

BioBot: Innovative Offloading of Astronauts for More Effective Exploration

NIAC Phase I Final Report

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Introduction

No parameter in the design of spacesuits for planetary exploration is more important than “weight on the back”: the weight of the suit system which must be supported by the wearer under the gravity of the Moon or Mars. The added weight of the spacesuit garment and portable life support system (PLSS) drives the required exertion level of the wearer, and ultimately sets limitations on EVA duration, distance traveled on foot, and productivity of the exploration mission.

As an example, the A7L-B suits worn on the later Apollo lunar missions had an Earth weight of 212 lbs, composed of 77 lbs for the garment assembly and 135 lbs for the PLSS. A 160 lb astronaut found their weight increased by 130% due to the suit, with the PLSS weight alone almost equal to his body weight. This system was capable of supporting a 6-hour nominal surface EVA, but strongly impacted the gaits, transport speeds, and energy expenditures of the astronauts. The PLSS weight was particularly burdensome, as it moved the astronaut's overall center of mass upwards and backwards. This could be seen in the convoluted motions of the crew when trying to bend over and pick up items, work with the long-handled sampling tools, or just maintain balance, especially when changing direction or starting and stopping.

Short-distance, short duration EVAs in microgravity have used umbilicals rather than PLSS units. This relieved the crew from the bulk and mass of the PLSS, at the cost of needing to control the motion of the flexible umbilical. For the deep-space EVAs of the J-class Apollo missions, one crewman would translate aft on the service module to retrieve film canisters, while another would be stationed in the command module hatch to handle the umbilical. Although umbilicals were briefly considered for the first Apollo surface missions, they were rejected due to the operational limitation of being tethered to the spacecraft, and the overhead burden of handling umbilical motions.

It is clear that planetary surface exploration activities would be greatly improved if the astronauts did not have to carry a PLSS to maintain life support functions. At the same time, additional restrictions on crew mobility or operational capabilities would be unacceptable. The concept for

this study is to accomplish these two seemingly conflicting requirements through the application of advanced robotic systems to deal with biological requirements (i.e., life support) for the astronauts: the “BioBot”.

The BioBot concept consists of a robotic rover which is capable of traversing the same terrain as a spacesuited human. It carries the primary life support system for the astronaut, including consumables, atmosphere revitalization systems (e.g., CO₂ scrubbing, humidity and temperature management, ventilation fan), power system (e.g., battery, power management and distribution), and thermal control system (e.g., water sublimator, cooling water pump), along with umbilical lines to connect to the supported astronaut. Although not technically part of life support, it would be logical for the BioBot to also provide long-range communications, video monitoring, tool and sample transport, and other functions to enable and enhance EVA productivity in planetary surface exploration.

The design reference scenario for this concept is that astronauts involved in future lunar or Mars exploration will be on the surface for weeks or months rather than days, and will be involved in regular EVA operations. It is not unreasonable to think of geologists spending several days in EVA exploration each week over a prolonged mission duration, with far more ambitious operational objectives than were typical of Apollo. In this scenario, each astronaut will be accompanied by a “BioBot”, which will transport their life support system and consumables, an extended umbilical and umbilical reel, and robotic systems capable of controlling the position and motion of the umbilical (Figure 1). The astronaut will be connected to the robot via the umbilical, carrying only a small emergency open-loop life support system similar to those contained in every PLSS. The robotic mobility base will be designed to be capable of traveling anywhere the astronaut can walk, and will also be useful as a transport for the EVA tools, science instrumentation, and collected samples. In addition, the BioBot can potentially carry the astronaut on traverses as well. Such a system will also be a significant enhancement to public engagement in these future exploration missions, as the robotic vehicles can also support high-resolution cameras and high-bandwidth communications gear to provide high-definition video coverage of each crew throughout each EVA sortie.

There are also architecture-level benefits to this concept. For example, in the drive to reduce suit weight to the absolute minimum due to the load of the PLSS, design elements which would enhance suit mobility (such as low-friction rotary bearings) are frequently deleted, resulting in a lighter but less flexible suit enclosure. By offloading the life support system electrical power and consumables, the relatively meager increase in garment mass to incorporate these mobility features would be



Figure 1: Notional Image of BioBot Concept

[The graphical image shows a spacesuited astronaut on a planetary surface, connected to a four-wheeled rover by a flexible umbilical. The astronaut wears no backpack, as the life support systems are on the rover.]

easily accommodated, resulting in not only a lighter, but also more flexible spacesuit system with an overall center of gravity very close to that of the wearer's body. Since the PLSS weight restrictions would be negated by placing the system and its consumables on an accompanying robot, the overall EVA system could easily adapt to longer sorties, higher capacity astronaut cooling systems, or higher levels of redundancy to enhance crew safety and minimize the possibility of a loss-of-crew event. When no longer constrained to fit within the mass and volume constraints of a spacesuit backpack, portable life support designers can consider technology alternatives better suited to extended exploration, such as radiators for cooling, solar panels to extend electrical power, or regenerable CO₂ scrubbing systems.

This document is the final report for NASA Grant 80NSSC18K0875, detailing the research performed on the BioBot concept as a result of a Phase I award under the NASA Innovative Advanced Concepts (NIAC) program. This activity was performed over nine months in 2018-2019.

Systems Design Trade Studies

An initial priority for the BioBot team was to explore the widest possible design space for the system. Since the BioBot represents a new category of system in an EVA surface exploration scenario, it was important to conceptualize as many different types of systems as possible, and compare them to select the most favorable design concept for further development.

As a way to better understand the design space, the BioBot team worked with different teams from a University of Maryland graduate course in Planetary Surface Robotics to produce detailed designs for six configurations of BioBot, based on size and functionality:

- (a) Minimum possible robot, capable of carrying only astronaut life support system and umbilical tending system (Figure 2)
- (b) Similar to (a) but also capable of transporting geological tools and samples (Figure 3)
- (c) Similar to (b) but including the capacity to nominally transport one EVA crew as well (Figure 4)
- (d) Similar to (c) but also including the capability to transport a second EVA crew as a contingency (Figure 5)
- (e) Two-person roving vehicle with dual life support systems and umbilical handling systems (Figure 6)
- (f) Two-person pressurized rover (e.g., NASA Space Exploration Vehicle) with dual life support systems and umbilical handling systems (Figure 7)

It should be noted that, as the umbilical handling technology development was being performed in parallel, these vehicle studies focused on trafficability, using a common requirements document based on assumed operational limits for regions accessible by walking EVA crew: slopes up to 30°, obstacles up to 30cm in height, and soil bearing parameters based on data from both lunar and Mars exploration missions. Top-level mass and volume requirements were given to the design teams to accommodate the design of mounting locations for life support and umbilical handling systems.

The parallel design efforts showed clearly that the BioBot concept could be implemented successfully across the entire spectrum of mobility system sizes and mission applications. The

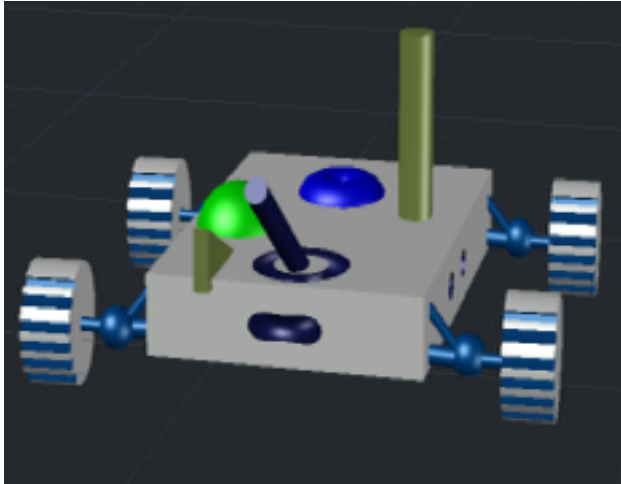


Figure 2: BioBot configuration (a) — transport of life support hardware only
[The CAD image shows a four-wheeled rover with a simple representation of two robot arms for manipulating the astronaut's umbilical.]

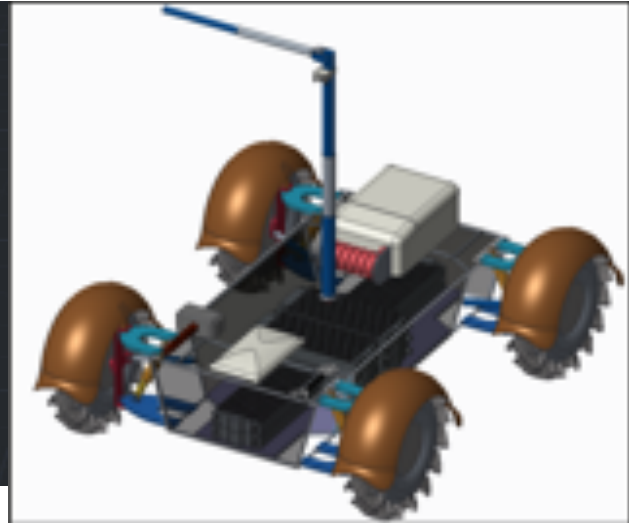


Figure 3: BioBot configuration (b) — life support and EVA equipment transport
[The CAD image shows a four-wheeled rover carrying various pieces of equipment and an umbilical handling robot arm.]



