gary Gregory
Sean Hicks

Programmable System on a Chip



Purpose

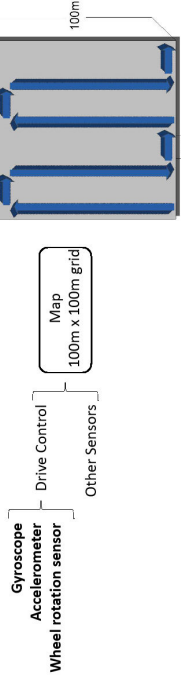
Create a reconfigurable solution capable of controlling both a lunar habitat and an autonomous vehicle (subordinate device)

Requirements

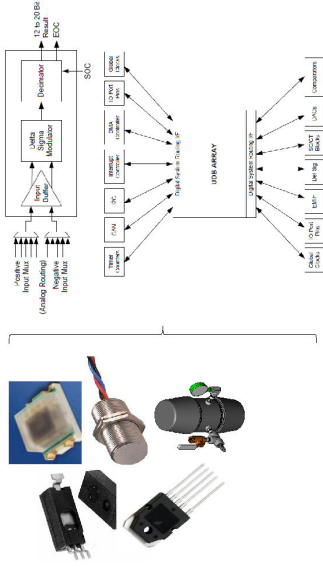
- Provide control signals to the subordinate device
- Connect to and draw power from the subordinate device
- Periodically poll the subordinate device's sensors and store the data

Developer Board Provided Courtesy of:
Cypress Semiconductor

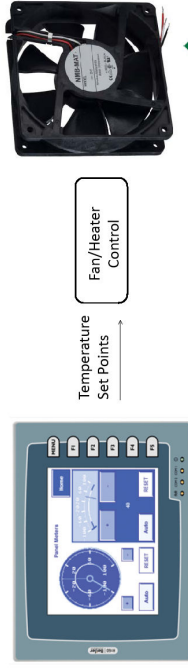
Autonomous Vehicle Functionality



Sensor Functionality (Common)



Lunar Habitat Functionality



PSoC Capabilities and Specifications

Digital System

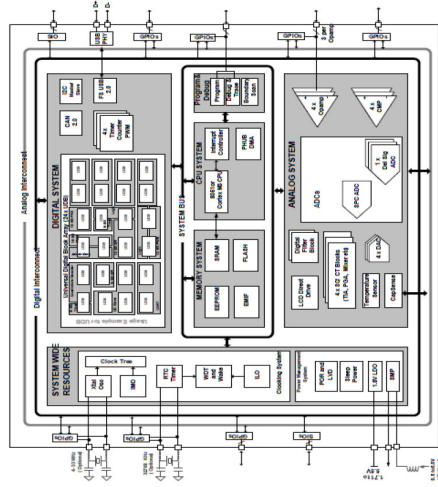
- 24 UDBs to instantiate any digital peripheral
- CAN support; 16 receive and 8 transmit buffers
- Support for 12 Mbps USB 2.0
- Four hardware timers

System Bus

- 8051 CPU capable of clock rates up to 67 MHz
- 64 KB available program flash memory
- 8 KB available temporary user SRAM
- External Memory Interface

Analog System

- Four op-amps for analog signal amplification
- Four switched cap/continuous time blocks
- High-definition delta-sigma ADC unit
- Four analog comparators





Avionics

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Curtis Austin
Charles Pritchard

Stephen Chapman
Stephen Pocher
Phu Phong
Gary Gregory
Sean Hicks

Lunar Habitat

Introduction:

The lunar habitat is designed to test the sensing and control functionality of the PSoC board. Variables inside the habitat are logged and controlled, allowing the user to monitor and adjust conditions via the touch screen.

Touch Panel Display

Displays habitat environmental data, temperature control, and internal lighting control



Arduino Mega

Serves as communications hub for all habitat functions
Utilizes XBee for wireless communication with PSoC



Solar Panel Charging

Demonstrates the ability to recharge the FPGA unit's battery from solar power



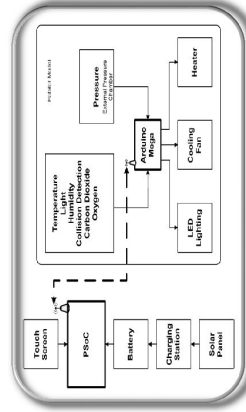
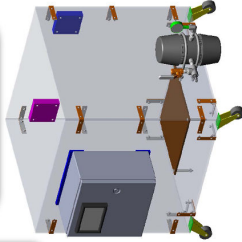
Temperature Control

In response to sensor data and user control, the temperature is maintained by a heater and fan



Pressure Chamber

Used to test and measure pressure inside the habitat



Autonomous Lunar Vehicle

Introduction:

The purpose of the lunar vehicle is to fully test the functionality of the PSoC board. To accomplish this, the robot will maneuver a 100m x 100m area while creating an environmental map and logging all sensor data.

Humidity Sensor

Detects the humidity of the atmosphere surrounding the vehicle



Accelerometer/ Gyroscope

Detects the terrain incline and angle displacement of vehicle



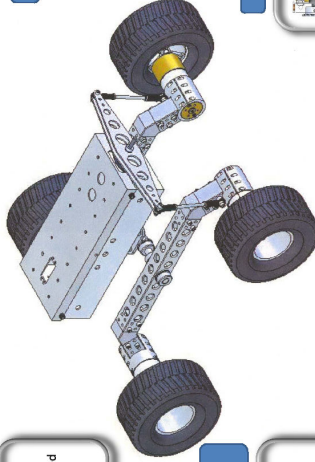
Light Sensor

Detects the amount of light emitted across the terrain



Ultra Sound Sensor

Detects objects that obstructs the path of the vehicle



Temperature Sensor

Detects the atmospheric temperature of the terrain



Wheel Motor

Controls direction of each wheel, moves either forward or reverse



Control Box

Contains PSoC and wiring interface



Hall Effect sensor

Counts the amount of tire rotations

