Human-Robotic Hybrids for Deep-Space EVA: the Space Construction and Orbital Utility Transport Concept

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Abstract

Recent National Aeronautics and Space Administration (NASA) studies have identified the utility of the Earth-Moon L1 libration point for the assembly and maintenance of future space systems including large science platforms such as optical telescopes. This work has culminated in the conceptual design of an L1 Gateway station, which could be used to support human operations on an as-needed basis.

While human presence will provide highly skilled and flexible capabilities for space operations, most of these need to be applied in Extravehicular Activities (EVA) associated with the large space structures construction and maintenance. The effort required to support humans at L1 will argue for much higher EVA rates than those supported on International Space Station (ISS); combined with the environmental effects of deep space, conventional pressure suit technologies may be inadequate for safe routine EVA at Gateway Station.

To address this issue, the University of Maryland has begun the development of SCOUT system. Drawing on concepts of "man-in-a-can" systems from past decades, SCOUT represents a hybrid between pressure suit design and dexterous robotic servicing systems. SCOUT is a self-contained spacecraft providing a shirt-sleeve environment for the operator and allowing zero-delay initiation of operations without need for denitrogenation. A conformal section of the vehicle, incorporating advanced pressure-suit arms, provides actual hands-on human operations analogous to traditional EVA for tasks demanding high levels of dexterity and tactility. Externally-mounted dexterous robotic manipulators provide physical restraint to the local work site, transport and handling of mission-related hardware, and performance of routine EVA operations not requiring high dexterity.

This paper presents an overview of the design of the SCOUT vehicle, including the station-mounted berthing and refurbishment module which supports the vehicle and recharges consumables between sorties. A nominal scenario is presented for the baseline design reference mission, which is a repetitive daily operation incorporating 1000m translation to the construction site, eight hours of actual operations, operator breaks for rest and meal, and return. Augmented operational scenarios are presented including extended distance and duration missions taking advantage of the ability of SCOUT to support multi-day operations. This paper also addresses the life support systems, the avionics of SCOUT, and the structural analysis that was done on the system. An overall view of SCOUT is shown in Figure 1.

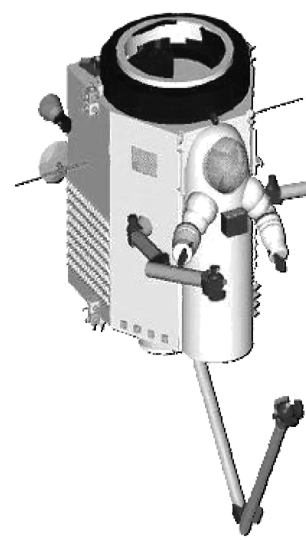

Figure 1 Overall View of SCOUT

Introduction to the Study

As future manned space exploration moves further from the cradle of Low Earth Orbit (LEO), the dangers of deep space present new challenges for space systems design. Our spacecraft design presents a more robust solution to extravehicular operations than current systems like the Extravehicular Mobility Unit (EMU). Present systems offer very little protection from radiation, both galactic background radiation or solar radiation. These systems also require time consuming prebreathing prior to an EVA. For human space exploration to move forward, many hours of extravehicular work will need to be completed, and progress will be slow if these problems are not addressed. The SCOUT system presents a potential solution to these issues, allowing space construction to be completed at an accelerated rate.

Inspiration for SCOUT comes from the concepts of Wernher von Braun and Arthur C. Clarke, who envisioned small pod-like vehicles being used to complete tasks in space. Our design is intended to be used at the proposed NASA Gateway space station, located at the Earth-Moon L1 Lagrange point. Specifically, a team of two SCOUT vehicles would be used during the construction of a next-generation space telescope near the Gateway station. Gateway is only one element of the NASA Orbital Aggregation and Space Infrastructure System (OASIS) program. OASIS includes other vehicles, such as Solar Electric Propulsion vehicles and Crew Transport Vehicle. SCOUT builds on this program, and provides a more flexible solution for required EVA work. SCOUT is also designed to meet requirements for operation at ISS, for test missions, or long-term operations.

The comparisons between SCOUT and existing EVA systems will be discussed further in later sections, as well as a description of systems included in the SCOUT design.

Systems Integration

SCOUT is a closed-cabin atmospheric system used for human EVA. SCOUT is a proposed element of the NASA OASIS program. OASIS will be the basis for future space commercialization and exploration. SCOUT will operate at the Gateway Station at the Earth/Moon L1 point. The SCOUT system includes two SCOUT pods, a docking module (DM), and an extended mission pallet (XMP).

General Design Requirements

The SCOUT system will operate from the L1 Gateway Station. SCOUT will interact with the work site using suit gloves and dexterous manipulators. SCOUT will attach to and control the work site using a cold gas propulsion system when in contamination-critical regions. SCOUT will provide for on-board human control, on-board autonomous control, supervisory control, and teleoperation. Between each use, there will be single-interface replenishment at the docking port capable of a single-person checkout and refurbishment of less than one hour. All safety-critical systems are two-fault tolerant and the SCOUT system supports extended missions. Along with functioning at the Gateway Station, SCOUT must be able to operate at the ISS with minimal modifications. The SCOUT system must at least meet the EVA capabilities demonstrated on Hubble Space Telescope (HST) and ISS. The entire SCOUT system must be designed in accordance with NASA Human-Rating Requirements. The system must have a technology readiness level (TRL) of three by the beginning of 2005 and a TRL of six by the beginning of 2008. The SCOUT pods, the DM, and the XMP must all launch on US launch vehicles that will be operational in 2005.

Design Constraints

Along with the general requirements, the class imposed design constraints upon itself through different design choices. These constraints include operation at 8.3psi and an internally opening docking mechanism.

Vehicle Mass and Power Breakdown

At the beginning of the semester, 2000kg was allotted to the SCOUT pod. The masses of different systems changed and currently, as shown in Table 1, the mass of SCOUT is less than the allotted mass, at 1850kg. The current nominal power requirement for SCOUT is 915W.

Table 1 Mass and Power Breakdown

System	Allotted Mass	Actual Mass	Power
Loads, Structures, and Mechanisms	850kg	796kg	240kg
Life Support and Human Factors	275kg	235kg	295kg
Avionics	200kg	190kg	295kg
Power, Propulsion, and Thermal	675kg	633kg	85kg
Total	2000kg	1850kg	915kg

Each SCOUT pod is approximately two meters tall, one and a half meters wide, and a little less than two meters deep.

