2004-01-2295

SCOUT: EVA Capabilities of the Space Construction and Orbital Utility Transport

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ABSTRACT

The University of Maryland has performed a detailed design for the space equivalent of an atmospheric diving suit. The Space Construction and Orbital Utility Transport (SCOUT) is a small single-person spacecraft, with all necessary utilities for extended sorties away from the host station. Through a pair of AX-5 style space suit arms integrated into the cabin wall, as well as a trio of dexterous manipulators, the SCOUT operator can directly interact with the work site environment, performing spacecraft servicing, structural assembly, or other tasks traditionally done by an astronaut in a space suit. Originally designed as an augmentation to the NASA Gateway station architecture for the Earth-Moon L1 system, studies indicate that a SCOUT-type EVA system would represent a substantial benefit to International Space Station operations as well. Due to the integrated robotics system, ISS extravehicular operations, which nomially require two EVA crew and one IVA robotics operator, can be done with a single SCOUT pod unaided.

One of the requirements to allow safe single-pod operations is a high-reliability system to ensure crew survival. To this end, SCOUT incorporates several design features to increase mission assurance and maximize the probability of crew survival following a catastrophic failure. Since SCOUT is designed around an 8.3 psi cabin pressure, there are no prebreathe requirements prior to start of operations. This will allow a second SCOUT pod to be kept on “ready alert” at the station, with its operator performing other tasks but ready to react in a contingency. The second SCOUT safety feature is the adoption of an innovative “bail-out” system. In the event of a failure which renders SCOUT uninhabitable, in less than a minute the operator can deploy an emergency bail-out system, normally kept in a small package on the SCOUT hull. A single valve actuation will inflate an all-fabric escape suit, consisting of a simple cylindrical body with polycarbonate face plate and adjustable-length arms, mounted to the SCOUT cabin via a pressure hatch. The operator will then move into the escape suit, close the hatch, then detach from SCOUT. The system provides three hours of life support, along with SAFER-style cold gas thrusters for mobility. Between the second SCOUT pod on ready alert and the self-rescue capability of the escape suit, a probabilistic risk assessment shows a 99.9% chance of performing a 600-EVA mission model without loss of crew.

Additional systems have also been designed to extend the operating range of the SCOUT system. A docking module was designed to support two SCOUT pods, providing docking interfaces to the host station and SCOUT-specific resupply/repair capabilities. The docking module docks to space station through the use of an International Space Station common berthing mechanism (CBM). An extended mission package provides support for SCOUT in remote operations, extending sortie times from 11 hours to several days. In conjunction with an orbital maneuvering vehicle, the extended mission package would allow an ISS-based SCOUT to be used for human servicing at geostationary orbit, and from an L1 base would allow SCOUT operations in lunar orbit.

1.0 INTRODUCTION

As future human space operations move beyond low earth orbit (LEO), the environment of deep space presents new challenges for space systems design. One of the greatest benefits of human operations is the ability to use human manual dexterity through extravehicular activity, but present EVA pressure suit systems offer very little protection from radiation (both galactic cosmic rays and solar particles), or from micrometeoroids and orbital debris. 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 1.8 meters deep, as may be better seen by the three-view drawing in Figure 2.

The SCOUT concept was designed for use at the proposed NASA Gateway space station, located at the Earth-Moon L1 Lagrange point, which is 84% of the way from the Earth to the Moon, and on the line directly connecting the two bodies. Specifically, a team of two SCOUT vehicles would

