Application of Multi-Mission Single-Person Spacecraft (MMSPS) to Gateway Mission

Kazuhiko Momose[1] and Olga Bannova[2]
University of Houston, Houston, TX, 77204, United States

This study was inspired by the idea of a Single-Person Spacecraft (SPS) proposed by Genesis Engineering Solutions, Inc. The goal of the study is to investigate SPS applicability for diverse environmental conditions, identify critical functionality, and expand its capability. Achieving SPS commonality would allow additional mission flexibility, facilitating future deep space explorations. The initial stage of the project was presented at ICES 2018 poster session and focused on; developing Functional Flow Block Diagrams (FFBDs) to define critical functionality, conducting tasks analysis to identify critical activities of the operator, and performing simple anthropometric test to design human-centered cabin. The anthropometric test provided baseline design considerations for Multi-Mission Single-Person Spacecraft (MMSPS) architecture advancement. This paper mainly discusses next stages of the research. The methodology used in this work includes a study of shape influencing factors such as; gravity gradient affecting crew operations mobility and position inside the module during different stages of operations, pressure vessel stress analysis, mobility systems attachments and operations for in-flight and on-surface activities, and interior systems configurations and ease of maintenance operations. The paper presents final design considerations of the vehicle for microgravity and partial gravity conditions, associated mobility systems, and its operational functionality using a Gateway reference mission. The paper concludes with evaluation of the presented design based on safety, crew comfort (habitability), and operational efficiency during EVA in orbit and on the surface of Moon.

Nomenclature

C&DH	=	Command and Data Handling
CG	=	Center of Gravity
DOF	=	Degrees of Freedom
ECLSS	=	Environmental Control and Life Support System
EPS	=	Electrical Power System
EVA	=	Extravehicular Activity
FFBDs	=	Functional Flow Block Diagrams
IDSS	=	International Docking System Standard
MEL	=	Master Equipment List
MLI	=	Multi-Layer Insulation
MMSEV	=	Multi-Mission Space Exploration Vehicle
MMSPS	=	Multi-Mission Single-Person Spacecraft
RCS	=	Reaction Control System
SD	=	Standard Deviation
SLS	=	Space Launch System
SPS	=	Single-Person Spacecraft
TCS	=	Thermal Control System

[1] Graduate Student, Cullen College of Engineering, 4722 Cullen Calhoun Rd. Houston TX 77204
[2] Research Associate Professor, Cullen College of Engineering, 4722 Cullen Calhoun Rd. Houston TX 77204

I. Introduction

A. Background

NASA and private space companies, including Boeing and Lookheed Martin are actively putting efforts into research and development of Gateway. Gateway will function as a lunar outpost, allowing for performing various scientific experiments and validating systems and technologies that are necessary for future manned deep space exploration. Extravehicular Activities (EVA) will be one of the most critical tasks in Gateway operations. At present, crew needs space suits to execute EVA tasks, however a suited operation is associated with many risks and complications. One of the disadvantages is that a suited EVA requires pre-breathing operation, resulting in low work efficiency. Also, space suits induce personal injuries due to low flexibility and mobility of joint parts. The idea of a Single-Person Spacecraft (SPS) proposed by Genesis Engineering Solutions, Inc. could potentially solve some operational problems. An SPS allows immediate access to space without pre-breathing or airlock operations, improving work efficiency. Its exterior structure provides better protection from radiation, micrometeoroid, and orbital debris hazards. Additionally, a shirtsleeve cabin enables the operator to work more comfortably during EVAs, reducing physical demands. Considering the operational efficiency, safety, and crew comfort, the SPS is favored for Gateway EVAs [1].

Although the idea of a one-person spacecraft is not new, few proposals have progressed beyond a preliminary design stage [2]. Development of the Genesis SPS has made considerable progress in design, analysis, and testing, including:

1) Neutral buoyancy testing
2) Canopy impact testing
3) Pressure testing

The weightless testing provided key design considerations for ingress/egress and associated mobility aids, and flight deck geometry and hand controller location [2]. During the impact testing, no cracks or breaks were observed on the dome window. The impact testing indicated that it may be prudent to add a maximum deflection requirement, allowing the operator to manipulate the vehicle in the event of an impact [2]. The pressure testing was performed at the facility of AMRO Fabricating Corp. The results demonstrated that the crew cabin could hold internal pressure even when one and half times more of the expected operational pressure was applied. Moreover, the SPS design had minimal air leaks from its joints and passed the leak test (https://www.space.com/42034-single-person-spacecraft-design-passes-test.html).

Figure 1. SPS.
Courtesy of Genesis Engineering

Physical mockups, including high-fidelity one were constructed for human factors assessments and subsystem packaging concepts. Genesis Engineering has partnered with Paragon Space Development Corporation in developing the SPS Air Management System (AMS). Together, they will develop a functional prototype that can be integrated and tested in ground demonstrators and the mockups [3]. This partnership has advanced the SPS concept into the next development phase, leading to flight testing in the future.

B. Objective

This study was inspired by the idea of the SPS. The objective of this study is to investigate SPS applicability for diverse environmental conditions, identify associated critical operational functionality, and potentially expand its capability. Achieving SPS adjustability would allow for additional mission flexibility, facilitating future human spaceflights. This paper proposes an initial idea of a Multi-Mission Single-Person Spacecraft (MMSPS) in relation to a Gateway mission. Common design approach can allow performing EVAs in-orbit and on-surface using the same cabin. The commonality would offer some benefits; reducing costs, improving safety, and simplifying training for nominal, maintenance, and contingency operations [4].

C. Previous MMSPS Study

The initial stage of the project "Baseline Design Considerations for a Multi-Mission Single-Person Spacecraft (MMSPS)" was presented at the ICES 2018 poster session. The poster discussed the first phase of the study of the MMSPS. The methodology used in the initial stage included following steps:

1) Developing the first and second levels Functional Flow Block Diagrams (FFBDs) to identify critical functions

2) Conducting a task analysis to clarify important and frequent activities of the operator inside the vehicle
3) Performing a simple anthropometric test to design a human-friendly cabin

The task analysis revealed that ingress/egress operations have the most impact on the overall vehicle design. Six design cases were created considering vehicle orientation, hatch location, and ingress/egress methods. After qualitative analysis of each case, three cases were selected for further investigation. A simple anthropometric test was carried out to quantitatively evaluate the selected three cases. A comparative analysis demonstrated that a vertical orientation with a rear hatch and a horizontal orientation with a side hatch would allow an operator to perform ingress/egress with less physical complexity than in other configurations. The findings of the anthropometric test provided baseline design considerations for advancing the MMSPS architecture.

The first part of this paper describes the initial stage of the study in detail, and presents its outcomes that affect design decisions for the vehicle configuration. The second part presents the next stages of the research. The methodology used in this work includes study of shape influencing factors such as:

1) Gravity gradient affecting crew operations mobility and position inside the module during different stages of operations
2) Pressure vessel stress analysis
3) Mobility systems attachments and operations for in-flight and on-surface activities
4) Interior systems configurations and ease of maintenance operations

In the summary, this paper presents evaluation of the proposed design based on safety, crew comfort (habitability), and operational efficiency during EVAs in orbit and on the surface of Moon. Future work objectives for further MMSPS development are suggested and discussed in relation to a mock-up development and testing of all components of an MMSPS vehicle.

II. Concept of Operations

A. Top-Level Requirements

In the beginning of the design process, top-level requirements were defined to clarify key design features. The MMSPS should

1) be modular
2) be operated in gravity levels ranging from microgravity to 1g
3) be operated for 8 hours and support an operator in emergency situations
4) accommodate 5th percentile female to 99th percentile male

A mobility system of the MMSPS has to be interchangeable to adapt to diverse environmental conditions, requiring a modular design approach. The vehicle needs to be operated in diverse gravity conditions up to 1g, allowing for testing the vehicle on Earth. Subsystems have to operate for 8 hours and support an operator in emergency providing supplemental power and gases. Considering a height requirement for NASA and ESA astronaut training, the cabin must accommodate 5th percentile female to 99th percentile male.