Cost Analysis

The cost was determined from mass-based heuristic formulas at the vehicle level for each component of the SCOUT system. The nonrecurring cost of SCOUT is $1180 million. The first unit production is $87 million. The second unit production is $70 million. The nonrecurring cost of the docking module is $260 million. The first unit production cost of the docking module is $71 million. The nonrecurring cost of the extended mission pallet is $142 million and the first unit production cost is $35 million. These costs come to a total cost for the SCOUT system, not including launch on the shuttle, of $1.85 billion.

EVA System Comparison

The current plan for the Gateway Station is for an astronaut to do EVA with Robonaut, a robot currently under development at NASA Johnson Spa ce Center. These three systems were compared in order to show that SCOUT meets and exceeds the capabilities of the other two systems. Table 2 shows the areas in which the systems were evaluated.

Table 2 EVA System Comparison[1]

	EMU w/ MMU	Robonaut	SCOUT
Max Sortie Duration	7hr	8hr	11hr
Max Sortie Distance	120m	25m	1000m
On Site Human Intel	Yes	No	Yes
Teleoperation Control	No	Yes	Yes
Human/Robotics Interaction	No	Yes	Yes
Autonomous Control	No	Yes	Yes
Single Person Op Capabilities	No	Yes	Yes
2-Hand Operation	No	Yes	Yes
Radiation Protection	3g/cm^2	N/A	4g/cm^2
Life Support	7hr + 0.5hr reserve	N/A	11hr + 2r reserve
Bailout Systems	No	N/A	SHEEP/ SAFER

Mission Planning and Analysis

Testing Facilities

SCOUT will be tested in four different types of facilities prior to permanent installation at the Gateway station. A neutral buoyancy facility will provide the ability to test the robotic manipulators and the human arms, provide astronaut training, and test the self-maintenance and refueling capabilities of SCOUT. The simulation of a microgravity environment will offer some information about problems that may arise while in the space environment. A docking simulator will give astronaut training in the form of docking and rendezvous procedures. A computer simulator will cover the areas tested in the neutral buoyancy facility and the docking simulator, along with arm change out procedures. The final check-out will occur at ISS at which point all systems will either be cleared for installation at Gateway or SCOUT will be sent back to the ground for more testing and redesign as needed.

Launch Overview and Resupply

The SCOUT system, which consists of two pods and a docking module, will be launched in the space shuttle payload bay up to Low Earth Orbit (LEO). The cost of launching the space shuttle will be approximately $500 million. Once in LEO and after a successful six month test mission checkout, the entire system will be attached to a Solar Electric Propulsion (SEP) stage for travel from LEO to the Earth-Moon L1 point. The benefit of launching the SCOUT system on a shuttle and then using the SEP to transfer the system out to Gateway is that it allows the system to be fully fueled and stocked with replacement parts for the first six month nominal mission.

When the system has reached the Gateway station located at the L1 point, the 25m remote manipulator system found on the station will be used to attach the Docking Module (DM) to Gateway and SCOUT to the DM. The arrival of the SCOUT system coincides with the arrival of the first schedule crew. Once attached to the DM, nominal operations can begin immediately.

With SCOUT ready to work, there needs to be the supplies to support the operations. For SCOUT resupply after every sortie, a connector from the DM International Berthing and Docking Mechanism (IBDM) will match up with the connector on the SCOUT IBDM and items such as fuel, atmospheric consumables, and power will be automatically resupplied to prepare the pod for the next sortie.

The DM is scheduled to receive supplies from the OASIS planned six month resupply missions. The DM provides storage for consumables including, but not limited to, suit arms and gloves, batteries, charcoal filters, and Micrometeoroid Protection Panels (MMPP). Should an aggressive mission be needed of SCOUT, an additional resupply occurring at three months will be necessary.

The OASIS resupply missions include three types of vehicles: Crew Transfer Vehicle (CTV), Hybrid Propellant Module (HPM), and Chemical Transfer Module (CTM). Every six months the CTV brings a new set of crew members from LEO, human consumables, replacement parts, and takes home the current set of crew members. In addition, every two years life support and further replacement parts are resupplied with this vehicle. The HPM resupplies liquid oxygen, liquid hydrogen, and xenon every six months. The CTM carries propellant and atmospheric consumables to the station every six months as well as ferrying payloads short distances, and providing a high impulse transfer from LEO to L1. These vehicles can be stacked together for transfer from LEO to L1.

Having the necessary replacement parts located in the DM allows for most servicing of SCOUT to occur at Gateway. The replacement of the human arm gloves is necessary approximately every five sorties, the charcoal filters must be replaced every 30 sorties and the on-board batteries every year. Other servicing scenarios are possible for the MMPP, the human arms, and repair of the robotic arms. If service cannot be completed at Gateway, the SCOUT pod must be sent to ISS for further repairs or component replacement.

SCOUT Missions

SCOUT is designed for three different types of missions: nominal, aggressive, and extended duration. A nominal mission allows two pods to complete a total of 30 eight hour sorties in six months. This comes out to 240 working hours and 330 hours spent inside the pods. The end of life for uninterrupted nominal missions occurs at 20 years. An example workday for a nominal mission is shown in Table 3. For the translation to and from the work site, a total Δv = 1.1m/s is required. Furthermore, assuming 80 translations at the work site per day, a Δv = 20m/s is necessary for a total daily requirement of Δv = 21.1m/s.

Table 3 Nominal Mission Workday

Start Time	Activity
00:00:00	Undocking and Travel
00:30:00	Translation at Work Site
01:00:00	Work Period 1
03:00:00	Break 1
03:15:00	Work Period 2
05:15:00	Lunch – Break 2
05:45:00	Work Period 3
07:45:00	Break 3
08:00:00	Work Period 4
10:00:00	Translation at Work Site
10:30:00	Docking and Travel
11:00:00	Total Sortie Time

An aggressive mission doubles the amount of sorties completed over the six month mission. This type of mission will be used if more tasks need to be completed than is offered by the nominal timeline. Due to the 100% increase in SCOUT usage, the end of life for uninterrupted aggressive missions will occur at 10 years, which is the lifetime of the Gateway station.

Extended duration missions from Gateway were addressed, and a preliminary mission into lunar orbit was created as an example mission. Using several OASIS components including the CTV, HPM, and CTM, a single SCOUT with an XMP will be ferried out to lunar orbit where all work will be completed. The XMP is required because a large, Δv = 707m/s, is necessary to reach lunar orbit and is unattainable using only the SCOUT propellant. Since SCOUT is not designed to land on the lunar surface, it will orbit with the stack until all tasks are complete, and then return home to Gateway.