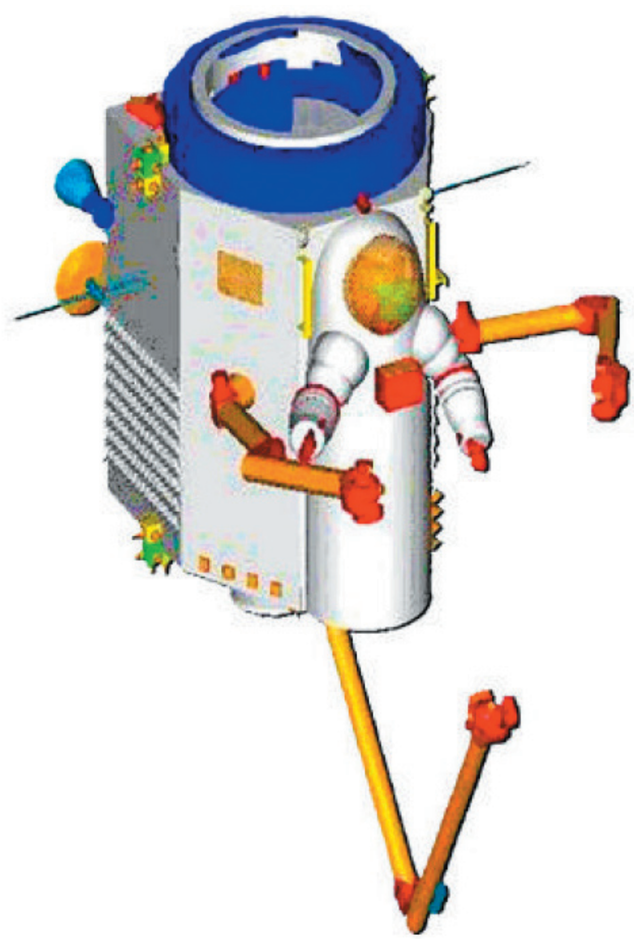

Figure 1
Space Construction and Orbital Utility Transport (SCOUT)

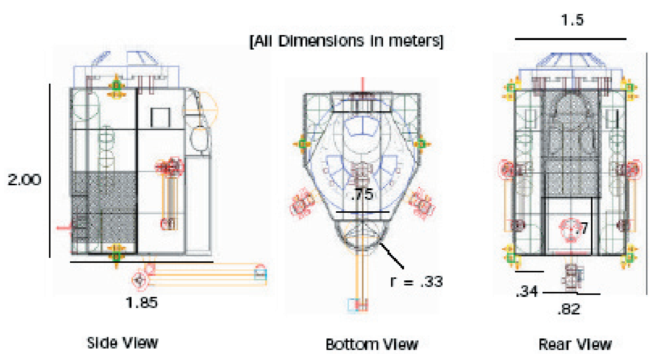

Figure 2
Dimensioned three-view diagram of SCOUT

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.[1] 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 either test missions or long-term operations.

2.0 CONCEPT OVERVIEW

2.1 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).

2.1.1 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 3 (laboratory breadboard demonstration) by the beginning of 2005 and a TRL of 6 (space flight qualified) 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.

2.1.2 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/ Mechanisms	850kg	796kg	240W
Life Support/ Human Factors	275kg	235kg	295W
Avionics	200kg	190kg	295W
Power/ Propulsion/ 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 size limitations. 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.

2.1.3 Cost Analysis - The cost was determined from NASA mass-based heuristic formulas at the vehicle level for each component of the SCOUT system[2]. The nonrecurring cost of SCOUT is $1.18 billion. 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.

2.2 MISSION PLANNING AND ANALYSIS - Since the design reference mission for SCOUT was to operate at the NASA Gateway Station, much of the following section is specific to that mission. However, SCOUT has applications both closer to Earth (International Space Station, Crew Exploration Vehicle) and farther away (human Lunar and Mars missions), which are briefly discussed in Section 3.

2.2.1 Launch Overview and Resupply - The SCOUT system was designed to 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 would 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 station remote manipulator system would be used to attach the docking module to Gateway and both SCOUT pods to the DM. Once attached to the DM, nominal SCOUT operations could begin immediately.

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 receives supplies from the OASIS-planned resupply missions at six-month intervals, over which time the two SCOUT pods would perform a total of 30 individual sorties. The DM provides storage for consumables including suit arms and gloves, batteries, charcoal filters, and micrometeoroid protection panels (MMPP). Should an extended period of higher mission rates be needed of SCOUT, additional resupply missions would be necessary.

Having the necessary replacement parts located in the DM allows for most SCOUT servicing to occur at Gateway. The replacement of the pressure suit gloves is planned to occur approximately every five sorties, based on wear from extended glove use on Hubble Space Telescope servicing missions, or more frequently to accommodate individual glove sizing for different astronauts using SCOUT. The charcoal air filters must be replaced every 30 sorties, and the on-board batteries every year. Contingency servicing would be scheduled as necessary 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.

2.2.2 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. 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 (assumed to be one kilometer from the Gateway station), and one hour of operator breaks interspersed throughout the day. This works out to 240 working hours and 330 total hours of sorties. The end of life for uninterrupted nominal missions occurs at 20 years, at 3300 hours/pod. Nominal translational ΔV for the reference mission was found to be 21.1 m/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 briefly 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 707 m/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 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.

2.2.3 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. The escape system could also be used to return the SCOUT operator to the station if the IBDM fails to successfully dock at the end of the sortie. In this case, SCOUT would be grappled by the station RMS to prevent its loss, and to provide short translations paths for the evacuating crew.