B. Assumptions

In this study, a Gateway reference mission was used to develop the MMSPS design concepts. As such, following two assumptions were created:

1) MMSPS can be launched with other payload elements using SLS Block IB or Falcon Heavy
2) MMSPS can also be delivered using a medium-class launch vehicle such as Falcon 9 and Antares

C. Constraints

To develop the mission architecture, it is also significant to consider launch vehicle capabilities such as payload and firing volume. Table 1 summarizes launch vehicle specification. All Gateway and lunar surface elements will be delivered using the launch vehicles.

Table 1. Launch Vehicle Specification.

	Agency	Payload	Fairing Size
SLS IB Cargo	NASA	40,000 kg to TLI*	537 m^3
SLS II Cargo	NASA	> 45,000 kg to TLI*	988 m^3
Falcon Heavy	SpaceX	16,800 kg to Mars	ϕ 5.2 m x 13.1 m
Falcon 9	SpaceX	4,020 kg to Mars	ϕ 5.2 m x 13.1 m
Antares	Northrop Grumman	8,000 kg to LEO**	ϕ 3.9 m x 9.9 m

*TLI: Trans-Lunar Injection **LEO: Low Earth Orbit
(https://www.nasa.gov/sites/default/files/atoms/files/sls_lift_capabilities_and_configurations_508_08202018_0.pdf)
(https://www.spacex.com/falcon-heavy) (https://www.spacex.com/falcon9)
(https://www.northropgrumman.com/Capabilities/Antares/Documents/Antares_Factsheet.pdf)

D. Mission Architecture

The mission architecture was developed based on a Gateway construction sequence proposed by Boeing [5]. The mission architecture is twofold; Gateway construction (Phase 1) and surface establishment (Phase 2). Figure 2 and 3 show the mission architecture of the two phases respectively. The Gateway construction will begin with delivering a Power Propulsion Element (PPE) in 2023. A node module and a habitat module will be sent in 2024 and 2025 respectively. In the following year, Falcon Heavy will deliver a logistics module and an MMSPS simultaneously or the MMSPS will independently be delivered by a medium-class vehicle such as Falcon 9 and Antares in case where the MMSPS cannot be packaged with the logistics module. After all Gateway elements are ready for crew arrival, the very first crewed orbital mission will be carried out. A crew of four will perform initial scientific experiments and test all Gateway systems for 30 days.

After the first orbital crewed mission, phase 2 begins with sending surface EVA systems; another MMSPS, one Multi-Mission Space Exploration Vehicle (MMSEV), one ATHLETE, and a lunar habitat. The MMSPS will serve in lunar surface elements and collect lunar samples in the vicinity of the lunar base. In 2028, a crew of four will carry out the second crewed orbital mission for 30 days and test all lunar surface elements tele-robotically. In the following year, SLS II will send an Ascent Module (AM) and Descent Module (DM) simultaneously to the Gateway for the upcoming crewed surface mission. Then, a crew of four will execute the first orbital and surface mission for 42 days. In the mission, two crewmembers will descend to lunar surface and perform sample collection in the vicinity of the base while other members will perform scientific experiments at the Gateway.

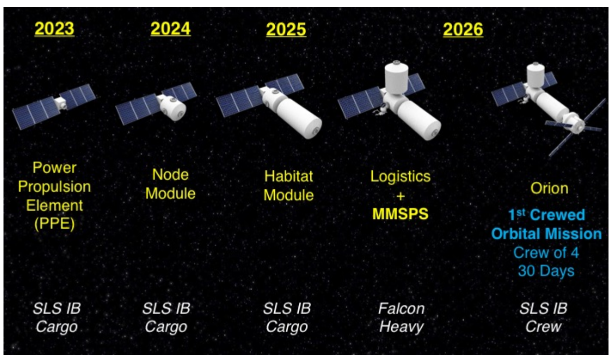


Figure 2. Mission Architecture (Phase 1).

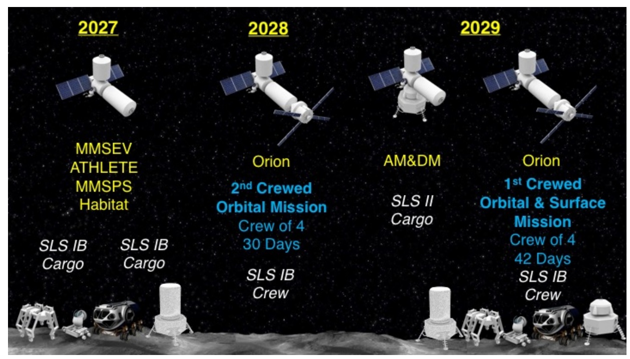


Figure 3. Mission Architecture (Phase 2).

III. Methodology

A. Functional Flow Block Diagrams (FFBDs)

Functional analysis is critical for identification of the tasks that a system must perform to fulfill mission goal and objectives. The FFBDs were developed in the study to perform functional analysis. FFBDs depict each functional event (represented by a block) occurring following the preceding function and identify "what" must happen [6]. Top-level FFBDs display the entire operational sequence. Figure 4 shows the top-level FFBDs of the Gateway operation and lunar surface operations. Also, an initial risk analysis was performed using a risk matrix to identify major hazards during the operations based on the top-level FFBDs (Appendix A). This high-level risk analysis revealed MMSPS components where critical hazards are involved.

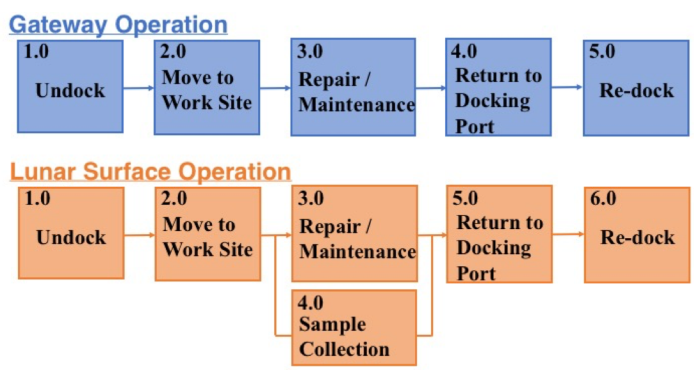


Figure 4. Top-Level FFBDs.

B. Task Analysis

In order to design a human centered design cabin, it is imperative to understand inside activities of the operator. Hence, a task analysis was conducted by decomposing the top-level FFBDs into second-level FFBDs. The second-level FFBDs revealed five important and frequent inside tasks, namely ingress/egress, maneuvering mobility systems and controlling manipulator, crew hygiene, communicating with other crewmembers, and taking nutrition. The five tasks were categorized in two scales; from more cognitive to more physical and from more flexible to more fixed. Figure 5 represents the five tasks on a four-quadrant diagram. For example, ingress/egress requires physical demands, and a docking hatch is a key design driver, which must be stationary. Therefore, ingress/egress was on the upper-right corner of the first quadrant. In the same way, other four tasks were classified as shown in Figure 5. The task analysis revealed that ingress/egress procedures play a critical role for the overall vehicle design. Therefore, smaller subsystems, including control devices and displays, have to be designed after making ingress/egress positioning design decision first.

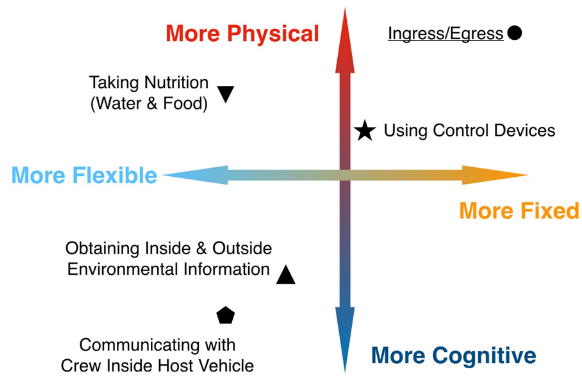


Figure 5. Five Tasks on Four-Quadrant Diagram.