Reliability

No matter the type of mission being completed, SCOUT is required to have a cumulative probability of safe crew return over the life of the program that exceeded 99%. Along with this requirement is an obligation that the system provides for emergency alternative access and EVA bailout options. To examine the reliability of SCOUT and determine what would be needed to meet the requirements, several assumptions were made. The failure of a pod would force the bailout of the astronaut. This is a worst case scenario because not every failure will result in the crew member having to leave SCOUT. The astronaut, in the case of a bailout, must rely on an independent propulsion system for safe return to Gateway. This could come in the form of another pod or a from an escape system. And finally, the escape components will consist of life support and propulsion systems. Several combinations of pods, Bailout Systems (BS), and Propulsion Equipped Bailout Systems (PEBS) were examined, and it was found that two pods with PEBS met the requirements and was a viable option.

Task Operations and Arms

Several task requirements were placed on SCOUT pertaining to operations of the human and robotic arms. Meeting or exceeding EVA capabilities demonstrated in ISS and Hubble Space Telescope (HST) operations encompassed the largest amount of tasks that SCOUT would need to accomplish. The types of hardware that SCOUT would encounter with these tasks range from Orbital Replacement Units (ORUs) the size of large telephone booths to fragile materials such as solar arrays and mirrors. In addition, assembly of a 25m infrared space telescope, maintenance of the OASIS infrastructure vehicles, maintenance of Gateway, and service on other SCOUT pods were task operations required of SCOUT. It was assumed that the parts of the maintainable vehicles that could be serviced would be ORUs similar to those that make up HST.

The robotic arms that are designed to work with such hardware were based on the Ranger dexterous manipulators. These arms are 8-DOF arms that use interchangeable end effectors to interact with the work site. It was decided that two arms would provide the best interaction with the work site. It was found that one arm did not allow the astronaut to grip the unit with one robotic arm while removing bolts and latches with the other. This stems from an EVA requirement that if something is being removed, then it must be attached either via a tether or by hand. Three arms created a concern about the interference of the five arms (three task arms and two human arms) with each other due to the increase of work envelope interaction of the arms, more so than with two task arms. These two task arms are located on the front sides of the pod just below the human arms to allow for the ability to reach the top and bottom of the largest ORU without maneuvering and to allow SCOUT to get in close to the work site.

The forces and torques required of the task arms were determined by using current EVA operations. A suited subject in foot restraints [is] able to create a straight-ahead push with a maximum magnitude of 200N.[2] It was assumed that this number is the maximum required force to insert or extract an ORU. From there the arm was assumed to be in the worst case pose shown in Figure 2(a). The torque required of the wrist, elbow, and shoulder to each produce this force was determined. Then, using only the shoulder torque of 340N-m, the arm was placed in the best case scenario, Figure 2(b), and the maximum force that the task arm could create was found to be 2620N.

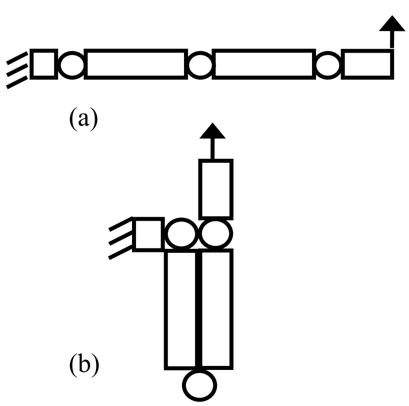

Figure 2 (a) Worst and (b) Best Case Poses

In current EVA operations, the maximum torque capability is 52.2N-m. On top of that, astronauts have the capability to choose a specific torque range and a number of turns to complete. The task arm will have the potential to replicate all three of these conditions along with an additional amount of torque for contingency operations.

Along with required forces and torques, SCOUT needs to have end effectors to interact with the hardware that it will come across while at a work site. A defined set of grasping interfaces is show in Table 4. These interfaces were used to select some of the end effector that SCOUT would need to complete tasks. A bare bolt drive was selected for driving bolts in a head-on fashion. A parallel jaw mechanism was chosen because of its adaptability. The fingers that make up the mechanism can be designed to fit around many different interfaces, resulting in several end effectors that are specific to a single task. Also, a microconical end effector was chosen for grasping micro fixtures and microconical interfaces. These three end effectors are just a simple list of possible tool the robot arms would have and its disposal. As new tools are developed, they can be sent to Gateway then installed, as needed, on SCOUT. Each end effector will have an interchangeable mechanism that allows it to be placed on any of the tool post found on SCOUT that holds the end effectors.

Table 4 Grasping Interfaces[3]

Interface	Guidelines
H-Fixture	Used to manipulate ORUs less than 600kg. Can be used for work site stabilization.
Micro Fixtures	Used to manipulate ORUs less than 227kg.Used to manipulate irregular shaped objects that provide sufficient area for the interface.
Parallel Jaw Interface	Used to manipulate irregularly shaped ORUs that do not have enough area for a full profile micro fixture of H-fixture
Micro-Conical Fitting	Used to manipulate ORUs less than 146kg.

The human tools follow a similar integration whereas new tools are developed, they can easily be assimilated into the astronaut's tool kit. If a system requires a very specific tool for a specific task, the tool should be launched with the system. Otherwise, if this is not feasible, the tool can be included in a CTV rotation.

To provide a base off which SCOUT can work, a grapple arm was placed on the underside of the pod. It will be able to withstand the forces, moments, and torsion created by the task arms in addition to the corrosive nature of hydrazine.

Life Support and Human Factors

Human Interaction with Work Site

One of the major challenges of the design of SCOUT concerned the ability of the crew member to interact with the work site. Several ideas were entertained but the universal concern was that SCOUT had to incorporate the characteristics of a spacesuit. In order to meet these characteristics, SCOUT needed to incorporate the following: large field of view similar to that of a Space Transport System (STS) EMU spacesuit, large range of motion, identical work envelope to that of current spacesuits, zero prebreathe use, and the accommodation of 5% Japanese females to 95% American males.

The first step was to research current existing spacesuits. The team looked at the STS EMU spacesuit, the Russian Orlan, NASA Ames AX-5, and the NASA Johnson Mark III. From the research two major design differences were found between all of the suits, the operating pressure and the construction of the suit. The Russian Orlan and the STS EMU are both soft component suits with low operating pressures. The AX-5 and Mark III are hard body suits and operated at much higher pressures. The first thing that drew the attention of the design team was that the hard body suits were designed for zero-prebreathe use with standard atmosphere. After much consideration, the Ames AX-5 was chosen as the primary design of the SCOUT spacesuit feature.

In order to incorporate the required large field of view, wide range of motion, and identical work envelopes of existing space suits, SCOUT will employ a contoured hull that mimics the design of a hard body suit. Below in Figure 3, is the design of the contoured hull of SCOUT. One important thing to note is that this design accommodates the large field of view by the use of a spherical helmet. The wide range of motion is made capable by the ability of the arm to rotate about the shoulders. Unlike other hard body suit designs, the contoured hull of SCOUT allows for varying shoulder berths through the adaptation of a two rotary seal bearing that is located at the attached point for the arm. This bearing allows for varying size crewmembers to use the same interface as every other member, without having to reshape the hull. Finally because the contoured hull mimics common hard body designs, it has been assumed that the attainable work volume is the same.

