HUMAN-ROBOTIC HYBRIDS FOR DEEP-SPACE EVA: THE SPACE CONSTRUCTION AND ORBITAL UTILITY TRANSPORT CONCEPT

David L. Akin*
Mary L. Bowden†

ABSTRACT

Recent 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 capable and flexible capabilities for space operations, most of these need to be applied in extravehicular activities associated with 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; because of this and 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 the Space Construction and Orbital Utility Transport (SCOUT) system. Drawing on concepts of "man-in-a-can" systems from past decades, SCOUT represents a hybrid between pressure suit design, human spacecraft technologies, and dexterous robotic servicing systems. SCOUT is a self-contained spacecraft providing a shirtsleeve environment for the operator, allowing zero-delay initiation of operations without need for denitrogenation. A conformal section of the vehicle, incorporating advanced pressure-suit arms and a helmet-like viewport with a wide field of view, provides actual human hands-on 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 the detailed design of the SCOUT vehicle, including the station-mounted berthing and refurbishment module which supports the vehicle and recharges consumables between sorties. A detailed scenario is presented for the baseline design reference mission, which is a repetitive daily operation incorporating 1000 m translation to the construction site, eight hours of actual operations, operator breaks for rest and meal, and return. The paper also presents augmented operational scenarios, including extended distance and duration missions taking advantage of the ability of SCOUT to support multi-day operations.

INTRODUCTION

As future human space operations move beyond low earth orbit (LEO), the environment of deep space presents new challenges for space systems design. A significant portion of the benefit of human operations involves the use of human manual dexterity through extravehicular activity, but present EVA pressure suit systems offer very little protection from radiation, both galactic background radiation and solar radiation. These systems also require time consuming prebreathing prior to an EVA. For human space exploration to move forward, many hundreds of hours of extravehicular work will be needed, which in the absence of ground maintenance and refurbishment would also exceed current EVA system capabilities.

The SCOUT system, shown in Figure 1, was developed as a potential solution to these issues, allowing augmented EVA operations at LEO and beyond. Each SCOUT pod is approximately two meters tall, one and a half meters wide, and two meters deep.

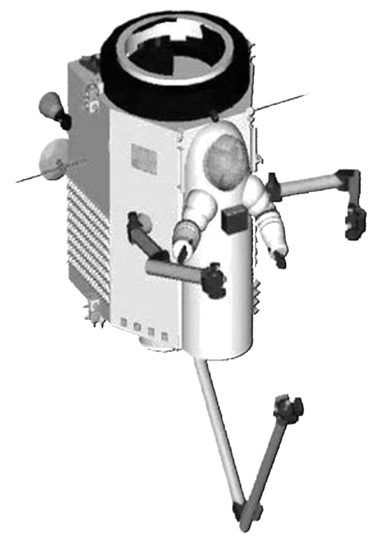

Figure 1: Overview of SCOUT

*Associate Professor of Aerospace Engineering and Director of Space Systems Laboratory, University of Maryland. Senior Member, AIAA
†Visiting Assistant Professor of Aerospace Engineering, University of Maryland. Member, AIAA

The SCOUT concept was designed 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 vehicles. 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 for long-term operations.

SYSTEMS INTEGRATION

SCOUT is a closed-cabin atmospheric vehicle used for human EVA. The system allows the single operator to interact with the local environment through pressure suit arms, dexterous robotic manipulators, and a six-axis maneuvering system. The nominal SCOUT system includes two SCOUT pods, a docking module (DM), and an extended mission pallet (XMP).

General Design Requirements

A series of Level 1 requirements were placed on the SCOUT system at the outset of the design process. These top-level requirements include:

- As a design reference mission, 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.
- There will be a single-interface replenishment fixture at the docking port capable of single-person checkout and refurbishment in less than one hour.
- All safety-critical systems shall be two-fault tolerant.
- Along with nominal local activities, the SCOUT system will support extended missions beyond the immediate vicinity of the basing station.
- In addition to 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.

The design team used these Level 1 requirements to "flow-down" into a detailed multilevel design requirement document.