C. Ingress/Egress Initial Analysis

Initially, six design cases were created considering vehicle orientation, hatch location, and ingress/egress methods (head-first or feet first). Figures 6 to 11 visually illustrate each case of ingress/egress. Then, a high-level trade study was performed to qualitatively evaluate the six design cases based on the physical demands during the ingress/egress operations (Table 2). Case 1, 3, and 5 were eliminated from design considerations because the egress in partial gravity conditions would be more demanding than others. As a result, remaining three cases were set for further investigations, namely case 2 (vertical orientation with a rear hatch), case 4 (horizontal orientation with a rear hatch), and case 6 (horizontal orientation with a side hatch).

Table 2. Qualitative Analysis.

	Microgravity		Partial Gravity	
	Ingress	Egress	Ingress	Egress
Case 1	Easy	Easy	Fair	Demanding
Case 2	Fair	Fair	Easy	Fair
Case 3	Fair	Fair	Fair	Demanding
Case 4	Easy	Easy	Fair	Fair
Case 5	Easy	Easy	Fair	Demanding
Case 6	Fair	Fair	Fair	Fair

Legend: ●: Easy ●(grey) :Fair ○ :Demanding

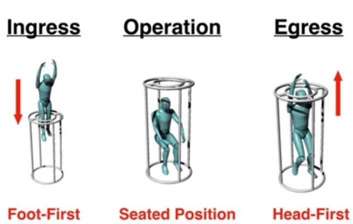


Figure 6. Case 1.

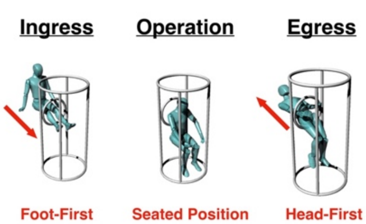


Figure 7. Case 2.

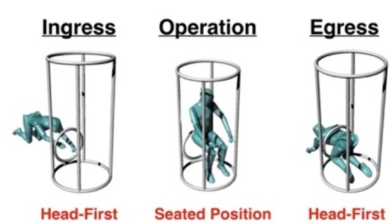


Figure 8. Case 3.

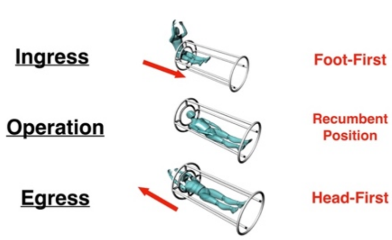


Figure 9. Case 4.

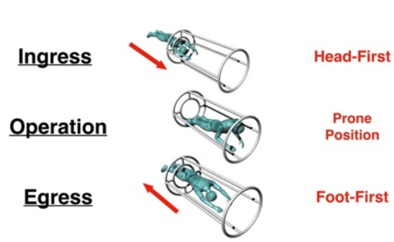


Figure 10. Case 5.

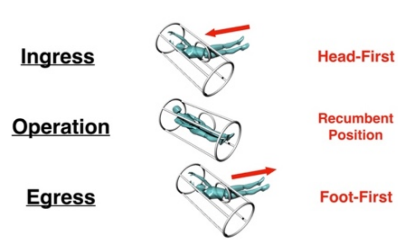


Figure 11. Case 6.

D. Anthropometric Test

D-1 Testing Methodology

In order to evaluate the selected three cases in more detail and obtain baseline design considerations, a simple anthropometric test was performed using a low-fidelity mockup. Ten students from the Sasakawa International Center for Space Architecture (SICSA) and Gerald D. Hines College of Architecture and Design were selected as test participants. Table 3 shows data of subjects' stature. Subject 9 exceeds the stature of the 99th percentile male, however the data was included because this was a preliminary study and testing required to receive maximum possible feedback. Figures 12 and 13 show a CAD model and a physical mockup respectively. The mockup was constructed using cardboard, strings, PVC pipes, and Styrofoam. The diameter of passageway of the Genesis SPS is 0.6 m, whereas the pass-through aisle of the mockup is 0.8 m, deriving from the International Docking System Standard (IDSS) [7]. There are many usability evaluation methods and method selection depends on the purpose and need of the evaluation. In this testing, a questionnaire addressed the ease of ingress/egress procedure in each case using a Likert-scale (1: Very Demanding, 5: Very Easy). The questionnaire also aimed to investigate subjects' handrail placement preferences. Subjects' commentary was also collected through the questionnaire (Appendix B).

Table 3. Demographic of Subjects.

Subject ID	Stature [cm]
1	165
2	190
3	173
4	163
5	170
6	177
7	157
8	188
9	197
10	180

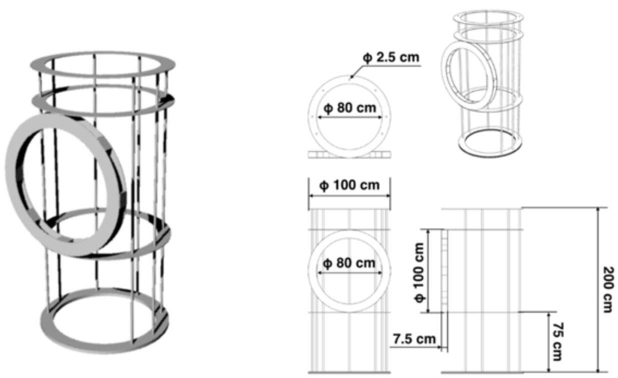


Figure 12. CAD Model of Mockup.

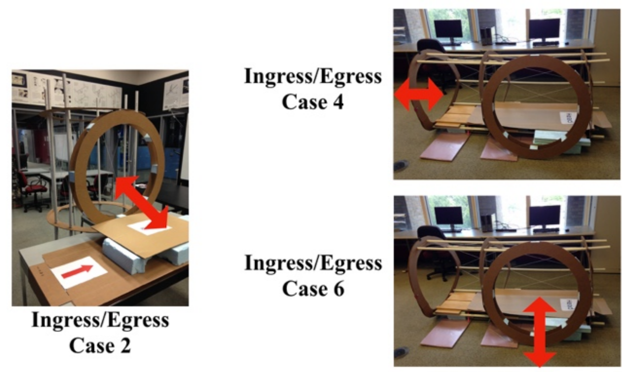


Figure 13. Physical Mockup.

D-2 Results and Feedback

Table 4 shows mean rank of each case (1: Best, 3: Worst). Appendix C discusses a statistical analysis in detail. Taking into account the results, case 4 was eliminated from design considerations since its ingress clearly requires more physical efforts than other two cases.

Table 4. Mean Rank.

Case	Ingress	Egress
2	1.50	2.30
4	2.80	2.35
6	1.70	1.35

Case 2 and case 6 were selected as baseline vehicle configurations, however this paper presents a prototype of the MMSPS based on the case 2 configuration for two reasons. First, a side hatch would reduce area of a window, narrowing the field of view. It is critical to provide the operator with broad field of view during EVAs, offering work site information in more detail. Second, the center of the center of gravity (CG) would shift to the side hatch. Even though it would be possible to offset the displacement of the CG by installing subsystems on the other side, it would slightly complicate the interior architecture.

Figure 14 shows participants' handrail placement preferences for ingress/egress of case 2. Red stands for the place where subjects think handrails should be attached. Most of subjects indicated that the handrail should be mounted on the top of the passageway whereas one participant suggested that they should be attached on both sides inside the cabin.

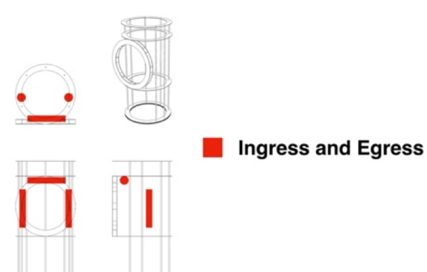


Figure 14. Handrail Placement.