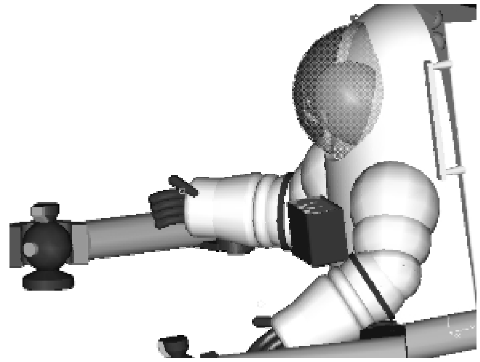

Figure 3 Crew Member Interaction with Work Site.

Atmosphere

In looking at the operating pressure that would be required of SCOUT, the team found that 4.3, 5.5 and 8.3psi were the choices of operating pressure. However, these pressures would not be the operation pressure of Gateway or ISS. Gateway would have an operating pressure of 9psi, while ISS uses an operating pressure of 14.7psi. Therefore whatever pressure was chosen for the atmosphere of SCOUT, it had to be such that no prebreathing would be required to go from either station into the vehicle, or SCOUT would have to provide the prebreathing capabilities. The design team decided to first attempt to have no prebreathing required for use with SCOUT. Since the Mark III and AX-5 were designed for zero prebreathe operation, they were chosen as possible design for SCOUT. It turns out that if one computes the nitrogen R value for Gateway (9psi) to SCOUT (8.3psi) the R value is only 0.65. This value of 0.65 is well below NASA's guidelines concerning depressurization that states a nitrogen R value below 1.2 is ideal and an R value below 1.4 is acceptable for zero-prebreathe operation.

If SCOUT would to employ an atmospheric pressure of 4.3psi, the nitrogen R value would be 1.25, which is above the ideal limit of 1.2. Using an atmospheric pressure of 5.5psi yields a nitrogen R value of approximately one. Therefore, either a 5.5 or 8.3psi atmosphere would suffice. However, because SCOUT will have a checkout mission at the ISS (14.7psi), if SCOUT were to have a 5.5psi atmosphere its nitrogen R value would be over 2 so the SCOUT atmosphere was chosen to be 8.3psi. One concern was that at this pressure the nitrogen R value would be 1.39, just below the acceptable limit. It was concluded that for ISS operation, the crew member would have to be made aware that they have a chance of depressurization issues.

Since 8.3psi was chosen as the operating pressure, the next step was to decide on the mixture of the atmosphere. After some research it was decided that the atmosphere of SCOUT would consist of 47% O_2 and 53% N_2. From the composition of gases in the atmosphere, the next step was to design the life support system.

Life Support System

The life support systems had to be designed such that it provided a climate in which the crew member could survive for a standard mission plus two hours. The design team developed a standard mission, which consist of 11 hours of total operation. Therefore the SCOUT life support systems had to operate for a minimum of 13 hours. With this timeframe in mind the physical crew requirements were designed. It was determined that a crew member needed the following for a standard mission plus two hours reserve: 3.1kg water, 0.45kg O_2, 0.3kg food, and expelled 0.5kg CO_2, 0.85kg urine, and 0.11kg solid waste.

Based on the crew members' needs, the following life support systems were developed. From the crewmember's requirement for oxygen, two standard 3000psi SCUBA bottles were used. Each bottle holds 0.727kg of O_2. This is enough oxygen to sustain the crewmember for 20.5 hours. SCOUT employs the second bottle as a back up incase the first one fails. Therefore, the absolute maximum oxygen capability of SCOUT is 40.5 hours. The required nitrogen for SCOUT is supplied by another standard SCUBA bottle. Because the crew member does not require nitrogen to survive, the nitrogen is used to provide the required addition pressure to the cabin and act as a fire retardant.

The next element of the life support systems is the CO_2 removal system. The choice of a CO_2 removal system proved to be a challenge. The choices for CO_2 removal systems were lithium hydroxide, Zeolites (2BMS), and metal oxide. Lithium hydroxide was lightweight, simple to use, required no power, reliable, and on-time use, 200W continual power. Metal oxide was similar to Zeolites (2BMS), except that it consisted of cartridges, like lithium hydroxide, that could be recharged. After many back and forth battles, metal oxide was chosen as the CO_2 removal system. Metal oxide allowed for the mass of SCOUT to be lower and required no power of the spacecraft. However, in order to recharge the cartridges, the recharge unit would be placed on the DM. This system would require 1000W for operating and could recharge two cartridges at a time.

Food, Water, Waste

Food, water, and waste, was a relatively simple design. The crewmember would simply take the meal they would have had on Gateway and bring it along with them on SCOUT. For water the crewmember would bring 105oz of water, as required by the water requirement per hour stated in the NASA-STD-3000 document. Waste collection would be proved by a smaller version of the Shuttle Waste Contamination System (WCS). The system would be similar in design to the shuttle WCS, except that instead of being designed for seven crewmembers for approximately 14 days, the SCOUT WCS would be designed for one crewmember for one day. The decision to use a WCS-type system as opposed to the typical "Apollo Bag" came from the desire to not restrict the diet of the crewmember. In order to use an "Apollo Bag" system, the crewmember diet had to be strictly regimented, while a WCS-type system requires no such restriction.

Cabin Layout

The cabin layout was developed over the entire semester. The first step in the development of the cabin of SCOUT was to determine an overall total interior volume. In looking at the NASA-STD-3000 Document, it was discovered that approximately 2.8m^3 was the optimal habitual volume for less than one month. This volume was the starting point for sizing the cabin, as well as developing the shape. Eventually the design of the cabin came to a hexagon with 0.75m sides.

Now that the shape of the cabin had been determined, the next step was to place all the internal components into the cabin along with the crewmember. The first step in this design was to develop any constraint volumes; after examining the NASA crew interface document it was found that two constraint volumes would have to be integrated in the design of the cabin. The first volume was the volume required to accommodate a 95% male in zero-g. The second volume is the volume required to make a controlled tumble in space. This volume was chosen because due to some procedures, the crewmember would have to possibly re-orient themselves 180^o about the vertical. After placing these volumes into the design of the internal cabin, all the internal components could be placed within remaining area of the cabin.

Figure 4 shows the final design of the internal cabin. Some important design characteristics to notice are:

- The front of the cabin is relatively empty compared to the back. This is because the crewmember will

be completing much of their work in the front of the cabin.
- The escape hatch is located on the bottom floor of the cabin.
- The electronics and computers are on one side of the cabin, while the life support components are on the other.