The final bailout system developed will be detailed in the life support section of this paper. Although bail-out failures are designed to be very rare, it is likely that at least one will occur in the lifetime of the SCOUT program. Provisions would have to be made for retrieval and/or deorbit of the abandoned pod to prevent violation of international conventions on orbital debris and uncontrolled deorbit.

2.2.4 Task Operations and Arms - Several task requirements were placed on SCOUT pertaining to operations of the human and robotic arms. Since the reference servicing missions for SCOUT were drawn from experience with International Space Station and Hubble Space Telescope, 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 the design reference tasks from ISS and HST.

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 design specifications. A suited subject in foot restraints is able to create a straight-ahead push with a maximum magnitude of 200N.[3] It was assumed that this number is the maximum required force to insert or extract an ORU.[4] 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 robotic task arm could create was found to be 2620 N.

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 standard grasping interfaces was defined to specify 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 and 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 mounted on the underside of the pod. It is designed to hold the pod in position while withstanding the forces, moments, and torsion created by the task arms, human arms, and other applied loads.

2.3 LIFE SUPPORT AND HUMAN FACTORS - Although all space suits can be correctly described as a "single-person spacecraft that has to bend along with the human body", SCOUT offers some interesting differences of focus in human factors design from a regular suit. While it has fewer suit-like components (and articulations), it has more spacecraft functions, and the complications of three human-controlled robotic arms.

2.3.1 Human Interaction with Work Site - One of the major challenges of the SCOUT design process is the requirement to have the crew member 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 a 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, no prebreathe requirement when operating from ISS or other sea-level pressure spacecraft, 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 feature 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 space suit torso. Figure 3 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.

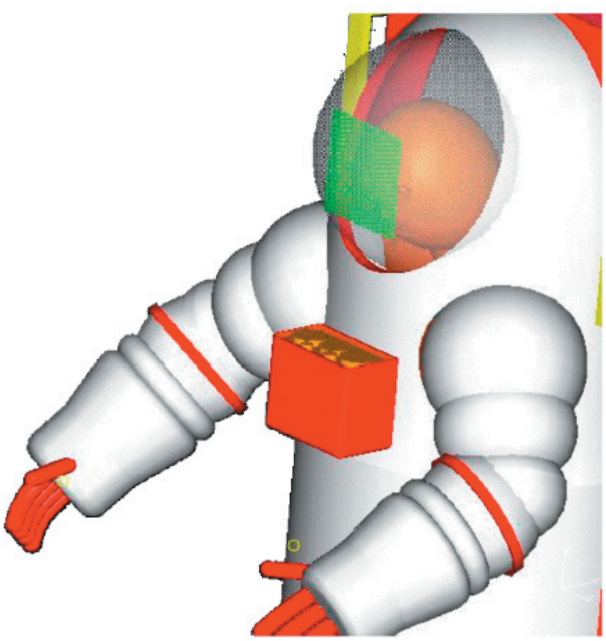

Figure 3
Conformal portion of SCOUT hull with helmet bubble, suit arms, and chest pack

2.3.2 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 nominal atmosphere of SCOUT was chosen as 47% O_2 and 53% N_2.

2.3.3 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 3.1 kg water, 0.45 kg O_2, and 0.3 kg food; over the same time, the operator would on average produce 0.5 kg CO_2, 0.85 kg urine, and 0.11 kg of solid waste.

From the crewmember's oxygen requirement, two standard commercial off-the-shelf (COTS) pressure tanks were used. Used at pressure levels in accordance with NASA design standards for compressed gas tanks, 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. Since exact O_2/N_2 ratios are not safety critical, there is no need for a backup to the nitrogen supply.

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; technological advances in that system will be incorporated in the SCOUT CO_2 reduction system as well to maintain commonality.

2.3.4 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 could bring any desired Gateway food packages that do not need cold storage or heating. NASA-STD-3000 mandates that the crewmember be supplied with 105oz of water for an EVA of equivalent duration to a standard SCOUT sortie; since SCOUT does not have the volume limitations of a traditional suit, any desired amount or variety of drinks could be carried onboard. The baseline plan for waste collection is to provide a smaller version of the Shuttle Waste Contamination System (WCS), although simpler and cheaper options from the Apollo era also exist and should be revisited.

2.3.5 Cabin Layout - The first step in the development of the cabin of SCOUT was to determine an overall total interior volume. Based on accepted heuristics for a single-person spacecraft with SCOUT sortie durations[3], a habitat volume of 2.8 m^3 was selected. After a number of structural trade studies on specific shapes, the design of the cabin came to a hexagon with 0.75 m sides and an interior height of 2.0 m.