Vehicle Mass and Power Breakdown

At the beginning of the design process, 2000kg was allotted to the SCOUT pod. A top-level summary of mass allocations and estimates is shown in Table 1, reflecting a current mass margin of 7.5%. The current nominal power requirement for SCOUT is 915W.

Table 1: Mass and Power Breakdown

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

The docking module and extended mission pallet were also designed in detail in this effort, but are covered in this report in a cursory manner due to page restrictions. The docking module has an installed mass of 4420 kg, and incorporates 3.3 kW of photovoltaic arrays to make the SCOUT system independent of the base station for power. The extended mission pallet, used for long-duration missions, has a mass of 995 kg.

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.

MISSION PLANNING AND ANALYSIS

Launch Overview and Resupply

The SCOUT system will be launched in the space shuttle to low Earth orbit (LEO). After a successful six month test mission checkout at the International Space Station, the entire system will be attached to an OASIS Solar Electric Propulsion (SEP) stage for travel from ISS to the Earth-Moon L1 point.

When the system has reached the Gateway station located at the L1 point, the 25m remote manipulator system based on the station will be used to attach the docking module to Gateway and both SCOUT pods to the DM. The arrival of the SCOUT system coincides with the arrival of the first scheduled crew. Once attached to the DM, nominal SCOUT operations can begin immediately.

With SCOUT ready to work, there needs to be an infrastructure for resupply to support the operations. For SCOUT resupply after each sortie, a connector in the DM International Berthing and Docking Mechanism (IBDM) will mate with a 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 month intervals will be necessary.

Having the necessary replacement parts located in the DM allows for most servicing of SCOUT to occur at Gateway. The replacement of the pressure suit 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 mission scenarios: nominal, aggressive, and extended duration. A nominal mission scenario allows two pods to complete a total of 30 eight working-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, at 3300 hours/pod. A nominal operational sortie is planned to be 11 hours long, including pre-mission preparation and checkout (limited by Level 1 requirement to be no more than one hour), an hour of translation to and from the work site, and one hour of operator breaks interspersed throughout the day. Nominal translational Δv for the reference mission was found to be 21.1m/s.

An aggressive mission scenario doubles the number of sorties completed over the six month mission. This type of mission will be used if a higher sortie rate is required for an extended period of time. Due to the 100% increase in SCOUT usage, the end of life for uninterrupted aggressive mission scenario will occur at 10 years, which is also the planned 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-provided transport components, a single SCOUT with an extended mission pallet will be ferried out to lunar orbit where all work will be completed. The XMP is required because a Δv of 707m/s is required to reach lunar orbit from L1, which is not feasible using only the SCOUT propulsion system. Since SCOUT is not designed to land on the lunar surface, it will orbit with the transport stack until all tasks are complete, and then return home to Gateway.

While the reference extended mission chosen was that of a lunar orbital mission in support of extended human lunar exploration, it should be noted that perhaps the most immediate benefit of SCOUT would be the ability to perform extended missions to geostationary orbit (GEO). This would provide human dexterity and on-site judgment in support of servicing of GEO communications satellites, with a high market value for this activity. Further analysis will be performed to examine the economic viability of this activity as a justification for SCOUT and L1 basing.

Reliability

No matter the type of mission being completed, SCOUT Level 1 requirements set a cumulative minimal probability of safe crew return over the life of the program at 99%. To achieve this level of reliability over an extensive number of sorties, the system must provide for emergency alternative access and EVA bailout options. The "failure" of a pod is defined as an event which would force the bailout of the astronaut. This is a worst case scenario, because not every actual 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 from an escape system. As finally designed, the escape components will consist of life support and propulsion systems. The final bailout system developed will be detailed in the life support section of this paper.

Task Operations and Arms

Several task requirements were placed on SCOUT pertaining to operations of the human and robotic arms. The types of hardware that SCOUT would encounter 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 on existing spacecraft.

The robotic arms chosen were based on the Ranger dexterous manipulators, developed at the University of Maryland Space Systems Laboratory. These are 8-DOF arms that use interchangeable end effectors. It was decided that two arms would provide the best interaction with the work site. 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.[1] 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, and the torque required of the wrist, elbow, and shoulder to produce this force was determined. Transferring these torques to the arm pose with optimal mechanical advantage, the maximum force that the task arm could create was found to be 2620N.