Figure 4: BioBot configuration (c) — single EVA crew transport
[The CAD image shows a six-wheeled rover with a seat for an astronaut, several pieces of equipment including one large box for life support, and an umbilical handling robot arm..]

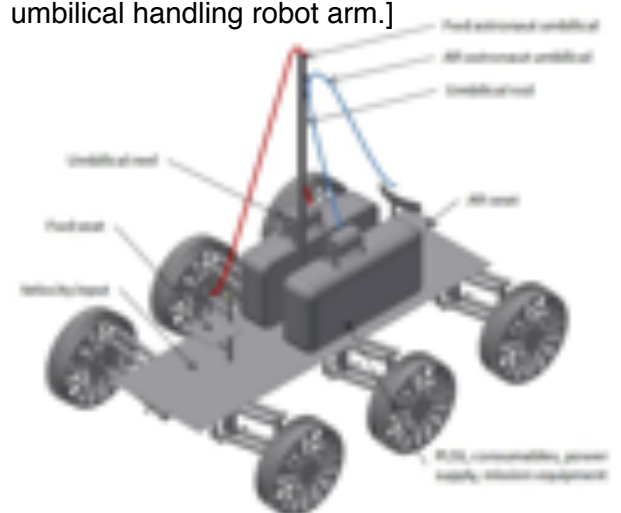


Figure 5: BioBot configuration (d) — transport of one EVA crew nominally, two in a contingency
[The CAD image shows a six-wheeled rover with two seats, one facing each end of the rover, and two umbilical handling robots, along with two life support systems.]

larger configurations — (e) and (f) — presented additional concerns in terms of multiple umbilical handling systems on the same vehicle, which could give rise to interference issues if the crew traverses were not carefully monitored to prevent collision of the umbilical handling systems with each other or with large elements of the rover, such as the pressurized cabin in (f).

To that end, an extensive trade study was undertaken to create a number of suit-mounted life support (SMLS) designs of varying duration and capabilities, in order to understand the relationship between SMLS usage and installed weight on the suit. While a nominal life support system would be based on a closed-loop design to minimize oxygen usage, short-duration suit-mounted systems (such as the Apollo and EMU secondary oxygen systems) are designed for open-loop use of oxygen for both breathing and gas cooling of the crew. The simplicity of an open-loop system minimizes mass on the suit, and the independent oxygen supply can be designed to be replenished during the time the crew is tethered to BioBot, eliminating restrictions on the number of times or cumulative duration of usage of the independent system. However, in longer durations it is more effective to return to a closed-loop system; if independent duration is long enough to allow substantial distances from the EVA crew to BioBot, it would even make sense to run a split system with a closed loop primary life support and a secondary open-loop system for contingencies. At this point the weight of the SMLS becomes similar to that of the current PLSS concepts, and use of the BioBot would have to be based on other considerations than reduction of total suit weight.

Primary Objectives: For the life support duration study, there were some key objectives that drove the designs of the various life support configurations. Two of the primary goals of this study included:

- **Minimum Mass:** Determine the minimum amount of additional life support that should be used for the suit-mounted life support (SMLS) system and the corresponding mass estimation. For this objective, a goal of developing a functional, stand-alone system between 12.9 kg – 25.6 kg was established. The reasoning behind these values is because according to [6], 25 – 30% of a person’s lean body mass can be carried (comfortably) throughout the day. According to [7], a 5th percentile female has a mass of 49.9 kg, and a 95th percentile male has a mass of 97.98 kg; these values served as the lower and upper bounds respectively for a crew member’s mass. Taking the upper limit of percentage of lean body mass, a person can, with reasonable comfort, carry per day (30%) yields a target SMLS mass between 15.0 kg – 29.4 kg. Since astronauts are physically fit, it was assumed that 86-87% of their body mass (for women and men, respectively) is considered lean mass as this is in the range of “athletes” from American Council on Exercise (ACE) body composition breakdown for percent body fat norms [8]. This reduces the target range between 12.9 kg – 25.6 kg. With the current technology, it is not possible to develop a full portable life support system (PLSS) capable of a full day’s worth of life support (approximately six - eight hours) within this target mass range, but reduced duration options were deemed possible.
- **Modularity:** Develop multiple configurations that could be used depending on the EVA type. The modular design objective was accomplished by building upon the base minimum mass design, and adding components/features (cooling, CO₂ scrubbing, etc.). The mission parameters to be considered include planned untethered operations, close proximity operations, and surface exploration activities. There were two primary Extravehicular Activities (EVA) categories that were considered when developing the various SMLS concepts: short duration/distance EVAs (any mission less than two hours or any mission in which the crew remains less than .75 km from the habitat), and long duration/distance EVAs (any mission greater than two hours or any mission in which the crew will travel beyond .75

km from the habitat). Any SMLS configuration beyond the two hour mark led to designs that either should operate in closed loop mode, or hybrid mode (a combination of open loop and closed loop modes) due to mass/volume constraints. Shorter range operations such as routine maintenance on BioBot or the habitat, installation of other equipment within close proximity of the habitat, etc. would require less additional life support for the astronaut since the amount of untethered time from the crew member’s BioBot would be brief, if at all. However, for surface exploration missions, the astronaut may require additional life support for extended planned untethered time from BioBot if the areas to be explored are not accessible by BioBot. The purpose of having a modular PLSS design is so that the astronaut will not have to be burdened with the mass of additional life support that would remain unused. This will ensure the astronaut is only carrying the amount of life support required so that he/she can focus more on the EVA tasks while reducing overall energy expenditure. The claim that reduced mass PLSS options reduce the energy expenditure by the crew is planned to be evaluated in future field tests.

Prior to determining which components would be necessary for each configuration, a review of various PLSS designs was conducted in order to understand what has been done in the past, and what the plans are for the future. The configurations presented in this paper are hybrids of the Apollo EMU and the new Advanced Extravehicular Mobility Unit (AEMU). Each configuration builds upon itself, starting with the C1 series configuration which has only the absolutely necessary components for a short duration functioning life support system, all the way through the full SMLS configuration C5 series options. Having the different configurations allow for greater flexibility and customization for each mission type. Each BioBot will be equipped with two life support systems, each with enough life support for an eight-hour work day. Every crew member will also carry their own life support system, but the crew will have multiple options to choose from based on the Extravehicular Activity (EVA) mission type. The options presented allow for flexibility in terms of overall SMLS structure mass, volume, and life support duration, all of which can be customized. A summary of each of the additional life support configurations can be seen in Table 1 below.

Table 1: Suit-mounted life support (SMLS) system reference configurations

Configuration	Mass [kg]	Backpack Height (cm)	O ₂ Available [kg]	O ₂ Flow Rate [kg/hr]*	Life Support Duration [min]	Standard Operating Mode
C1.1	18	22	1.2	3.7	20	Open Loop
C1.2	21	22	2.4	3.7	40	Open Loop
C2.1	28	30	1.2	1.9	80	Open Loop
C2.2	31	30	2.4	1.9	120	Open Loop
C3	44	43	1.0	1.2	240	Closed Loop
C4.1	55	60	2.2	1.2/1.9	280	Closed/Open
C4.2	58	60	3.4	1.2/1.9	320	Closed/Open
C5.1	61	60	2.2	1.2/1.9	400	Closed/Open
C5.2	65	60	3.4	1.2/1.9	440	Closed/Open
C5.3	68	60	4.6	1.2/1.9	480	Closed/Open

*Values based on standard operating pressures from references.^{1,3}

Mass estimation values for each configuration were determined by establishing the necessary components for the configuration to be functional, and then finding components that met the loop specifications outlined in [2], as most of the sub-systems were based on those for the AEMU. The structure size is one way in which the various SMLS configurations are modular and mass/volume efficient. Since certain mission scenarios may not require the standard full size PLSS, it makes sense to have smaller SMLS housing structures for configurations with less equipment. Smaller structures not only reduce the overall mass, but are also less cumbersome/bulky, allowing the crew to focus more on the task at hand; the idea of reducing structure/packing mass has been investigated before, as evident from [4]. Each structure option has the same width and depth dimension, and only varies in height/length. The width and depth dimensions for all of the structure configurations are .50 m and .22 m respectively. The S1 configuration has a length of .22 m, followed by S2, S3, and S4 lengths of .30 m, .43 m, and .60 m respectively.

The oxygen flow rate values in the table were determined from [1] and [3], as these were the approximate flow rate values used in the Apollo PLSS Oxygen Purge System (OPS) and primary oxygen loop flowrate values for the AEMU. The standard operation column is for indicating if the SMLS operates in an open loop mode, closed loop mode, or hybrid. The mass ranges for the additional life support range from 20 minutes of additional life support at 18 kg to 480 minutes of additional life support with a PLSS mass of 68 kg. The various configuration options are described below, and the mass vs. duration plot for each configuration outlined in Table 1 can be seen below in Figure 8.