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. Figure 4 shows the final design of the internal cabin.

2.3.6 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.

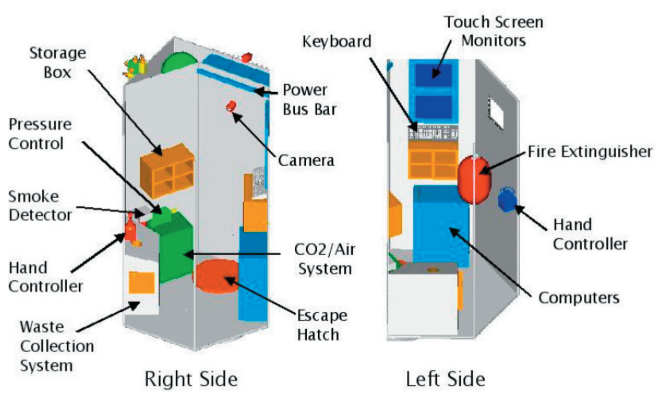

Figure 4
SCOUT internal layout

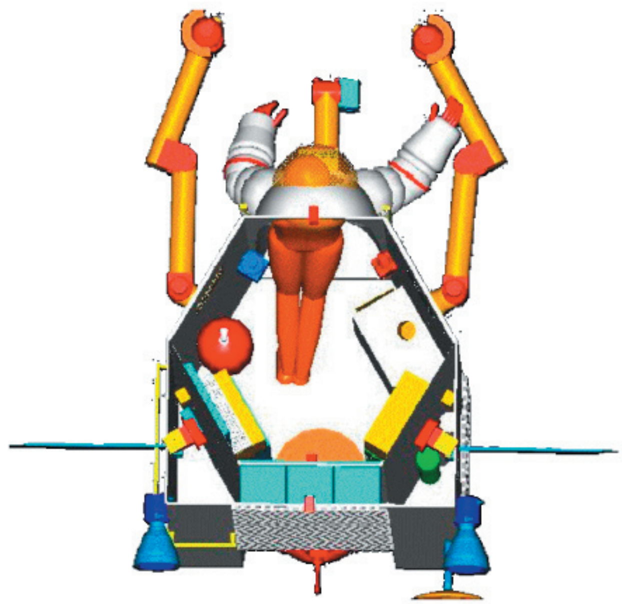

Figure 5
Top view of SCOUT showing operator position for suit arm operations

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

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 depth 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 in the hands-on mode, but they can control the robotic arms and/or vehicle flight control system via the hand controllers and voice command.

2.3.7 Bailout Provisions - One of the revolutionary concepts of SCOUT is that it contains a bailout system. The bailout system is an externally expandable “soft” (conventional fabric) spacesuit. In the event of an emergency, the crewmember would activate the bailout system, which would inflate the bailout suit externally. The crew member would then open the escape hatch, ingress into the escape suit, and shut the hatch, thereby sealing themselves into the bailout system. The escape system will allow three hours of useable atmosphere, supplied by an oxygen tank which is mounted on the suit. This system is planned to operate in a “blow-down” mode similar to secondary oxygen packs on both Apollo and Shuttle portable life support systems. Oxygen will flow through the suit for pressurization and breathing purposes, then will be exhausted through calibrated orifices to carry away CO2 and body heat. The three-hour life support limit is set by the volume of oxygen required for the open-loop breathing system, and was judged to be more than adequate for the design case of a separation limit of one kilometer from the L1 Gateway station. To cover that distance in allowable time, the suit will also incorporate self-rescue propulsion capabilities through a modified version of NASA's Simplified Aid For EVA Rescue (SAFER) System. A notional sketch of the overall system is pictured in Figure 6.

2.4 LOADS, STRUCTURES, AND MECHANISMS - The space suit components of SCOUT dramatically increase the complexity of this section, as there are many more degrees of freedom on this vehicle than on a typical spacecraft. While ensuring that all NASA structural design standards are met, there is also a need to explore inovative design spaces to accomplish the disparate operational requirements in the SCOUT reference mission.

2.4.1 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 mechanisms 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 withstanding all loading conditions.

The SCOUT pod is designed as a two part vehicle. The first part of the vehicle is a load bearing hexagonal pressure hull, 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.

2.4.2 Launching the SCOUT System - As the baseline design case, 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 of the SLP and to the SCOUT pods, DM and XMP. Given the recent announcement of the upcoming termination of the space shuttle program, a clear priority in the near future will be to identify other launch vehicle options that match SCOUT launch requirements.