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 set of canonical grasping interfaces was defined to select some of the end effectors 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. A microconical end effector was also chosen for grasping ISS robot-standard interfaces. As new tools are developed, they can be sent to Gateway then installed, as needed, on SCOUT. Each end effector will have an interchange mechanism that allows it to be placed on any of the tool posts found on SCOUT that holds the unused end effectors during a sortie.

To stabilize SCOUT during dexterous operations, a grapple arm was placed on the underside of the pod. It will be able to hold the pod in position while withstanding the forces, moments, and torsion created by the task arm, human arms, and other applied loads.

LIFE SUPPORT AND HUMAN FACTORS

Human Interaction with Work Site

One of the major challenges of the SCOUT design process is the requirement to allow the crew member to directly interact with the work site. To achieve the full potential of this concept, it was decided from the outset that SCOUT had to incorporate the inherent manual dexterity and vision characteristics of a conventional spacesuit. To meet these characteristics, SCOUT needed to incorporate the following: large field of view similar to that of a space shuttle extravehicular mobility unit (EMU), identical or better arm work envelope compared to that of current spacesuits, zero prebreathe use, and (as per the Level 1 requirements) the accommodation of 5% Japanese females to 95% American males.

The team looked at the STS EMU spacesuit, the Russian Orlan, NASA Ames AX-5, and the NASA Johnson Mark III. While all of these suit designs had benefits and liabilities, the hard-suit aspect of the AX-5 had significant advantages in terms of robustness, maintainability, and simple sizing. The suit arms were therefore designed based on the AX-5 pressure suit technologies.

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. Figure 2 shows the design of the contoured hull portion of SCOUT. One important thing to note is that this design accommodates the large field of view by the use of a hemispherical helmet. Unlike other hard body suit designs, the contoured hull of SCOUT allows for varying shoulder berths through the incorporation of a dual rotary seal bearing that is located at the attachment 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.

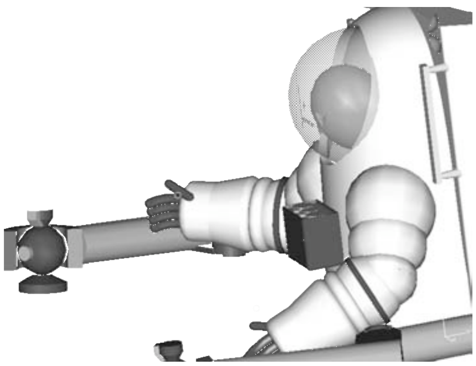

Figure 2: Crew Member Interaction with Work Site

Cabin Atmosphere

In looking at the operating pressure that would be required of SCOUT, the team examined 4.3, 5.5 and 8.3 psi cabin pressures. Of the two design SCOUT basing locations, Gateway is planned for an operating pressure of 9 psi, while ISS uses an operating pressure of 14.7 psi.

Given the Level 1 requirement for zero prebreathe at all operating locations, the 8.3 psi SCOUT pressure level provides a minimally acceptable decompression ratio for operating from ISS, and a close match to the nominal pressure of Gateway. Since the AX-5 technology suit components were originally designed and tested at 8.3 psi, this pressure was adopted as the nominal operating cabin pressure in SCOUT. To maintain appropriate partial pressures while improving flammability limits, the atmosphere of SCOUT was chosen as 47% O_2 and 53% N_2.

Life Support System

The life support system had to be designed such that it provides a climate in which the crew member could survive for a standard mission plus two hours. Given the nominal portal-to-portal sortie duration of 11 hours, the SCOUT life support systems had to operate for a minimum of 13 hours. Over this period, the nominal mission human requirements were 3.1kg water, 0.45kg O_2, and 0.3kg food; over the same time, the operator would on average produce 0.5kg CO_2, 0.85kg urine, and 0.11kg of solid waste.

From the crewmember's oxygen requirement, two standard commercial off-the-shelf (COTS) pressure tanks were used. Each holds 0.727kg of O_2: enough oxygen to sustain the crewmember for 20.5 hours. SCOUT employs the second bottle as a back up in case the first one fails. Therefore, the absolute maximum oxygen capability of SCOUT is 40.5 hours. A third identical tank carries nitrogen for required atmosphere make-up.