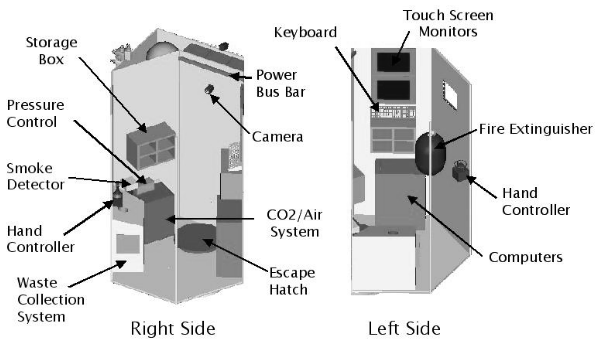

Figure 4 Internal Layout of Cabin

Primary Crew Orientation

During a nominal mission the crewmember would have to re-orient themselves into two distinct orientations. The first orientation is the hands-on mode shown in Figure 5. In this position the crew member will be located with the contoured hull of SCOUT, their head will be within the helmet, their arms will be in the suit arms, and their feet will be restrained by a foot restraint located on the floor. The primary function of the position is to provide the crew member the ability to interact with the work site via the suit arms of SCOUT. Additionally, from this position the crew can control the robotic arms via the master/slave and voice command. Currently it is perceived that the crew will spend 40-50% of their time in this position.

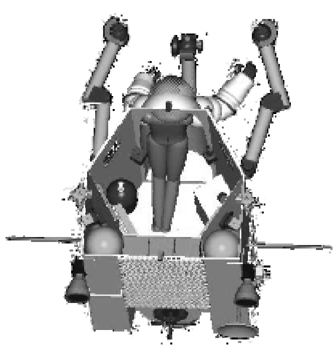

Figure 5 Crew “Hands-on” Orientation

The other crew orientation is known as the flight/robotic arm control orientation. In this position the crew member will re-orient themselves so that they span the length of the cabin. The key elements of their orientation are that the crew member will once again have their head with in the helmet, their feet will be restrained in an additional foot restraint located on the back wall, and their hands will have the ability to interact with the two 3-DOF hand controllers. In this position the crewmember has the same lines of sight as the hands-on mode, but can only control the robotic arms via the hand controller and voice command.

Bailout

One of the revolutionary concepts of SCOUT is that it contains a bailout system. The bailout system is an externally expandable hybrid spacesuit. In the event of an emergency the crewmember would activate the bailout system, which would expand the spacesuit into space. The crew members would then open the escape hatch, ingress into the escape pod, shut the escape hatch, and seal themselves into the bailout system. The concept of this system is a hybrid design of NASA’s personal rescue sphere and Rockwell’s conceptual design of a rib stiffened expandable escape system. The escape system will allow for three hours of useable atmosphere, supplied by an emergency air tank within SCOUT, and will provide minimal propulsion capabilities through a modified version of NASA’s Simplified Aid For EVA Rescue System (SAFER). This system is known as the SCOUT Hybrid Expandable Escape System (SHEEP) and is pictured in Figure 6.

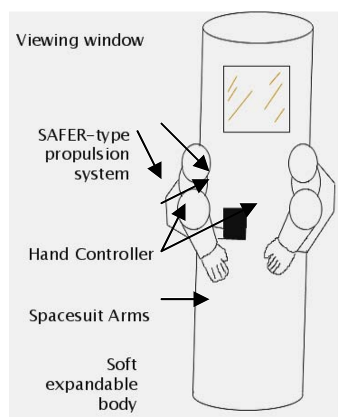

Figure 6 SHEEP

Loads, Structures, and Mechanisms

Structural Design

The SCOUT spacecraft must have a non-negative margin of safety with given factors of safety and all safety critical systems must have redundant actuation. The factors of safety, dictated by the SCOUT requirements, are given in Table 5. With this being noted, the goal of the structural analysis was to look at every force and torque in every configuration to ensure that the SCOUT spacecraft will be capable of handling all loading conditions.

Table 5 Required Factors of Safety

Type of Structure	Factor of Safety
Secondary	1.5
Primary	2.0
Pressurized Tanks	3.0
Pressure Lines	4.0

The SCOUT pod is designed as a two part vehicle. This first part of the vehicle is a load bearing hexagonal pressure hull. This is where the all the needs of the astronaut and all the components that need to be pressurized will be located. On the back half of the hexagon will be an outer panel structure which will protect all the components of the spacecraft that are not pressurized. Both parts of SCOUT will be radiation protected, and have both Micrometeoroid (MM) and Orbital Debris (OD) protection.

Launching the SCOUT System

As previously mentioned, the SCOUT system will be launched on the Space Shuttle. Each of the four components will utilize a Spacelab Logistics Pallet (SLP). The SLP provides a five point attachment to the Space Shuttle. A truss structure will be attached to the inside the SLP and to the SCOUT pods, DM and XMP. An example of how the SCOUT will launch in shown in Figure 7.

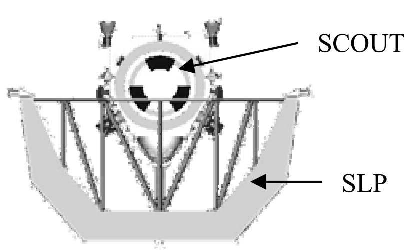

Figure 7 SCOUT in SLP

After launch all the vehicles will be move from the SLP via the Remote Manipulator System (RMS). Each pod, the DM, and XMP have a RMS grapple fixture located on them.

Loading Configurations

Launch Conditions

Launch loads were considered to be major inertia loads on the vehicle. Any component over 2kg was considered in this loading configuration and then was multiplied by the shuttle g-force loads of launch. The Space Shuttle launch g-force loads used were x = 5.8g, y = 4.85g, z = 8.5g. The launch axis directions are shown in Figure 8.

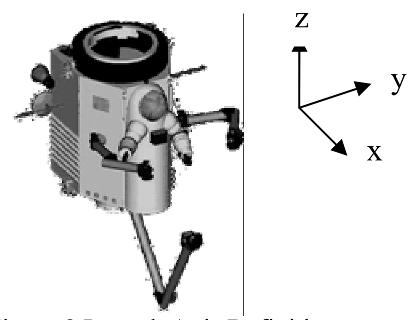

Figure 8 Launch Axis Definitions

Launch abort loads were similar to the launch loads. Launch acoustics, random launch vibration and thermal variation were smaller then the launch loads, therefore were assumed to be not as significant in the analysis.