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.

2.4.3 Loading Configurations - Launch loads were considered to be major inertia loads on the vehicle. Any component over 2 kg 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 = 5.8 g, y = 4.85 g, z = 8.5 g[4]. The vehicle axis conventions are shown in Figure 7.

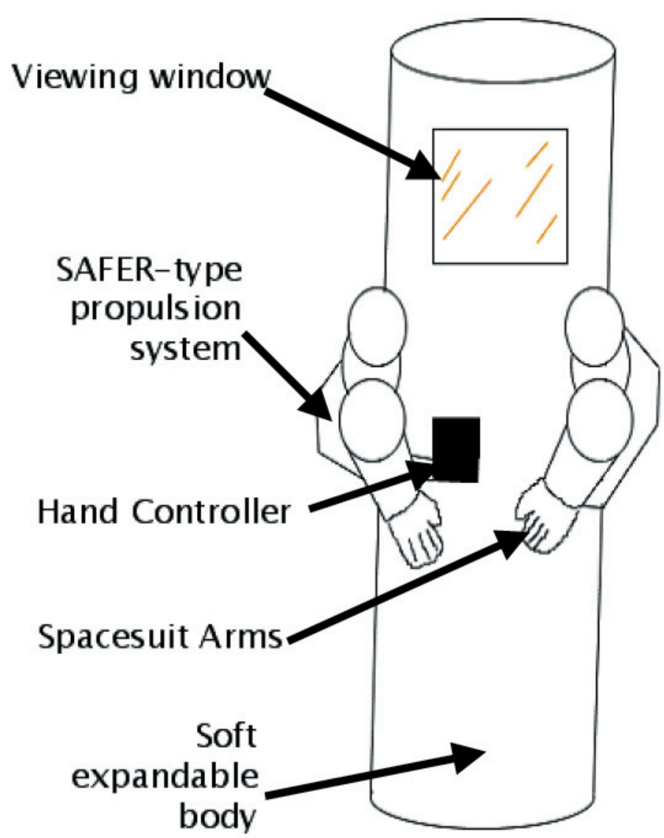

Figure 6
Notional sketch of SCOUT bailout system

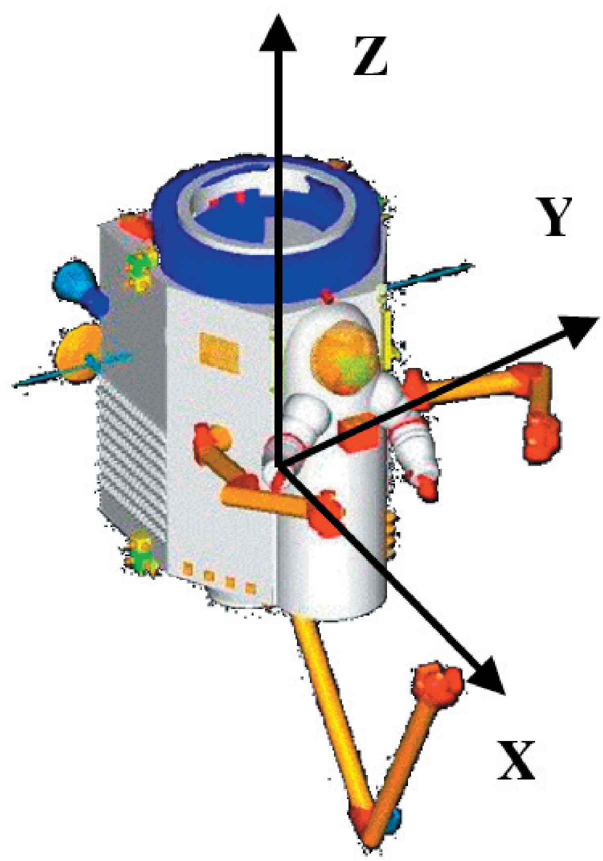

Figure 7
SCOUT coordinate system

During SCOUT operations at the work site, there will be several loading conditions. The SCOUT cabin will be pressurized at 57 kPa. The dexterous manipulators are designed to apply a nominal torque of 52.2 N-m as mentioned previously. This torque, along with the 2620 N 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. Analysis of structural margins has to account for all of these loads being applied simultaneously.

There were some other loading configurations looked at for the SCOUT pod structural analysis. The thrusters produce a 1 N and a 6 N impulse depending on the thruster. When docking, an impulsive load of approximately 120 N for one second was assumed.