Configuration 1 (C1): The C1 configurations have the same components as the Apollo Oxygen Purge System (OPS). The primary components in the OPS include a heater for controlling the oxygen temperature, battery for the heater, pressure regulator, and oxygen tank(s) as outlined in [1]. The original Apollo OPS could support a range between 30 minutes of oxygen and 75 minutes of oxygen, depending on whether or not the Buddy Secondary Life Support System (BSLSS) was in use [1]. If the BSLSS was not in use, the oxygen flow rate for the OPS was 8.3 pounds per hour (3.7 kilograms per hour), but if the BSLSS was in use, the oxygen flow rate in the OPS was 4.2 pounds per hour (1.9 kilograms per hour) [1]. The higher 3.7 kg/hr oxygen flow rate is sufficient to satisfy the astronaut's breathing, cooling, and suit pressurization requirements [1]. Since the BSLSS could be used to cool the astronaut, a reduced oxygen flow rate could be used, allowing for an increase in OPS life support duration time [1]. The C1 configurations for this design do not have a cooling system, and so the oxygen flow rate for all of the C1 configurations is 3.7 kg/hr, which was determined to be an acceptable value based on [1]. The difference between each C1 sub-configuration (C1.1 and C1.2) is related to the number of oxygen tanks present, as each small oxygen tank can provide 20 minutes of additional life support. The C1.1 configuration (Figure 9) has one oxygen tank and the C1.2 configuration (Figure 10) has two oxygen tanks, allowing for an additional 40 minutes of life support. Like the original Apollo OPS, the C1 configurations operate in a fully open loop/purge mode. Because less components are required for the C1 options, they are the least massive options, resulting in a total mass of 18 and 21 kg for the C1.1 and C1.2 configuration, respectively. Both of these configurations are within the goal SMLS range of 12.9 kg – 25.6 kg.

Configuration 2 (C2): The C2 configurations have the same components as the C1 configurations, but each sub-configuration also has the addition of a thermal loop. The thermal

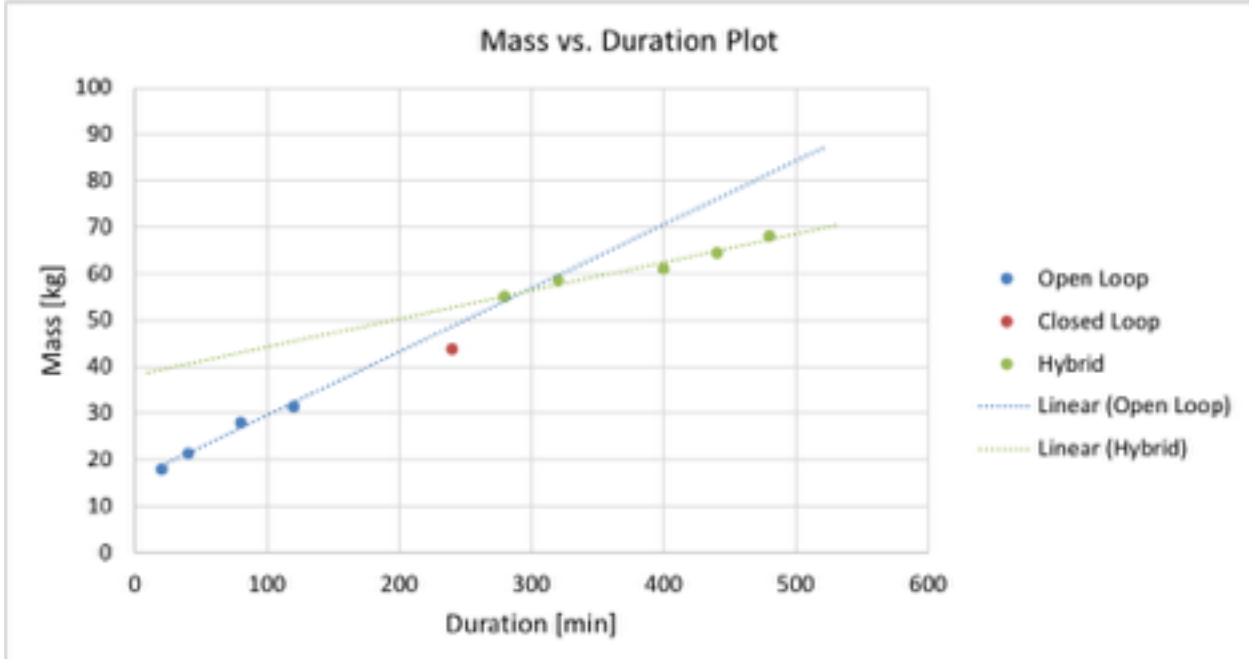


Figure 8: Suit-mounted life support (SMLS) system reference configurations

[The graphic is a linear plot of duration of the life support system on the horizontal axis and suit-mounted life support system mass on the vertical axis. The graph shows that the lowest mass solution for short duration systems is an open-loop system using oxygen for both breathing and user cooling. For longer duration systems, it is more mass efficient to use closed-loop systems with a separate cooling system, or a hybrid system that uses cooling but can become open loop following a failure. The cross-over duration between the two system occurs at about 300 minutes.]

loop design used for these configurations is based on the Auxiliary Thermal Control Loop (ATCL) for the AEMU, which is described in [2]. The primary components in the ATCL are a pump, stepper motor, sensors, relief valves, water tank/water, and tubing to circulate the water.

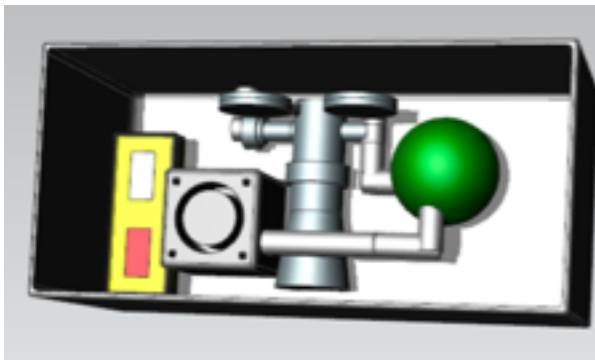


Figure 9: Internal view of suit-mounted life support (SMLS) system configuration 1.1

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 22cm. It contains a heater, battery, pressure regulator, fan, and a single oxygen bottle.]

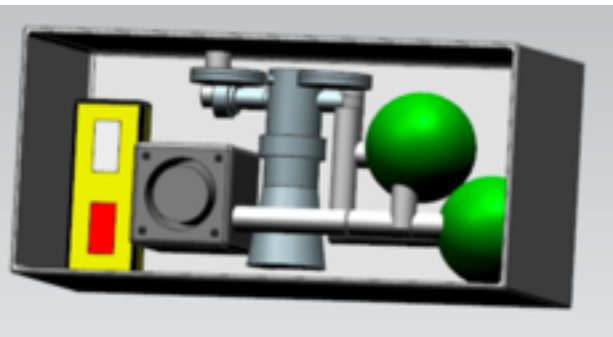


Figure 10: Internal view of SMLS system configuration 1.2

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 22cm. It contains a heater, battery, pressure regulator, fan, and two oxygen bottles.]

The ATCL for the AEMU operates the same as the primary thermal control loop in the AEMU, but provides cooling for a reduced time of 60 minutes [2]. The water tank in the auxiliary thermal control loop used in the C2 configurations is designed to store approximately .3 kg of water for 120 minutes of cooling, which was based on [1]. The equivalent OPS will operate in the same manner as outlined for the C1 configurations, except instead of regulating the oxygen flow at 3.7 kg/hr, a reduced flow rate of 1.9 kg/hr will be used. Because a cooling system is included in this configuration, a reduction in flow rate is acceptable based on [1], as the oxygen flow is now only serving as breathable oxygen and suit pressurization, and does not need to serve as the cooling function as well. The C2.1 (Figure 11) and C2.2 (Figure 12) configurations provide up to 80 minutes and 120 minutes additional life support, and have a mass of 28 kg and 31 kg, respectively.

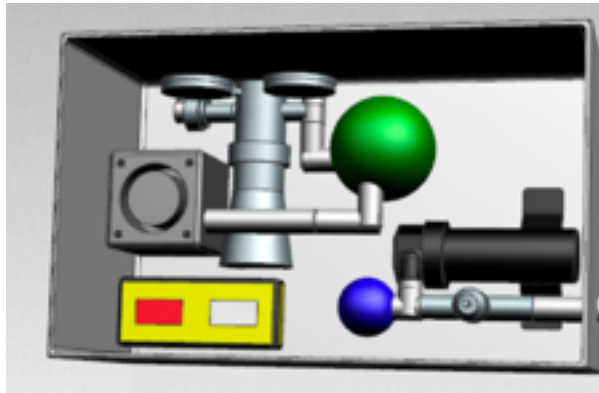


Figure 11: Internal view of SMLS system configuration 2.1

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 30cm. It is equivalent to configuration 1.1 with the addition of a thermal control loop.]

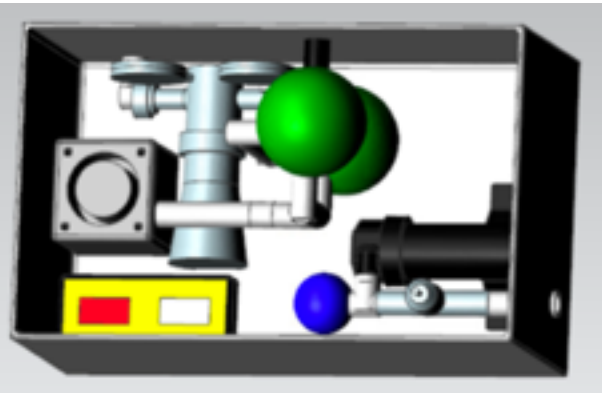


Figure 12: Internal view of SMLS system configuration 2.2

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 30cm. It is equivalent to configuration 1.2 with the addition of a thermal control loop.]