Operational Conditions

During SCOUT operations at the work site there will be several loading conditions. The interior pressure volume when SCOUT is operating will be pressurized at 57kPa. The dexterous manipulators are designed to apply a nominal torque of 52.2N-m as mentioned previously. This torque along with the 2620N worst case load was used for this analysis. This load causes a 1170N-m bending moment on the arm. The astronaut can apply a load of 1140N at the shoulders in the AX-5 arms. The RMS causes an 890N force applied to vehicle when this system is utilized.

Other Conditions

There were some other loading configurations looked at for the SCOUT pod structural analysis. The thrusters gave a 1N and a 6N load depending on thruster. When docking an impulsive load of approximately 120N for one second was assumed. With the capability of the RMS, the SCOUT pod could berth to the docking module and this load would be the same as the load when moved out from the SLP as mentioned in the operational conditions.

Micrometeoroid and Orbital Debris Protection

MM and OD protection is used to minimize the risk of impacts that can damage spacecraft systems, and the goal of the protection design is to attain an acceptable failure probability with minimal shielding mass.

The designed debris protection of a spacecraft provides guards against two types of debris: meteoroids and orbital. Meteoroids are solid particles in space that are of natural origin, whereas orbital debris, sometimes referred as space debris, are man-made objects that no longer serve a useful purpose. For the use of SCOUT at the Earth-Moon L1 Gateway Station, the population of orbital debris is negligible since the major populations of space debris are within the altitude range of 350 to 2,000km. However, since SCOUT is also intended for use at ISS, the orbital debris impacts must be taken into account.[4]

For the purpose of environmental modeling, a micrometeoroid is defined as a particle that has a mass in the range of 10^{-18} to 1.0g. With currently available technology, a meteoroid protection shielding up to the order of 1cm in particle diameter, or 1g in mass, is attainable. Thus, the shielding for the SCOUT spacecraft will be ineffective for meteoroids greater than 1g in mass.[4]

The shielding on SCOUT will be a dual wall system made from Aluminum 6061-T6. The outer wall, bumper wall, will be 0.06cm thick. This wall will slow down and break up any micrometeoroids hitting the space craft. The inner wall, back-up wall, will have a required minimum thickness of 0.24cm. Between these two walls will be 1cm spacing. Figure 9 shows a design of a dual system. Figure 10 shows that actual protection on a corner of the SCOUT pod

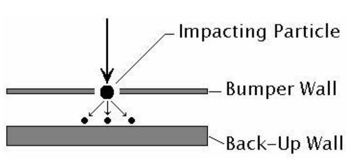

Figure 9 Design of a Dual Wall System

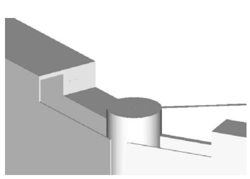
Figure 10 SCOUT Protection at Corner

Radiation Protection

Astronauts that are assigned to the SCOUT spacecraft will have to deal with the radiation levels from the L1 point. Based on these values and NASA's standard that no astronaut will exceed a 3% lifetime increase in excess fatal cancer, a shield was designed.

Annual radiation limit exposure to blood forming organs is limited to 50 allowable rem/year. This means that total allowed radiation exposure for all the time in the SCOUT pod during a nominal mission is 1.4 allowable rem. Based on data from STS-89, $4g/cm^2$ of aluminum shielding allows a 0.6% increase in excess fatal cancer over a 62 day period in the deep space environment. With this information and the choice of using $4g/cm^2$, SCOUT will have a 0.2% increase in excess fatal cancer to the astronaut based on the 15 sorties for the nominal six month mission.

The mass that this radiation protection required for the entire SCOUT pod was approximately 800kg at the start of the design. With all the components of the spacecraft begin used as radiation protection, the shielding mass was optimized. Each component's mass and surface area was used to minimize the radiation panel thickness where those components are located. The current plan of the SCOUT pod is to have extra panels added for radiation protection were it is needed. The only three panels that needed extra radiation protection were the front, left front and right front panels. All other panels were optimized to have more than $4g/cm^2$ protection. These three panels would be added as extra aluminum panels, though they are not needed to be load bearing structural components of SCOUT. With future innovation in radiation protection any material that will meet the radiation criteria can be used for the extra shielding that is required. For missions that may require more stringent radiation requirements, panels can be in any location requiring more protection.

Structural Analysis

Calculations were done to determine the thickness of the SCOUT pod panels. All the loading conditions that were previously mentioned were analyzed. Each panel was optimized such that the minimum thickness could be determined based on the lowest non-negative margin of safety. Equations were used to solve for the pressure load stress, axial load stress and the shear load stress on each panel; including the extra radiation panels needed for protection of the astronaut.[5,6]

As Table 6 shows, each panel was separated out from the system, the arms were broken down into segments and the propellant tanks and lines were analyzed. All margins of safety are non-negative.

Table 6 Structural Components

Notes: AL – Allowable Stress, Yield – Yield Stress, MOS – Margin of Safety

Name	Mass (kg)	AL (MPa)	MOS
Top panel	13.7	136	0.057
Front panel	11.3	124	0.042
Front panel, extra	48.6	124	27.1
Left front panel	23.5	131	0.048
Left front panel, extra	36.5	131	5.44
Left back pressure panel	21.9	135	0.019
Right front panel	26.3	132	0.047
Right front panel, extra	33.6	132	4.14
Right back pressure panel	21.9	135	0.019
Back panel	19.4	N/A	N/A
Bottom panel	26.5	125	0.034
Right back panel	11.3	106	0.443
Back pressure panel	13.8	135	0.019
Left back panel	11.3	101	0.52
Task arm, segment 1	0.279	38.9	2.535
Task arm, segment 2	1.116	37.1	2.703
Task arm, segment 3	1.116	30.1	3.575
Task arm, segment 4	0.558	23.0	4.983
Grapple arm, segment 1	0.279	100.0	1.139
Grapple arm, segment2	2.323	98.4	0.486
Grapple arm, segment 3	2.323	84.2	0.138
Grapple arm, segment 4	0.558	70.1	0.075
N_2 task	97.9	367	0.0018
Hydrazine task	1.76	367	0.0018
N_2 Pressurant tank	1.74	367	0.0018
N_2 lines	5.22	275	0.0027
Hydrazine lines	5.91	275	0.0027
N_2 Pressurant lines	1.74	275	0.0027

Thermal Control

The interior of the SCOUT pod, specifically the pressure hull, will be maintained thermally by utilizing a series of different systems. Heat exchangers will transfer heat from the circulating cabin air to working fluid in the heat pipe. The heat pipe will transport heat to the radiator using Freon via capillary action. The radiators, which are shown in Figure 11, will radiate the heat into space. There will also be heater on SCOUT to trim the temperature during colder conditions.[7]

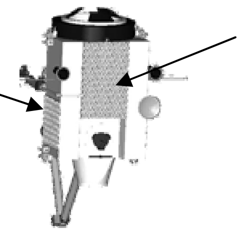

Figure 11 Radiator Placement on SCOUT

The battery subsystem will be controlled thermally by an active radiator system. The radiators will radiate heat generated from battery packs using a system of cooling loops and a working fluid consisting of Freon. The pump will circulate Freon through the radiator.[7]

Multi-Layer Insulation (MLI) will be used to keep the fuel tanks at nominal temperature. MLI will also surround the spacecraft to help regulate the temperature of the vehicle.[7]

Propulsion System Components

The propulsion tanks and lines on SCOUT were designed based on the volume of fuel needed and the space available on the vehicle. Once a tank was designed, the operating pressure was used to dictate the wall thickness for that tank or line. As was shown in Table 6, all the MOS for the tanks and tank lines are non-negative. For attaching the tanks to SCOUT, pads and rods will be used along with hooks, as shown in Figure 12.