2.4.4 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 impacts: meteoroids and orbital debris. Meteoroids are solid particles in space that are of natural origin, whereas orbital debris are man-made objects. 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.[5]

For the purpose of environmental modeling, a micrometeoroid is defined as a particle that has a mass in the range of 10^{-18} to 1.0 g. With currently available technology, a meteoroid protection shielding up to the order of 1 cm in particle diameter, or 1 g in mass, is feasible. Since the probabilistic risk of encountering particles larget than this size is very low,no attempt will be made to shield SCOUT for particles greater than 1 g in mass.

The shielding on SCOUT will be a dual wall system made from 6061-T6 aluminum. The outer wall, or bumper wall, will be 0.06 cm 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 0.24 cm. Between these two walls will be 1cm spacing.

2.4.5 Radiation Protection - Astronauts that are assigned to the SCOUT spacecraft in the baseline mission will have to deal with the radiation levels extant at the L1 point. A radiation shielding protocol was designed based on these values, and the Level 1 mission requirement that no astronaut will exceed a 3% lifetime increase in excess fatal cancer.

Annual radiation 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, 4 g/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 population based on the 15 sorties for the nominal six month mission.

With all the components of the spacecraft being 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 or polyethylene panels, as 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.

2.5 THERMAL CONTROL 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, mounted on the side covers to the unpressurized equipment bays, will radiate the heat into space. There will also be heaters on SCOUT to trim the temperature during colder conditions, as well as crew comfort heaters in the space suit gloves.[6]

The battery subsystem will be controlled thermally by a separate active radiator system. The radiators will radiate heat generated from battery packs using a system of cooling loops and Freon as the working fluid. The pump will circulate Freon through the radiator, mounted on the battery compartment door.

Multi-Layer Insulation (MLI) will be used to keep the fuel tanks within their nominal temperature range. MLI will also surround the spacecraft to help moderate the effect of solar impingement on the vehicle.

2.6 PROPULSION SYSTEMS - 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. This value is based on analysis of maneuvering capability required for the baseline large telescope assembly mission at L1; it is likely that the maneuvering reserve requirements will change if the basing location and reference sortie task sets are modified.

On the SCOUT pod there are sixteen 1 N nitrogen cold-gas thrusters. These thrusters are used for contamination-critical sites, and are set up in four quads. For non-sensitive sites there are sixteen 6 N hydrazine monopropellant thrusters. Figure 8 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.

Both propulsion systems will be designed for routine refuelling at the docking module. Consumables transfer lines in the IBDM will be used for replenishing hydrazine, and for recharging nitrogen pressure tanks for both cold gas propulsion and for hydrazine pressure feed.

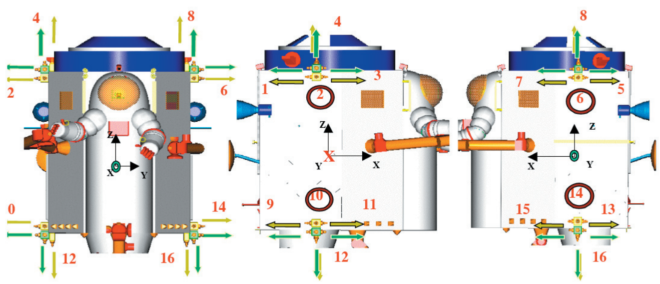

Figure 8
SCOUT thruster locations and orientations

2.7 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, reducing the number of discrete wires in the wiring bundle. 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 accurate attitude information, available whenever either sensor has an unobstructed view and vehicle rates are lower than 10 deg/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.[7] 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 cabin atmosphere partial pressures. 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. Since this is an EVA support system, the avionics system will also be equipped to interface with biomedical sensors for the operator, with real-time relay to mission control on the ground, or to the host station if desired.

Another group of sensors onboard SCOUT is the crew interface equipment. The interfaces for manual flight control are 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 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, 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.

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. 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. Critical vehicle telemetry will be transmitted over both Ka and UHF links, to ensure that basic performance data is logged in the event of a loss of a SCOUT vehicle.

2.8 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 savings over 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. Placing the batteries exterior to the pressurized compartment was done for safety considerations (isolating the operator from the energy storage systems), as well as the need to minimize liens on interior volume from components which could be packaged for vacuum.

As shown in Figure 9, 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.