The open-ended question item provided baseline design considerations pertaining to the dimensions of the vehicle. The test subjects gave following feedback:

1) The 0.8 m diameter passageway was fine
2) The 0.8 m inner diameter was acceptable, however it should be larger
3) The operator would want to stretch legs and arms during a long EVA operation
4) Footrest would help to perform ingress/egress

Most of subjects performed ingress/egress through the 0.8 m diameter passageway comfortably, however some of them, especially larger participants (more than 1.80 m), complained about the 0.8 m inner diameter. They had few clearance and could not stretch their legs and arms. Therefore, it is imperative to increase the inner diameter, allowing for stretching during EVAs. Moreover, some participants suggested that footrest should help the operator to perform ingress/egress as well as handrails.

IV. Conceptual Design of MMSPS

A. MMSPS Cabin

The MMSPS cabin must accommodate 5th percentile female to 99th percentile male. Adjustable and flexible interior systems allow for dealing with smaller users whereas it is significant to create clearance for larger users. As such, anthropometric data of 99th percentile male [8] was considered as the worst-case scenario. Figure 15 outlines the MMSPS cabin with anthropometric data used for the sketch. The cabin sketch started with a bottom 0.8 m circle, deriving from the dimension of the mockup. 1) Functional leg length was referred and it is approximately 1.26 m. The 1.2 m circle allows the largest operator to stretch legs almost fully. 2) Reach distance was considered for work space and it is approximately 1.00 m. 3) The cabin has 1.9 m height, allowing the 99th percentile male to stand inside of the cabin. 4) A window was mounted on the cabin with approximately 45 degrees. This window was inspired by the idea of a bubble window and would allow the operator to look at work site slightly closer. The MMSPS cabin was designed based on the sketch and Figure 16 shows an exploded diagram of the cabin. The cabin consists of five components, namely a pressure vessel, a window, framing, enclosure, and a docking system.

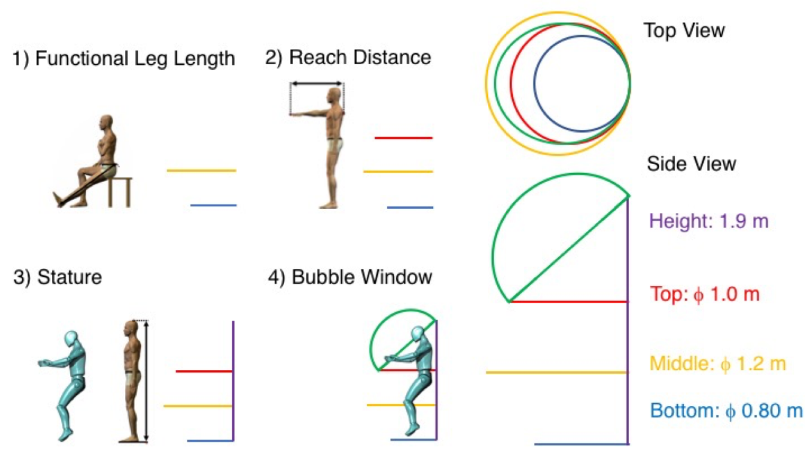


Figure 15. Cabin Sketch.

A-1 Pressure Vessel and Window

The pressure vessel uses a carbon composite with glass fiber. The vessel with 1.0 cm thickness has a factor of safety of 2.11 (Figure 17). Polycarbonate is selected as the window material, which is the same as that of the Genesis SPS. The window with 5 mm has a factor of safety of 6.36 (Figure 18).

A-2 Framing

The framing shown in Figure 19 is placed between the pressure vessel and enclosure, and has 2 cm thickness of the carbon composite with glass fiber. The framing functions as a guidance for harnesses. Also, polyethylene and Multi-Layer Insulation (MLI) are inserted here.

Figure 16. Exploded Diagram of Cabin.

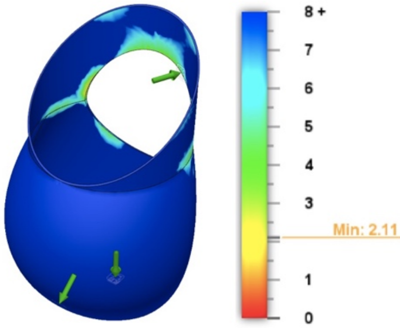


Figure 17. Pressure Vessel.

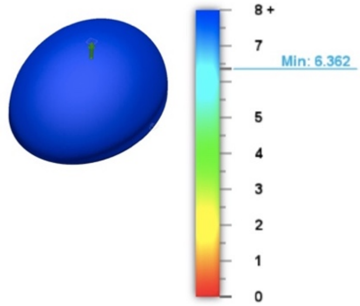


Figure 18. Window.

Figure 19. Framing.

A-3 Enclosure

The enclosure also uses the carbon composite with glass fiber and has 2 cm thickness. There is a mobility systems docking interface on the bottom of the enclosure as shown in Figure 20. A Reaction Control System (RCS) and a chassis are attached on the interface for the Gateway and lunar surface operation respectively.

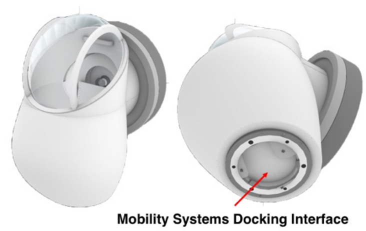
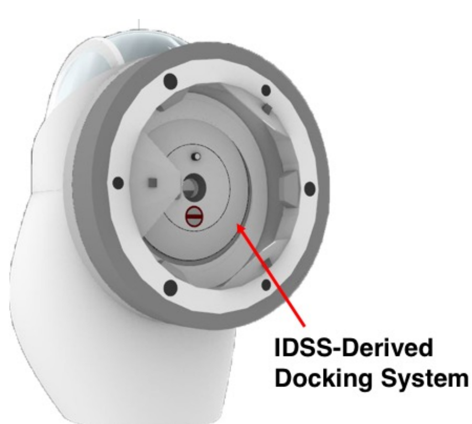
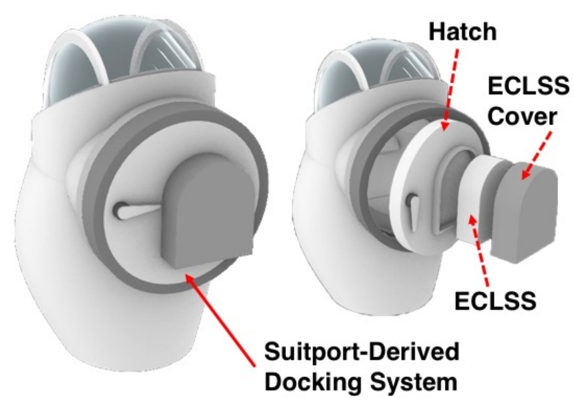


Figure 20. Mobility Systems Docking Interface.

A-4 Docking System

This paper presents two types of docking systems; an IDSS derived docking system and a suitport derived one. Table 5 summarizes pros and cons of docking system applications. The IDSS-derived docking system is compatible with Gateway elements, however it may be difficult to use it in partial gravity conditions. The suitport type docking system was inspired by the NASA Z-2 rear-entry spacesuit. Although it requires development of a unique adapter, the suitport-derived docking system could possibly be lighter than the IDSS. In addition, the suitport technology may enable crew to perform Environmental Control and Life Support Systems (ECLSS) maintenance operations more easily. It would also allow for MMSPS habitable volume increase since the ECLSS will not be accommodated inside the cabin. Future work should address key design considerations about the suitport docking system and its unique adapter structure requirements.

Table 5. Comparison of Two Types of Docking Systems.