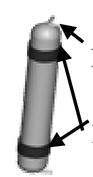

Figure 12 Tank Attachment

Thrusters

On the SCOUT pod there are 16 1N nitrogen thrusters. These thrusters are used for contamination-critical sites and are setup up in four quads. For non-sensitive sites there are 16 6N hydrazine thrusters. It is assumed that the total Δv of the vehicle is split equally between the two propellants. These thrusters are set up in four triads and four singles. Figure 13 shows the placement of the thrusters with respect to each other. The thrusters are configured such that smaller groups can be turned off separately from the system should a valve become stuck open.

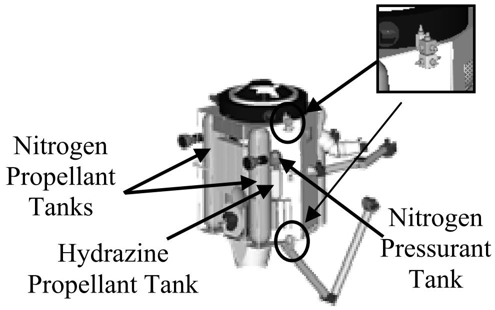

Figure 13 Tank and Thruster Placement

Avionics

The avionics system onboard SCOUT is responsible for flight control, dexterous manipulator control, vehicle health monitoring and command/data handling. The primary components of the avionics system are the Flight and Data Control Computers (FDCC). There are three identical FDCCs onboard SCOUT, for distributed computing in addition to redundancy. Each is a single-board computer linked by a CompactPCI bus. Also on that bus are two solid state recorder cards, two video interface cards and two IEEE-1394 (Firewire) data bus cards. From the Firewire interface, the FDCCs are able to communicate with all of the subsystems on SCOUT.

Computer System

The FDCCs each utilize a RAD-750 processor, the radiation-hardened version of the Macintosh PowerPC 750 processor. Based on processors projected to be available during the SCOUT mission timeline, the RAD-750 is the most capable processor available with enough radiation tolerance to function reliably outside of LEO.

Data Transfer System

IEEE-1394, or Firewire, was selected for the SCOUT data bus because it has very high bandwidth capability while using less power than competing systems. Ethernet, for example, requires a larger wattage for similar performance. Firewire has the added capability of providing power to low-wattage components, lowering the amount of necessary power harness. It can be connected to the data bus at the root, or connect to the system by daisy-chaining to another component, offering another method of lowering harness mass. The ability to hot-swap components means that a SCOUT pilot can disconnect and reconnect components without shutting down any of the flight computers. Since Firewire is a standard interface on personal computers, it should lower the cost and complexity of ground support equipment.

Flight Sensors

For flight control, the avionics system uses attitude position, attitude rate and vehicle relative position sensors. Two redundant star trackers provide very accurate attitude information, available whenever either sensor has an unobstructed view and vehicle rates are lower than 10deg/sec. Two redundant Interferometric Fiber Optic Gyroscopes (IFOGs) provide vehicle rotation rate information to the FDCCs. This data is used in the vehicle control law as well as updating the attitude estimate. To facilitate automated rendezvous and docking, two Visual Guidance Sensor (VGS) emitters are located on the IBDM.[8] These emitters are positioned to align with a passive sensor on each IBDM on the DM. For longer distance range information and rendezvous with a work site, a laser rangefinder, located on the grapple arm, will be used. This rangefinder is capable of providing distance-to-target, as well as 3-dimensional scanning of the target, which can be used by the computer system and the SCOUT pilot to ease proximity operations around a work site. These 3-D images of objects within close proximity of SCOUT will be integrated into a collision-avoidance algorithm in the flight computer, which uses models of known objects as the primary data source. Video cameras located on the front and rear of the vehicle can also be used by a SCOUT pilot, especially if it is being operated remotely.

System Sensors

The avionics system also interfaces with sensors and embedded processors in all other vehicle subsystems. These sensors are redundantly placed such that any failure can be positively diagnosed. The life support equipment provides relevant data on partial pressures of cabin atmosphere. Power distribution electronics provide power system health information, including voltage, electrical current and temperatures of SCOUT components. Sensors positioned throughout the propulsion system provide pressures and temperatures of tank and line, as well as open/closed status of control valves and regulators. Fiber optic sensors in the dexterous manipulators will measure structural loads.

Crew Interface

Another group of sensors onboard SCOUT is the crew interface equipment. The interface for manual flight control is the two 3-DOF hand controllers in the front of SCOUT. From this location, the astronaut can see through the bubble window in the contoured hull, using a Heads-Up Display (HUD) for data monitoring. Voice recognition can interpret commands given by the pilot for a variety of functions. For example, high-level commands such as "Return to Gateway" or "Change to end effector B" can be given, in addition to lower-level commands like "Translate forward nine meters" or "Roll left arm section three by 30 degrees". Sensors located within the human AX-5 arms and gloves allow an astronaut to control the robotic arms without removing their hands from the gloves. A voice command of "slave on" or "slave off" will allow the astronaut to switch between these control modes. This mode also has the advantage of allowing the astronaut to use directly use their eye-hand coordination when operating the dexterous manipulators.

When facing the rear of the vehicle, at the Command, Control and Communication station shown in Figure 14, the astronaut can visually monitor the health of any SCOUT subsystem on two reconfigurable touch screen displays. From this station, the pilot can also view video from any of the cameras on SCOUT, or participate in a video teleconference.