Configuration 3 (C3): The C3 configuration switches from operating in an open loop mode to a closed loop mode. The reason for doing so is due to mass and volume constraints. While the C1 and C2 configurations are mass efficient for shorter duration (less than 120 minutes of additional life support) missions, adding additional oxygen and tank storage beyond that did not result in significant mass savings, and continuing to add extra oxygen/oxygen tanks would not be efficient from a volume perspective. The C3 configuration (Figure 13) combines aspects from the AEMU design, and utilizes a primary oxygen loop, thermal loop (TL), and oxygen ventilation loop [2]. The main difference between this configuration and the AEMU is that it does not include a secondary oxygen loop (also known as a secondary oxygen assembly) for redundancy for the primary oxygen loop, nor does it include an ATCL for redundancy for the TL like the AEMU does [2]. However, the rest of the configuration operates much like the AEMU, with the primary oxygen loop providing breathable oxygen and suit pressurization, the TL providing cooling for the astronaut, and the oxygen ventilation loop providing CO₂ washout capabilities and contaminant removal capabilities [2]. The primary oxygen loop consists of several components with the main ones being pressure regulating valves, pressure vessel, pressure transducers, motor, and the necessary tubing for the loop; these components were determined by looking at

the AEMU schematics in [2]. The primary components of the oxygen ventilation loop include the Rapid Cycle Amine (RCA), check valves, a controller to regulate airflow for monitoring CO₂ levels, relief valves, motor, and necessary tubing for the loop, as outlined for the AEMU [2]. Most of these components are standard for an oxygen ventilation loop, but one important design choice that was using an RCA as opposed to LiOH canisters, which were used during Apollo. The thermal loop has essentially the same components as the auxiliary thermal control loop, with the primary difference being the water tank sizing/amount of water of stored. For this configuration, the water tank can hold .9 kg of water, which is sufficient for up to 360 minutes of cooling (the thermal loop in the various SMLS concepts presented is designed to cool for 75% of a full day's worth of cooling (~eight hours), and the auxiliary thermal control loop is intended to supply the remaining 25%), based on [1]. The C3 configuration has a mass of 44 kg, housed in structure S3, and can be used to supply up to an additional 240 minutes of life support.

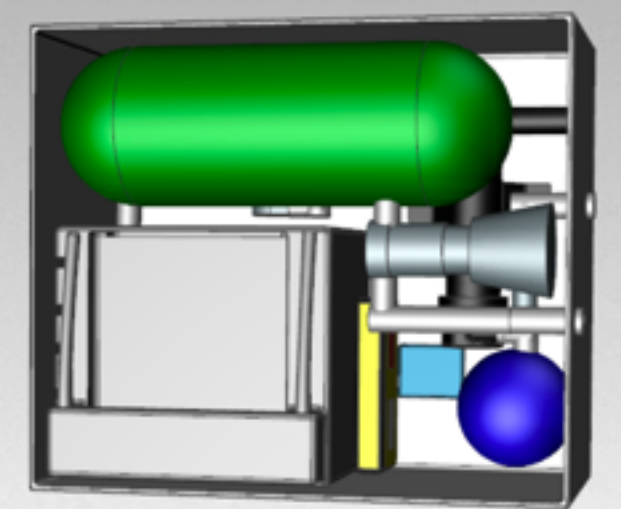


Figure 13: Internal view of SMLS system configuration 3

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 43cm. It is equivalent to configuration 2.1 with the addition of a primary oxygen tank, CO₂ scrubber, and a closed-loop control system.]

Configuration 4 (C4): The C4 configuration is a combination of the C2 and C3 configuration. The C4 series options have a primary oxygen loop, thermal loop, and an oxygen ventilation loop similar to the AEMU [2], and an oxygen purge system similar to the Apollo PLSS [1]. The primary oxygen loop, thermal loop, and oxygen ventilation loop all operate in a closed loop mode, and can support a minimum of an additional 240 minutes of life support on its own, as it is equivalent to the C3 configuration. Similar to how the AEMU will operate, once the space suit pressure drops below a certain value (~3.8 psi), the redundant life support system will be activated, which in this case is the open loop OPS [3]. The thermal loop cooling is designed for up to 360 minutes of cooling, so once the OPS is activated, the OPS can be used in conjunction with the thermal control loop, allowing the OPS to operate with the reduced flow rate of 1.9 kg/hr. Similar to the C3 configuration, the primary oxygen loop will operate with an oxygen flow rate of 1.2 kg/hr [2]. For the C4.1 (Figure 14) and C4.2 (Figure 15) configurations, the OPS can provide up to an additional 40 minutes and 80 minutes of life support respectively, totaling 280 minutes of life support for the C4.1 configuration, and 320 minutes of life support for the C4.2 configuration. The total mass for the C4.1 configuration is 55 kg, and the total mass for the C4.2 configuration is 58 kg, which are both housed in structure S4.

Configuration 5 (C5): The C5 configurations are the same as the C4 configurations, except there is the addition of the auxiliary thermal control loop, which was used in the C2 series configurations. The addition of the auxiliary thermal control loop extends the cooling capacity allowing for longer EVAs. The addition of the auxiliary thermal control makes the C5

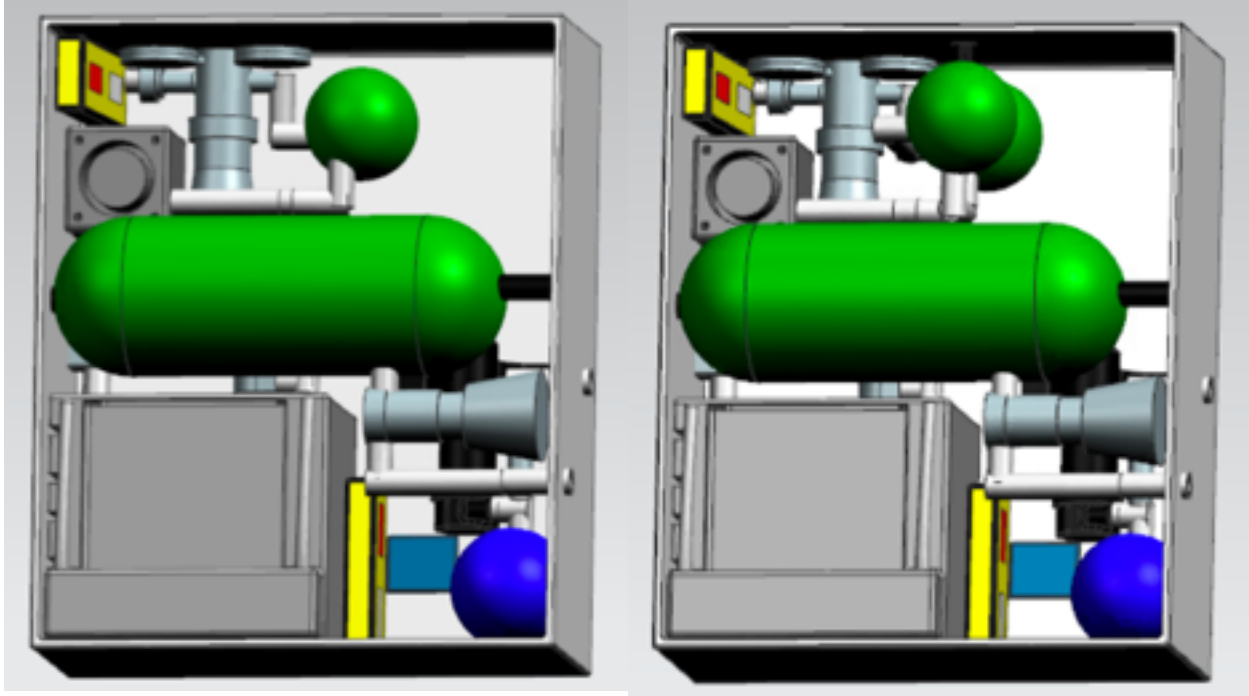


Figure 14: Internal view of SMLS system configuration 4.1

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 60cm. It is equivalent to configuration 3 with the addition of a secondary oxygen tank for use as an open-loop backup system.]

Figure 15: Internal view of SMLS system configuration 4.2

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 60cm. It is equivalent to configuration 4.1 with the addition of a second secondary oxygen tank.]

configuration analogous to the AEMU described in [3], with the primary difference being an OPS is used rather than a secondary oxygen loop/secondary oxygen assembly for the redundant system. Similar to the C4 configurations, the flow rate for the oxygen in the primary oxygen loop is 1.2 kg/hr in closed loop mode, and the flow rate for the OPS in open loop purge mode is 1.9 kg/hr. The C5.1 configuration (Figure 16) will provide 360 minutes of life support from the primary oxygen loop, plus an additional 40 minutes of life support from the OPS, totaling 400 minutes of additional life support. The C 5.2 (Figure 17) and C 5.3 (Figure 18) configurations provide the same 360 minutes of life support from the primary oxygen loop, plus an additional 80 minutes and 120 minutes of life support from the OPS, totaling 440 minutes and 480 minutes of additional life support, respectively. The C 5.1, C 5.2, and C 5.3 configurations have a mass of 61 kg, 65 kg, and 68 kg, and all use structure S4.