The choices for CO_2 removal systems were lithium hydroxide, zeolite dual-bed molecular sieves (2BMS), and metal oxide. After a detailed trade study, metal oxide was chosen as the CO_2 removal system. This system reduced the mass of SCOUT and required no additional pod power. However, in order to recharge the cartridges, the recharge unit would be needed on the DM. This system would require 1000W for operating and could recharge two cartridges at a time. This system is directly compatible with the metal oxide cartridge system in the ISS airlock module.

Food, Water, Waste

Given the relatively short duration of a SCOUT sortie, food, water, and waste management was a relatively simple design task. 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).

Cabin Layout

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 the planned sortie duration. 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 perform a controlled body reorientation in space. 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 3 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.

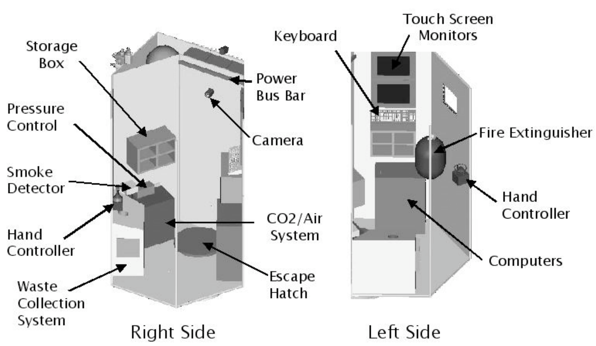

Figure 3: Internal Layout of Cabin

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 4. 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 estimated that the crew will spend 40-50% of their time in this position.

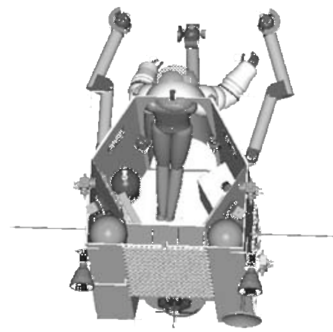
Figure 4: Crew “Hands-on” Orientation

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 control the robotic arms and/or vehicle flight control system via the hand controllers and voice command.

Bailout Provisions

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 member would then open the escape hatch, ingress into the escape pod, shut the escape hatch, and seal themselves into the bailout 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 (SAFER) System. This system is known as the SCOUT Hybrid Expandable Escape System (SHEEP) and is pictured in Figure 5.

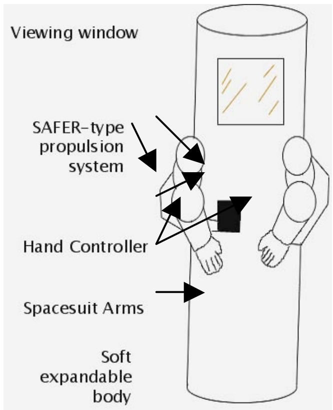

Figure 5: SHEEP

LOADS, STRUCTURES, AND MECHANISMS

Structural Design

The SCOUT spacecraft must have non-negative margins of safety with NASA standard factors of safety for inhabited spacecraft, and all safety critical systems must have redundant actuation. 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.

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 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 and orbital debris (MMOD) protection.

Launching the SCOUT System

As previously mentioned, the SCOUT system will be launched on the space Shuttle. Each of the four components (two pods, docking module, and extended mission pod) 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 6.

After launch all the vehicles will be moved from the SLP via the Remote Manipulator System (RMS). Each pod, the DM, and XMP incorporates a standard RMS grapple fixture.

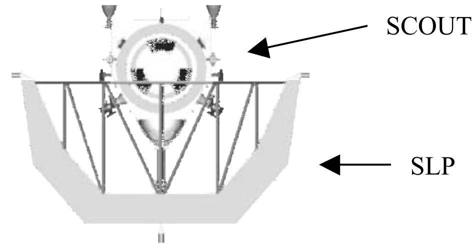

Figure 6: SCOUT in SLP

Loading Configurations

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 vehicle axis conventions are shown in Figure 7.