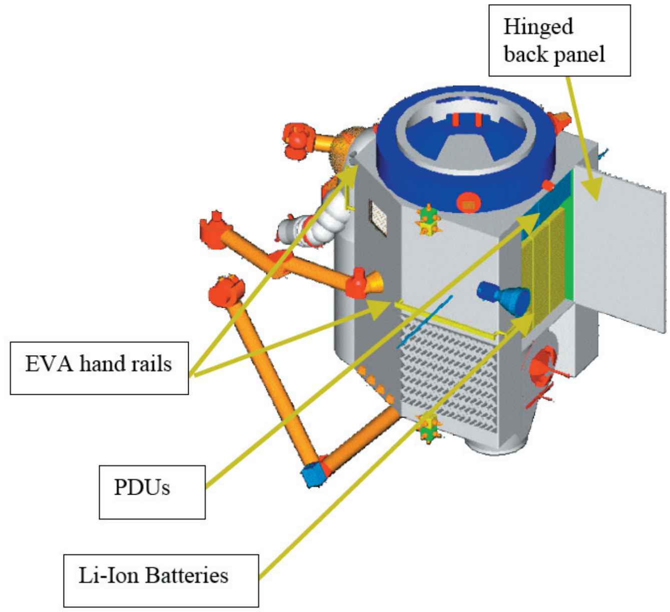

Figure 9
SCOUT batteries and power distribution equipment

3.0 FUTURE RESEARCH DIRECTIONS

3.1 DESIGN REVISIONS - Even in the time since the original team created the SCOUT system described here, events have dramatically changed the programmatic context for SCOUT. The libration-point stations are no longer being actively considered by NASA, in favor of immediate progress towards human missions to the Moon and Mars. The shuttle is planned to fly only in support of ISS assembly, and to be phased out at the start of the next decade. On a smaller scale, additional analysis and concept development have identified areas in which SCOUT might benefit greatly from a “paradigm shift” in the original design approach. These necessary studies will be briefly summarized here.

3.1.1 Expand Reference Missions - Two new directions for SCOUT to consider as early operational applications would be International Space Station and Crew Exploration Vehicle (CEV) operations. The benefit to single-person EVA on ISS, particularly in the current situation of only two long-duration crew, was mentioned earlier. Some issues to be revisited if ISS is the permanent base for SCOUT would include establishing a meaningful baseline for “remote operations”, which can be used to flow down requirements for systems such as propulsion systems and communications requirements.

SCOUT has perhaps the greatest potential to make a contribution in conjunction with the Crew Exploration Vehicle, launched on an evolved expendable launch vehicle (EELV). Assuming CEV will be similar to Apollo, there will be little capability for continuing the stellar shuttle heritage in spacecraft servicing from CEV, due to the lack of any serving support infrastructure. If, however, a SCOUT pod were to be launched with CEV on servicing flights, SCOUT could perform the servicing activities with

CEV standing by in a support role. In one concept, SCOUT would be launched below CEV in a manner analogous to the Apollo lunar module. CEV transposition and docking after orbital insertion would allow crew to enter SCOUT and use it for orbital servicing and assembly operations. (It should be noted that it is quite likely that CEV will be designed using the IBDM as its standard docking interface.) CEV and transport stages could take the place of the extended mission pallet, supporting SCOUT for operations throughout cis-lunar space in support of advanced exploration missions.

3.1.2 Modifications to Configuration - Based on both new analysis and changes to baseline missions described above, some of the major configuration decisions on SCOUT might be beneficially revisited. Should the lower base mounting of the grappling arm and the escape suit be changed to allow another IBDM? This would provide alternate crew shirtsleeve egress in the event of a primary IBDM failure. It also allows a CEV/SCOUT pair to dock to a space station or exploration vehicle, rather than SCOUT usurping the only CEV docking interface. Is there a way to add “mission kits” and to adopt a more modular approach to SCOUT configurations, in order to adapt to the widest possible range of missions? Should SCOUT be “space based”, or launched from Earth on specific missions? Is there a way to recover and reuse the spacecraft? It is important to design SCOUT to be a system in an overall “system of systems”, and to examine SCOUT design choices in the context of optimizing the overall program, rather than a single vehicle design.

3.1.3 Modifications to Subsystems - As designs evolve, subsystem specifications will change, and choices of subsystem components need to be reexamined. How necessary is a hydrazine or other “hot gas” propulsion system, and what operational inplications are there in its use? If SCOUT is only used around ISS and in the immediate vicinity of CEV, which has its own high-capacity propulsion system, perhaps a pure cold-gas approach would be more logical for SCOUT? How would launch vehicle interfaces change when SCOUT moves from a shuttle to an EELV launch vehicle? As SCOUT is applied at more locations in space, what crew displays and controls are necessary? How does the communications systems adapt to continuously changing locations?