	IDSS-Derived	Suiport-Derived
		
Pros	• Compatibility with Gateway elements	• Possibly lighter than the IDSS-derived system • More affordable ECLSS maintenance operations • More effective cabin volume utilization
Cons	• Mass penalty • Difficult to use in partial gravity conditions	• Require a unique adapter

B. Interior Systems

B-1 Interior Systems Configurations

It is essential to allocate interior systems effectively to maximize crew comfort, which requires a better understanding of maintenance operations as well as the task performance during EVAs. There are six functional areas (A to F) in the cabin as shown in Figure 21. To optimize interior systems allocations within six functional areas, the interior functional analysis was performed categorizing the interior each area, considering three factors; volume, mass, and accessibility. To utilize the interior space efficiently, it is necessary to understand the maximum volumetric capacity of each area. It is also significant to consider mass to minimize risks during maintenance operations and EVAs. For instance, Area A involves a risk that mounted subsystems may fall during operations (in case of surface operations), and therefore it is preferred not to equip heavy systems in the area A. From a surface operation perspective, it is also reasonable to install heavier interior systems on lower areas to stabilize the vehicle during EVAs. Furthermore, accessibility has a great influence on ease of maintenance and repair operations. Area A to F were evaluated based on the three criteria and Table 6 summarizes the result. Figure 22 shows the interior systems configurations of the MMSPS cabin with the IDSS-derived docking system.

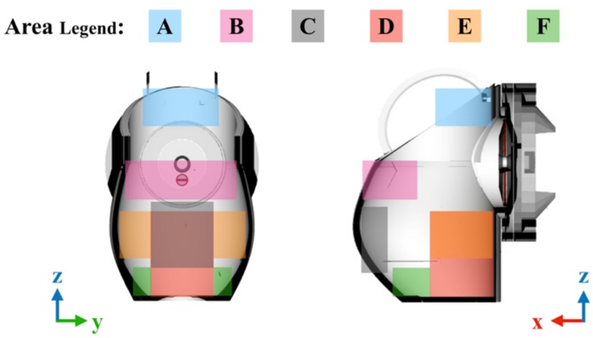


Figure 21. Cross-Sections with Six Functional Areas.

Table 6. Interior Functional Analysis.

	Volume	Mass	Accessibility	Suggested Systems
A	Fair	Poor	Plenty / Good	Overhead Interior Lights / Speakers
B	Fair	Fair	Plenty / Good	Control Devices / C&DH / Communication
C	Poor	Fair	Fair	Footrestraint
D	Plenty / Good	Plenty / Good	Fair	ECLSS / EPS / TCS
E	Fair	Plenty / Good	Fair	Personal Gear / Emergency Equipment
F	Fair	Plenty / Good	Poor	Supplemental Gas / ECLSS / EPS / TCS

Legend ●: Plenty / Good ◍: Fair ○: Poor

Area A has a good accessibility, however as described earlier, it should be avoided to attach heavy systems over the operator's head. Thus, this area houses small systems, including speakers and overhead interior lights as well as handrails. Area B also allows for an easy access and has capability of equipping heavier systems. As such, subsystems, including Command & Data Handling (C&DH), communications, and control systems should be placed in the area B. Based on the feedback from the anthropometric test, Area C should be as open as possible so that an operator has room to stretch legs during EVAs on the surface. Area D accommodates heavy and large systems, and therefore this area is for critical subsystems, including ECLSS, Electrical Power System (EPS), and Thermal Control System (TCS). Area E is occupied with personal gear, food, water, and emergency equipment such as radiation vest, medical kit, and fire extinguisher. Area F lacks of accessibility, and therefore this area should contain additional systems such as supplemental gas tanks and redundancies of critical subsystems.

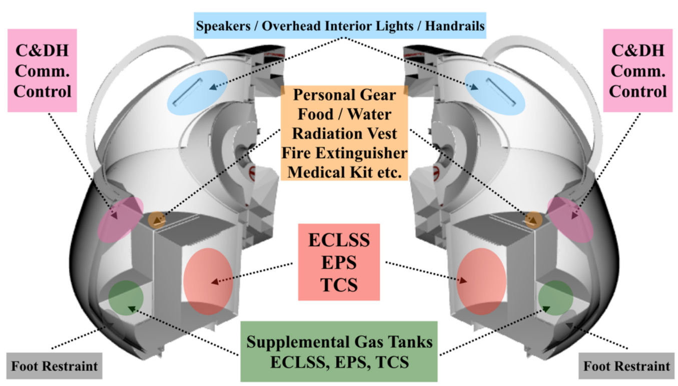


Figure 22. MMSPS Cabin Interior Systems Configurations.

B-2 Ease of Maintenance and Repair

There are two kinds of maintenance operations; preventive and corrective maintenance. Preventive maintenance is vital to minimize risks of malfunctions of systems whereas corrective maintenance requires crew to repair systems quickly and precisely. Ease of maintenance is a key consideration to accomplish both types of maintenance operations. The initial risk analysis indicated that critical hazards involve ECLSS, EPS, TCS, C&DH, communications, and control systems, and therefore these subsystems would need more frequent maintenance operations. As mentioned above, accessibility influences the ease of maintenance and repair. Though the operator has an easy access to C&DH, communications, and control systems, it is necessary to improve the accessibility of other three subsystems. One of probable solutions is to utilize flexible mounted fixtures such as slide rails. Although it may slightly complicate vehicle interior design, railings would offer easier access and require less physical demands.

B-3 Adjustable Seat and Control Devices

Adjustable and flexible interior systems can accommodate an operator ranging from 5th percentile female to 99th percentile male in diverse gravity conditions. Figure 23 illustrates the use of the adjustable seat and foot restraint in microgravity and partial gravity conditions. The head rest and leg rest are detachable, and an operator can change the angle of the seat base. For surface operations, the crew can attach the head rest and leg rest, allowing the operator to work comfortably. The operator maneuvers the vehicle using joysticks mounted on the arm rests and get information through extendable monitors (Figure 24). These control devices were inspired by the idea of MMSEV's cockpit.

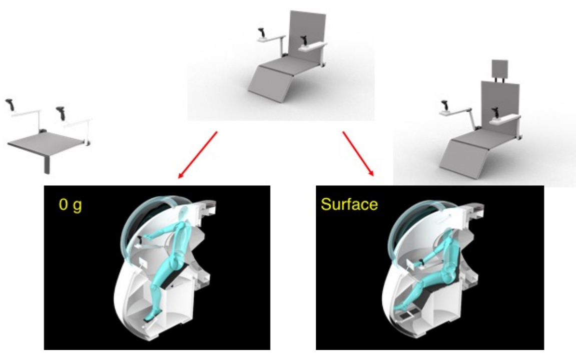


Figure 23. Adjustable Seat.

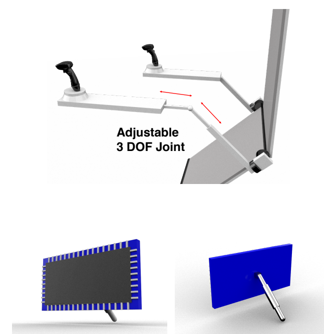


Figure 24. Joysticks and Monitors.

C. Master Equipment List (MEL)

A Master Equipment List (MEL) was developed to estimate an approximate mass of the MMSPS cabin (Table 7). At present, the mass of each subsystem was estimated based on that of the Genesis SPS [2]. The protection mass such as polyethylene and MLI was calculated based on the MMSEV [9]. Generally, 25 % growth margin is recommended in the early stage of conceptual design [10], however 30 % was applied to each subsystem. This is because the Genesis SPS' subsystems require additional modifications for planetary operations. Interior layout in Table 7 includes the adjustable seat, personal gear, emergency equipment, and so on.

Table 7. MEL of MMSPS Cabin.

	Basic Mass [kg]	Growth [%]	Predicted Mass [kg]
Pressure Vessel	76.5	25	95.6
Window	11.1	25	13.9
Framing	20.2	25	25.3
Enclosure	347	25	434
Docking System	324*	25	405
Protection	17.2	25	21.5
Power	40.9	30	53.2
Life Support System	62.4	30	81.1
Thermal Control System	31.6	30	41.1
Avionics / Software	9.50	30	12.4
Control	3.60	30	4.68
Interior Layout	6.35	30	8.26
Total	950	-	1,196

*Mass of NASA Docking System Block 1 (NDSB1) was input [11].