Primary Design Consideration Trade Offs: There were three primary system design considerations: deciding on the backup oxygen loop system (OPS used in the Apollo EMU vs. the SOA that will be used in the AEMU), determining the method for CO₂ scrubbing and humidity control that should be used, and determining oxygen tank pressures. In all cases, mass and volume impacts were considered, and were minimized when it made sense to do so/when possible since minimizing mass was one of the primary goals of this study.

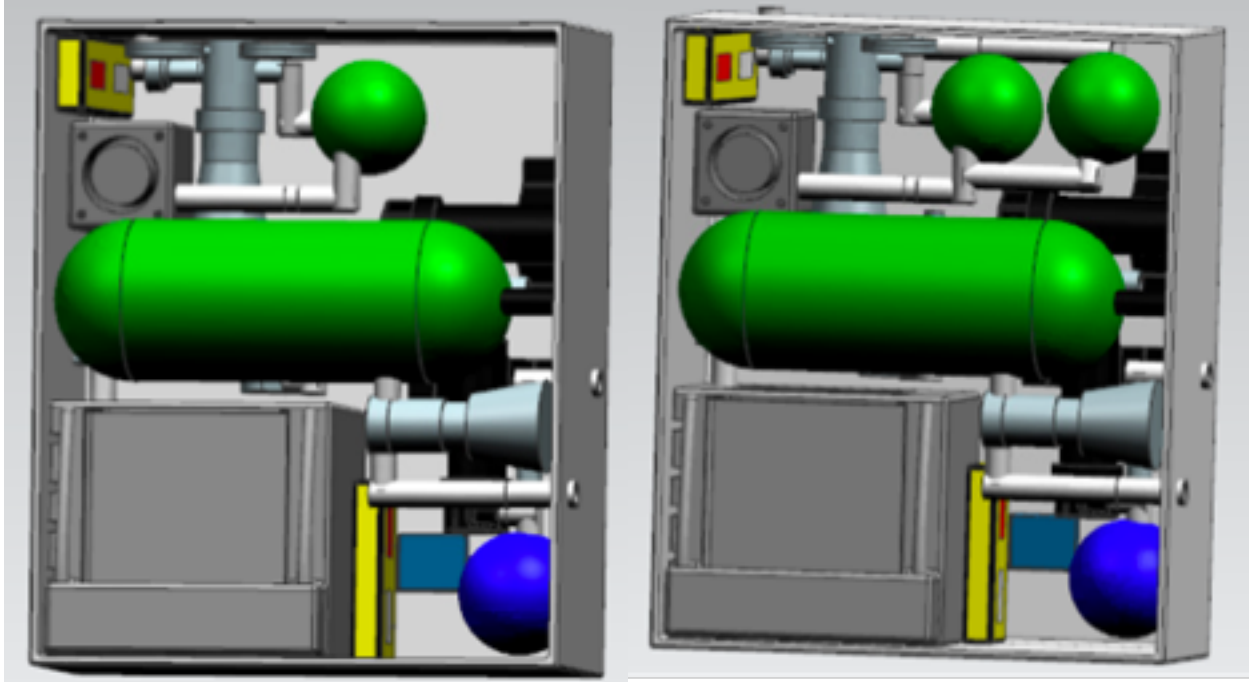


Figure 16: Internal view of SMLS system configuration 5.1

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 60cm. It is equivalent to configuration 4.1 with the addition of thermal cooling loop.]

Figure 17: Internal view of SMLS system configuration 5.2

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 60cm. It is equivalent to configuration 5.1 with the addition of a second secondary oxygen tank.]

- OPS vs. Secondary Oxygen Loop: The primary reason for choosing the OPS over the secondary oxygen loop is the fact that the OPS can operate independently from the rest of the PLSS. This was an important design consideration because as mentioned, one of the objectives of the modular SMLS concept was to minimize mass when possible. For this objective to be met, the minimum mass system must only include the absolutely necessary components, which was achieved in an open loop configuration. Another advantage is that the OPS is isolated from the rest of the PLSS, so if the OPS were to fail in either the C4 or C5 series configurations, it would not impact the rest of the system, and a new OPS could be installed. Likewise, the oxygen ventilation loop and thermal loops are also kept separate from the rest of the PLSS, so if a problem arises, it too can be isolated and more easily replaced. Keeping the subsystems separate allowed for flexibility in creating the modular SMLS concepts, as one system is not necessarily dependent on another, and can either be included or not included depending on the mission type and requirements.
- RCA vs. LiOH canisters: The second primary design trade off that was considered was the choice to use either a Rapid Cycle Amine (RCA) system or LiOH canisters for CO₂ removal/humidity control. One of the main benefits of the RCA over the LiOH canisters is that the RCA reduces overall system mass and volume because the RCA is also capable of removing humidity, unlike the LiOH canisters, which require additional components for humidity control [5]. In addition, LiOH canisters are for one time use only, and restrict the EVA duration time [5], whereas the RCA is also able to continually remove CO₂ and control

humidity levels in real time [5]. Another benefit is that the RCA allows for the water loop and the ventilation loop to be separated, which is beneficial for the modularity design objective, and in addition, helps to reduce contaminants/microorganisms in the thermal control loop [3]. For these reasons, it was determined that an RCA system would be the better option for the SMLS configurations than LiOH canisters.

- **Tank Storage Pressures:** There are two tank sizes; small oxygen tanks stored at 6000 psi, and large oxygen tanks stored at 3000 psi. For nominal oxygen pressures, the oxygen stored for the primary oxygen loop (large oxygen tanks) will be kept at 3000 psi. This value was chosen since this is the same value the AEMU plans to use [2]. One benefit to having the primary oxygen loop oxygen storage be maintained at 3000 psi is that there have already been systems developed and certified capable of recharging the oxygen at 3000 psi [3]. In addition, lower pressure systems are generally less hazardous than higher pressure systems, making it less dangerous than storing the oxygen at 6000 psi as is for the OPS [3]. However, storing oxygen at a higher pressure allows for smaller tank volume, which is why the OPS oxygen supply will be stored at 6000 psi. One of the objectives of the baseline configurations (C1.1 and C1.2) was to minimize both mass and volume, so a higher tank pressure was chosen to reduce tank volume. According to [2], systems have been developed that are capable of recharging oxygen systems at 6000 psi, but including these systems on a flight could potentially introduce additional risk, and would need to be certified.

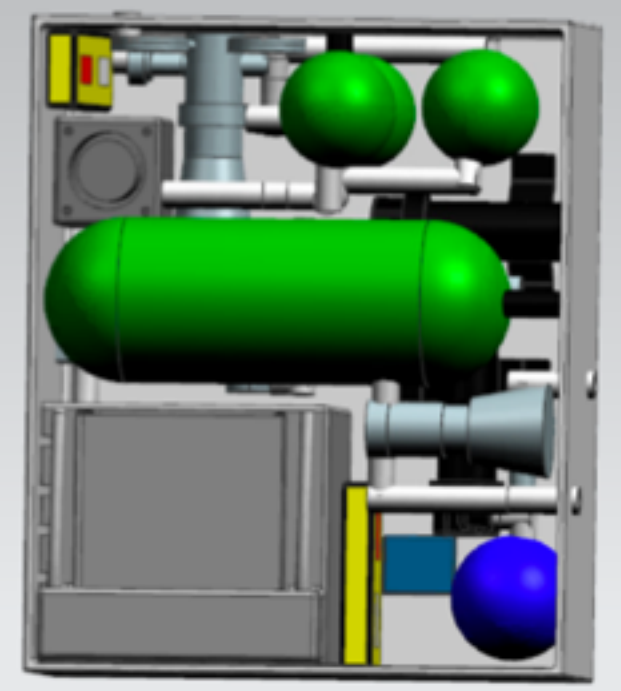


Figure 18: Internal view of SMLS system configuration 5.3

[The image is of the interior of a rectangular housing with a width of 50cm, depth of 22cm, and height of 60cm. It is equivalent to configuration 5.1 with the addition of two additional secondary oxygen tanks.]

Standard Operations Scenarios: This section describes the different operation scenarios based on life support configuration chosen, number of crew, and number of BioBots for the mission.

Scenario 1: One BioBot, One Crew Member (CM) — For operations that only require one CM and one BioBot, the CM is required to remain tethered to BioBot for the duration of the EVA (unless there is a safety reason for why the CM would need to detach from BioBot). The reason for this is for risk mitigation purposes. Since BioBot will have strict requirements on the types of terrain/hills it can traverse, the CM is less likely to find himself/herself in a situation in which he/she becomes stuck or unable to move. The maximum distance the CM can travel away from the habitat is 7.2 km. While this is not the theoretical maximum distance, it is approximately half of one full PLSS life support duration away from the habitat, assuming each full PLSS configuration provides eight hours of life support, and the CM has a walking speed of 0.5 m/s

(~1.1 mph). Past analog studies have shown an average crew traverse velocity of 1.76 m/sec in a simulated 10km talkback scenario[10]; the 0.5 m/sec assumption was made to be conservative, and to reflect the fact that open-loop life support systems do not have the same level of cooling as a closed-loop system. If the CM becomes injured and cannot return to the habitat by himself/herself, there needs to be enough time for one of the CMs at the habitat to don a life support configuration, attach to BioBot, locate, and retrieve the injured CM. The type of mission scenario that would only require one crew and one BioBot would be sample collection missions, taking readings off of any already deployed science instruments/experiments, setting up a local experiment, and visual habitat inspection. Local surface exploration is allowed as long as a distance of 7.2 km is not exceeded, but the primary focus of a single crew, single BioBot mission is for one of the mission scenarios listed above.