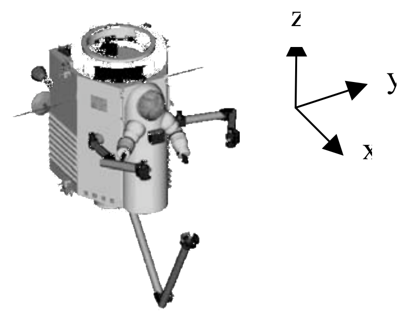

Figure 7: SCOUT Vehicle Axis Definitions

During SCOUT operations at the work site there will be several loading conditions. When SCOUT is operating, the cabin 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.

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

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

The designed debris protection of the spacecraft guards against two types of debris: meteoroids and orbital debris. 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 LEO 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.[2]

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, or bumper wall, will be 0.06cm thick. This wall will break up any micrometeoroids hitting the spacecraft. The inner wall, which is also the pressure hull, will have a required minimum thickness of 0.24cm. Between these two walls will be 1cm spacing.

Radiation Protection

Astronauts that are assigned to the SCOUT spacecraft will have to deal with the radiation levels extant at the L1 point. A radiation shielding protocal was designed based on these values and NASA’s standard that no astronaut will exceed a 3% lifetime increase in excess fatal cancer.

Annual radiation limit exposure to blood forming organs is limited to 50 rem/year. This means that total allowed radiation exposure for all the time in the SCOUT pod during a nominal mission is 1.4 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.

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 where it is needed. The only three panels that needed extra radiation protection were the front, left front and right front panels. These three panels would be added as extra aluminum panels, though they are not needed to be load bearing structural components of SCOUT. For missions that may require more stringent radiation requirements, panels can be in added in any location requiring more protection.

THERMAL CONTROL AND PROPULSION SYSTEMS

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 8, will radiate the heat into space. There will also be heaters on SCOUT to trim the temperature during colder conditions.[3]

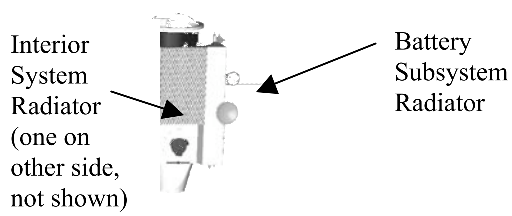

Figure 8: Radiator Placement on SCOUT

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]

The requirement for low-contamination operations around sensitive hardware (such as optical instruments) drove the adoption of dual parallel propulsion systems.

The SCOUT pods incorporate both a pressurized nitrogen cold-gas propulsion system for low contamination, and a hydrazine monopropellant system for high performance when contamination is a lesser concern. Each system is designed for a nominal ΔV of 36 m/sec over the entire sortie.

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. Figure 9 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.

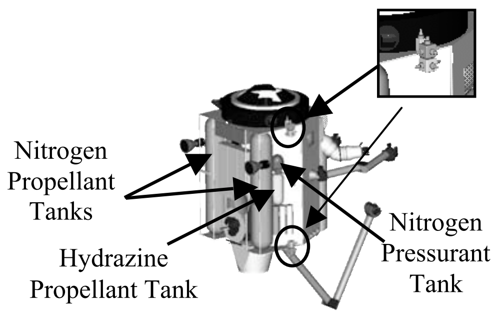

Figure 9: Tank and Thruster Placement

AVIONICS SYSTEMS

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 data bus cards. From the 1394 interface, the FDCCs are able to communicate with all of the subsystems on SCOUT.

The FDCCs each utilize a RAD-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.

IEEE-1394 was selected for the SCOUT data bus because it has very high bandwidth capability while using less power than competing systems. 1394 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 connected 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 operator can disconnect and reconnect components without shutting down any of the flight computers.

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.[4] 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.

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.

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. 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 10, 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.

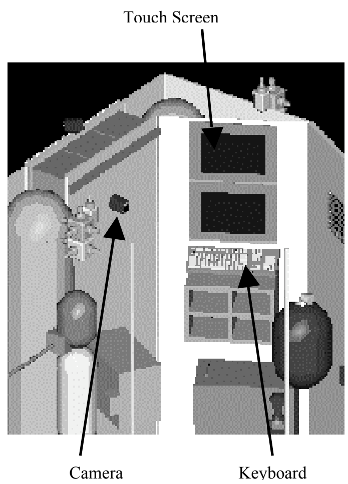

Figure 10: Command, Control, and Communication Station

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.[5] 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 SYSTEMS

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. 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 EVA or by another SCOUT. There is an extra battery for each SCOUT stored in the docking module.