D. Associated Mobility Systems

D-1 Reaction Control System (RCS)

The crew maneuvers the vehicle using the RCS in microgravity. The RCS consists of four main components, namely manipulators, storage, propulsion systems, and a platform with the mobility system interface as shown in Figure 25. The manipulator has 1.6 m length and 6 Degrees of Freedom (DOF) in total, allowing the operator to reach out work site everywhere. Additionally, a small robotic arm with a camera is mounted on each manipulator. The small robotic arm also has 6 DOF, providing more detailed information regarding work site. During the maintenance operation, the storage can install broken and new parts. The MMSPS uses the same propellant gas as that of the SPS, which is also used for Extravehicular Mobility Unit (EMU). The thrusters are mounted on the platform and thruster arms. The platform equips with the mobility system interface to connect with the bottom of the enclosure. While the MMSPS docks with a host vehicle, a battery of the RCS is charged through the interface. The predicted total mass of the RCS is 179 kg.

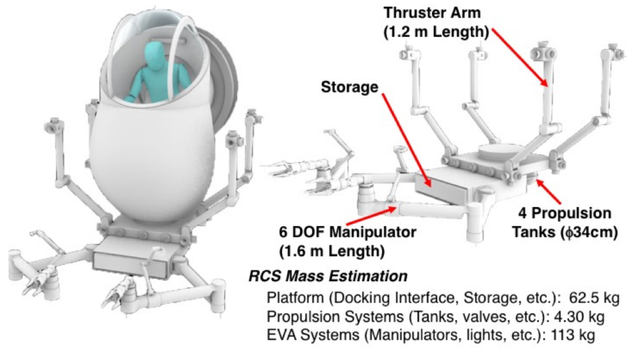


Figure 25. RCS.

The Gateway operation is fivefold and Figures 26 to 29 show an example of a Gateway operation. The operator opens the hatch, performs ingress using handrails (Figure 26). Once the operator sets the adjustable seat and foot restraint, the operator checks all systems of the MMSPS before undocking. Then, the operator undocks and maneuvers the vehicle using thrusters. Once the vehicle approaches work site, the operator stops using thrusters (Figure 27). The operator conducts repair of Orion's solar array as shown in Figure 28. The operator activates EVA systems such as manipulators, storage, and lights, and fixes the solar array. After the operator completes the maintenance, the operator deactivates the EVA systems and returns to the docking port. Finally, the MMSPS re-docks with the mothership and the operator performs egress as shown in Figure 29.

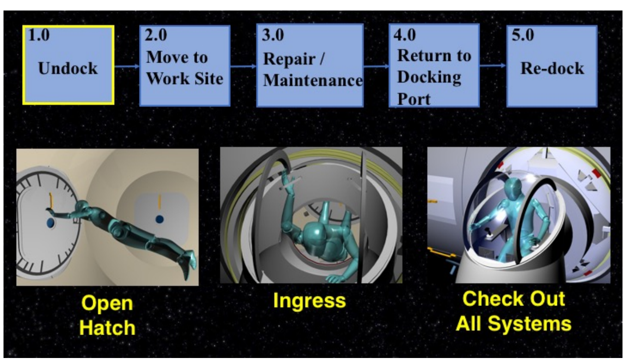


Figure 26. Gateway Operation (Phase 1).

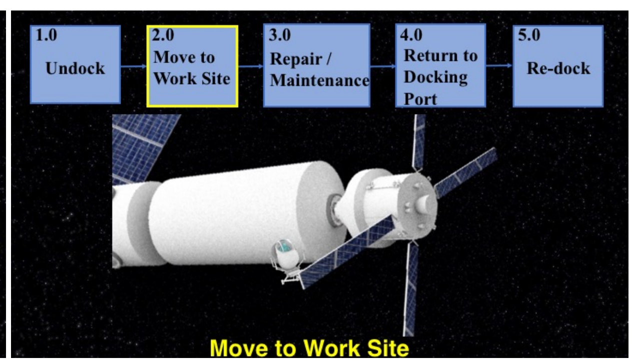


Figure 27. Gateway Operation (Phase 2).

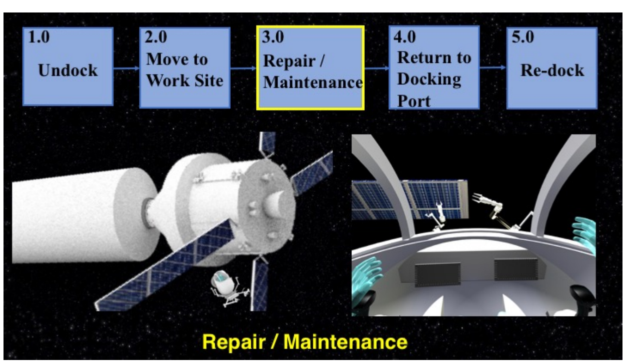


Figure 28. Gateway Operation (Phase 3).

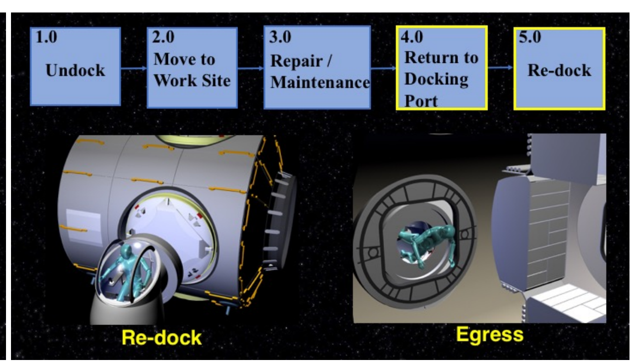


Figure 29. Gateway Operation (Phase 4 and 5).

D-2 Chassis

The chassis involves three main components, namely robotic arms, multi-purpose storage, and a scissor jack system as shown in Figure 30. The robotic arm has approximately 4.0 m full length and 6 DOF. End-effectors of the robotic arms are interchangeable, and therefore geological equipment such as a drill can be mounted. Each robotic arm equips another 6 DOF robotic arm with a camera, allowing the operator to interact with work site. The multi-purpose storage is for installing repair parts, collecting samples, and geological equipment. The scissor jack system lifts up and down the MMSPS cabin to dock and undock with a surface habitat because there is a certain gap between lunar surface and a hatch of a habitat. The scissor jack system has a capability of lifting the cabin approximately 1.0 m. The predicted total mass of the chassis is 638 kg.

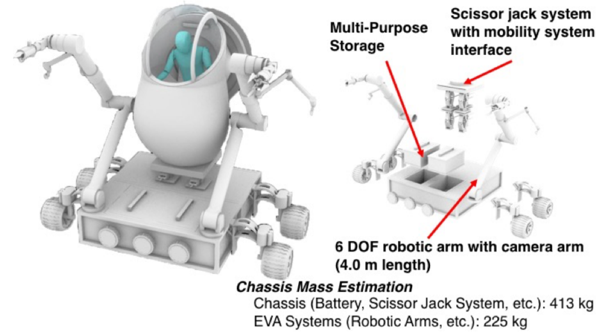


Figure 30. Chassis.

Figure 31 shows the first phase of lunar operation. The crew opens the hatch, gets in the cabin, and closes the hatch. Once the operator sets the adjustable seat and foot restraint, the operator checks out all systems. Afterward, the operator undocks with the habitat, lowers the MMSPS cabin using the scissor jack system, and manipulates the vehicle as shown in Figure 32. The MMSPS performs lunar samples collecting as well as maintenance and repair of surface elements such as habitats and rovers (Figure 33). The 4.0 m robotic arms with 6 DOF enables the MMSPS to reach out top of habitats and rovers. The geological equipment mounted on the robotic arm can extract lunar samples and install them into the multi-purpose storage. The mounted camera enables the operator to obtain detailed information, allowing for interacting with work site. After completing maintenance or sample collecting, the MMSPS returns to the lunar base and the operator lifts the cabin using the scissor jack system. Lastly, the operator re-docks with the habitat and performs egress (Figure 34).