Scenario 2: One BioBot, Two Crew Members — If two crew members are operating off of one BioBot, the maximum allowable distance traveled radially outward from the habitat is 3.6 km assuming an average walking speed of .5 m/s. Each BioBot will have two fully equipped PLSS capable of up to eight hours of additional life support. This would mean there is one PLSS per crew member. However, if one of the two life support systems fail, two crew would need to operate off of one PLSS. If the failure occurs when half of each life support has been used, there must be enough remaining life support in functional PLSS for both crew to return to the habitat. So, each CM would need half of the remaining life support, or approximately 120 minutes worth of life support, and 3.6 km is the maximum theoretical distance that could be traveled in this time assuming 0.5 m/s walking speed. The crew would each also have an additional amount of life support depending on the SMLS configuration they are wearing. Scenario 2 mission types are primarily for missions that remain close to the habitat, such as those similar to Scenario 1 mission types (habitat inspection, setting up a local experiment, etc.).

Scenario 3: Two BioBots, Two Crew Members — For operations that require two BioBots and two CMs, the CMs are allowed to untether themselves from BioBot and use their additional life support system. The maximum distance each CM can travel from BioBot is based on which SMLS configuration is worn, as seen in Table 2. The overall maximum distance the CMs and BioBots can travel from the habitat is dependent on the choice of life support configuration for that mission. While the theoretical maximum distance traveled from the habitat would be up to 14.4 km, for safety reasons, the distance is maximized at 10.8 km. This value is based on assuming an average walking speed of 0.5 m/s (~1.1 mph) and that the crew walks radially outward from the habitat at this speed. Since each BioBot will have two fully equipped PLSS's, each CM can travel up to approximately three quarters of a full life support's distance away from the habitat. The reason this value is chosen is so that if one of the four of the BioBot life support systems fails, there are still three fully functional BioBot life support systems available, leaving 1.5 fully equipped life support systems for each CM to return to the habitat (in addition to whatever remaining amount of life support is left in their SMLS). Assuming a worst case scenario in which one life support system fails when the crew is at the maximum distance away (.75 worth of life support has been used per crew member) from the habitat, that would leave .75 worth of a full life support system for each crew member to return to the habitat (excluding any additional amount from the SMLS). This would be enough to allow the crew to return safely to the habitat, assuming the same walking speed. The crew would also have a minimum of 20 minutes of additional life support with them as well via the SMLS, if it was needed to be

Table 2: Allowable straight-line traverse distances for SMLS system configurations

Configuration	Mass [kg]	Life Support Duration [min]	Un-tethered Operations Duration [min]	Maximum Allowed Un-Tethered Distance from BioBot [km]
C1.1	18	20	N/A	N/A
C1.2	21	40	20	0.6
C2.1	28	80	60	1.8
C2.2	31	120	100	3.0
C3	44	240	220	6.6
C4.1	55	280	260	7.8
C4.2	58	320	300	9.0
C5.1	61	400	380	11.4
C5.2	65	440	420	12.6
C5.3	68	480	460	13.8

activated. Two crew as opposed to one allows for further distance beyond the habitat to be traveled, as there is another CM to assist if one of the of the CMs becomes injured in some way. Since the maximum allowable distance is much higher for this scenario, and two crew members are present, the type of operations for this scenario are mainly for extended surface exploration missions and sample collection. Each BioBot will be equipped with approximately .108 m³ of tool stowage space, and .8 m³ of sample collection stowage space, based on tool and sample stowage volumes from Apollo missions in [9]. Adding a second BioBot allows for additional life support and redundancy, as the likelihood that more than two BioBot PLSS’s would fail on the same mission is highly unlikely.

Untethered Operation Scenarios: While the astronauts will be tethered to BioBot via an umbilical for providing life support to the crew member, there are cases in which the crew may want to detach from BioBot. Untethered operations could provide advantages over tethered operations in situations in which it may be difficult or impossible for BioBot to traverse a certain terrain. Table 2 shows the amount of untethered time a crew member may have from BioBot, as well as the maximum distance that crew member may travel away from BioBot from being untethered. The maximum allowable distance that the crew member can travel away from BioBot untethered was determined by assuming an average walking speed of 0.5 m/s. For determining this maximum value, it was assumed that the crew member would walk radially outward in one direction from BioBot, and then return to BioBot and re-attach to use BioBot’s life support. An additional reduction factor of two was placed on the maximum theoretical distance in case the crew member does not only walk in one direction and/or walks slower than 0.5 m/s (for example, walking up or down a hill may affect the crew member’s assumed average walking speed).

All configurations allow for untethered time, except for the C1.1 configuration. The reason for this is because the crew member shall always have a minimum of 20 minutes of additional life support in reserve when untethered from BioBot (unless an emergency situation arises that calls for use of the remaining 20 minutes of additional life support). For example, if there is a case in which the crew member has completed a task untethered from BioBot and then resumes using

BioBot's life support, but then both of the life support systems on a crew member's BioBot fails, the crew member would still have a minimum of 20 minutes of life support in reserve. This would allow for enough time for the crew to either return to the habitat (if the crew member was within range), or connect to another crew member's BioBot's life support system.

Life Support Failures Contingency Operations: This section addresses potential life support failure scenarios, and how each will be resolved. Other potential hazardous scenarios could arise, such as BioBot equipment failure, BioBot becomes stuck, etc., but this section focuses on life support-related problems.

While each full PLSS is has a redundant oxygen loop and cooling loop, it is still possible that one of the life support systems on BioBot fails. If this occurs, the secondary PLSS on BioBot can immediately be activated. The crew will be alerted of the system failure, and can use the back-up life support system (one of the SMLS configurations that the crew will be wearing), until the umbilical can be switched from the primary PLSS on BioBot to the secondary PLSS. If a BioBot PLSS failure occurs, the crew will be allowed to continue with the EVA. In addition, the crew must return to within the maximum untethered distance from BioBot that is allowed for the SMLS configuration the crew is wearing. The reason for this is because if the second life support system on BioBot fails, the crew must be within a range of the habitat that their own SMLS can support. A dual PLSS BioBot failure results in immediate termination of the EVA, activation of the SMLS system, and for the crew to return to the habitat.

If a crew member is performing untethered operations from BioBot and is notified from the caution and warning system that the additional life support system is failing, the crew member must return immediately to BioBot and re-tether him/herself. A failure could be losing suit pressure, losing CO₂ washout capabilities, etc. Assuming both life support systems are fully operable on BioBot, the mission can go on, as long as the crew member remains tethered to BioBot. If there are two crew on the mission, the CM with the functioning back-up life support system may still be untethered from BioBot. The way the failures in the additional life support system are mitigated is by having redundancy (for the more complex configurations). For the C1 series, there is no redundancy, as that baseline configuration itself only has the necessary components to have a functional limited duration PLSS. The C2 series configurations have an auxiliary thermal loop for cooling, which, if that fails, the oxygen flow rate in the C2 configuration could be increased from 1.9 kg/hr to 3.7 kg/hr to satisfy both cooling and breathing requirements. However, the CM would still be required to return to BioBot and remain tethered to BioBot. For the C3 configuration, if the thermal control loop fails, the oxygen flow rate could be increased from 1.2 kg/hr to 3.7 kg/hr, and the CM would then be required to re-tether to BioBot. For the C4 configurations, if the thermal control loop fails, the CM could still remain untethered from BioBot by increasing the oxygen flow rate from 1.2 kg/hr to 3.7 kg/hr, however, the amount of untethered time allowed would be reduced for the C4.2 configuration (if the loop fails for the C4.1 configuration, the CM must return to BioBot and remain tethered). The untethered time allowed would drop from 300 minutes for the C4.2 configuration, to 20 minutes, as this is the amount of untethered time allowed for the C1.2 configuration which includes the components for an Apollo OPS. For the C5 series configurations, if the primary thermal control loop fails, the CM could remain untethered from BioBot for a reduced amount of time, since the auxiliary thermal control loop would automatically be activated. However, the untethered

allowable time would be reduced from a maximum of 380 minutes, 420 minutes, and 460 minutes for the C5.1, C5.2, and C5.3 configurations (when all systems are functional) to 100 minutes (when the primary thermal control loop fails, but the auxiliary thermal control loop is still operational).

Initial Prototype Development and Testing

Although hardware development is not traditionally a large part of a Phase I NIAC effort, it was felt that the BioBot concept could only be adequately evaluated on the basis of a realistic implementation of the system to allow direct human evaluations. To that end, the BioBot team adapted an existing Segway RMP440LE mobility base for use in BioBot testing through the addition of an external framework for payload mounting, fenders to protect humans and payloads from adjacent wheels, and the implementation of a control system using the Robotic Operating Systems (ROS), an open-source platform for robot control. A radio controlled E-Stop was added to command the robot to stop/brake. The RMP440LE is suboptimal for realistic testing of the concept largely because of its lack of a suspension system, which limits its ability to overcome obstacles in field testing. It did prove to be an excellent development platform for the Phase I studies, however, and has been used extensively for laboratory and light field testing of various BioBot concepts and candidate system designs.