3.2 EXPERIMENTAL INVESTIGATIONS - Although “man-in-a-can” system concepts are documented as early as the late 1940’s, evidently nothing has ever been done experimentally in support of the concept. There is no record of any organization ever building a laboratory or simulation model, or even a foam-core mockup for engineering visualization purposes. The University of Maryland Space Systems Laboratory has a long history of low-cost, innovative experimental research into novel EVA and robotic systems, and has been planning an initial series of experimental investigations in support of the SCOUT concept.

3.2.1 Cabin Layout and Operations - This is perhaps the most critical near-term investigation, as the cabin size and configuration drives the overall size of the spacecraft, which in turn controls launch opportunities and bottom-line costs. Can the operator move quickly and easily between a posture with both arms in the suit arms, to an alternate body position when using hand controllers to fly the vehicle or to manuver the robotic arms? Is there sufficient room to “flip around” to reach the lower levels of the cabin without getting stuck or hitting instrument panels? Does the bubble helmet provide sufficient visibility in all tasks, or would the design be improved by incorporating external cameras and video controls, or more windows, or a combination of both?

To begin to explore these questions and others, the SSL is developing a low-fidelity simulation of the SCOUT pressure hull for neutral buoyancy simulations. The simple plywood shape (Figure 10) will be used underwater to assess limits of operator motion, fields of view, and external situational awareness.

3.2.2 Robotic Control - One of the most interesting research questions to grow out of the SCOUT design is how to control three dexterous robotic arms while allowing the use of the suit arms at the same time. The same structure described above will be used (both in the laboratory and underwater) in conjunction with existing

Figure 10
Initial test assembly of low-fidelity SCOUT internal volume neutral buoyancy simulator

SSL dexterous manipulators to investigate the use of various control modalities for robotic manipulation. These will include gestural master-slave control, voice recognition, and simple point-to-point proprogrammed motions. This test series will also examine the use of an external human controller to coordinate with the SCOUT operator to perform dexterous tasks, both with and without representative time delays.

3.2.3 Mission Performance - Ultimately, the goal is to obtain unequivocal data from ground-based simulations on the effectiveness of the SCOUT concept, in order to make an informed decision on whether or not to press to flight demonstrations. To do this, two "all-up" simulators will be necessary. The first is a pressurized air-filled system, capable of both laboratory and underwater operations. This system will be used to understand the limitations of suited activities when built into the SCOUT pressure cabin, and will permit end-to-end simulations of manipulative operations (both manual and robotic). However, making this system neutrally buoyant will require a vehicle mass on the order of 3000 kg. Since the operator will be in a full gravity field internally, any motion of the human will move the system center of gravity away from the center of buoyancy, causing unacceptable buoyancy-induced rotations. For this reason, this system will only be able to operate underwater when externally fixed in position, and neutrally buoyancy task elements will be manipulated in relation to SCOUT.

The second vehicle would be an alternative neutral buoyancy vehicle, which is filled with water and pressurized to the same differential pressure as the air-filled vehicle. This system will provide a neutrally buoyant environment for the operator, allowing full translation and rotational motions for the SCOUT vehicle underwater. Differential pressurization allows the use of suit arms in a manner identical to the air-filled unit. Clearly, the test subject will have to be supplied with self-contained air systems, and controls and displays internal to the vehicle will have to be independently waterproofed. A similar approach as taken with an neutral buoyancy suit simulator developed for the European Space Agency; this is just a larger scale for the same concept. This system, though, will be invaluable for understanding body motions in support of free-flight and manipulative operations, and will be more representative of end-to-end human operations than the air-filled simulator.

4.0 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 or check the archival web site (http://spacecraft.ssl.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.

5.0 ACKNOWLEDGEMENTS

The authors, who were the instructors for the ENAE 484 course, would like to express their sincere thanks and appreciation to the students who did the bulk of the engineering design work documented here over the course of the Spring 2003 semester: Cagatay Aymergen, Meghan Baker, Matthew Beres, Christopher Bowen, Kathryn Catlin, Jason Christy, Jesse Colville, Avi Edery, Wendy Frank, John Hintz, Kirstin Hollingsworth, Aaron Hoskins, Robyn Jones, Alexandra Langley, Andrew Long, Sadie Michael, William Miller, Nathan Moulton, Lynn Pierson, Jacqueline Reilly, Justin Richeson, Eric Rodriguez, Oliver Sadorra, Ernest Silva, Gregory Stamp, Christopher Work, Yudai Yoshimura

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