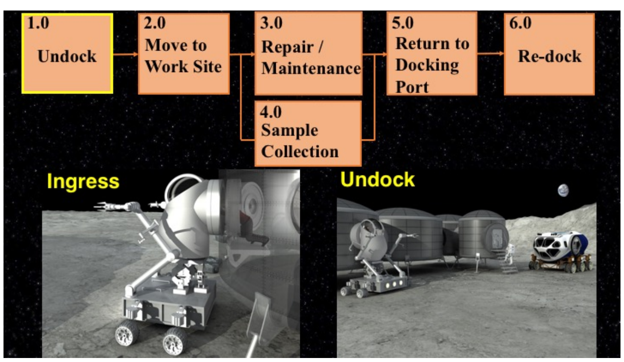


Figure 31. Surface Operation (Phase 1).

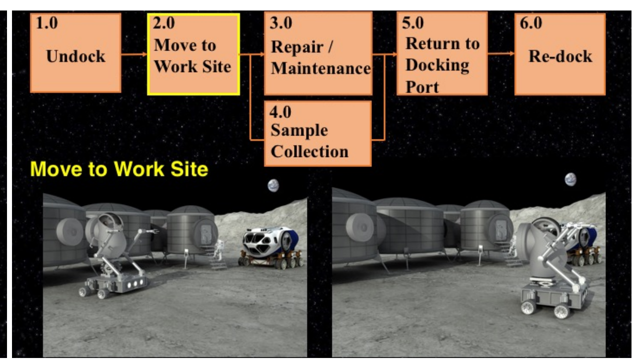


Figure 32. Surface Operation (Phase 2).

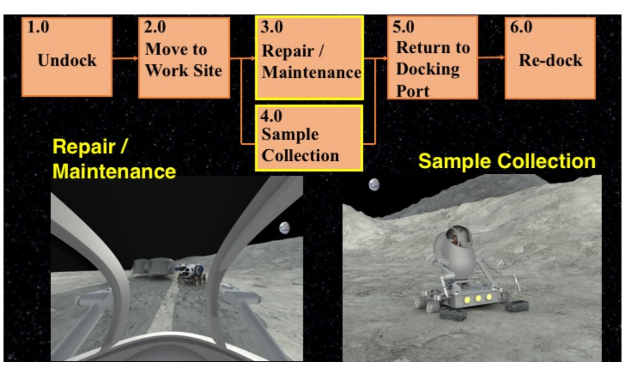


Figure 33. Surface Operation (Phase 3 and 4).

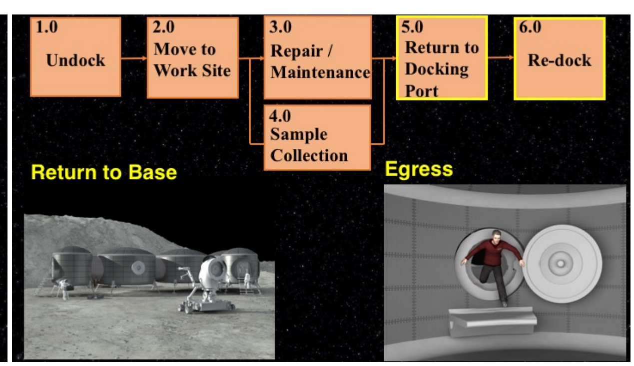


Figure 34. Surface Operation (Phase 5 and 6).

V. Summary and Future Work

This paper presented the initial idea of the MMSPS in relation to Gateway and lunar surface missions. In order to improve safety, crew comfort, and operational efficiency, this study performed following analyses:

1) Initial risk analysis using the risk matrix
2) Simple anthropometric test using the low-fidelity mockup
3) Interior functional analysis based on three evaluation criteria

The risk matrix revealed critical risks and hazards during MMSPS operations, and mitigation strategies were applied to each risk. The simple anthropometric test helped to make a more informed decision about the vehicle configuration and provided baseline design considerations. The interior functional analysis was conducted considering three factors; volume, mass, and accessibility, allowing for optimal interior systems configurations. In particular, ease of maintenance operation should be taken into account to enhance operational efficiency.

This paper also presented the required mobility systems and showed examples of Gateway and surface operation in conjunction with the top-level FFBDs. Using a common cabin would provide benefits such as offering additional mission flexibility and reducing development costs. The cabin and chassis could also perform repair operations and geological sample collection on a planetary surface with minimal modifications.

For advancement of the MMSPS architecture, future works should involve:

1) Developing a higher-fidelity mockup
2) Analyzing interior architecture focusing more on cognitive aspects
3) Creating associated mobility systems

The performed anthropometric test in this study only addressed ingress/egress in partial gravity conditions, and therefore it is imperative to develop a higher-fidelity mockup and perform another testing in weightless condition. This study focused on ergonomics for ingress/egress operations, however it is critical to consider cognitive human factors to design a human-centered spacecraft cabin, requiring a further task analysis. Finally, this paper presented the conceptual design of the associated mobility systems, however critical design features, including power requirements have not been discussed. Thus, it is necessary to develop the MEL of the cabin and mobility systems, and define critical functional and performance requirements.

Appendix

A. Initial Risk Analysis

There are ten major hazards during MMSPS operations. In particular, life support system failure and electrical power system failure are the most critical risk factors. To mitigate these risks, it is vital to increase the number of redundancies of these systems and perform maintenance operations frequently. Rapid depressurization and fire can result in loss of life. Mitigation strategies may involve, supplying supplemental nitrogen and oxygen, sensors installation, comprehensive fire alarm system and a fire extinguisher. Malfunction of C&DH, Communications, and Control Systems (C3) can result in loss of crew and mission as well. Increasing the redundancies of these systems mitigates the risk. The risk of malfunction of TCS may be mitigated by performing maintenance operations frequently. Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR) are also critical hazards, and therefore it is important to provide better radiation protection and radiation monitoring systems. Malfunction of docking interface and mobility systems is another critical risk. Additional life support capability offers more recovery time to fix these malfunctions. Finally, personal injury inside the vehicle should also be considered. It can be mitigated, for instance, by reducing the number of sharp edges inside the cabin.

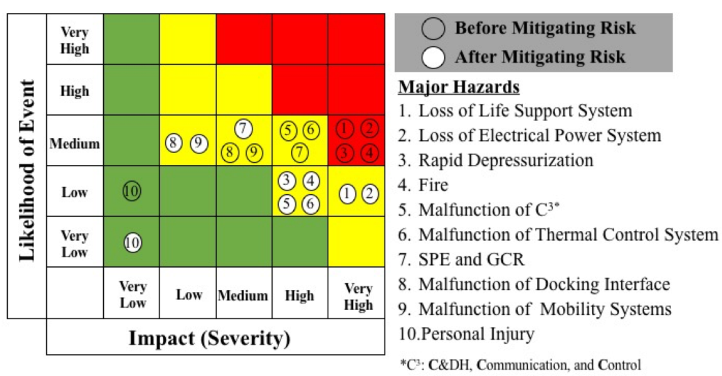
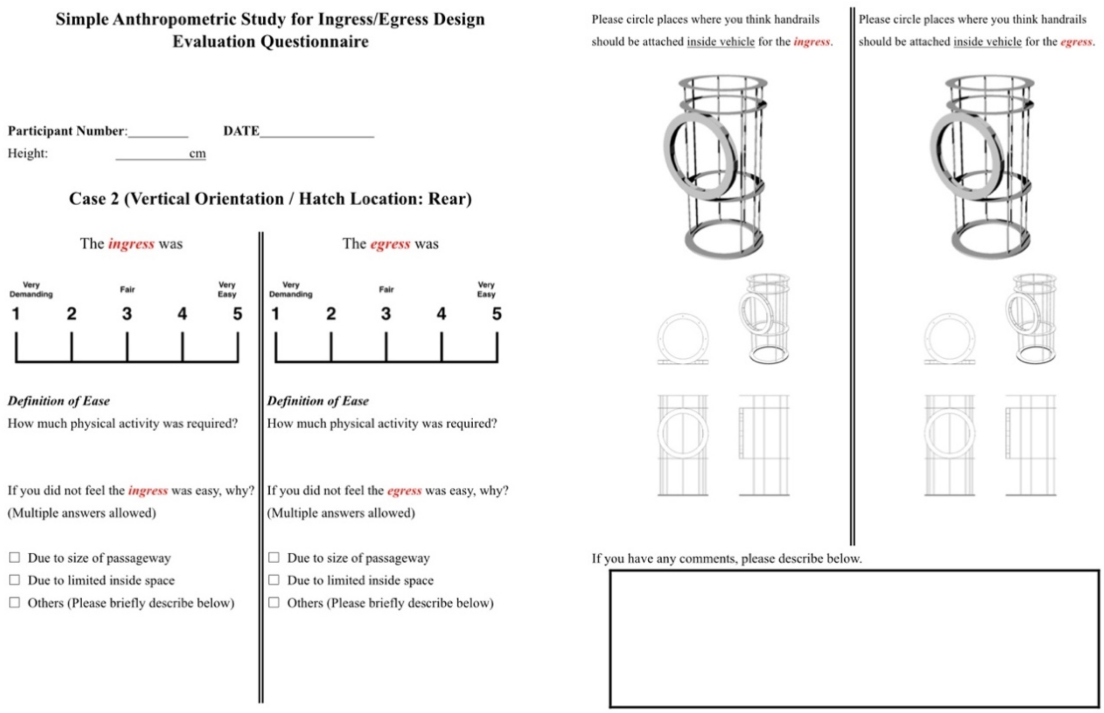