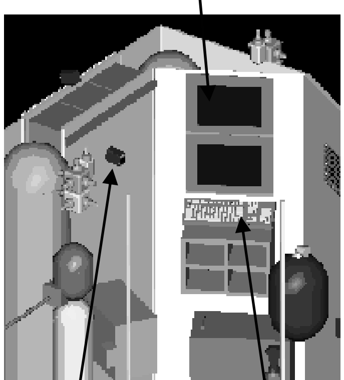

Figure 14 Command, Control, and Communication Station

Communications

SCOUT will use Ultra High Frequency (UHF) band transmissions for nominal short-range communications to the hosting station or another vehicle, like a second SCOUT pod. Two omni-directional antennas, positioned on the sides of the vehicle, are used to transmit and receive the UHF signals. The distance from the host station is assumed to be less than 1500m, so the system is capable of a bidirectional data rate of 10Mbps using very little power.[9] For emergency communication to Earth, or during a failure of the UHF system, a Ka band system can be used. This system uses a gimbaled parabolic antenna on the rear of the vehicle.

Power System

The power system consists of three lithium-ion batteries, which are charged while SCOUT is connected to the docking module. These batteries provide an average power of 915W, with a peak power draw of about 2.9kW. Lithium-ion batteries were selected due to the mass increase required for nickel-metal-hydride or nickel-hydrogen batteries, and their improved performance at end-of-life over lithium-polymer batteries. Batteries were selected over fuel cells due to their lower volume requirements, which would force overall vehicle mass to increase greatly. Fuel cells also present other challenges, like required venting every 12 hours of use, a 25 minute warm-up period, frequent servicing, and increased complexity of resupply. SCOUT can return safely from a sortie even if two of the three batteries suffer a non-catastrophic failure. The lithium-ion batteries need to be replaced once a year, which can be done during EVA or by another SCOUT. There is an extra battery for each SCOUT stored in the docking module.

Power Distribution

As shown in Figure 15, three Power Distribution Units (PDUs) are located above the batteries on the back panel of SCOUT. The PDUs connect to the primary power source on the docking module, and then control that electrical input to charge the batteries. The PDUs then control voltage distribution levels from the batteries to SCOUT systems. A higher voltage is distributed to the dexterous manipulators, and 28V DC is distributed to other systems.

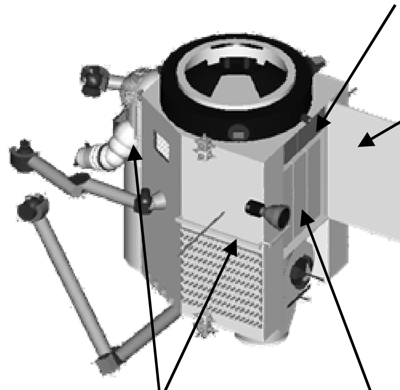

Figure 15 Battery and PDU Placement

Procedure

At the beginning of the semester the design team had no idea of the project, problem, or design requirements. On the first day of Spring semester (Feb 2003) the design team was given the above information. During the first week of class, the design team was broken into six groups and initial conceptual designs were developed. Over the next two weeks the design team conducted research into the different systems of SCOUT and their configurations. At the end of this period the class held a trade study review where each group discussed their current designs for SCOUT and its systems. After the trade study review, the design team spent the next couple of weeks further refining their design ideas, developing life size mock-ups in order to judge sizing and placement concerns, and begin the process of dimensioning SCOUT.

One month after the start of the class, the design team held a preliminary design review where the team discussed its current ideas and solutions to the development of SCOUT. Out of the review came roughly 100 action items for the design team to address. The action items would be addressed over the next two months. During this period the design team held two complete systems review sessions, began the development of a CAD model, began the structural analysis and refined level two and level three requirements.

Two months after the preliminary design review, the design team held its critical design review. The critical design review was five sessions in which all the current systems of SCOUT were presented in detail. Out of this review can only a dozen or so minor action items. These action items were then responded to over the next two weeks.

In the last two weeks of the class, the design team finalized the design of SCOUT, developed a 1/14 scale model, presented to the University of Maryland's Aerospace Department and the Aerospace Technology Working Group (ATWG) Conference.

The class will conclude with the development of a final project report, as well as a presentation at the RASC-AL conference in Cocoa Beach, Florida.

Outreach

During the course of the Spring 2003 semester, the SCOUT team has made several presentations as well as displaying a poster. These outreach efforts were done to not only present our work to the general public, but also to the leaders in the Aerospace Engineering community.

On March 6, 2003, the entire class participated in a Preliminary Design Review (PDR). Invitations for the PDR were sent out to the NASA Space Architecture Team members who were meeting at the time in Washington D.C.

In each of the past five years, the University of Maryland campus opens up to the general public so everyone can see all the research being conducted at the university. On April 26, 2003, a few SCOUT team members stood with our poster and explained the project to children, their parents and professors who were touring the A. James Clark School of Engineering.

A Critical Design Review (CDR) on March 4, 2003 was a major outreach effort on the part of the class. Invitations were sent out to NASA Goddard engineers. The five hour presentation of the SCOUT project was very well received by all in attendance.

On May 12, 2003, the RASC-AL away team that are the five members of the class chosen to present SCOUT at this year's conference, gave a one hour Aerospace Engineering briefing. All members of the department and anyone else interested were invited to watch the first SCOUT overview presentation.

After the CDR, the SCOUT team was approached to with a great opportunity for a presentation. On May 13, 2003, two SCOUT team members gave a short 20 minute briefing at the Aerospace Technology Working Group (ATWG) Conference held at NASA Goddard Space Flight Center. The next day the Conference visited the University of Maryland Space Systems Laboratory for a tour and the SCOUT poster was placed along the tour path with team members available for any questions. Those who participated in this year's ATWG conference were very interested in Project SCOUT and this outreach provided a great opportunity to build a link between the SCOUT team and leaders in the Aerospace Engineering community.

Lessons Learned

Working with such a large group of people creates an environment where many lessons are learned. The main lesson learned is that communication is key. Online discussion boards were the main form of communicating and even with the constant opportunity for discussion, parts of the project were still overlooked or heavily concentrated on for a small part of the semester. Another lesson learned by everyone is that no matter what the differences in personality, everyone is still on the same team. Conflicts of interest and style existed throughout every stage of development, yet by the end, the entire class was able to come together with a finished product.

Future Work

Although there was much progress throughout the semester, many items remain open and await attention. The robotic manipulators need to be better developed. The reliability analysis of the SCOUT system needs to be checked and redone. The internal components can be optimized for less space, mass, and cost. The internal cabin volume can be reduced in order to save space and mass. Once the internal volume is reduced, the outside of the structure can be redesigned and a new launching configuration can be determined. A more efficient way of protecting from radiation needs to be developed. The velocity used during translation to and from the work site needs to be optimized to reduce the amount of propellant needed for six months. The composite tanks used on the docking module should be evaluated for use on board SCOUT. While there are many items listed here, design is an iterative process and another iteration is always needed.

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