The BioBot concept is clearly predicated on the development of robotic technologies to autonomously tend the umbilicals attaching the EVA crew to BioBot, ensuring the continual supply of life support to the suit without snagging the local terrain or interfering with crew mobility. The original concept was to provide single or double lifting points to the umbilical, to keep the catenaries far enough above the ground to prevent contact. This was mocked up and tested with materials on hand, mounted on the Segway robotic mobility base (Figure 19). As an early proof of concept, a student researcher manually actuated the “robotic manipulator” for controlling the umbilical while another student acted as the test subject.



This initial mockup was made to test different umbilical lengths, supports on the umbilical, and feasible areas of operation for the astronaut tethered to Biobot. A retractable umbilical on a reel was mounted to the back side of the rails, and a person seated on the Segway controlled the umbilical support structure. The initial assessment goal was to see how much assistance the umbilical needed to allow the EVA crew free movement around obstructions, and to keep the umbilical from touching the ground or elevated obstacles (Figure 19). While these tests were promising from the standpoint of avoiding snag hazards, the simulated EVA

Figure 19: Initial test of umbilical management

[The rover is a small four-wheeled vehicle with a person seated on it between the wheels. He is holding a pole which controls the near end of the simulated umbilical. The far end is held by another person serving as the EVA astronaut. A third person walks behind the rover and controls the take-up reel for the umbilical.]

crew had to support half of the umbilical weight, reducing the effectiveness of the overall concept in terms of reducing loads on the astronaut. There were also some concerns about lateral swinging of the umbilical catenary, which would induce cyclic side-to-side loads on the astronaut. On the basis of these tests, a major effort was undertaken to examine options for more fully supporting and controlling the umbilical with the goal of minimizing physical and cognitive loads on the BioBot user.

Umbilical Handling Technology Development

Subsequent development focused on manipulators with extended kinematics to keep the umbilical elevated, connect to the EVA suit in its immediate vicinity to minimize weight load, and track crew motions within a 5-10m radius of the mobility base. Two approaches were implemented in this stage of development: an actively-controlled manipulator, and a pantograph-type passive kinematic chain for automatic umbilical handling. The powered manipulator (Figure 20) was implemented using engineering prototyping extrusions and electromechanical linear actuators for high torque. While this worked satisfactorily, the computational complexity of performing inverse kinematics as the EVA crew moves about presented an interesting control challenge beyond the scope of this initial proof-of-concept testing. This test apparatus did demonstrate the ability to easily rotate the umbilical handling system on a passive base yaw joint, eliminating the need for actuation and control in that axis.

The ease of passive actuation in base yaw led to a focused effort to produce an entirely passive umbilical handling system (UHS). An isokinetic structure inspired by the Hoberman sphere kinematics was prototyped in quarter-scale in laser-cut acrylic to validate the design. The full-scale prototype was then fabricated using a computer numerically controlled router from 3/16in plywood, with 3D printed internal spacers and routing blocks for the umbilical. This system was



Figure 20: Actively controlled robotic umbilical handling mechanism

[There are three serial links in the robot arm on top of the four-wheeled rover, each approximately 1.5 meters long. The arm holds an umbilical 3 meters out and over the head of a test subject on an inclined surface.]



Figure 21: Passive pantographic umbilical handling mechanism

[A scissors-type multilink mechanism holds the umbilical out approximately two meters to the test subject, who is wearing a simulated spacesuit. The linkage is attached to the back of the spacesuit, and the umbilical connects over the shoulder onto the front of the torso.]

then integrated onto the RMP440LE motion platform for testing (Figure 21), which included the use of the University of Maryland MX-C suit simulator for the first time. The passive system was also found to be feasible, and offered functionality without control or power requirements, but needs to be redesigned to increase torsional stiffness and to suppress an over-center “latching” behavior.

At this point, development of the umbilical handling system is proceeding on both the active and passive concepts. The active system appears to be lighter and more easily stowed, but is more complex and requires continual autonomous control inputs. The passive system has more rotational joints and kinematically complex, but had lower reaction forces at the spacesuit than the current active system, and does not add power or control requirements to the BioBot. Both systems will be further refined and tested before settling on the best design for a protoflight unit.

Autonomy Technology Development

Since the aim of the BioBot is to increase crew mobility without imposing new restrictions or requiring additional crew resources, it is critical that the rover be able to navigate without need of human intervention. The BioBot's navigation system must be able to autonomously follow its user, avoid unknown obstacles, and maintain a safe and consistent following distance so as to prevent collisions with its crew member. Autonomous following and obstacle avoidance is accomplished through the Robotic Operating System (ROS) and the integration of the ROS navigation stack with the AprilTags visual fiducial system.

The software operates in the following sequence. A camera on board Biobot streams video data to the AprilTags software, which detects the fiducial tags (Figure 22) worn by the astronaut, and outputs data concerning the tags' position and orientation to the navigation stack. While the astronaut is only required to wear one tag for the system to operate, multiple tags provide robustness to the system in the event that one of the tags is obstructed from the view of the camera.

The navigation stack then uses the position data sent from the AprilTags software to set a new navigation goal. To prevent the rover from colliding with crew members, the goal is offset from the astronaut by one meter while maintaining the original orientation and polar coordinate angle of the tag. In the event that the astronaut comes within one meter of the robot, the software sends zero velocity commands. This adjusted goal is combined with data published from a visual depth sensor, which sends information to the navigation stack about obstacles in the robot's path. Since the navigation stack requires a laser scanner (rather than a depth sensor), an intermediate ROS



Figure 22: Examples of AprilTag markers

[Five samples are shown of block black and white patterns used for automatic target recognition. Each marker is square with a black outer frame. The patterns inside the samples are either 5x5 or 6x6 grids with random patterns of white and black squares in each grid.]

node converts the depth sensor data to laser-scan data. Finally, the stack combines the navigation goal with the laser-scan data to plan paths around the detected obstacles. The flow chart in Figure 23 summarizes this process.

Each component — the camera, depth-sensor, AprilTags, and navigation stack — uses ROS to send and receive messages. Since the components are independent of one another from a software perspective, ROS allows for great modularity, and thus the software package can easily accommodate new laser scanners and cameras or even be implemented on a robotic platform other than the Segway RMP.

Testing hardware includes an Xbox 360 Kinect, which houses a visual depth sensor and camera and is powered by the Segway RMP's auxiliary battery (12V, 1.2A). Both the Kinect and Segway are connected to a laptop running Linux Ubuntu 16.04 with ROS Kinetic. For future iterations, the laptop will be replaced by an on-board computer dedicated solely to Biobot, and the Kinect will be replaced by a more robust laser scanner that can operate in brighter, outdoor environments.

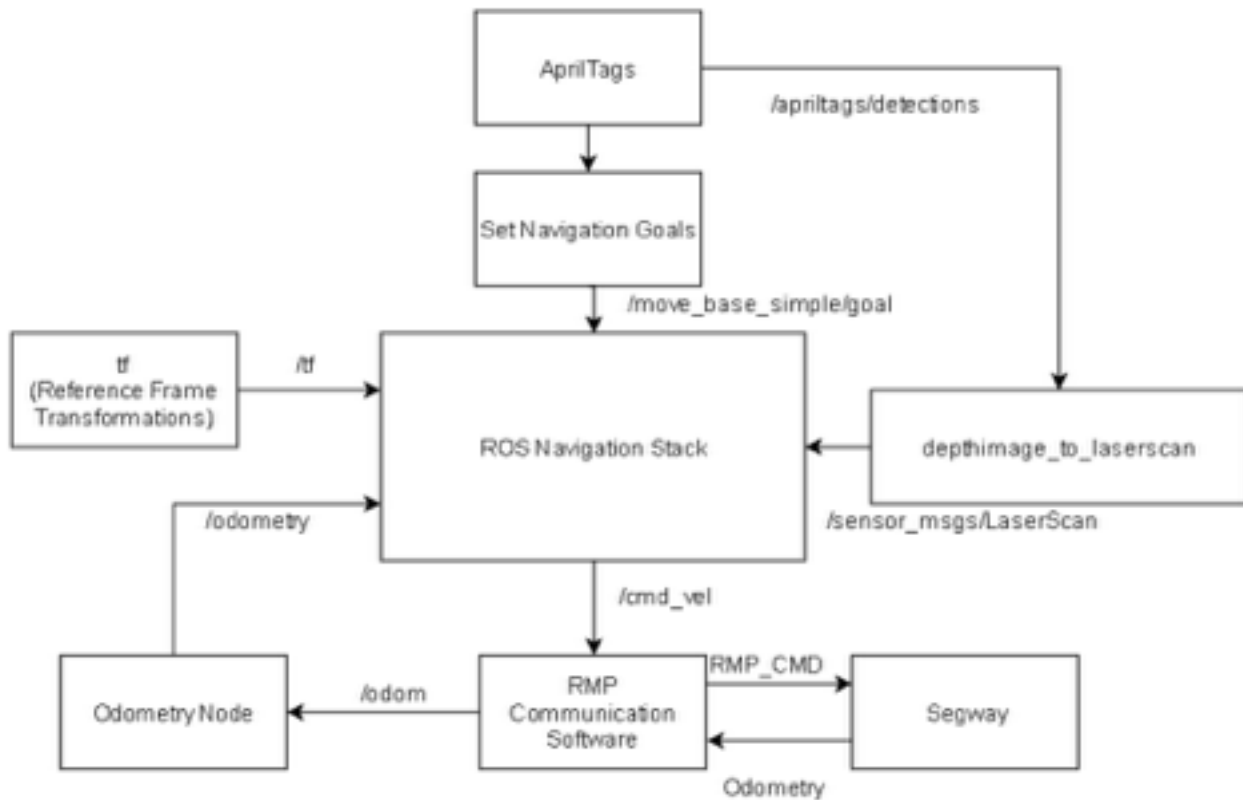


Figure 23: Autonomy software architecture — boxes represent ROS nodes, arrows are topics

[There are eight boxes in the flowchart. The center box is “ROS Navigation Stack”. “AprilTags” and “Set Navigation Goals” feed into the navigation stack from above. “Reference Frame Transformations” and “Odometry Node” feed in from the left. “AprilTags” connects to “depthimage to laserscan”, which feeds in from the right. The navigation stack outputs to “RMP (rover) Communications Software”, which talks to the odometry node and to the “Segway” node.]