Figure A1. Risk Matrix.

B. Questionnaire (Case 2)


Simple Anthropometric Study for Ingress/Egress Design
Evaluation Questionnaire

Participant Number:________ DATE________________
Height: ___________cm

Case 2 (Vertical Orientation / Hatch Location: Rear)

The *ingress* was

Very Demanding — Fair — Very Easy
1 2 3 4 5

Definition of Ease
How much physical activity was required?

If you did not feel the *ingress* was easy, why? (Multiple answers allowed)

☐ Due to size of passageway
☐ Due to limited inside space
☐ Others (Please briefly describe below)

The *egress* was

Very Demanding — Fair — Very Easy
1 2 3 4 5

Definition of Ease
How much physical activity was required?

If you did not feel the *egress* was easy, why? (Multiple answers allowed)

☐ Due to size of passageway
☐ Due to limited inside space
☐ Others (Please briefly describe below)

Please circle places where you think handrails should be attached inside vehicle for the *ingress*.

Please circle places where you think handrails should be attached inside vehicle for the *egress*.

If you have any comments, please describe below.

C. Statistical Analysis

The ratings that subjects provided were ordinal and three measurements with different vehicle configurations were taken from the same 10 test subjects. Hence, a Friedman's test was performed using the ratings and the significant level was set to $p = 0.05$. A significant difference was shown both in the ingress ($X^2(2) = 8{,}19$, $p = 0.0166$) and in the egress ($X^2(2) = 11.4$, $p = 0.00342$). The Friedman's test does not provide a post hoc analysis to indicate where the differences lie, and therefore a Wilcoxon Signed-Rank test was performed using the ratings. Table C1 shows the results of the Wilcoxon Signed-Rank test. The results showed that there was a significant difference between case 2 and case 4, and case 4 and 6 in the ingress. As for the egress, there was a significant difference between case 2 and 6.

Table C1. Results of Wilcoxon Signed-Rank Test.

	Ingress			Egress		
	Case 2 Case 4	Case 2 Case 6	Case 4 Case 6	Case 2 Case 4	Case 2 Case 6	Case 4 Case 6
p-Value	0.00391	1.00	0.0156	1.00	0.0156	0.0781

The results of the ingress indicated that case 4 would require more physical demands than case 2 and case 6. The results regarding the egress may need more careful data interpretation. Case 4 has the higher mean rank score of the egress than case 2 by 0.05, and there was no significant difference between case 4 and 6. However, there was a significant difference between case 2 and 6. One of the possible reasons for this involves the small sample numbers. Using a small number of test subjects makes the statistical analysis less powerful and more likely to show "no significance." [12]

Table C2. Mean and Standard Deviation (SD) on Ratings.

	Case 2		Case 4		Case 6	
	Ingress	Egress	Ingress	Egress	Ingress	Egress
Mean	3.9	3.1	2.6	3.1	3.9	4.1
SD	0.57	0.74	1.1	1.1	0.88	0.74

Table C2 shows mean and Standard Deviation (SD) on the ratings. In some cases, the SDs are approximately one-third of the mean values, which indicates there was high variability. For future work, it is significant to conduct another testing with more subjects using a higher fidelity mockup, stratify them into sub-groups (ex. Short, Average, and Tall), and perform statistical analysis, which may minimize variability and allow for making a more informed decision.

Acknowledgments

The authors would like to express our great appreciation to Mr. Brand Griffin for his expertise in the field and valuable feedback on the study. Additionally, we would like to offer our special thanks to Prof. Larry Bell and Prof. Kriss Kennedy for their feedback throughout the study. We would also like to show our gratitude to Dr. Gordon Vos for his feedback on the statistical analysis. Lastly, we would like to thank Ms. Mahsa Moghimi Esfandabadi for assisting in the MMSPS visualization.

References

[1] Brand Griffin, Robert Rashford, Matthew Stephens, Samuel Gaylin, Caleb Woo, Joshua Lutter, and David Harvey, "Single-Person Spacecraft Favored for Gateway EVA," AIAA Space Forum, Orland, FL, September 17-19, 2018

[2] Brand Griffin, Robert Rashford, Joshua Lutter, Caleb Woo, Samuel Gaylin, Robert Bousquet, Mark Klappenberger, Mark Belz, David Harvey, Elin Wolf, and M. Stephens, "Single-Person Spacecraft Progress toward Flight Testing," AIAA Space Forum, Orland, FL, September 12-14, 2017

[3] Barry W. Finger, Brittany Zimmerman, Chad Bower, Brand Griffin, and Caleb Woo, "A Tailored Life Support System for the Single-Person Spacecraft," 48th International Conference on Environmental Systems, NM, Albuquerque, July 8-12, 2018

[4] Brand Griffin, Roger Lepsch, John Martin, Robert Howard, Michelle Rucker, Edgar Zapata, Carey McCleskey, Scott Howe, Natalie Mary, and Philip Nerren, "Small Habitat Commonality Ruduces Cost for Human Mars Missions," AIAA Space, 2015

[5] James Engle, Travis Moseman, Matthew Duggan, and Xavier Simon, "An Extensible and AffordableExploration Architecture Utilizing the Deep Space Gateway," AIAA Space Forum, Orland, FL, September 12-14 2017

[6] NASA Systems Engineering Handbook, NASA/SP-2007-6105, 2007, p.52

[7] International Docking System Standard (IDSS) Interface Definition Document (IDD) Revision E, October 2016, 3-5

[8] Claire C. Gordon, Cynthia L. Blackwell, Bruce Bradmiller, Joseph L. parham, Patricia Barrientos, Stephen P. Paquette, Brian D. Corner, Jeremy M. Carson, Joseph C. Venezia, Belva M. Rockwell, Micheal Mucher, and Shirley kristensen, "2012 Anthropometric Survey of U.S. Army Personal: Methods and Summary Statistics, Technical Report NATICK/TR-15/007

[9] Larry Toups, Stephen J. Hoffman, and Kevin Watts, "Mars Surface Systems Common Capabilities and Challenges for Human Missions," IEEE Aerospace Conference, Big Sky, MT, March 5-12, 2016

[10] Wiley J. Larson and Linda K. Pranke, "Human Spaceflight Mission Analysis and Design," McGraw-Hill Companies, Inc. 1999, p. 410-412

[11] NASA Docking System (NDS) Interface Definitions Document (IDD). Revision H, November 16, 2013, p.11

[12] Christopher D. Wickens, John D. Lee, Yuli Liu, Sallie E. Gordon Becker, "An Introduction to Human Factors Engineering Second Edition," PHI, 2011, p.27