As shown in Figure 11, 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 control that electrical input to charge the batteries. The PDUs then control voltage distribution levels from the batteries to SCOUT systems. 48V DC is distributed to the dexterous manipulators, and 28V DC is distributed to other systems.

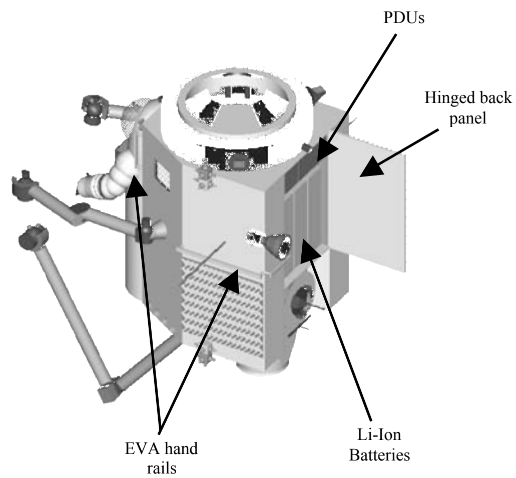

Figure 11: Battery and PDU Placement

CONCLUSIONS AND RECOMMENDATIONS

Although the generic SCOUT concept dates back at least to the 1950's, this effort in a single semester undergraduate capstone design class represents one of the few known detailed examinations of the paradigm of a shirt-sleeve environment space operations system. This paper can provide only a cursory overview of the results of this effort; interested readers are encouraged to contact the authors (dakin@umd.edu; maryb@umd.edu) for electronic copies of the 450-page final report.

All of the results of this detailed design effort indicates that a SCOUT-type system would be of great value in future space operations, whether based at International Space Station or future deep-space venues. With the combination of EVA-type arms and hands, robotic task arms, and a grappling arm for system positioning, a single person can perform EVA operations currently requiring two EVA crew and an internal RMS operator. This would be of singular importance in the current two-person ISS operating mode, where traditional EVA is constrained other than contingencies due to the lack of an IVA crew member.

While the class design exercise is completed, the University of Maryland Space Systems Laboratory intends to further pursue the SCOUT concept to obtain more detailed information on requirements and operating capabilities. Through the use of low-fidelity mockups in the UMd Neutral Buoyancy Research Facility, early efforts will be aimed at getting a more detailed understanding of cabin layout, with the hope of reducing cabin dimensions and thereby system mass. Simple adaptations of the Maryland Advanced Research/Simulation (MARS) Suit spacesuit simulator, along with the underwater versions of the Ranger manipulators, will allow a detailed mapping of crew capabilities, and direct testing of the optimal interactions between the use of suit arms and robot arms for a variety of operational tasks. As more detailed knowledge is obtained on SCOUT expected operational capabilities, these will be applied to time-and-motion analysis of past EVAs on ISS and Hubble Space Telescope to obtain a supportable estimate of the benefit of the SCOUT system, and to provide quantitative guidelines for further development of the SCOUT concept.

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[1] Lyndon B. Johnson Space Center. Space Shuttle System Payload Accommodations: Volume XIV, Revision K. NSTS 07700. Houston: March 1993.

[2] Williamsen, Joel. "Meteoroid and Orbital Debris Design Considerations for Space Operations." 2001 Core Technologies for Space Systems Conference Colorado Springs, CO. Nov 28, 2001.

[3] Gilmore, David G. Satellite Thermal Control Handbook, The Aerospace Corporation Press: El Segundo, 1994.

[4] Howard, R.T. et al. "Active Sensor System for Automatic Rendezvous and Docking." Laser Radar Technology and Applications II. Proceedings of SPIE Volume 365, April 1997: 106-15.

[5] Mohanty, Nirode. Space Communication and Nuclear Scintillation. Van Nostrand Reinhold: New York, 1991.