The process is illustrated (Figure 25) with RVIZ, a ROS visualization software package. As shown, the software sets its goal (shown as a purple arrow) a meter ahead of the AprilTag marker, which is represented by a purple box. The base of the arrow indicates the position of the goal in the world map, and its direction indicates the orientation of the goal. The software uses data sent from the depth sensor and laser scan node, depicted as white lines, to construct a cost map which identifies low cost areas as light gray and high cost areas as black. Any object within the inflation radius is considered an obstacle and assigned a high cost. The navigation stack then uses Dijkstra's algorithm to operate over the cost map and identify the lowest cost path from the robot to the goal pose, shown as a green line. On the right, the real-world image is also displayed as a reference. The marker is placed on the gray bin in the center of the image.

Additional Innovations Enabled by BioBot System

As the design process proceeded and the various BioBot configurations emerged, it became clear that the BioBot concept would enable a number of other capabilities to enhance future planetary surface research. Obviously, a rover accompanying an EVA crew would be a logical place to locate communications, video cameras, and science systems such as sampling robotics or core drills. Beyond those “mundane” augmentations, relieving the mass limitations on the suit and crew simultaneously eases logistics-based constraints such as distance and duration. At minimal impact to the overall design, a BioBot could carry oxygen, cooling water, CO2 scrubbing, and

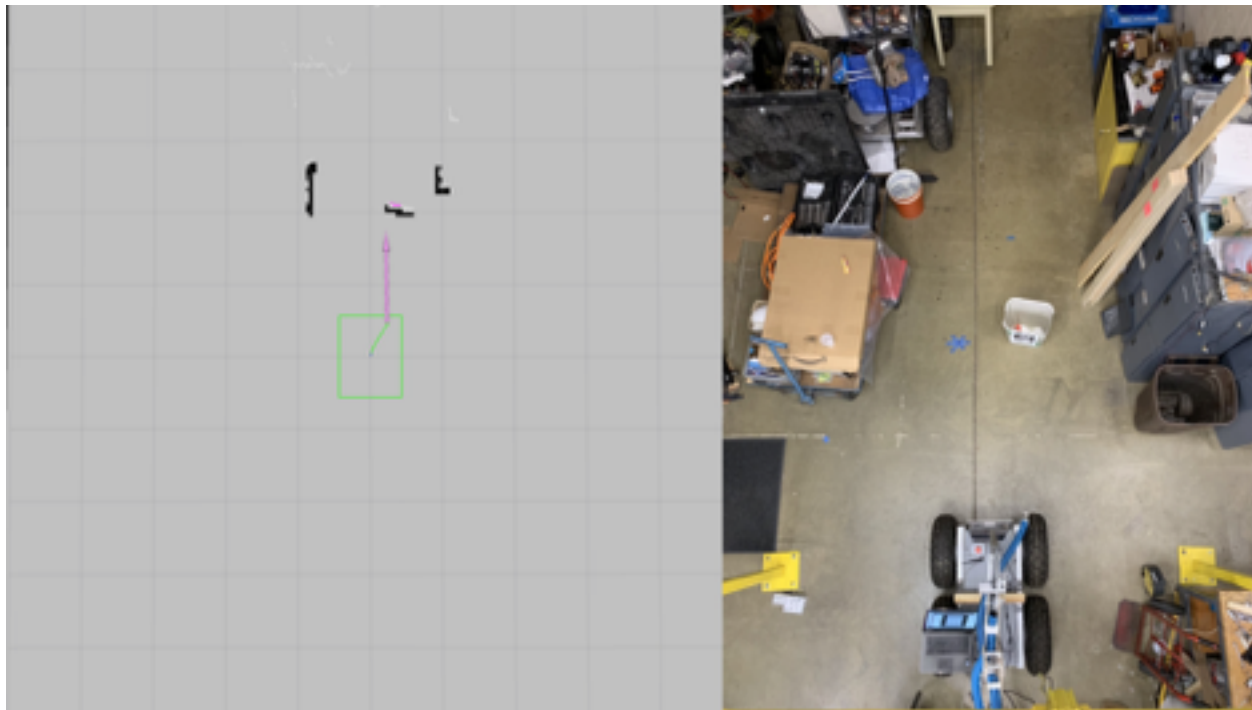


Figure 25: (left) RVIZ representation of navigation software (right) Corresponding real-world environment

[The side is a gridded grey surface with a number of black and white markings representing obstacles in the sensor space. A green rectangle represents the rover, and a purple arrow shows the position and orientation of the goal. The right side is a photo of the test setup from above. The markings on the left can be identified as physical obstacles in the photo.]

power far beyond the current six-hour nominal limitation. The endurance of the EVA system would be limited only by the crew's physiological limits of wearing and operating in a pressure suit.

One of the concerns for Mars exploration is that the density of the Martian atmosphere is too great to allow the use of sublimation cooling, which has been the standard practice in all PLSS designs to date. A BioBot system would allow the use of "low-tech" solutions such as an ice reservoir to dissipate waste heat via water phase change and specific heat. On the other hand, eliminating the volumetric and surface area limitations of a backpack-mounted PLSS would make the use of radiators feasible, particularly with innovative concepts such as the use of Peltier junctions to increase the temperature of the radiators[11]. Similarly, EVA duration could be augmented by photovoltaic arrays on the BioBot for real-time power generation. Alternatives to canister-based CO₂ scrubbing could minimize resupplies between EVA sorties, and further reduce limitations on EVA duration. Innovative logistics concepts such as the use of hydrogen peroxide as a single source of oxygen, power, and cooling water (a previous NIAC study) would become a viable candidate for consideration[12].

Conclusions and Future Plans

At the end of the nine-month NIAC Phase 1 program, the University of Maryland team has shown that the BioBot concept is feasible. All of the critical elements of the concept — autonomous tracking of a suited subject, provision and tendering of life support umbilicals, and reduction of PLSS weight — have been demonstrated both analytically and in hardware/software on a prototype system. Trade studies have examined the ability of the user to adopt various suit-mounted life support systems to allow various periods of independent activity ranging from 20 minutes to a nominal six hours. A risk assessment showed that the ideal architecture for a two-person EVA using BioBots would be two individual units, each with the ability to carry and support both crew in the event of a life support or mobility unit failure; however, the BioBot concept was found to be feasible across a range of rover capabilities from small dedicated life support carriers to multicrew unpressurized and pressurized rovers.

At this point, the most critical task remaining is that of proving trafficability of the BioBot vehicle while accompanying an EVA crew into regions at the extremes of viable EVA traverse. A successful Phase II NIAC grant will focus on the development of a BioBot end-to-end prototype for analog field trials, including a highly capable mobility chassis, an optimized umbilical handling system, and a vehicle-mounted life support system (ventilation air, cooling water, communications, and monitoring electronics) compatible with a next-generation spacesuit simulator: the MX-D, currently under separate development. The focus for this program phase will be to perform field testing at the NASA Johnson Space Center "Rockyard" planetary surface simulation facility, to elicit feedback and evaluations from the EVA and robotics branches of NASA. The robotics and crew systems divisions of JSC have been very helpful, and have shown enthusiasm for participating in these activities.

Subsequent follow-on activities, such as a Phase III NIAC grant, would be to assess the end-to-end BioBot prototype at extended-duration analog test sites, such as the Mars Desert Research Station or HI-SEAS facility. This would allow the collection of user data during extended operations, again using an MX-D or equivalent spacesuit simulator. In parallel, it would be ideal

to develop a BioBot system capable of supporting a full pressure suit in analog field trials such as the NASA Desert RATS tests, to assess the effect of the robot-transported life support system based on previously-developed systems such as the NASA JSC Mk. III suit and Oceanering liquid-air backpack.

Work done to date has met the letter and spirit of the NIAC program: taken a “blue-sky” concept, demonstrated basic feasibility, and identified both benefits of a successful implementation for future space missions and a path forward for further development. More detailed design, fabrication, and testing will be necessary to bring the BioBot concept to the technology readiness level where it will become a viable candidate for use in a future exploration surface architecture.

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